ELECTRICAL ENGINEERING PRACTICE

ELECTRICAL ENGINEERING PRACTICE

A PRACTICAL TREATISE
FOR ELECTRICAL, CIVIL, AND MECHANICAL ENGINEERS

WITH
MANY TABLES AND ILLUSTRATIONS

BY

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PREFACE.

THIS, the fifth edition of Volume I of what is now generally known in the electrical world as "E.E.P." has been thoroughly revised, taking into account advances in equipment and practice, and the radical alterations in the supply situation resulting from the operations of the Central Electricity Board in Great Britain and corresponding developments in other countries.

The general plan of the book remains unaltered. Part I dealing with definitions, materials and measurements; Part II with the generation and sale of electrical energy, power-house equipment and water power, and the various factors bearing on economical operation; and Part III with transmission and control, including switchgear and the protection of machinery and circuits.

As in the previous editions, it has been the authors' aim to present information and explanations likely to be of maximum utility to engineers in practice and to students desirous of studying the methods and data of practice. Fundamental facts and principles are dealt with in detail warranted by their importance as the foundation of all practice. Numerical examples, based on practice, are given freely, and while every care has been devoted to bringing the book into line with the latest requirements, information on older methods and equipment is retained where it is likely to be useful in relation to plant still good for years of service.

The length of the book has been increased by nearly 200 pages, compared with the fourth edition, and a comprehensive index to all three volumes of the work is now provided. Apart from additional matter in every chapter, the whole of the material, including the technical and statistical tables, has been thoroughly revised. New illustrations have been added where helpful and the bibliographies appended to each chapter have been brought up to date.

The authors are indebted to the British Standards Institution for permission to refer freely to its invaluable publications, and to the

Institution of Electrical Engineers for permission to quote from the I.E.E. Regulations for the Electrical Equipment of Buildings. The excerpts given from these documents are, however, only for general information and convenient reference on individual points. The latest edition of the respective publications can always be purchased at nominal cost, and the full text should always be consulted where compliance with official requirements is concerned. The authors are also indebted to Mr. G. W. Stubbings, B.Sc., A.M.I.E.E., for valuable notes on vector diagrams, instruments, measurements and cognate matters, and for much assistance in the incorporating of new and revised information.

J. W. MEARES.
R. E. NEALE.

June, 1938.

NEW INDEX.

In reprinting this volume, the opportunity has been taken to include a new Index covering all three volumes of the work and embodying the latest additions. Certain minor corrections have also been introduced in the text, in some instances thanks to notification by readers whose courteous assistance is gratefully acknowledged by the authors.

J. W. M.
R. E. N.

April, 1944.

EXTRACT FROM PREFACE TO THIRD EDITION.

N.B.—In reprinting this Preface, those portions which are not in any way applicable to the present edition have been omitted.)

GREATLY daring, an endeavour has been made to fill the gap between the many excellent pocket-books of bare data and the highly technical works written for specialists in various branches of electrical engineering. The demand for the first two editions proves that this endeavour was successful so far as India was concerned, and no pains have been spared to make the present edition equally useful to engineers and students in this country. It is believed that the book will appeal to civil, mechanical, and electrical engineers alike ; and though the whole field covered cannot be dealt with exhaustively in a single volume, the treatment presented should give the information and guidance meeting the needs of a very wide circle of readers.

Some of the matter presented is quite elementary and, from experience with the previous editions, by no means unnecessary or unappreciated. Even the hydraulic analogy has not been allowed to rest in the place to which it has so often been consigned. One point, in particular, which it helps to bring home to the first-year student is that we use as one of our chief electrical units a *rate*, the ampere instead of the corresponding *quantity*, the coulomb. The irrigation engineer in India has coined the word 'cusec' (1 cubic foot per second) to express a *unit rate of flow* of water, which is exactly analogous to the ampere. Coulombs are seldom mentioned in practical electrical engineering, and the average engineer undoubtedly regards the coulomb in a roundabout way as an ampere-second—a multiple of a rate by a time—instead of as a definite quantity in itself. Even where ampere-hours are mentioned the electrical engineer often forgets that this larger unit of quantity would be one of the primary units in other branches of engineering, equivalent (say) to a gallon of water. Conceptions such as a yard or a gallon offer no difficulty to any intelligent being, but every one must have met with persons completely lacking in the geometrical sense, to whom an angle meant absolutely nothing. Further up the scale difficulty is experienced in explaining such compound terms as 'pounds-feet' or 'feet per second per second,' and when we arrive at the maximum demand system of charging for electrical energy, the average man frankly gives up attempting to grasp its significance. If, then, the explanations in this book appear at times too elementary, it is a lapse in the right direction.

It has been the author's aim to be severely practical; hence many terms used in electrical literature find no place in this volume, either because the reader will not need them in his daily work or, in so far as they deal with the elements of electricity and magnetism, because they are assumed to be already known to him. Where a term is used which has not so far been defined, the explanation will be found on a later page, and, in the absence of a forward reference, the index will guide the reader. Where definitions of terms are given, they are complete and for the most part accepted internationally; but it does not follow that they are self-explanatory in every case.

Practical examples have been used freely for the purpose of illustration, no amount of mere description being so effective in explaining rules and formulæ. For the same reason, diagrams of strictly utilitarian nature have been used to show plainly the connections and so forth described in the text. The examples chosen all make use of British standard frequencies, pressures, etc., and numerical results are those obtained by using the slide rule and omitting unnecessary figures. It is still often overlooked that the accuracy of any result is limited by that of the measurements and data which yield it; and that, whereas half a dozen significant figures may be accurate and necessary in scientific work, an accuracy to within even 1 per cent. is only accidental where commercial calculations or measurements with commercial instruments are concerned.

The lists of contents, tables, and illustrations will give a general idea of the scope and limitations of the book, and the index will guide the reader who uses the volume merely as a book of reference. Pains have been taken to make the index as complete as possible, and it should be noted that cross-references and index-references are to paragraphs, and that *paragraph numbers are shown at the head of the pages* and page numbers at the foot. The symbols which have been accepted internationally to represent electrical quantities are used throughout this edition; their convenience and space-saving qualities are obvious, and it is curious that they have not yet come into general use.

J. W. MEARES.

LONDON, 21*st September*, 1916.

CONTENTS.

FOR CONTENTS OF VOLUMES II. AND III. SEE P. 710.

PAGE

Preface v

Extract from Preface to Third Edition vii

List of Tables xi

PART I.

Definitions: Materials: Measurements.

CHAPTER 1.

Explanation of Electro-Technical Terms. Units and Definitions . 1

CHAPTER 2.

Materials 70

CHAPTER 3.

Instruments and Measurements 136

PART II.

Generation: Prime Movers: Sale of Electrical Energy.

CHAPTER 4.

Generators and their Accessories 212

CHAPTER 5.

Power Factor and its Improvement 264

CHAPTER 6.

Sources of Energy and Prime Movers 287

CHAPTER 7.

Power Plant Development and Data 331

CHAPTER 8.

Water-Power: General Considerations 366

CHAPTER 9.

Water-Power (*contd.*): Developments on Low and Medium Heads . 408

CONTENTS

PAGE

CHAPTER 10.

Water-Power (*contd.*): Development of High Falls 433

CHAPTER 11.

Maximum Demand, Load Factor, and Diversity Factor 458

CHAPTER 12.

Electricity Costs and Tariffs 472

PART III.

Transmission and Control.

CHAPTER 13.

Insulated Wires and Cables 499

CHAPTER 14.

Transmission of Power: Overhead and Underground 542

CHAPTER 15.

Protection of Circuits and Apparatus 601

CHAPTER 16.

Switchgear and Switchboards 651

Combined Index to Vols. I., II., III. 711

For List of Abbreviations see page 17.

LIST OF TABLES.

(References here *alone* to pages.)

NO.		PAGE
1	Absolute and Practical Units	2
1A	Calculation of Maximum Current which will Normally Flow in an Installation	8
2	Letter Symbols in Electro-technics	16
3	Abbreviations for names of Units	17
4	Conventional Signs for Electrical Diagrams	19
5	Constants for Different Wave Forms	40
6	Approximate Constants of Electrical Conductors and Resistance Materials	82
7	Approximate Constants of Insulating Materials	96
7A	Characteristics of Permalloy and other Magnetic Materials	124
7B	Characteristics of Mumetal and other Magnetic Materials	125
7C	Permanent Magnet Steels	129
8	Volt-Amperes for Full-Scale Deflection of Indicating Instruments	144
9	E.M.F. and Temperature Limits for Thermo-Couples	206
10	Electro-chemical Series of Metals	214
11	Synchronous Speed at Various Frequencies	226
12	Temperature Limits for Industrial Motors and Generators	230
12A	Overload Rating of Motors and Generators	231
13	Power Factor at Receiving End of Line with Various Loads	271
14	Addition of Loads of Different Power Factors	273
15	Thermal Efficiency of Prime Movers, with derived Fuel Consumption Data	295
16	Power Generation with and without By-Product Recovery	301
17	Average Boiler Data	302
18	Effect of Vacuum on Steam Turbine Efficiency	314
19	Data for Calculating the Output of Internal Combustion Engines	322
20	Horse-Power, Fuel Consumption and Thermal Efficiency of Internal Combustion Engines	324
21	Cost of Combined Sets (Steam)	340
22, 22A	Fuel Consumption of Generating Stations in Great Britain	343, 344
23	Approximate Limits of Efficiency in Steam-Driven Generating Stations	345
24	Approximate Distribution of Losses in an Electrical System and Relative Value of Efficiency Improvements	351
25	Composition of Total Costs of Electricity Supply	352
26	Analysis of Working Costs and Capital Expenditure in British Central Stations	353
27	Approximate Capital Costs of Power Plant Components	355
28	Approximate Pre-War Capital Costs of Large Gas and Steam Plants	356
29	Generating Plant Installed and Capital Expenditure for Authorised Public Supply in Great Britain	357
29A	Number and Output of Central Stations in Great Britain	361
29B	Sales of Electricity per Head of Population per Annum in Great Britain	362

LIST OF TABLES

NO.		PAGE
29C	Distribution of and Revenue from Electricity Sold for Various Purposes in Great Britain	362
30	Constants of Water for Hydro-electric Work	368
31	Multipliers for Mean Velocity of Water in Channels	384
32	Grunsky's Coefficients	385
33	Values of *m* in Bazin's Formula	392
34	Values of *n* in Manning's Formula	393
35	Approximate Capital Cost of some Indian Hydro-Electric Developments	403
36	Values of *m* for Flow in Pipes	446
37	Illustrating Conditions of Supply	467
38	Works Costs per Unit (kWh) in Great Britain	476
38A	Approximate Analysis of Costs per Unit Sold	477
39	Old and New British Standard Sizes for Insulated Annealed Copper Conductors	501
40	Dimensions, Weight, and Resistance of Solid and Stranded Circular Copper Conductors	503
40A-H	V.I.R. Cables and Paper Cables (I.E.E. Tables)	504-514
40J	Bare Copper Conductors: Current Ratings (I.E.E.)	515
40K	Insulation Resistance of Cables (I.E.E.)	516
41-41C	Flexible Cables and Cords (I.E.E. Tables)	522-525
41D	Size of Conductor, on Basis of Voltage Drop	526
42	Voltage Components and Power in Single-Phase Overhead Line	548
43	Voltage Components and Power in 3-Phase Overhead Line	551
44	Constants of Hard-drawn Copper Wire	556
45	Constants of Steel Conductors	559
46	Electrostatic Capacity of 3-core, Paper-insulated Lead-covered Cables	561
47	Voltage Components, Current and Power in 3-Phase Overhead Line with Transformers	564
47A	Minimum Elongation, Breaking Load and Elasticity of Solid Conductors of Copper and Aluminium	577
48	Velocity and Force of Wind	579
49	Constants of Aluminium, Cadmium-Copper, Bronze, and Steel Conductors	591
50	Cost of 11 000 V Overhead Lines, on Wooden Poles, in Bedford Rural Demonstration Area	591
51	Fusing Current of Wires	610
51A	Approximate Current Rating of Fuse-Links	611
52	B.S. Class A and B Clearances for Indoor Type Circuit-Breakers	675
52A	B.S. Clearance Distances for Outdoor Types of Circuit-Breakers	676

ELECTRICAL ENGINEERING PRACTICE

PART I.—DEFINITIONS: MATERIALS: MEASUREMENTS.

CHAPTER 1.

EXPLANATION OF ELECTRO-TECHNICAL TERMS.

UNITS AND DEFINITIONS.

(NOTE.—*A list of the Symbols and Abbreviations used throughout this book will be found in* §§ 6 *and* 7.)

1. **Units.**—As in most other branches of science, there are two systems of units for the measurement of electrical quantities, *viz. absolute units* and *practical units.* Absolute units are physical constants which are easily defined, but the measurement and actual reproduction of these units are difficult, and the units themselves are not of convenient magnitude for practical purposes. To overcome this objection, practical units have been adopted which are convenient multiples or sub-multiples of the corresponding absolute units. The accurate measurement and reproduction of practical units on this basis alone offer the same difficulties as in the case of the absolute units themselves, but special apparatus is installed in the various standardisation laboratories of the world to make possible comparisons between absolute standards and practical standards, the latter being constructed or established by international agreement. The instructions for materialising practical units are subject to periodical revision as the technology of precision measurements is improved.

2. **Absolute Units.**—Though absolute units are seldom employed in practical work (§ 1), it is desirable that the practical engineer should be familiar with the definitions and magnitudes of these units. Short definitions of the absolute units and values of the practical units in terms of the absolute units are given in Table 1.

TABLE 1.—*Absolute and Practical Units.*

Quantity.	Definition of Absolute Unit.	Practical Unit.	
		Name.	In Terms of the Absolute Unit.
Force.	*Unit Force* (1 *dyne*), acting on a mass * of 1 gramme for 1 second, imparts to it a velocity of 1 cm. per sec.	Gramme-weight	= 981 dynes.
	In foot-pound-second units, the unit of force is the *poundal* which, acting on a mass * of 1 pound for 1 second, imparts to it a velocity of 1 ft. per sec.	Pound-weight	= 32·2 poundals
Work (energy).	*C.G.S. Unit Work* (1 *erg*) is done by a force of 1 dyne moving its point of application through a distance of 1 cm.	Foot-poundal Foot-pound Gramme-centimetre Joule Kilowatt-hour	= 421 390 ergs. = 13 568 760 ergs. = 981 ergs. = 10^7 ergs. = $3{\cdot}6 \times 10^{13}$ ergs.
Power.	*C.G.S. Unit Power* is that power which is capable of performing 1 erg per sec.	Watt	= 10^7 ergs per sec.
Unit pole or charge.	*Unit Magnetic Pole or Electrical Charge*, when distant 1 cm. in air from a like and equal pole or charge, repels (and is repelled) with a force of 1 dyne.	—	—
Magnetic flux-density.	The magnetic flux density B is a vector which represents, in magnitude and in direction, the state of total polarisation due to a magnetic field.	Gauss †	= 1 line per sq. cm. = flux density of field of unit strength.
Magnetic flux.	The flux of magnetic induction Φ passing through a surface S is equal to the surface integral of the induction B: $\Phi = \int B_n ds$, B_n being the normal component of B.	Maxwell	Pramaxwell or Weber (10^8 Maxwell) (still under consideration).

* The distinction between *mass* and *weight* is important. The mass, *m*, of a weight, *W*, is given by: $m = W/g$, where $g = 32{\cdot}2$ ft. per sec. per sec. = 981 cm. per sec. per sec.

† This definition of Gauss has been agreed to by the I.E.C. Hitherto it has been used by some writers for the C.G.S. unit of magnetising force H, and by others for the C.G.S. unit of magnetic flux density, B, and again by others for both B and H indiscriminately.

TABLE 1 (*continued*).

Quantity.	Definition of Absolute Unit.	Practical Unit. Name.	Practical Unit. In Terms of the Absolute Unit.
Magnetic field strength.	The magnitude H (magnetic field strength, or, briefly, magnetic field) is the quotient of the mechanical force F exerted by the magnetic field upon a quantity of magnetism m divided by that quantity. $H = \frac{F}{m}$.	Oersted	
Magneto-motive force.	The magnetomotive force $\mathfrak{F}$ is the line integral of the magnetic field strength H along a line $\mathfrak{F} = \int H_t dl$, H_t being the tangential component of H.	Gilbert	
Reluctance.	The reluctance of a magnetic circuit is the ratio of the magnetomotive force acting in the circuit to the resulting magnetic flux. (Definition B.S. Glossary).		
Quantity of electricity.	*C.G.S. Electrostatic Unit Quantity* when distant 1 cm. in air from an equal quantity of like polarity, repels it with a force of 1 dyne.	Coulomb (1 ampere-second)	$= 3 \times 10^9$ C.G.S. electrostatic units.
	C.G.S. Electromagnetic Unit Quantity is conveyed by 1 C.G.S. electromagnetic unit of current flowing for 1 sec.	Coulomb (1 ampere-second)	$= \frac{1}{10} \times$ C.G.S. electromagnetic unit.
Current.	*C.G.S. Electrostatic Unit Current* is the current corresponding to the flow of 1 C.G.S. electrostatic unit of quantity in 1 sec.	Ampere	$= 3 \times 10^9$ C.G.S. electrostatic units.
	C.G.S. Electromagnetic Unit Current in a wire 1 cm. long bent into an arc of 1 cm. radius exerts a force of 1 dyne on unit pole placed at the centre.	Ampere	$= \frac{1}{10} \times$ C.G.S. electromagnetic unit.
Potential.	A point is at *C.G.S. Electrostatic Unit Potential* if the work done on or by positive unit charge in moving from infinity to the point is 1 erg.	Volt	$= \frac{1}{300} \times$ C.G.S. electrostatic unit.

TABLE 1 (*continued*).

Quantity.	Definition of Absolute Unit.	Practical Unit.	
		Name.	In Terms of the Absolute Unit.
Potential.	There is *C.G.S. Electromagnetic Unit Difference of Potential* between two points if the work done in transferring C.G.S. electromagnetic unit quantity from one point to the other is 1 erg.	Volt	$= 10^8 \times$ C.G.S. electromagnetic units.
Resistance.	*C.G.S. Electromagnetic Unit Resistance* is the resistance of a conductor in which C.G.S. electromagnetic unit current is produced by C.G.S. electromagnetic unit potential difference between the ends of the conductor.	Ohm	$= 10^9 \times$ C.G.S. electromagnetic unit. $= [1/(9 \times 10^{11})] \times$ C.G.S. electrostatic unit.
Capacity.	*C.G.S. Electrostatic (Electromagnetic) Unit Capacity* is brought to a potential difference of 1 C.G.S. electrostatic (electromagnetic) unit by the application of C.G.S. electrostatic (electromagnetic) unit quantity of electricity.	Microfarad * (10^{-6} farad)	$= 9 \times 10^5$ C.G.S. electrostatic units. $= 10^{-15} \times$ C.G.S. electromagnetic unit.
Self (or mutual) inductance.	The coefficient of self-induction of a circuit is the number of lines of force linked with the circuit when the latter carries C.G.S. electromagnetic unit current. Two circuits have C.G.S. electromagnetic unit coefficient of mutual inductance when unit current passed through one circuit produces in the other a quantity of current = 1/R C.G.S. electromagnetic units of quantity (R being the resistance of the second coil in electromagnetic units).	Henry	$= 10^9 \times$ C.G.S. electromagnetic unit.

It will be seen that there are two systems of absolute units, *viz.* the C.G.S. centimetre-gramme-second) electrostatic units and the C.G.S. electromagnetic units. The relations between the units in each of these systems are the same, but the actual dimensions of the electrostatic and electromagnetic units are not the

* 1 electrostatic unit = the capacity of a sphere of 1 cm. radius (and hence is commonly called a 'centimetre') = 1·11 micro-microfarads, and is a convenient unit for very small capacities such as are used in wireless telegraphy.

same. This is because specific inductive capacity (§ 46) is taken as a numeral in the electrostatic system of units, whilst permeability (§ 43) is taken as a numeral in the electromagnetic system of units. There is a definite ratio between corresponding electrostatic and electromagnetic units, 1 C.G.S. electrostatic unit of potential being equal to 3×10^{10} C.G.S. electromagnetic units. The factor 3×10^{10} is the velocity of light, in cm. per sec. The electromagnetic unit of quantity is larger than the electrostatic unit in the ratio $3 \times 10^{10} : 1$, hence the electromagnetic unit of capacity (*see* definition in Table 1) is $(3 \times 10^{10})^2$ or 9×10^{20} times as great as the electrostatic unit.

The C.G.S. electromagnetic absolute units are the ones to which the units of the practical electrical engineer are generally referred. Combined research by the American Bureau of Standards,* the National Physical Laboratory, and the French and German standardising bodies give the value of the international ohm as 1· 000 463 absolute ohms and of the international ampere as 0· 999 96 absolute ampere.

3. International Definitions.—The international definitions of the practical electrical units, *viz.* resistance, R, the ohm; electromotive force or pressure, E, the volt; and current, I, the ampere, were adopted at a conference held in London in 1908, and were legalised by Order in Council in 1910. The explanatory notes that follow will make clearer the definitions of these quantities and their derivatives. The preliminary explanations are by no means exhaustive, and most of the matters dealt with will be treated more fully in subsequent chapters, as occasion arises. The actual definitions do not greatly concern the average engineer, but they may be set forth for completeness (*see also* § 2).

The International Ohm (Ω) is the resistance offered to an unvarying electric current by a column of mercury at the temperature of melting ice 14· 452 1 grammes in mass of a constant cross-sectional area and of a length of 106· 300 centimetres.

Note.—The use of Ω as the symbol for megohm is no longer permissible; *see* footnote to Table 3, § 6.

The International Ampere (A) is the unvarying electric current which when passed through a solution of nitrate of silver in water deposits silver at the rate of 0· 001 118 00 of a gramme per second.

The International Volt (V) is the electrical pressure which when steadily applied to a conductor whose resistance is one International Ohm will produce a current of one International Ampere.

These definitions are further expanded in the Order in Council, where the particular standards and methods of determination are set forth.† To these may be added also the accepted definition of the unit of power, the watt (W).

The Watt is the practical unit of power. It is the amount of energy expended per second by an unvarying current of one ampere under a voltage of one volt.

* *The Law Relating to Electricity*, by C. M. Knowles, part i, p. 417.
† Annual Report of the Director, 1932.

With alternating current, the product of the instantaneous value of the amperes and the instantaneous value of the volts gives the instantaneous value of the power in watts and the mean value, over a whole period, is the power in watts. A watt is equal to 10^7 ergs per second, or one joule per second.

Even at the present day misconception exists among some engineers with regard to this definition, owing to the use of the phrase 'per second' in it. The omission of these two words would make the whole meaningless, since power is *not* energy, but *a rate of expenditure* of energy, *i.e.* the amount of energy expended in unit time, *viz.* the second.

4. **Definitions from the Wiring Rules of the Institution of Electrical Engineers.**—In the course of this work, especially in the chapters on installing wiring in buildings, reference will frequently be made to the I.E.E. Regulations for the Electrical Equipment of Buildings (formerly I.E.E. Wiring Rules), and the authors' thanks are due to the Institution for permission to quote from them. The following statements concerning the scope of the Rules are included in the introduction to the tenth edition* :—

These Regulations, which enumerate the main requirements and precautions for ensuring satisfactory results, including safety from fire and shock, relate to the distribution of electrical energy in and about all types of dwelling houses, business premises, public buildings, and factories, whether the electric supply is derived from an external source or from private generating plant. They also relate to the generation and storage of electrical energy for private purposes. . . . The Regulations are not intended either to take the place of a detailed specification or to instruct untrained persons, and they are supplementary to the following statutory Regulations wherever these are applicable:—

The Regulations made by the Electricity Commissioners.

The Home Office 'Regulations for the Generation, Transformation, Distribution, and Use of Electrical Energy in Premises under the Factory and Workshop Acts, 1901 to 1929,' and the 'Cinematograph Regulations made under the Cinematograph Act, 1909.'

* Owing to the much increased length of the I.E.E. Regulations, and the impossibility of keeping successive editions of the three volumes of this book uniformly in step with new editions of the Regulations, quotations from the latter in the fifth edition of our Vol. 1 are greatly curtailed, compared with the fourth edition. The same policy will be adopted in the fifth edition of Vol. 2, and, in due course, in Vol. 3, the fourth edition of which contains excerpts from the ninth edition of the I.E.E. Regulations. The latest edition of the Regulations can always be purchased at nominal cost (usually 1s. paper, 1s. 6d. cloth) from the I.E.E. or Messrs. E. and F. N. Spon, Ltd. (London), and the Regulations themselves should always be consulted when working to comply with them. Such excerpts as are given in this volume are intended only for general information and convenient reference on individual points.

'General Regulations as to the Installation and Use of Electricity under The Coal Mines Act, 1911,' issued by the Mines Department.

The regulations and requirements of (*a*) the respective licensing authorities for theatres and other places of public resort, and (*b*) other local government authorities having statutory powers in respect of the installations in certain specified buildings. (Application for information concerning such regulations and requirements should be made to the authorities concerned.)

Various methods of carrying out the electrical equipment of buildings are provided for, and in order to guard against the risk of fire and shock the method selected should be suitable for the voltage, the atmospheric conditions, the size of the installation, and the type of building.

Only existing proved materials, appliances, and methods are considered. It is not intended, however, to discourage invention or to exclude other materials, appliances, and methods, which may be developed in the future.

Notice of the intention to install electrical equipment should in all cases be given by the consumer to the fire office with whom the premises are insured and, where the supply is obtained from an external source, also to the supply authority concerned.

Where the fire risks of the premises are of an unusual character the special requirements of the fire office insuring the risk should be ascertained and complied with.

The I.E.E. Regulations are intended to be applicable primarily to installations in which the voltage between conductors does not normally exceed 650 V. Some requirements for high-voltage circuits and apparatus will be found in Regulations 714, 715 (§ 633), and 1341 (§ 405(A)), and also in Section 8 (§ 590(A)). The general requirements imposed by Regulations 1-4 are:—

1. *Workmanship.*—Good workmanship is an essential requirement for compliance with these Regulations.

2. *Work covered by Contract.*—Where a contract requires any work, material or apparatus to be in accordance with these Regulations, this requirement shall not apply to any work, material or apparatus that is outside the contract or an extension thereof.

3. *Addition to an Installation.*—An addition, temporary or permanent, shall not be made to the authorised load of an existing installation until it has been definitely ascertained that the current-carrying capacity and the condition of the existing accessories, conductors, switchgear, etc., affected are adequate for the increased load.

4. *Provision for Maximum Load.*—(A) All conductors, switchgear, and accessories, shall be of such size as to be capable of carrying, without their respective ratings being exceeded, the maximum current which can normally flow through them.

(B) A diversity factor may, subject to the provisions of clauses (C), (D), (E), and (F) below, be applied in calculating the cross-sectional area of the conductors of all circuits.

Note.—It is impossible to specify in these Regulations the value of the diversity factor for every type of installation, but Table 1 may be taken as a guide.*

* Table 1 of the I.E.E. rules is here reproduced as our Table 1A; it is a valuable addition to the rules.

TABLE 1A.—*Calculation of the Maximum Current which will normally flow in an Installation [for use in computing the Sizes of Cables (other than those of final Sub-circuits), Switchgear, etc.]; being Table 1 of the I.E.E. Regulations, 10th Edition.*

NOTE.—The values in this Table refer to percentage of connected load, or, where followed by the letters 'F.L.,' to the percentage of full-load current of a heating appliance, motor, or other current-using device, or a socket-outlet. In calculating the maximum current, appliances and socket-outlets shall be considered in the order of their current ratings, the largest first. For the purposes of this Table an 'intermittent' water-heater is deemed to be a water-heater consuming more than 3000 watts which, by reason of the relative rate of consumption of electrical energy with respect to its water capacity, is obviously intended for intermittent use.

Type of Installation 1.	Lighting 2.	Fixed heating and power appliances other than motors, cookers, and water-heaters 3.	General-purpose socket-outlets 4.	Fixed cooking appliances 5.	Motors, other than lift motors (also see Regulation 706) 6.
Individual Domestic Installations, including individual Flats of a Block	66%	100% F.L. up to 10 amperes +50% of any load in excess of 10 amperes	100% F.L. of largest outlet +40% F.L. of other outlets	100% F.L. up to 10 amperes +50% of any load in excess of 10 amperes	—
Blocks of Residential Flats	66%	100% F.L. of largest appliance +50% F.L. of 2nd largest appliance + 33% F.L. of 3rd largest appliance + 25% F.L. of 4th largest appliance +20% F.L.of remaining appliances	100% F.L. of largest outlet +40% F.L. of other outlets	100% F.L. of largest appliance +50% F.L. of 2nd largest appliance +33% F.L. of 3rd largest appliance +25% F.L. of 4th largest appliance +20% F.L. of remaining appliances	—
Hotels, Boarding Houses, Lodging Houses, etc.	75%	100% F.L. of largest appliance +80% F.L. of 2nd largest appliance +60% F.L. of remaining appliances	100% F.L. of largest outlet +75% F.L. of outlets in main rooms (dining-rooms, etc.) +40% F.L. of remaining outlets	100% F.L. of largest appliance +80% F.L.of 2nd largest appliance +60% F.L.of remaining appliances	100% F.L. of largest motor +50% F.L. of remaining motors
Shops, Stores, Offices, and Business Premises, other than Factories	90%	100% F.L. of largest appliance +75% F.L. of remaining appliances	100% F.L. of largest outlet +75% F.L. of other outlets	100% F.L. of largest appliance +80% F.L. of 2nd largest appliance +60% F.L.of remaining appliances	100% F.L. of largest motor +80% F.L. of 2nd largest motor +60% F.L. of remaining motors
Lifts	100% F.L. of largest lift motor + 75% F.L. of 2nd largest lift motor + 50% F.L. of remaining lift motors				
Water-Heaters	If of constant type :— F.L. in all cases. If of 'intermittent' type :—(i) Residential premises (including flats, hotels, etc.): 100% F.L. of largest and 2nd largest water-heaters + 25% F.L. of remaining water-heaters. (ii) Other premises: To be assessed by competent authority.				

(C) The maximum current referred to in clause (A) above shall for each socket-outlet of 2 amperes rating be deemed to be not less than ½ ampere, and for socket-outlets rated at 5 amperes and 15 amperes be deemed to be not less than 5 and 15 amperes respectively.

(D) Where in a final sub-circuit serving 5-ampere or 15-ampere socket-outlets diversity appears to be justified, additional points may be connected, provided that the total connected load of all the points does not exceed 140 °/o of the current rating of the cable.

(E) For lighting points, the maximum current referred to in clause (A) above shall be deemed to be not less than provided for in Table 1.

(F) For circuits supplying electric motors, the maximum current in any individual motor shall be deemed to be its full-load current.

The following definitions indicate the sense in which the expressions defined are used in the I.E.E. Regulations.

Accessory.—Any device, other than a lighting fitting, associated with the wiring and current-using appliances of an installation; for example, a switch, a cut-out, a plug, a socket-outlet, a lamp-holder, or a ceiling rose.

Adaptor, Socket-outlet.—An accessory for insertion into a socket-outlet and containing metal contacts to which may be fitted one or more plugs for the purpose of connecting to the supply portable lighting fittings or other current-using appliances.

Bonding Conductor.—A wire, cable, clamp, or other conductor, used to connect together the uninsulated current-carrying parts of an installation, e.g. the 'external' conductor of earthed concentric wiring.

Bunched.—Cables are said to be 'bunched' when two or more are contained within a single conduit, duct, or groove, or, if not enclosed, are not separated from each other.

Cable.—A length of insulated single conductor (solid or stranded), or of two or more such conductors, each provided with its own insulation, which are laid up together. The insulated conductor or conductors may or may not be provided with an overall mechanical protective covering.

Cable, Armoured.—A cable provided with a wrapping of metal (usually tapes or wires), primarily for the purpose of mechanical protection.

Cable, Flexible.—A cable consisting of one or more cores, each formed of a group of wires, the diameters of the wires and the insulating material being such as to afford flexibility.

Cable, Lead-covered.—A cable provided with a lead sheath for the purpose of excluding moisture from the conductors and insulation thereof, such sheath consisting either entirely of commercially pure lead or, alternatively, of commercially pure lead to which a small percentage of rarer metals has been added for hardening purposes.

Circuit.—An arrangement of conductors for the purpose of carrying current.

Circuit, Final Sub-.—An outgoing circuit connected to one way on a distribution fuse-board and intended to supply electrical energy at one or more points to current-using appliances, without the intervention of a further distribution fuse-board. It includes all branches and extensions which are derived from that particular way on the board.

Circuit Breaker.—A switch designed for opening automatically a circuit under abnormal conditions such as those of overload.

Conductor (*of a Core or Cable*).—The conducting portion, consisting of a single wire or of a group of wires.

Conductor, Bare.—A conductor which is not covered with insulating material.

Conductor, Uninsulated.—A conductor with no provision made for its insulation from earth.

Consumer's Terminals.—The ends of the electric conductors situate upon any consumer's premises and belonging to him, at which the supply of energy is delivered from the service lines.

Core (*of a Cable*).—The conductor with its insulation but not including any mechanical protective covering.

Cut-out (*Fusible Cut-out*).—A device for protecting apparatus from damage due to overload, by opening a circuit through the fusion of a specially-designed part thereof. It comprises all the parts which, together with their mounting, base, and containing case or cover (if any), form the complete device.

Damp Situation.—A situation in which moisture is either permanently present, or intermittently present to such an extent as to be likely to impair the effectiveness of an installation which otherwise conforms to the requirements for ordinary situations.

Distribution Fuse-board.—An assemblage of cut-outs arranged for the distribution of electrical energy to final sub-circuits or to other distribution fuse-boards.

NOTE.—Overload protective devices may be substituted for cut-outs in a distribution fuse-board.

Earth.—A connection to the general mass of earth by means of an earth electrode. An object is said to be 'earthed' when it is electrically connected to an earth electrode; and a conductor is said to be 'solidly earthed' when it is electrically connected to an earth electrode without a fuse-link, switch, circuit breaker, resister, or impedance, in the earth connection.

Earth Continuity Conductor.—The wire, cable, clamp, or other conductor, connecting to the earthing lead or to each other those parts of an installation which have to be earthed. It may be in whole or in part the metal conduit or the metal sheath of the cables, or the special continuity wire (see Table 19) of a cable or cord incorporating such a wire.

Earth Electrode.—A metal plate, water pipe, or other conductor, which is electrically connected to the general mass of earth in such a manner as to comply with these Regulations.

Earthed Concentric Wiring.—A system of wiring in which one of the conductors (known as the 'external' conductor) is effectually earthed and completely surrounds the other (known as the 'internal' conductor) throughout its length.

Earthing Lead.—The final conductor by which the connection to the earth electrode is made.

Electric Sign.—A word, letter, model, border, outline, box, device, representation, announcement, or direction, including the framework and backing, and the means of attachment to the building or supporting structure, illuminated by means of filament lamps and/or luminous discharge tubes, the means of illumination forming an integral part thereof.

Electrode Boiler.—A boiler in which water is designedly boiled by the passage through it of electric current between immersed electrodes.

Electrode Water-heater.—A water-heater in which water is designedly heated by the passage through it of electric current between immersed electrodes.

Final Sub-circuit. (*See* Circuit, Final Sub-).

Fire-resistance.—That property by virtue of which an element of a structure as a whole functions satisfactorily, whilst subjected to a prescribed heat influence and load, for a period as specified in British Standard Specification No. 476.

Fitting, Lighting.—A device for supporting or containing a lamp or lamps, together with any holder, shade, or reflector; for example, a bracket, a pendant with ceiling rose, an electrolier, or a portable standard.

Fittings Wire.—An insulated wire, generally of small conductor and overall diameter, only suitable for the internal wiring of fittings having small bore or aperture and when not subject to interference or mechanical damage.

Flame-proof.—A flame-proof enclosure for electrical apparatus is one which will withstand, without injury, any explosion that may occur in practice within it under the conditions of operation within the rating (and recognised overloads, if any, associated therewith) of the apparatus enclosed by it, and will prevent the transmission of flame such as will ignite any inflammable mixture which may be present in the surrounding atmosphere.

Flexible Cable. (*See* Cable, Flexible.)

Flexible Cord.—A flexible cable in which the cross-sectional area of each conductor does not exceed 0·007 sq. in.

Fuse-link.—That part of a cut-out which is designed to melt and thus open the circuit. It comprises the fusible metal, with attached contacts (if any).

Fuse-switch.—A switch the moving part of which carries one or more fuse-links (as distinct from a *switch-fuse*, which is a cut-out embodying a removable fuse-link carrier suitable for use as a switch).

Incombustible (Non-ignitable).—An incombustible material is one which neither burns nor gives off inflammable vapours in sufficient quantity to ignite at a pilot flame when heated in the manner specified in British Standard Specification No. 476.

Inflammable.—An inflammable material is one which is capable of being easily ignited.

Insulation (of a Cable).—That part of a cable which is relied upon to insulate the conductor.

Insulation, Double.—A conductor is said to have 'double insulation' when insulating material intervenes not only between the conductor and its surrounding envelope (if a cable) or immediate support (if bare), but also between the envelope or the support, as the case may be, and earth.

Lampholder Plug.—An accessory for insertion into a lampholder for the purpose of connecting to the supply a current-using appliance.

NOTE.—This device was termed a 'Lampholder Adaptor' in the Ninth Edition of these Regulations.

Lead-covered. (*See* Cable, Lead Covered).

Lighting Fitting. (*See* Fitting, Lighting).

Live.—An object is said to be 'live' when:—

(*a*) a difference of potential exists between it and earth; or

(*b*) it is connected to the 'middle wire,' 'common return,' or 'neutral,' of a supply system in which such 'middle wire,' 'common return,' or 'neutral,' is not permanently and solidly earthed.

NOTE.—See Note at the head of Section 9 for exception applying to valve amplifying and radio apparatus connected to public or private supply mains.

Luminous Discharge Tube.—*See* Regulation 802 (§ 590(A)).

Non-Inflammable.—A non-inflammable material is one which, when tested in the manner described in British Standard Specification No. 476, does not glow or carry flame and is neither charred nor scorched in excess of the amount permitted therein.

Plug. (*See* Socket-outlet and Plug).

Plug, Lampholder. (*See* Lampholder Plug.)

Point (in Wiring).—Any termination of the fixed wiring intended for the attachment of a lighting fitting or of a device for connecting to the supply a current-using appliance.

Resistance Area (for an Earth Electrode only).—The area of ground (round an earth electrode) within which a measurable voltage gradient exists when the electrode is being tested.

NOTE.—Beyond the resistance area the voltage gradient is too small to be measured. When measuring earth resistance it is important to ensure that the resistance areas of the electrodes do not overlap. (*See* Regulation 1110.)

Resistor.—A piece of apparatus used primarily because it possesses the property of electrical resistance.

Self-Extinguishing.—A self-extinguishing material is one in which the flame persists for a less period than 5 seconds after removal of the material from the source of heat in the manner described in Appendix IX of British Standard Specification No. 488—1933.

Socket-outlet Adaptor. (*See* Adaptor, Socket-outlet.)

Socket-outlet and Plug.—A device consisting of two portions for easily connecting to the supply portable lighting fittings and other current-using appliances. The plug portion carries two or more metal contacts which connect with corresponding metal contacts in the socket portion. The latter is so designed as to be suitable for fixing to a wall, floor, ceiling, or other flat surface.

Sub-circuit, Final. (*See* Circuit, Final Sub-.)

Switch.—A device for closing or opening an electrical circuit. (*Also see* Circuit Breaker.)

Switch, Single-pole.—A switch suitable for closing or opening a circuit on one pole or phase only.

Switch, Double-pole.—A switch suitable for closing or opening a circuit on two poles or phases simultaneously.

Switch Multi-pole.—A switch suitable for closing or opening a circuit on two or more poles or phases simultaneously.

Switch Triple-pole.—A switch suitable for closing or opening a circuit on three poles or phases simultaneously.

Switch Four-pole.—A switch suitable for closing or opening a circuit on four poles or phases simultaneously.

Switch, Linked.—A switch the blades of which are so linked together mechanically as to operate simultaneously or in definite sequence.

Switchboard.—An assemblage of switchgear with or without instruments. (The term does not, however, apply to a group of local switches on a final sub-circuit where each switch has its own insulating base.)

NOTE.—In the Home Office Regulations for Factories and Workshops the term 'Switchboard' includes 'Distribution Board.'

Switchboard, Open-type.—A switchboard in which the current-carrying parts of the switchgear are not provided with protecting covers.

Switchgear.—Apparatus for controlling the distribution of electrical energy, or for controlling or protecting electrical circuits, machines, and current-using appliances.

Tough Rubber.—A tough-rubber compound used as a sheathing or protection of a cable, or as both, and complying with the requirements of Regulation 1308 (C).

Voltage, Extra-low, Low, Medium, High.—Potential differences, between conductors, of the following values at the point at which the supply is delivered, subject to such variations as are permissible under the Regulations issued by the Electricity Commissioners:—

Extra-low.—Normally not exceeding 30 volts alternating current or 115 volts direct current.

Low.—Normally exceeding 30 volts alternating current or 115 volts direct current, but not exceeding 250 volts in either case.

Medium.—Normally exceeding 250 volts, but not exceeding 650 volts.

High.—Normally exceeding 650 volts.

Weatherproof.—Accessories, lighting fittings, and current-using appliances, are said to be of the 'weatherproof' type if they are so constructed that, when installed, rain, snow, and splashings are excluded.

Many of the foregoing definitions will be expanded and further explained in the following chapters.

5. Definitions in Regulations and Standard Reports.—In official regulations, such as those relating to the use of electricity in factories, workshops, and mines (§§ 10, 48 *et seq.*, Vol. 3), and in standardisation reports such as those issued by the British Standards Institution, formerly the B.E.S.A. or British Engineering Standards Association (*ibid.*), special definitions are given of the meanings to be attached to certain terms for the purposes of the regulations, etc. Some of these definitions differ from the meanings commonly attached to the terms in question, and it is important that the official interpretations should be studied carefully.

Owing to their paramount importance to the industry, and the frequent references to them in this work (especially in Vols. 2 and 3), the definitions in *Electricity Supply Regulations, 1934,** are here set out in full. It should be mentioned that these Regulations superseded those 'prior Regulations' quoted in Vol. 2 (4th ed.) and Vol. 3, as from January, 1934, for new works, and after January 1, 1935, for existing works, *except those relating to Overhead Lines* (El. C. 53), which remain in force.

'*Apparatus*' means electrical apparatus and includes all machines, apparatus and fittings in which conductors are used or of which they form a part.

'*Authorized person*' means a person employed, appointed or selected by the Undertakers or by a consumer or jointly in cases where any electric lines or apparatus are in the joint charge of the Undertakers and another body, company or person, to carry out duties incidental to the generation, transformation, distribution or use of energy, such person being competent for the purposes of the Regulation in which the term is used.

* For reference to 1937 code see § 469.

'*Circuit*' means an electrical circuit forming a system or branch of a system.

'*Conductor*' means an electrical conductor arranged to be electrically connected to a system.

'*Connected with earth*' means connected with the general mass of earth in such manner as will ensure at all times an immediate and safe discharge of energy.

'*Consumer*' means any body or person supplied or entitled to be supplied with energy by the Undertakers.

'*Consumers' installation*' means the consumers wiring together with any apparatus upon the premises connected or intended to be connected thereto.

'*Consumers' wiring*' means the electric lines situate upon the consumers' side of the supply terminals.

'*Daily penalty*' means a penalty for each day on which any offence is continued after conviction therefor.

'*Dead*' means at or about earth potential and disconnected from any live system.

'*Distributing main*' means the portion of any main which is used or intended to be used for the purpose of giving origin to service lines for the purposes of general supply.

'*Electric line*' means a wire or wires, conductor or other means used for the purpose of conveying, transmitting or distributing electricity with any casing, coating, covering, tube, pipe or insulator enclosing, surrounding or supporting the same, or any part thereof, or any apparatus connected therewith for the purpose of conveying, transmitting or distributing electricity or electric currents.

'*Electricity*' means electricity, electric current or any like agency.

'*Energy*' means electrical energy, and for the purposes of applying the provisions of the Electricity (Supply) Acts to any Act or Order relating to the undertaking of the Undertakers, electrical energy shall be deemed to be an agency within the meaning of electricity as defined in these Regulations.

'*General supply*' means the general supply of energy to ordinary consumers and includes, unless otherwise specially agreed with the local authority, the general supply of energy to the public lamps where the local authority are not themselves the Undertakers, but shall not include the supply of energy to any one or more particular consumers under special agreement.

'*Generating station*' means any station for generating electricity, including any buildings and plant used for the purpose and the site thereof, and a site intended to be used for a generating station, but does not include any station for transforming, converting or distributing electricity.

'*High voltage*' means a voltage normally exceeding 650 volts.

'*Home Office Electricity Regulations*' means any Regulations for the time being in force relating to the generation, transformation, distribution or use of electricity and made by the Secretary of State in pursuance of powers conferred by (*a*) the Factory and Workshop Acts, 1901 to 1929, in relation to any factory, workshop or other place to which the provisions of Section 79 of the Factory and Workshop Act, 1901, are applied by those Acts, or (*b*) the Cinematograph Act, 1909, in relation to any buildings or cinematograph exhibition to which the provisions of that Act apply.

'*Insulation*' means non-conducting material enclosing, surrounding or supporting a conductor or any part thereof and of such quality and thickness as to be suitable for the purposes of the Regulation in which the term is used.

'*Live*' means electrically charged.

'*Low voltage*' means a voltage not exceeding 250 volts under normal conditions, subject however to the percentage variation allowed by these Regulations.

'*Main*' means any electric line through which energy may be supplied or intended to be supplied by the Undertakers for the purposes of general supply.

'*Medium voltage*' means a voltage exceeding 250 volts but not exceeding 650 volts under normal conditions, subject however to the percentage variation allowed by these Regulations.

'*Mines Department Electricity Regulations*' means in relation to any mine or quarry as the case may require any Regulations or Rules for the time being in force in pursuance of any enactment relating to mines and quarries and relating to the generation, transformation, distribution or use of electricity.

'*Outdoor substation*' means any ground or place whereon apparatus of the kind included within the definition of substation is situate in the open air, and includes the said apparatus.

'*Outdoor switch station*' means any ground or place whereon apparatus of the kind included within the definition of switch station is situate in the open air, and includes the said apparatus.

'*Overhead line*' means any electric line which is placed above ground and in the open air.

'*Service line*' means any electric line through which energy may be supplied or intended to be supplied by the Undertakers to a consumer either from any main or directly from the premises of the Undertakers.

'*Substation*' means any premises or enclosure or part thereof, being large enough to admit the entrance of a person after the apparatus therein is in position, containing apparatus for transforming or converting energy to or from a voltage above medium voltage (other than transforming or converting solely for the operation of switchgear or instruments) with or without any other apparatus for switching, controlling or otherwise regulating the energy, and includes the apparatus therein.

'*Supply of electricity in bulk*' means a supply of electricity to any local authority, company, body or person authorised to supply electricity.

'*Supply terminals*' means the point or points at which the supply of energy is delivered to the consumer from the service line.

'*Switch station*' means any premises or enclosure or part thereof, being large enough to admit the entrance of a person after the apparatus therein is in position, containing apparatus for switching, controlling or otherwise regulating energy at a voltage above medium voltage but *not* for transforming or converting energy (other than transforming or converting solely for the operation of switchgear or instruments), and includes the apparatus therein.

'*System*' means an electrical system in which all the conductors and apparatus are electrically connected to a common source of voltage, and includes all the said conductors and apparatus.

'*Voltage*' means electro-motive force and in particular the voltage, as measured by a suitable voltmeter, between any pair of conductors forming part of a system or between any part of either conductor and the earth.

'*Works*' means and includes electric lines, also any buildings, machinery, engines, works, matters or things of whatever description required to supply electricity and to carry into effect the object of the Undertakers under the Electricity (Supply) Acts.

Any other words, terms and expressions to which meanings are assigned by the Electricity (Supply) Acts, 1882 to 1933, and the Schedule to the Electric Lighting (Clauses) Act, 1899, shall have in these Regulations the same respective meanings.

SYMBOLS, SIGNS, ETC.

6. Abbreviations and Symbols.—Except where otherwise stated, the symbols recommended by the International Electrotechnical Commission are used throughout this book. Though all the symbols are not here required the list is reproduced in full, save for the omission of alternative symbols which are recommended by the Commission for cases in which the principal letter symbol is not suitable.*

A list of letter symbols most frequently needed in electrotechnics is given in Table 2. Abbreviations for names of units are given in Table 3.

TABLE 2.—*Letter Symbols Most Frequently Needed in Electro-technics.*

Name of Quantity.	Letter Symbol.	Name of Quantity.	Letter Symbol.
Length	l	Resistivity	ρ
Mass	m	Conductance	G
Time	t	Quantity of electricity	Q
Angles	α, β, γ	Flux-density, electrostatic	D
Acceleration of gravity	g	Capacity	C
Work	A	Dielectric constant	ϵ
Energy	W	Self-inductance	L
Power	P	Mutual inductance	M
Efficiency	η	Reactance†	X
Number of turns in unit of time	n	Impedance	Z
Temperature centigrade	t	Reluctance	S
Temperature absolute	T	Magnetic flux	Φ
Period	T	Flux density, magnetic	B
$2\pi/T(=2\pi f)$	ω	Magnetic field	H
Frequency	f	Intensity of magnetisation	J
Phase displacement	ϕ	Permeability	μ
Electromotive force	E	Susceptibility	κ
Current	I	Difference of potential, electric	V
Resistance	R	Magnetomotive force †	

Rules for Quantities.—(*a*) Instantaneous values of electrical quantities which vary with the time to be represented by small letters. In case of ambiguity, they may be followed by the subscript 't.'

(*b*) Virtual or constant values of electrical quantities to be represented by capital letters.

(*c*) Maximum values of periodic electrical and magnetic quantities to be represented by capital letters followed by the subscript 'm.'

(*d*) In cases where it is desirable to distinguish between magnetic and electric quantities, constant or variable, magnetic quantities to be represented by capital

(*Contd. on p.* 18.)

* The complete Report (No. 27) may be purchased from the International Electro-technical Commission at 28 Victoria Street, Westminster, S.W. 1.

† Symbol to be proposed by the National Committee.

TABLE 3.—*Abbreviations for Names of Units; to be used only after Numerical Values.*

Name of Unit.	Abbreviation.*	Name of Unit.	Abbreviation.*
Ampere	A	Volt-coulomb	VC
Volt	V	Watt-hour	Wh
Ohm	Ω†	Volt-ampere	VA
Coulomb	C	Ampere-hour	Ah
Joule	J	Milliampere	mA
Watt	W	Kilowatt	kW
Farad	F	Kilovolt-ampere	kVA
Henry	H	Kilowatt-hour	kWh

m for milli-
k for kilo-
μ for micro- or micr-
M for mega- or meg-

Other abbreviations used in this book are as follows :—

Inch	in.	Standard wire-gauge	S.W.G.
$\frac{1}{1000}$ inch	mil.	Home Office	H.O.
Foot	ft.	Board of Trade	B.O.T.
Yard	yd.	Electricity Commissioners, publication of	El. C. No
Mile	ml.	International Electrotechnical Commission	I.E.C.
Metre	m.	British Standards Institution (formerly the British Engineering Standards Association; B.E.S.A.)	B.S.I.
Kilometre	km.	British Standard Specification, publication of	B.S.S. No.
Centimetre	cm.	Institution of Electrical Engineers	I.E.E.
Millimetre	mm.	British Electrical and Allied Manufacturers' Association	B.E.A.M.A.
Square	sq.	British Electrical and Allied Industries Research Association	B.E.R.A.
Cubic	cu.		
Gramme	grm.		
Kilogramme	kg.		
Continuous or direct current	C.C. or D.C.		
Alternating current	A.C.		
Positive pole	+		
Negative pole	−		
Neutral, D.C.	±		
Neutral, A.C.	N.		
Earth	E.		
Horse-power (indicated or brake)	I.H.P.; B.H.P.		
Electrical horse-power	E.H.P.		
Power factor	P.F. or cos φ.		
Maximum Demand	M.D.		
British Thermal Unit	B.Th.U.		
Board of Trade Unit (or Kelvin)	B.T.U. or unit (kWh).		

* The I.E.C. recommends that these abbreviations should be in heavy-faced type, but for economy in printing, and following the practice adopted in the *I.E.E. Journal* and in the technical press, ordinary type is used for them throughout this book.

† The letters O and Ω are recommended provisionally. Ω is used in this book because O is liable to be confused with the numeral zero. The letter Ω should no longer be used for megohm.

letters of either script, heavy-faced or any special type. Script letters to be only employed for magnetic quantities.

(*e*) Angles to be represented by small Greek letters.

(*f*) Dimensionless and specific quantities to be represented, wherever possible, by small Greek letters.

7. Conventional Signs for Electrical Diagrams.—A number of conventional signs for electrical apparatus are given in Table 4. British Standard Graphical Symbols for general electrical purposes are given in B.S.S. No. 108/1933. The main utility of the Standard Symbols is in the preparation of plans and connection diagrams for commercial purposes, and it is most desirable that they should be used in all such work.

Notes.—(*a*) Conductors are represented by lines, the thickness of which may often be varied to discriminate between main (heavy current) circuits and instrument (or other weak current) circuits. Diagrams may frequently be simplified with advantage by using single lines to represent *circuits* (lead and return), the number of wires in the circuit being then denoted by an equal number of *diagonal* strokes across the circuit-line (*see* (4), Table 4). Strokes at *right angles* to the circuit-line are taken to represent that number of complete circuits connected in parallel (*see* (5) Table 4).

(*b*) Connections between conductors should be represented by a dot at the junction. Lines crossing without a dot are often used to represent conductors which cross without connection between them, but the authors prefer the method of indicating this definitely by a semicircle in one conductor at the point of crossing.

(*c*) Single-phase, two-phase, and three-phase alternating currents are frequently represented in diagrams by 1 ~, 2 ~, and 3 ~ respectively. The only objection to this is that ~ is even more commonly used to represent the frequency in cycles per sec., thus 50 ~, 100 ~, etc. The risk of confusion is slight because frequencies of 1, 2, and 3 cycles per sec. are never used for commercial purposes. There are, however, 'slip' currents of very low frequencies in some A.C. motors (*see* Chapter 28) so that to avoid possibility of confusion it seems best to use the symbols 1ϕ, 2ϕ, and 3ϕ where a graphical representation is required for single-, two-, and three-phase currents. British Standard practice is now to use the abbreviations 1 ph, 2 ph, 3 ph.

(*d*) Instruments may be represented by a circle, or by an outline of the shape of the instrument, within which is a letter symbol indicating the purpose of the instrument. Relays may be represented by a rectangular outline containing appropriate letter symbols. An alphabetical list of code letters for electrical apparatus of all kinds is given in B.S.S. No. 108/1933. In general, the code designation consists of the initial letters of the name of the apparatus, for example, CT—current transformer; EB—electric bell; EPS—earthing plug socket; FS—field switch; FWRes—field-weakening resistor; NLK—neutral link; OCB—oil

(*Contd. on p.* 20.)

* In B.S.S. No. 108, there are given various graphical symbols for insertion in the square frame representing a sub-station, to denote the equipment installed.

‡ Where it is necessary to discriminate, the triangular zig-zag should be used for resistances which are nearly non-inductive, and the rectangular zig-zag for those which are absolutely non-inductive.

§ The dotted line outside the battery is *not* part of the conventional sign but is added for the purpose of the explanation given in Note (*e*).

TABLE 4.—*Conventional Signs for Electrical Diagrams.*

No.		Conventional Sign.
1	Conductors (*a*) Main. (*b*) Small.	(*a*) (*b*)
2	Conductors (*a*) Connected. (*b*) Crossing.	*a* *a* or *a* *a* *b* *b*
3	Twin flexible conductors.	
4	Two (*a*) and three (*b*) wire *circuits* (lead and return).	(*a*) (*b*)
5	Two (*a*) and three (*b*) *circuits* in parallel.	(*a*) (*b*)
6	Bus bar.	
7	Bus bar with terminals.	
8	Link.	
9	Cut-out.	
10	Earth connection (*a*), and plate (*b*).	E (*a*) (*b*)
11	Generating station (*a*) Thermal (*b*) Hydraulic.	(*a*) (*b*)
12	Sub-station.*	
13	Direct current (*a*) Generator. (*b*) Motor.	G or (*a*) G M or (*b*) M
14	Single-phase (*a*) Generator. (*b*) Motor (i) synchronous. (ii) asynchronous.	(*a*) G See Note (*c*) M M (i) (*b*) (ii)
15	Two-phase, 3-wire: (*a*) Generator; (*b*) Motor.	(*a*) (*b*)
16	Two-phase, 4-wire: (*a*) Generator; (*b*) Motor.	(*a*) (*b*)
17	Three-phase (*a*) Generator. (*b*) Motor (i) synchronous. (ii) asynchronous.	(*a*) G See Note (*c*) M M (i) (*b*) (ii)
18	Three - phase generator: (*a*) Mesh; (*b*) Star.	(*a*) (*b*)
19	Rotary converter.	
20	Motor-generator.	M-G
21	Motor-converter.	M-C
22	Mechanically coupled machines (motor and generator in the case shown).	M G
23	Non-inductive resistance.‡	or
24	Inductive winding (field coil, etc.)	
25	Commutating-pole winding.	
26	Transformer.	or
27	Socket for plug.	
28	Plug and socket.	
29	Tumbler switch (*a*) Single-pole. (*b*) Double-pole.	(*a*) (*b*)
30	Rotating switch, single-pole.	
31	Single-pole switch: (*a*) Air break; (*b*) Oil-immersed.	(*a*) (*b*)
32	Air-break circuit breaker (maximum trip).	
33	Contactor.	
34	Instruments and relays.	See Note (*d*)
35	Incandescent (glow) lamp.	or or L
36	Arc lamp.	
37	Fan.	
38	Battery of cells.§	+ −

N.B.—For notes (*a*)-(*e*) see § 7; for footnotes see opposite page.

circuit-breaker; OCDTR—over-current definite time-limit relay; UVR—under-voltage relay; UVRel—under-voltage release, and so on. Bearing in mind the basis of the code, the significance of any particular designation, is generally clear from the context or from the position of the apparatus in the circuit.

(e) In the conventional sign for a primary cell (*see* No. 38, Table 4), the thick stroke should represent the *electro-positive element of the cell* (*e.g.* the zinc in a primary battery or the spongy lead in an accumulator) which is the *negative pole* of the battery and the thin stroke the electro-negative element which is the positive pole. There is much confusion over this matter. Inside a cell the current travels from the electro-positive to the electro-negative element; from the zinc to the carbon; from the lead to the lead peroxide; so in the external circuit these directions are necessarily reversed. The arrows in diagram 38, Table 4, show this.

Some further conventional signs used in connection with wiring diagrams for lighting installations, are given in § 519, Vol. 2.

Elementary Conceptions.

8. Elementary Conception of Electrical Quantities.—The analogy between hydraulics and electricity is not in great favour amongst electrical engineers, but it is nevertheless very useful —so far as it goes—in explaining elementary electrical ideas. Voltage in an electric circuit is analogous to water pressure in an hydraulic system, and the rate of flow of electricity, measured in amperes, corresponds to the rate of flow of water. Though there is no actual identity, volts may be likened to lbs. per sq. in., and amperes may be likened to gallons per min. or cusecs.

Take, for example, the case of the pressure pipe in a water turbine installation. The power available at the nozzle in foot-pounds of energy per sec. (550 ft.-lbs. per sec. = 1 H.P.) is the product of the quantity of water flowing per sec. (*i.e.* the rate of flow) and the net head or pressure. We have a pipe of a certain size, with a certain weight of water flowing through it per sec. under a certain net head, which is the gross head diminished by the loss in frictional resistance in the pipe; the larger the diameter of the pipe, the smaller is this resistance loss. Similarly, in an electrical circuit, the power available in watts (100 W = 0·134 H.P. = 74 ft.-lbs. per sec.) is the product of the current or rate of flow in amperes, I, and the pressure in volts, E. Here, in the place of the pipe, we have a conductor of a certain size, and the pressure available for doing work is the initial pressure diminished by the loss due to the resistance, R, of the conductor to the flow of the current; and the larger the diameter of the conductor the smaller is the loss of pressure.

9. Elementary Conception of a Circuit.—This analogy, however, fails to explain the idea of an electric circuit (§ 436, *et seq.*, Vol. 2), and for this purpose the circulation in an ordinary hot-water installation may be cited. From the top of the boiler, as is well known, a pipe rises to the highest point in the system, and a current flows up this pipe. The fire supplies the motive force, which may be likened to the electromotive force of an electric battery or generator, and the hot-water pipe is the out-going conductor or 'lead.' But no circulation of water can take place unless there is a return circuit back to the boiler, and for this purpose a return pipe comes down from the top of the building to the lower part of the boiler. This pipe corresponds to the 'return' wire of an electric circuit. Whereas the closing of a valve on the water pipe breaks the circuit and stops the current, so the opening of a switch connected in the electrical conductor opens or breaks the circuit and stops the electric current. There is a difference, however, in that the temperature of, and total heat in, the water stored in the tank at the top increase when no supply is being drawn off, and the circulation continues all the time; but in an electrical circuit there is no such storage or circulation of energy when it is not being utilised. The lamps or other consuming devices bridge over and complete the circuit between the lead and return wires; and if the lamps are removed (or if the switch controlling them is opened, which comes to the same thing) then no current can flow. The electromotive force, or the difference of electric potential, between the two wires remains, but as there is no conducting circuit no current can flow. Here the analogy with a hot-water supply system holds good again; for, although the closing of a valve causes the circulation to cease, the pressure remains, and with it the tendency for the flow to restart as soon as it has a path open; and the same may be said in the case of the electric circuit. If the pressure is excessive it may in either case break down the opposing barrier, by bursting the pipe or valve in the one case and by sparking across the gap in the circuit in the other. A further interesting link in this analogy may be forged from the heat losses in the two circuits: * the hot-water pipes are radiating energy away to the air, according to their temperature, and heat units

* This analogy must not be carried beyond the fact that there is a loss in transmission in both cases. The I^2R electrical loss is an internal wastage arising from overcoming the resistance of the conductor and is therefore comparable to the loss arising from friction in pipes.

supplied by the fuel are thus wasted; similarly the electrical conductors are raised in temperature by the current in them, and heat units supplied by the fuel are wasted in the form of I^2R watts (§§ 17, 49). A good grasp of this general idea of an electric circuit will make it easier to understand the explanations which follow.

Again, analogy may assist in imparting a clear elementary idea of the advantages of transmitting power at high pressure for use at low pressure. Suppose a householder to have only cold water laid on in his bathroom upstairs, and only a gas stove downstairs for all purposes. If he wants a 20 gallon hot bath, he has the option of heating and carrying upstairs 20 gallons of water at bath temperature or 10 gallons at boiling-point, to be diluted from the cold tap. The amount of gas, or therms of heat, used will be about the same in both cases; but obviously he will save labour by using the concentrated heat of the smaller quantity of boiling water for transmission from one floor to the other, even though boiling water is more dangerous to handle than merely hot water, and requires also to be brought back to the lower temperature before use. Just in the same way, the supplier of electrical energy will concentrate his energy into a small quantity flowing, or current (requiring only small wires to carry it) by generating it at a dangerously high pressure, and will then re-convert it and deliver it at a safe low pressure for use. Transformers and motor-generators, etc., may in this way be looked upon as concentrators or diluters of energy.

Kinds of Current.

10. Alternating and Continuous Currents.—The international definitions of the practical units of resistance, current, and pressure (§ 3) make specific mention of 'an unvarying electric current,' *i.e.* an electric current which is constant in magnitude and direction. Such a current may be produced by electrochemical action in a primary battery (§ 127), but the electric currents used for commercial purposes are induced in the windings of dynamo-electric machines by alternately increasing and decreasing the magnetic flux which passes through or is 'linked' with these windings. The process is described in detail in § 132, but for our present purpose it is sufficient to say that the periodic increase and decrease in the flux linked with the winding induces in the latter an electromotive force which varies periodically between positive and negative maxima. In other words, the electromotive force (and the current, if there is a closed circuit, § 9) alternates in direction and varies in magnitude. The currents induced in the windings of all dynamo-electric machines (excepting unipolar machines, § 137) are *alternating*, but the alternating electromotive forces and currents of the individual windings can be commutated or rectified (§§ 13, 132) and added together so as to produce a substantially unvarying electromotive force and current in the circuit supplied by the machine (§ 14).

So far as the internal arrangements in an installation are concerned, whether for lights, fans, or heating, etc., it generally makes no practical difference whether the supply is continuous or alternating current. If large motors or other inductive apparatus are involved the case is different; and where the design of machinery or the laying out of a large scheme is in question the essential differences in the systems must be properly understood.

11. Single-Phase Alternating Current.—When a coil of wire passes successively the two poles of a magnet, as in Fig. 1, so as to cut the lines of magnetic force at right angles, a wave of E.M.F. is generated, which rises to a positive maximum as one pole is passed, falls to zero, and then rises to a negative maximum

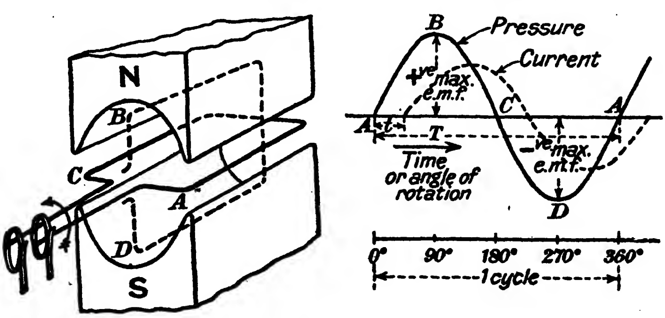

Fig. 1.—Alternating pressure and current.

as the other pole is passed, as shown by the full curve in Fig. 1. The points A, B, C, D, on the pressure curve represent the E.M.F. induced in the coil when the latter is successively in the equidistant positions marked A, B, C, D, in the left-hand diagram. Assuming the ends of the coil to be joined, so as to make a circuit this E.M.F. causes a corresponding cycle of waves of current to flow, and we have a simple 'single-phase' alternating current as represented in Fig. 1 by the dotted curve. The wave of E.M.F. and the consequent wave of current may or may not be coincident with respect to time, *i.e.* the maxima and minima may or may not occur simultaneously; in the figure the waves are shown as not coincident, *i.e.* they are somewhat 'out of phase.' Time and/or angle of rotation of the winding being plotted from left to right in Fig. 1, the dotted wave is behind, or 'lags' with regard to the full-line wave by a time interval t which is equivalent to $(t / T) \times 360°$, *i.e.* about 45° in the case illustrated. In some cases (*see also* §§ 46 and 47 and Chapter 5) the current wave is 'lead ing,' *i.e.* ahead of the pressure wave as regards relative position or 'phase.' The further explanation of this phenomenon, and of the peculiarities of alternating currents generally, is deferred to §§ 29-31, 44-47, 56; for the present it will be sufficient to assume that the current or pressure will be what is indicated in amperes or volts on a suitable measuring instrument.

Theoretically the wave is treated as a simple harmonic wave or 'sine wave.' By means of the oscillograph the exact shape of the wave form can be seen or photographically recorded, just as the inner working of the steam in an engine cylinder can be shown by an indicator diagram. In this way the irregularities from the true sine wave form can be examined, and in some cases they may be of considerable importance. As in an alternating current the direction is reversed each half-cycle, alternating current cannot be used for electrochemical deposition or any work of that nature; for the work done in one half-cycle would be undone in the other half. A continuous current must be used in such cases, and its (conventional) direction must be correct when the circuit is made (§ 127). For electric lighting or heating or motive power either continuous or alternating current can be used. To obtain D.C. from an A.C. supply a motor-generator (§ 388, Vol. 2), converter (§ 408 *et seq.*, Vol. 2), or rectifier (§ 415 *et seq.*, Vol. 2), must be used.

12. Cycles or Periods.—The complete double wave of an alternating E.M.F. or current is called a 'cycle' or 'period,' and the number of periods per sec. is called the 'frequency' or 'periodicity.' The standard frequency of the British Standards Institution is 50 periods per sec. with 25 periods as a secondary standard to meet special cases. American practice favours 60 cycles per sec. as the standard (§ 135). For electric traction work, a frequency of 15 periods is often used; with this low frequency a glow-lamp actually shows the alternations, for as the wave of current dies down to zero the filament of the lamp cools down and the light diminishes. The result is a succession of flickers. On the other hand, it may be mentioned that frequencies of 10 000 alternations or more per sec. are used in wireless telegraphy.

12a. Vector Diagrams.—When the variation of an alternating current or voltage follow the harmonic law, this variation can be shown in a very simple geometrical way. In Fig. 1*a* conceive that OR_1 represents to scale the maximum value of an alternating current, and that this line rotates uniformly about O so that it executes one revolution per cycle. Then, if the line OX represents a zero of time, at any instant the value of the alternating current will be given by the projection OY_1 on the vertical through O of the rotating vector in the position it would occupy at that instant. When the projection OY is measured above O, the direction of the current is positive, and when below O, the direction is negative. The angular travel of OR_1, from the initial position, R_1OX, is called the phase.

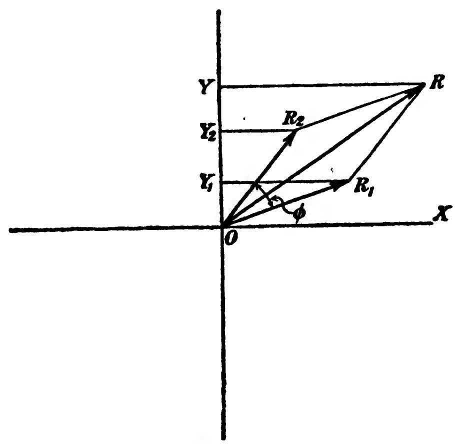

FIG. 1*a*.—Illustrating principles of vector diagrams.

Conceive now another alternating current of the same frequency. This can be represented by a second rotating vector OR_2, which will always be displaced in angle by the same amount from OR. This angular displacement, or difference of phase of the vectors of two alternating quantities is generally denoted by the symbol ϕ. The variations of this second alternating current will be represented by the variations of the projection OY_2 of OR_2 on the vertical through O.

Consider now that the two alternating currents are combined into a single resultant current. The instantaneous value of the resultant will always be equal to the sum of the instantaneous values of the components. It is easily seen from the diagram that a vector OR which is the diagonal of a parallelogram having OR_1 and OR_2 as sides, will have its projection OY on the vertical equal to the sum of OY_1 and OY_2. Thus an A.C. represented by a rotating vector OR is the same as the sum of two A.C.'s represented by OR_1 and OR_2. Instead of considering the vectors as rotating, the axes of reference may be conceived to rotate whilst the vectors are stationary. Thus we arrive at the important principle that alternating currents of the same frequency are added as vectors, by the parallelogram rule. Vector diagrams are drawn according to a standard convention that counter-clockwise rotation represents a lead in phase. Thus the current represented by OR_2 leads on that represented by OR_1 by an angle ϕ, that is to say OR_2 attains a positive maximum value earlier than OR_1 by a fraction of a period equal to the fraction $\phi° / 360$.

As two alternating currents can be added or compounded by this vector construction, so a single current may be considered to be the resultant of two components. Consider Fig. 1*b*. Here OV is the vector of an alternating voltage, and OI is that of the current it produces. The current lags on the voltage by an angle ϕ. The causes of this lag will be explained later (§ 44). The vector OI is the resultant of two components at right-angles as shown. So the A.C. represented by OI can be considered to be the resultant of two component currents represented by the vectors I_a and I_r. The component I_a, known as the active component is in phase with the voltage. This, as will be seen later, is the component which associated with the voltage produces power (§ 55). The second component I_r lags 90° on the voltage. This is called the reactive component, and it is wattless, or it gives rise to no power. It is seen that the power in an A.C. current depends not only upon the magnitudes of current and voltage, but also upon the cosine of ϕ, the angle of phase difference, which determines the active or power producing component of the current.

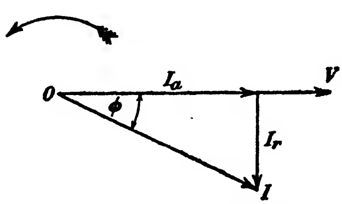

FIG. 1*b*.—Active and reactive components.

13. Rectified Current.—If the arrangements, are such that the waves below the zero line in Fig. 1 are reversed, we then have a unidirectional or rectified alternating current (*see* Chapter 17).

The generator illustrated in Fig. 1, having only a single armature coil, would give such a current. Fig. 2 shows the form of the rectified wave. If there is a definite break between successive waves, this becomes an 'interrupted current' such as is found in an electric bell or an X-ray coil, whether worked by an ordinary 'make and break' magnet and spring or by a mechanical interrupter.

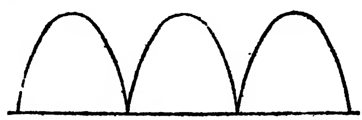

FIG. 2.—Rectified alternating current.

14. Continuous Current.—A very near approach to a steady unidirectional or 'continuous' current, such as is given by a battery, is generated by a dynamo, in which the waves of current generated by each coil successively are rectified by the commutator and, rapidly succeeding one another, give almost a straight line on the crest of the resultant wave. This is shown developed gradually in Fig. 3. If the generator makes 15 or 20 revs. per sec. and the commutator has 60 or 80 sections, it is evident that there can be no appreciable fluctuation as the collecting brush passes from one section to the next.

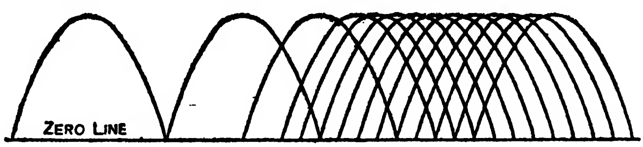

FIG. 3.—Continuous current.

15. Three-Phase Current.—For transmission of power over long distances '3-phase' alternating current is now almost universal. Referring back to Fig. 1, one complete cycle of pressure or current (corresponding in a two-pole machine, to one revolution, *i.e.* 360° rotation of the armature) may be represented as starting at zero, rising to a positive maximum at 90°, cutting the zero line again at 180,° rising to a negative maximum at 270°, and ending at 360°. In a 3-phase generator, there are three windings (represented by *I*, *II*, *III*, Fig. 4) spaced 120° apart. Thus, in addition to the pressure wave *I*, there is a second independent wave generated in the winding *II*, and a third wave generated in the winding *III*. The three waves are exactly similar, but are displaced 120° from each other. As shown in the diagram the three windings are 'star-connected' (§ 143) to a common neutral point

O, but the action is just the same if each winding be led out to a separate pair of slip-rings. The use of six slip-rings and six wires in the external circuit is unnecessary because the algebraic sum of the currents in any two phases of a 3-phase, 3-wire system is always equal and opposite to the current in the third phase, hence

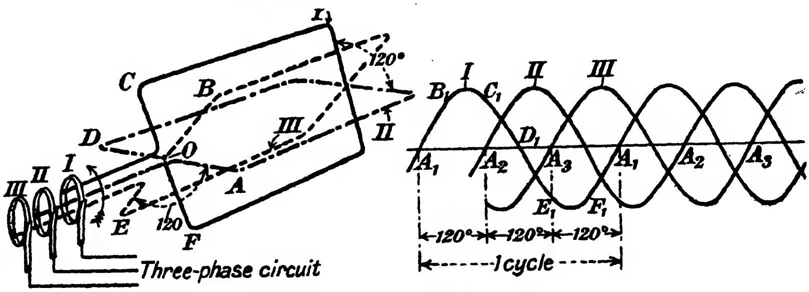

Fig. 4.—Three-phase current.

each pair of conductors can be considered to act as the return path for the current in the third conductor. There are, however, three separate and distinct waves of E.M.F., each producing a separate current when the circuit is closed. The 3-phase system makes possible the greatest practical economy in the transmission of power (*but see* § 298); it is explained further in Chapters 14 and 20.

16. Two-Phase Current.—It is only necessary to mention that 2-phase supply—with an angle of 90° between the phases—

Fig. 5.—Two-phase current.

has been used considerably in the past; but the greater economy of 3-phase current has rendered this system almost obsolete. The 2-phase system is not dealt with in this book.

For the sake of completeness, Fig. 5 is included. This diagram is arranged similarly to Figs. 1 and 4, and is self-explanatory.

Ohm's Law.

17. Ohm's Law.—The relation between resistance, *R*, pressure or electromotive force, *E*, and current or intensity of current, *I*, assuming all to be unvarying, is expressed by Ohm's Law as follows: The strength of the current varies directly as the electromotive force and inversely as the resistance of the circuit, or—

$$I = E/R, \text{ or } R = E/I, \text{ or } E = IR.$$

As mentioned already in § 8, the product of *E* and *I* expresses the power in the circuit in watts, W, which is directly comparable to, and convertible into, horse-power. By definition watts = *EI*. But $E = IR$. Therefore watts = I^2R (§§ 48-50). In succeeding paragraphs examples will be given of the practical working of this rule; its application is not always so simple as may appear at first sight (§§ 21, 28, 44, 49, etc.).

The resistance of a conductor is independent of the magnitude of the current it carries, provided its temperature remains constant. This is the fundamental physical fact established by the researches of Ohm. Thus Ohm's law is more than a mere definition of resistance in terms of current and voltage (compare: reluctance, § 42).

Ohmic resistance does not alone determine the resistance to current flow in A.C. circuits, hence a modified form of Ohm's Law must be used for these circuits (§ 44).

Resistance.

18. Resistivity and Conductance.—The resistivity or specific resistance of a material is the electrical resistance between opposite faces of a unit-cube of the material at specified temperature. Generally the specific resistance is expressed in microhms per centimetre-cube * (or per inch-cube) at 0° C. (§ 61), or in ohms per mil-foot., *i.e.* per foot of wire of 1 mil diameter. (1 Ω per mil-foot = 0·166 microhm per cm.-cube. 1 microhm per cm.-cube = 6·015 Ω per mil-foot.)

* It is essential to use the term centimetre-cube (or inch-cube) and *not* the term cubic centimetre (or cubic inch) in this connection. The resistance of 1 cm.-cube of copper is about 1·6 microhms at 0° C, if the metal is in the form of a 1 cm.-cube, but since the resistance of a conductor is directly proportional to its length and inversely proportional to its cross-sectional area, it is 1·6 × 100 × 100 = 16 000 microhms = 0·016 Ω if the 1 cu. cm. of metal is in the form of a wire 1 m. long and 1 sq. mm. cross-section.

The resistance between two opposite faces of a 1 cm.-cube of a material is termed the *volume resistivity* of the material. Denoting this by $\rho_v\ \Omega$, the resistance R of a uniform wire of length l cm. and cross-section A sq. cm. is: $R = \rho_v l / A\ \Omega$. If the density of the material be D grm. / cu. cm., the mass m of the wire considered is: $m = lAD$ grm., hence $A = m / lD$. Substituting this value for A we have $R = \rho_v\ Dl^2 / m$. The product $\rho_v D$ does not vary with the dimensions of the wire, and is called the *mass resistivity* (ρ_m) of the material. The coefficients ρ_v, D, and ρ_m all vary with temperature.

It is usual to express ρ_v in microhms per cm.-cube. The resistance $R\ \Omega$ of a uniform wire L metres long and of mass m grm. is then given by $R = \rho_m L^2 / m$ where $\rho_m = \rho_v D / 100$. Thus for copper $\rho_m = 0{\cdot}153\ 28\ \Omega$ at 20° C. (§ 62) and the resistance of a wire 5 metres long and of mass 50 grm. is $R = 0{\cdot}153 \times (5)^2 / 50 = 0{\cdot}076\ 5\ \Omega$ (approx.).

Conductance is the reciprocal of resistance, $1 / R$, and is expressed in 'mhos,' a coined word obtained by writing 'ohm' backwards. The use of this term is explained further in Chapter 19. A proposal to use the name 'Siemens' for the practical unit of conductance was made to the I.E.C. in London, 1931, but has not been adopted at the time of writing.

19. Ohms, Megohms.—Resistance is expressed in 'ohms' in all ordinary cases, when dealing with conductors or conducting circuits. If, however, the resistance of a nominally insulating body is required a higher unit is desirable, and the result is expressed in 'megohms,' *i.e.* millions of ohms. Thus, in the case of insulated wires and cables, the covering or 'dielectric' of a particular quality will be guaranteed to have an 'insulation resistance' of not less than 300, 600, or 2 000 megohms per ml. at a certain temperature, as explained more particularly in § 281.

20. Standard Resistances.—For accurate electrical measurements by means of the potentiometer (§ 95) standard comparison coils of 1 Ω, and decimal multiples up to a megohm or submultiples down to 0·001 of an ohm, are used; for these the alloy manganin is generally employed, as its temperature coefficient is almost negligible. These are called 'standard resistances'; they are also used in some portable testing sets (*see* § 106). In order to reduce the amount of metal used in standard resistances for large currents they are frequently made tubular and water circulates through them.

21. Internal and External Resistance.—In a complete circuit, carrying a current from a battery or other source of power included in it, the total resistance is made up of the 'internal resistance' of the battery or generator and the 'external resistance' consisting of the remainder or working part of the circuit. This must not be overlooked in applying Ohm's Law. A battery (§ 127) of small cells may easily be connected in series so as to have a total pressure of 1 000 V on 'open circuit,' *i.e.* with no *external* connection from pole to pole; but if a conductor having a resistance of 1 Ω is connected across its terminals the current in the circuit will not be 1 000 A or perhaps not even 1 A; for to the external resistance of 1 Ω must be added the very high internal resistance of the whole of the cells. In this case Ohm's Law must be written $I = E / (R + r)$, where R and r are the external and internal resistances respectively.

Pressure.

22. Definition of Pressure.—The term 'pressure' or electromotive force (E. or E.M.F.) is defined in more than one way in the Regulations of the Electricity Commissioners (formerly the Regulations were made by the Board of Trade) and the Home Office, but the variations are not material. The following is explicit:—

Pressure means the difference of electrical potential between any two conductors through which a supply of energy is given, or between any part of either conductor and the earth, as read by a hot-wire or electrostatic voltmeter.

Low Pressure means a pressure in a system normally not exceeding 250 V where the electrical energy is used.

Medium Pressure means a pressure in a system normally above 250 V, but not exceeding 650 V, where the electrical energy is used.

High Pressure means a pressure in a system normally above 650 V, but not exceeding 3 000 V, where the electrical energy is used or supplied.

Extra-high Pressure means a pressure in a system normally exceeding 3 000 V where the electrical energy is used or supplied.

See also I.E.E. definitions, § 4.

The reference to *normal* pressure refers to the variations which are permitted by the regulations for public supply.

The phrase 'difference of potential' or 'potential difference' (P.D.), used in the above definition, is frequently used in discussing the electrical conditions in a circuit; the technical distinction between the two modes of expression will be grasped as the reader proceeds. The nature of alternating, as opposed to continuous current has already been discussed (§§ 11-16), and the meaning of the term 'pressure' as applied to an alternating current supply is further elucidated in §§ 29-31.

23. British Standard Voltages.—In B.S.S. No. 77, 1932, the B.S.I. specifies British standard electrical voltages for new systems and installations as follows:—

(a) *Direct Current Systems and Installations.*

(i) Consumer's voltages.*—230, 460 V.

(ii) Station voltages.†—250, 500 V.

(b) *Alternating Current (3-phase) Systems and Installations.*

(i) Consumer's voltages.*—230 V between neutral and each of the phase conductors; 400 V between phases.

(ii) Station voltages.†—250 V between neutral and each of the phase conductors; 440 V between phases.

(c) *High Voltages.*

(i) Delivered voltages.‡—3 000, 10 000 §, 30 000.

(ii) Station voltages.†—3 300, 11 000 §, 33 000.

(d) *Nominal Voltage.*

As applied to a high-voltage interconnected network, 'nominal voltage' denotes the mean voltage of the network. Standard values are 66 000 and 132 000 V. The 'operating voltage' in such a network may not vary from the nominal voltage by more than ± 10 %.

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* 'Consumer's voltage' (described as the 'declared pressure' in the Electric Lighting Acts) denotes the voltage at the consumer's terminals declared by the supplier.

† 'Station voltage' denotes the normal voltage applied to the terminals of the transmission line at the generating station or substation.

‡ 'Delivered voltage' (described as the 'declared pressure' in the Regulations of the Electricity Commissioners as to Extra-High Pressure) denotes the normal voltage at the terminals of the transmission line at the delivery end.

§ Recommended for rural electrification schemes.

The consumer's or declared pressures are the standard pressures, the station pressure being derived in each case by adding to the declared pressure the pressure lost (§ 24) in the line when carrying its full load; unless otherwise specified, this loss shall be assumed to be such as to give the station pressures shown above.

Earlier standards of pressure for D.C. and A.C. systems (given in the third edition of this book, p. 10, and fourth edition, p. 20) may be represented in existing installations for years to come. The actual consumer's voltages in different supply areas are given in various annual publications.*

Pressures up to 232 000 V are already in use for the transmission of power.

24. Loss of Pressure.—In any conductor carrying a current there is a drop of pressure, increasing both as the length and consequent resistance of the conductor increases, and also in direct proportion to the current. Professor (Sir Ambrose) Fleming pointed out many years ago that the hydraulic gradient in a water pipe offers an exact analogy to the pressure gradient in a conductor. Between any two points in a pipe line, connected to a reservoir at one end and discharging at the other, there is a difference of 'water motive force' or pressure, urging a flow of so many gallons per sec. (according to the resistance of the pipe) between those points; there is thus a gradual fall of pressure (the hydraulic gradient) all along the pipe. Similarly, along an electric conductor there is a gradual fall of pressure or pressure gradient; and it is the difference of pressure or potential between any two points which causes a current to flow, the strength depending on the resistance offered by the conductor. The loss in volts in any part of the circuit is the product of the current in amperes and the resistance of that part of the circuit in ohms. Thus if a uniform wire 100 ft. long has a steady current flowing in it that causes a drop of pressure of 100 V in the whole length, then there will be a drop of 1 V per foot run; this principle is utilised in the potentiometer (§ 95).

By way of example, let it be assumed that 100 A are transmitted from a source of supply to a piece of apparatus by a pair of wires each a mile long, having a total resistance of 0·79 Ω

* The most nearly complete list is probably that in the *Practical Electrician's Pocket Book* (Published by *Electrica Trading and Electricity*; Odham's Press).

(= No. 3/0 S.W.G. copper wire), then the drop in pressure on the line will, by Ohm's Law, be 0·79 × 100 = 79 V. If, then, the pressure at the generator is 2 200 V, the available pressure for use at the far end will be 2 121 V. The difference is called the 'lost volts' (especially in the case of the drop of pressure in the conductors or 'windings' of a generator) or simply the 'drop in pressure.' In the case of alternating current supply the problem is less simple than in the above example, and is referred to later (§ 44 and Chapter 14).

Although in a particular case we may be dealing either with the pressure between two conductors or with that between one conductor and 'earth,' the latter case is perhaps the best to consider from the elementary standpoint, as it is also when dealing with 3-phase alternating currents (§§ 302, 313). Just as the pressure or degree of vacuum of air or water is ordinarily reckoned by its departure above or below normal atmospheric pressure, so electrical pressures may be expressed in relation to 'earth potential,' either positively or negatively. There will be a pressure gradient along a wire carrying a current, and it can be measured by voltmeters connected between line and earth at different points, just as a pressure gauge would show different readings at various points along a horizontal water pipe discharging under an imposed pressure. In both cases, the instruments would show a steady static pressure at all points if the flow ceased.

Current.

25. **Amperes.**—That a clear conception of an electric current or of an ampere is difficult to inculcate is evident from the references, so common in newspapers, to 'currents of 2 000 V' and the like. Such ideas are survivals from the days before a scientific system of units had been evolved and co-ordinated in Ohm's Law (§ 17). From what has been written above it will be seen that the strength of current in a circuit, in amperes, depends on the other two factors of resistance and pressure. By Ohm's Law, if the standard pressure of a supply is (say) 220 V, a piece of apparatus connected thereto, and taking a current of 1 A, will have a resistance of 220 Ω; and another apparatus, having a resistance of 80 Ω will take 2¾ A. A reference, however, to § 17 will show that this is only true of an *unvarying* current, and therefore when alternating currents are being considered the

statement requires modification, as explained in due course (§ 44); the meaning of the term 'ampere' when applied to an alternating current is explained in § 29 and the examples following refer to continuous current. A pressure of no matter how many thousand volts may exist between two wires, side by side, but it will produce no flow of current unless and until there is a path or circuit for it from one wire to the other. If there is no such circuit the resistance is infinite and the current zero. For example, a steam engine is driving a large dynamo, maintaining a pressure of 500 V between its terminals, but if the external circuit is not closed there will be no current. If a crowbar is now dropped across these terminals the circuit will be closed; the resistance of the crowbar is so small that the current momentarily flowing will only be limited by the internal resistance of the coils of wire in the generator, and it may amount to many thousands of amperes The power supplied to this 'short-circuit' from the plant may, for a moment, be enormously in excess of that which either engine or generator is intended to give, or is capable of giving for any length of time, as the whole of the stored mechanical energy of the revolving machinery is dissipated in heat in an instant; and the dynamo—or what is left of it—comes to rest immediately in consequence.

The difficulty that students certainly experience in coming to grips with the ampere as a unit arises no doubt from the fact that it is a complex unit instead of a simple one like the pound or the gallon. As mentioned in the preface to the third edition (p. vii), an exact parallel to the ampere is the term 'cusec' (§ 201) often used in hydro-electric work, representing water-flow at the rate of one cubic foot per second or a 'second-foot.' The ampere is, properly speaking, a coulomb-second or a flow of the definite quantity of electricity represented by a coulomb (§ 28) per second of time. As ordinarily used, however, the factors are so defined that it appears as though the coulomb were derived from the ampere instead of *vice versa*. This is in fact a much more convenient way in dealing with power problems, while in physics the quantity basis is more generally used.

26. Milliamperes.—When dealing with very small currents it is convenient to have a smaller unit than the ampere, and the milliampere, mA (= one-thousandth part of an ampere) is used. In dealing with voltmeter currents, telegraphy, and electromedical work this term (or the still smaller micro-ampere = one-millionth ampere) is generally used. Leakage currents in a domestic installation are generally of this order, as shown by the requirements for testing (§ 1037).

27. Currents in Wires; Current Density.—As the pressure of supply is generally a fixed quantity, the power taken by any piece of apparatus (expressed in watts = $E \times I$) will be proportional to the current. The size of the wires used depends primarily on the current they have to carry; if a wire is too small the loss of volts due to its resistance may be such as to affect the use of the apparatus. For example, if a house is supplied at 100 V pressure, and the loss of pressure between the point of entry and a certain lamp is 6 V, that lamp will only get 94 V; if it is designed for 100 V the actual candle-power will not be nearly what it should be. Again, the wire may be overheated if carrying more than its proper current; the amount of the heat developed is proportional to the square of the current, and is exactly commensurate with the watts I^2R dissipated in the conductor. (This is true also of alternating currents.) The cross-sectional area of copper wires is given in the tables (which will be found later on in §§ 280 and 307) in decimals of an inch, so that the current they will carry at 1 000 A per sq. in 'current density' can be read off directly; thus, area 0·100, current 100, etc. Until recently 1 000 A per sq. in. was generally adopted as the rule-of-thumb limit of safety for the current carrying capacity of wires used in house wiring; now, as the tables referred to will show, it has ceased to be significant, and the permissible current is determined by formulæ with an experimental basis. The reason of this is that the heat dissipating surface of a round conductor of given length is proportional to its diameter, whereas the cross-sectional area is proportional to the square of its diameter. As the size of a conductor increases its heat dissipating surface becomes relatively smaller, so that, if a constant current density is maintained, the temperature of the large conductor must be higher in order to dissipate to the I^2R loss. Further, a bare wire, or one thinly covered only, will radiate its heat much more rapidly than a heavily insulated wire (§ 328); and the radiating surface of the insulating covering of a small wire will be relatively greater than that of a large wire, if the radial thickness of the insulation is the same in both cases.

28. Ampere-hours.—As shown at the end of § 25 a coulomb is a definite quantity of electricity, comparable to a quantity of any ordinary matter, and it is equal to 10^{-1} absolute C.G.S. units of electricity (*see* Table 1, § 2). In practice, however, it is more convenient to regard the coulomb as the quantity of electricity due to a flow of 1 ampere in one second, *i.e.* an 'ampere-second.' More commonly, quantities of electricity are expressed in 'ampere-hours,' the ampere-hour (1 Ah = 3 600 C) being in fact the practical unit of quantity of electricity.

The term ampere-hour is used in the charging and discharging of batteries, electroplating, or any other electro-chemical process. Take, for example, a battery consisting of three motor-car 'ignition cells,' having a working pressure of 6 V; the pressure, be it noted, is 2 V per cell without any regard to their size (§ 431, Vol. 2). A particular size, from a catalogue, is stated to have a 'capacity' of 60 Ah. If the working current is kept within recognised limits the 60 Ah could be given by a current of 2 A for 30 hours or 1 A for 60 hours, and so on; the capacity of the cells for discharging would in actual practice be slightly larger as the current decreases and the time increases, but this may be waived for the present. The battery in question would ordinarily be charged at the rate of 4 A for a period of about 15 hours, after a complete discharge within the allowable limits. This affords an opportunity for another illustration of the working of Ohm's Law. Suppose that the owner desires to buy a small generator for charging these cells. Now the pressure of the three cells, as stated above, is 6 V, and this pressure is a 'back E.M.F.' in direct opposition to the pressure of the generator. If therefore the latter were incapable of a greater pressure than 6 V the two pressures would exactly balance, and no current would flow. In point of fact the generator pressure would, towards the end of the charging process, have to rise nearly to 9 V in order to force 4 A through the cells. There is no contradiction of Ohm's Law here; the effective pressure E is in this case the *difference* between the two opposing pressures of generator and cells, and it must be sufficient to overcome the resistance R made up of the internal resistance of the cells and the external resistance of the circuit; *i.e.* $I = (E - e) / (R + r)$. Returning, after this digression, to the consideration of ampere-hours, let us assume that the applied pressure in any particular case is sufficient to overcome the opposing pressure of the cell or plating bath, etc., so that a current will flow through the latter; the total electro-chemical effect of this current then depends on the number of ampere-hours. For example, the international definition of an ampere, already referred to in § 3, states that under the conditions laid down it will deposit silver from silver nitrate at the rate of 0·001 118 of a grm. per sec. or 4·024 8 grms. per hour.

The weight of metal deposited electrically from a solution per ampere-second or coulomb is different for different metals, but is a physical constant (the 'electro-chemical equivalent') for each particular metal (§ 970, Vol. 3).

Effective, Virtual, or R.M.S. Values.

29. Effective Value of a Varying Pressure or Current.—An unvarying electric current or pressure is easy to define (§ 3), but there is an obvious difficulty when we come to consider an alternating current or pressure the instantaneous values of which rise from zero to a positive maximum, decrease to zero, rise to a negative maximum, and again return to zero (§ 11). The algebraic average of a symmetrical wave is clearly zero; in other words, as much current flows in one direction during one half-cycle as flows in the other direction during the next half-cycle. For this reason alternating current as such is useless for electro-chemical work (battery charging, electroplating, etc.) which depends upon quantity (ampere-hours) of electricity flowing in a definite direction (§ 28). If, however, the alternating wave be 'rectified' (§ 13 and § 415, Vol. 2) we obtain a more or less discontinuous unidirectional current, the effective value of which for electro-chemical purposes is represented by the mean ordinate of the rectified wave. This is the only connection in which the mean or average value of an alternating wave has any practical importance, and it will be seen that it is the average value of the half-wave which is then of importance—not the average of the complete wave, which is zero.

The heating effect of an electric current varies with the square of the current (§ 49) and, in general, the power dissipated by an unvarying current I (amperes) flowing through a resistance R (ohms) is: W (watts) = I^2R (§ 17), *i.e.* the power varies with the square of the current. For this reason, the effective value of an alternating current is defined as being numerically equal to the unvarying (direct) current which produces the same heating. A hot-wire ammeter (§ 99) is equally correct for measuring continuous or alternating currents.

Referring to Fig. 6, I represents an alternating current of ideal, sinusoidal wave form. The power or heating corresponding to any instantaneous current i (*whether positive or negative*) is proportional to i^2 and is always positive, *i.e.* the curve I^2 represents instantaneous heating effect and consists of a series of positive loops. The mean ordinate of I^2 is represented by the line I_e^2 and represents the 'mean-square' value of the current I. Taking the square root of I_e^2 we obtain I_e the 'root-mean-square' value of I, and this is clearly the value of the unvarying current which produces the same heating as the alternating current I. In other words, I_e is the 'effective' value of the alternating current, and is sometimes called the 'virtual' value or the 'root-mean-square' (R.M.S.) value. The term root-mean-square is best, in that it is self-explanatory.

The R.M.S. value of any wave form may be found by the above-described combination of graphical and numerical working, but the wave forms of all commercial A.C. supplies are close approximations to a sine wave, the average and effective values of which are geometrical constants.

30. Average and Effective Values of Sine Waves.—The *average value* of any sine wave, *i.e.* the arithmetical average of its instantaneous ordinates throughout a half-cycle, is equal to its maximum value × 2 / π. Thus, referring to Fig. 6,

$$I_a = 2I_m / \pi = 0{\cdot}64 I_m \text{ (nearly)}.$$

The useful value of the alternating current I, when rectified, for electro-chemical work would be $0{\cdot}64I_m$ if both half-cycles were utilised, and $\frac{1}{2} \times 0{\cdot}64I_m = 0{\cdot}32I_m$ if only the alternate half-cycles were utilised (*see also* Chapter 17).

The *effective, virtual or R.M.S. value* of any sine wave is equal to the maximum value / $\sqrt{2}$. Thus, in Fig. 6,

$$I_e = I_m / \sqrt{2} = 0{\cdot}707 I_m.$$

The *form factor* of any periodic wave is defined as the ratio of its effective to its average value, hence the form factor of a sine wave

$$= \frac{I_m}{\sqrt{2}} \times \frac{\pi}{2I_m} = \frac{\pi}{2\sqrt{2}} = 1{\cdot}11.$$

The form factor is a useful means of comparing different wave forms (*see also* § 34). Another factor, which is also useful in this connection, is the *peak* or *crest factor*, *i.e.* the ratio of the maximum to the effective value of the wave. The crest factor of any pure sine wave is $\sqrt{2} = 1 \cdot 414$. The crest factor of the A.C. voltage used to test cable insulation should not exceed 1·5.

Table 5 gives an instructive comparison between the above-mentioned constants for different wave forms. In practice, wave forms are generally determined by oscillograph (§ 118).

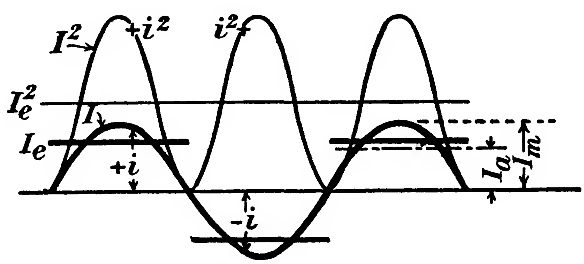

FIG. 6.—Effective value of alternating current.

TABLE 5.—*Constants for Different Wave Forms.*

Wave Form.	Average Value (Half-cycle).	Effective Value.	Form Factor.	Crest Factor.
Sinusoidal .	Max × $2/\pi$ = max × 0·64	Max/$\sqrt{2}$ = max × 0·707	1·11	1·414
Rectangular .	Max × 1·00	Max × 1·00	1·00	1·00
Triangular .	Max × 0·5	Max × 0·577	1·15	1·74
Semi-circular	Max × 0·785	Max × 0·816	1·04	1·23

31. Maximum Pressure and Current.—While the minimum value of a sinusoidal alternating pressure or current during each period is zero, the maximum instantaneous value is the virtual or 'root-mean-square' value multiplied by $\sqrt{2}$ or 1·41. In the case of alternating pressures the maximum value is important, as, although only instantaneous, it tends to break down the insulation of the circuit (§ 298). Thus if the pressure is said to be 220 V —*i.e.* the virtual or root-mean-square pressure as shown by a correctly calibrated voltmeter—then the maximum value will rise twice in each period, to 220 × $\sqrt{2}$ or 312 V. If the wave is more pointed than a sine wave the maximum value may even be considerably higher (see Table 5). The maximum value is also of importance in relation to electric shock, for at the same virtual pressure of supply the shock pressure obtained on an alternating circuit is $\sqrt{2} = 1{\cdot}4$ times that on a continuous current system with the corresponding effective pressure.

MAGNETIC EFFECTS OF ELECTRIC CURRENT.

32. Permanent and Electro-magnets.—The familiar 'horse-shoe' magnet is constructed of hardened steel, and when once magnetised retains its power of attracting iron or steel more or less indefinitely. It is used in certain classes of electrical measuring instruments and in 'magneto' generators, etc. Annealed iron and certain steels, on the other hand, are incapable of retaining magnetism, although they can be very powerfully magnetised by suitable means involving the expenditure of power. If a number of turns of insulated wire are wound round a soft iron core, and a current is then passed through this 'magnetising coil,' the core becomes strongly magnetic for so long as the current is flowing. By varying the intensity of current the strength of the magnetism can be altered (§ 42); in the case of alternating current the magnetism is constantly altering (§§ 34, 39). When the current ceases the magnetism almost entirely disappears. Into the elements of magnetism it is not necessary to go, as this knowledge is assumed; it must, however, be pointed out that a magnet must necessarily always have a north-seeking pole and a south-seeking pole, whatever its shape or construction. If it is an electro-magnet the relation between the polarity and direction of the magnetising current is fixed, and will be seen at once from Fig. 7, from Professor Thompson's *Elementary Lessons*. It matters nothing whether the turns are wound right- or left-handed, or what the shape of the iron core is. The arrows show the direction of the current, from + to −, or positive to negative.

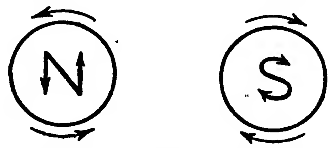

FIG. 7.—Polarity of electro-magnet.

A wire, whether straight or bent into a loop, always creates a magnetic field around it when it is carrying a current, and an iron core serves to augment the strength of this magnetic field. In considering the field created by a wire, Maxwell's 'corkscrew rule' is useful, and it will be found to apply to the conditions shown in Fig. 7. The rule runs: The direction of the current (from + to −) and that of the resulting magnetic force (from N. to S.) are related to one another as are the rotation and forward travel of an ordinary right-handed corkscrew. An alternative means of memorising the relationship between polarity and direction of current circulation is provided by the fact that arrow-heads (directed outwards) on the tails of the letters N. and S. indicate the direction of current rotation producing north and south polarity respectively.

This magnetic effect in conductors is by no means negligible. A case cited in § 327 shows that it may have serious effects on overhead lines, and it is a factor of primary importance under short-circuit conditions (§ 338). It frequently gives rise to errors in electrical instruments placed too near switchboard conductors carrying heavy currents (§ 92). It also causes the apparent rise of resistance known as skin effect (§§ 38, 309, 637, Vol. 2; and § 905, Vol. 3), which is most marked in steel conductor rails on electric railways.

Apart from the use of electro-magnets in dynamo-electric machinery and instruments, they are also used extensively for their direct effect in attracting iron or other paramagnetic metals; the practical applications vary from lifting magnets (§ 806, Vol. 3), for raising girders and the like, whether on land or below water, to the extraction of splinters from the human body. Until recently the latter use was mainly confined to the oculist, but of late giant electromagnets, taking several kilowatts, have been used in hospitals for extracting shell-splinters and ferro-nickel cased bullets. While iron and steel are by far the most important, there are other metals, especially nickel and cobalt, which are paramagnetic in a less degree; substances which are repelled from a magnet are called diamagnetic, and include bismuth, antimony, and many others.

33. Polarity (Direction of Flow) of Current.—The direction of a current is a matter of convention, for the work of the engineer is not seriously affected by the truth or otherwise of the modern electronic theory of matter, and it matters little to him whether there is an actual transfer of corpuscles or merely a molecular or ultra-molecular vibration around the conductor. The adopted convention concerning the direction of current flow arose from the consideration of the primary cell, and is explained in that relation in § 127. The positive pole of any other generator is taken to be that which behaves in the same way as the positive pole of a battery. Since the current in any conductor produces a magnetic field, it will, like any other magnet, deflect a compass needle to one side or the other according to its polarity. This property enables the conventional direction to be determined by Ampère's rule, *viz.:* Suppose a man swimming in the wire with the current, and that he turns so as to face the needle, then the North-seeking pole of the needle will be deflected towards his left hand. A useful old mnemonic in this connection is Crompton's SNOW rule; *viz.:* Place a compass needle under a wire placed in the meridian, and the current entering at South turns the North-seeking pole of the needle Over to West.

34. **Hysteresis.**—If a core be magnetised by alternating current it is alternately magnetised in one direction, demagnetised on the reversal of the current wave, and then magnetised in the opposite direction. These cycles continue so long as the current is maintained, and have the same periodicity as the current, *i.e.* generally 50 cycles per sec. (§ 12); but the magnetic changes lag slightly behind the current reversals. The abrupt reversal of the direction of the magnetism, involving a change in the molecular arrangement of the iron, involves also a certain expenditure of power known as the 'hysteresis watts.' The energy so wasted heats up the iron core. Such losses occur in transformers and all alternating current machinery, and to a lesser degree in continuous current machines (in those parts of the magnetic circuit which are subjected to varying or alternating magnetic flux).

The power dissipated by hysteresis is proportional to the frequency (cycles per sec.) and varies approximately with the 1·6th power of the maximum flux density in the iron. Since the *maximum* flux density is here involved the hysteresis loss is affected by the form factor (§ 30) of the voltage wave; the hysteresis loss is less with a peaked wave than with a flat-top wave for the same effective voltage.

35. **Induction.**—So long as the magnetic field of a conductor, or a solenoid, or an electromagnet is steady and uniform in value, it produces no E.M.F. in its own or any neighbouring circuit at rest in relation to it; but as soon as there is a change in the strength of the field, no matter how it is produced, an electromotive force is set up in every conductor within the varying field. In a continuous current circuit, such an E.M.F. can only be

produced by varying the strength of the current or by moving one of the elements in the circuit in relation to the other; but with alternating current there must necessarily be induced a continually varying E.M.F., whether the elements of the circuits are stationary or in relative motion. Thus when a conductor is moved across the lines of force of a magnet or *vice versâ* (as in a generator, § 132) an electromotive force is 'induced' in the conductor; and if the conductor makes a closed circuit, a current flows in it in consequence of this pressure. Again, if a conductor is wound upon an electromagnet [as in a transformer (§ 391, Vol. 2) or induction coil] and the strength of the magnetism alters (§§ 32, 34), an E.M.F. is induced. Similarly each of two conductors carrying currents varying in magnitude will mutually induce an E.M.F. in the other; and a varying current in a single conductor will induce a secondary E.M.F. in opposition to itself. In all such cases except the last there is no metallic connection between the circuits; the electromagnetic induction takes place across an air-gap. The essential condition is that the wire in which an E.M.F. is induced shall cut, or be traversed by, varying magnetic lines of force.

The relation between the lines of force, direction of motion, and direction of induced current is given by the following rule: * Extend the forefinger and thumb of the *right* hand at right angles, and the middle finger at right angles to the plane containing the forefinger and thumb; then, if the forefinger be set in the direction of the magnetic field (N. to S.), and the thumb in the direction of motion, the middle finger will indicate the direction of current flow (+ to −).

This property of self-induction has been compared with inertia; it is that property of electricity which causes it to resist any change in its rate of flow. It will be seen that three separate cases may arise. First we have the induction in a single conductor due to a magnetic field around it, which is for some reason varying, but with which we are not for the moment concerned;

* *Note.*—This useful rule was devised many years ago by Sir Ambrose Fleming, F.R.S., together with the mnemonic: 'FORefinger, force; thuMb, motion; mIddle, induced.' As thus used with the *right hand*, the rule covers induction of current in a moving conductor, *i.e.* is a dynamo rule. If the *left hand* be used in the same way the fingers and thumb give the relation for a current-carrying conductor moving in an electric field, *i.e.* for a motor.

secondly, the mutual induction of two conductors each affecting the other; thirdly, the self-induction of a conductor on itself, which corresponds to inertia in matter. In every case, as with mechanical reactions, the tendency is for the induced E.M.F. to resist the change which produces it. A concrete example, which can be put to the test, is ready to hand in the field magnets of an ordinary shunt-wound generator, or any other large electromagnet. If the full pressure the coil is intended to bear is applied suddenly to the terminals, the growing field produces a counter E.M.F. opposing the applied E.M.F., and it is some seconds before the current attains its full strength. On the other hand, if the circuit be opened suddenly when the magnet is at full strength, the field cannot vanish immediately. As it dies down, it produces an E.M.F. tending to keep the current going. This E.M.F. may be enormously in excess of the applied E.M.F., and may cause a serious arc at the switch contacts, or even break down the insulation of the field coils. If the operator is careless he may receive a most unpleasant shock in this way from a circuit which, in ordinary working, could be handled with impunity.

It follows from what has been written above that if two wires close together are carrying the same current in opposite directions, their magnetic and inductive effects balance and neutralise one another. This fact is utilised to prevent induction in telegraph or telephone lines carried near power circuits (§ 335). If it is desired to wind a coil of wire that shall be 'non-inductive,' the wire is doubled from the middle point, bringing the two ends together; it is wound thus on the bobbin, so that each turn consists of two mutually antagonistic wires carrying the same current in opposite directions.

36. Unit (Henry) of Induction.—The self-induction of a winding or circuit, or the mutual-induction between two windings or circuits, is generally expressed in terms of the E.M.F. induced by a change in current at the rate of 1 A per sec., the unit of self- or mutual-induction being the 'henry.' Thus the self-induction of a circuit is 1 henry if current changing at the rate of 1 A per sec. induces an E.M.F. of 1 V opposing the current change. Similarly, the mutual induction of two circuits is 1 henry if current changing in one circuit at the rate of 1 A per sec. induces an E.M.F. of 1 V in the other circuit.

An alternative definition is that the self-induction of a circuit is numerically equal to the number of 'linkages' per ampere, divided by 10^8. The 'linkage' = number of magnetic lines × number of turns in coil, etc., with which they are linked. Both definitions lead to the same result.

37. **Wattless Currents.**—In a D.C. circuit, current flow inevitably involves power expenditure (§§ 17, 48), but this is not necessarily the case in an A.C. circuit. In a choking coil (§ 45), for instance, the effect of self-induction (§ 35) is to cause the current wave to lag nearly 90° out of phase with the pressure wave. Similarly, the primary coil of a transformer, although connected directly across the full supply pressure, only takes power approximately in proportion to the power drawn off at the secondary. If the secondary circuit is open, then the choking effect of self-induction causes the primary current wave to be out of phase with the primary pressure wave; the current is there, and is magnetising the core at each cycle, but the power amounts to very little in true watts (§§ 12*a*, 56). In the limiting case, when the lag of current on voltage is 90 degrees, the current is said to be a 'wattless current'; the volt-amperes may have a high value and yet the true watts in the circuit are negligible. The importance of this peculiarity will be seen when dealing with A.C. transmission of power (Chapter 14).

The diagrams in Figs. 8 and 9 illustrate the distinction between watt and wattless currents. (*See also* §§ 56, 154.) Fig. 8 represents the case where there is only ohmic resistance present in one phase of an alternating current circuit; consequently the current wave is in step or 'in phase' with the pressure wave and the power is the product of volts and amperes, as shown by the tall curve. In the first half-cycle both current and pressure are positive, while in the second half both are negative, so that the product is in both cases positive. In Fig. 9 the other limit is reached and the current lags 90° behind the pressure. The resulting power curve, obtained by the product of corresponding instantaneous values of pressure and current, is partly positive and partly negative, in quarter cycles; the power consumed during one quarter cycle is returned to the circuit in the next. It will thus be seen that the generator or transformer must be built to generate and withstand the full pressure; its coils must be able to carry the full current; the I^2R losses occurring are as usual; but the useful output is nil. (*See also* § 12*a* and Chapter 5).

38. Skin Effect.—Any current-carrying conductor may be regarded as consisting of a number of filaments, each carrying part of the total current and each producing round itself a magnetic field which 'links' (§ 36) with other filaments in the conductor. The number of linkages is greater for the central filaments than for the filaments in the surface or skin of the conductor, hence the self-induction is greater for the central filaments, and there is a tendency for current to concentrate in the outer layers of the conductor. As a result, the effective resistance of the conductor is greater to alternating current than to direct current, quite apart from the question of reactance

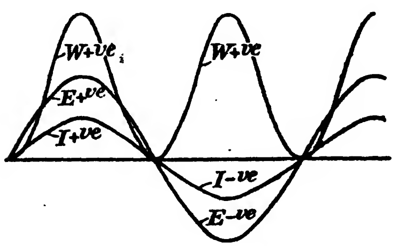

FIG. 8.—Current and voltage in phase.

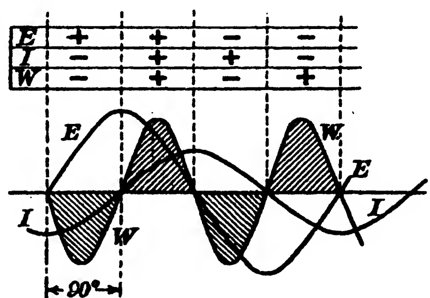

FIG. 9.—Current 90° out of phase with voltage.

(§ 44). This so-called 'skin effect' is more pronounced in magnetic conductors (*e.g.* steel wires and rails; § 309 and §§ 901-905, Vol. 3) than in non-magnetic conductors, because the self-induction is greater in the former case. For the same reason, skin effect is more pronounced the larger the cross-section of the conductor and the higher the frequency of the current. At very high frequencies, such as those concerned in lightning discharges, skin effect increases the effective resistance to such an extent that the high frequency current will break down an air-gap (leading to an earth connection, § 346) rather than flow through a reactance coil which offers very low resistance to direct current or to alternating current of commercial frequency.

39. Eddy Currents.—An E.M.F. is induced in any conductor situated in a varying field (§ 35) whether the variation is due to the conductor moving from one part of the field to a part where the magnetic flux density is greater or smaller, or whether the variation is due to variations in the value of current in a neighbouring conductor. If the conductor in which the E.M.F. is induced forms part of a regular electric circuit there is a definite current flow in the latter, but if the conductor is simply a mass of metal—such as an armature core, an iron girder, or a metal tank or case—the induced E.M.F. causes currents to circulate locally in the metal, these currents being aptly termed 'eddy currents.' The magnitude of the induced E.M.F., and therefore of the eddy currents, is greater the stronger the magnetic field and is therefore increased by the presence of iron. Also, for given field variation, the E.M.F. induced is greater the higher the frequency. The eddy current produced by given induced E.M.F. is lower the higher the resistance of the path through which the current flows. One method of reducing eddy currents is therefore to use material of higher electrical resistance for the parts concerned. For this reason high electrical resistance is desirable in the sheets used for armature and transformer cores (§ 82). The eddy currents are dissipated in the form of heat and the loss which they occasion varies with I^2R (§ 49), hence reducing the current I (by increasing R) reduces the loss to a greater extent than it is increased by the increase in resistance R. For example, if I be halved by doubling R, the value of I^2R is reduced to half its original value.

Eddy currents are induced in conductors carrying alternating current as well as in all adjacent metal. They may produce a dangerous degree of heating, they may cause errors in instrument readings, and in all cases they represent wastage of energy. A useful application of this is to be found in the 'eddy current brake,' which is often used as an artificial load when testing electric motors. Eddy currents are induced in a metal disc driven by the motor and the energy dissipated by these currents constitutes a load for the motor. Under ordinary circumstances, however, eddy currents are objectionable, and they may be reduced by excluding iron (where possible) from the path of the varying field, by using non-magnetic material where applicable (§ 84), and by interrupting or reducing the cross-section of the paths for eddy current flow by saw-cuts. If mechanical continuity be required the saw-cuts are filled with insulating material. Eddy currents in armature and transformer cores are reduced by building the latter from thin sheets of special steel (§ 82) insulated from each other by varnish or paper. The plane of the sheets is parallel to the direction of the main field so as not to interrupt the flow of the latter. The laminations are clamped together by bolts which are insulated to prevent short-circuiting the laminations. If slots, etc., in the laminations be filed the laminations may be short-circuited by particles of metal, and the relatively heavy current flowing through these particles may cause such heating as to damage the insulation on adjacent windings.

MAGNETIC CIRCUITS.

40. Magnetic Field.—A magnetic field is the region round a magnet or current-carrying conductor (§ 32) within which magnetic effects are exerted on magnetic materials (§ 32) or electrical conductors. The unit strength of magnetic field (Table 1, § 2) is represented conventionally by 1 line (of magnetic flux) per sq. cm.; this, the unit of 'flux density,' is termed the 'gauss.' *

In every magnet a north pole is necessarily associated with a south pole and similar conditions obtain in the magnetic fields established by electric currents, so that magnetic flux has always a closed magnetic circuit. Unlike the electric circuit, the magnetic circuit cannot be 'opened' because, although some substances have a higher permeability (or magnetic conductivity) than others, there is no magnetic insulator.

41. Magnetic Circuits.—The magnetic circuit of a permanent magnet consists of the metal of the magnet itself and the air path between its poles; the 'magnetomotive force' (M.M.F., § 43) driving the flux round this path is determined by the pole strength of the magnet. Such circuits are found in permanent magnet generators ('magnetos') used for medical purposes, for ignition, and for small lighting sets, but in motors and generators for commercial supply the magnetic circuit comprises the field and armature cores and the small air gap between them, whilst the M.M.F. is provided by electromagnets (the field cores and their windings).

In any magnetic circuit the conditions are largely analogous to

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* There is a field of 5 gauss at 40 cm. from a very long straight conductor carrying 1 000 A, the return conductor being a long way off. A field of 10 gauss is produced at and near the centre of a plane circular coil 100 cm. diameter and of 800 ampere-turns (§ 42). See definition in Table 1, § 2.

those in an electric circuit, and may be stated in a form similar to Ohm's Law, *viz.*:—

$$\text{Flux} = \frac{\text{Magnetomotive Force}}{\text{Reluctance}}.$$

The magnetic flux, or total number of 'lines of force' in the magnetic circuit, corresponds to the current. The magnetomotive force, corresponding to E.M.F., is proportional to the pole strength in the case of permanent magnets and, in the case of electromagnets, is proportional to the ampere-turns on the magnet, upon which the flux depends. The reluctance is the resistance of the magnetic circuit to the passage of the lines of force; it is not generally constant, but varies with the degree of magnetic saturation (§ 43).

42. **Magnetomotive Force: Ampere Turns.**—In any form of apparatus using electromagnets the phrase 'ampere-turns' (A-T) is used for the product of the current in amperes and the number of complete convolutions or turns of the wire carrying it. This is the practical unit of magnetomotive force. The magnetomotive force (in 'gilberts')* produced by a solenoid of T turns carrying a current of I amperesis given by the formula $4\pi IT/10$ and thus increases indefinitely in direct proportion to both the current and the number of turns. Due to increasing reluctance (§ 43), however, the strength of field produced is not proportional to the current when the iron approaches magnetic saturation.

Under all practical conditions the magnetising effect of a certain number of ampere-turns (A-T) is the same whatever the value of the terms I amperes and T turns in the constant product IT; thus 100 turns of a wire carrying 1 A will have the same magnetising effect on a bar of iron within the coil as a single turn carrying 100 A; in each case there are 100 ampere-turns.

43. **Reluctance.**—The reluctance of a magnetic circuit corresponds to the resistance of an electric circuit. It increases in proportion to the length of the circuit and varies inversely with the cross-sectional area of the circuit. Whereas 'specific resistance' (§ 18) is used as a measure of the resistance offered by various materials to the flow of electric current, the corresponding term used in connection with magnetic circuits is 'permeability' which is analogous to the conductance (§ 18) of an electric circuit.

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* *See* Table 1, p. 2. A M.M.F. of 1 gilbert is produced by $\frac{10}{4\pi} = 0{\cdot}796$ ampere-turns; 1 gilbert/cm. = 2·02 A.T./in.

The permeability, μ, of a material is defined as the ratio of the flux density (or 'magnetic induction'), B, produced in that material to the flux density, H, produced in air by the same magnetising force; *i.e.* $\mu = B / H$. The permeability of iron may be several thousand times that of air (which is taken as unity), but the permeability varies with the kind of iron (§§ 81-84) and with the flux density therein, *i.e.* with the degree of magnetic saturation.

In the case of a solenoid or a coil of wire without any magnetic core, the strength of the field produced is proportional to the current, *i.e.* to the number of ampere-turns, without any limit; but when an iron core is inserted in the coil this proportionality drops as the core becomes incapable of further saturation, until at last the increase is only that due to the coil alone. Thus according to the requirements of each case an electromagnet may be designed to work either saturated, or approaching saturation, or at a point where the change in the current produces the maximum change in the field strength.

The reluctance, S, of a magnetic circuit (= M.M.F./Flux) is given by the formula: $S = l / (a\mu)$; where l = length of magnetic circuit in cm., a = cross-section of circuit in sq. cm., and μ = permeability *at the flux density produced in the iron.* Because of the variation in permeability with the flux density, the flux produced by a given number of ampere-turns can only be determined by successive approximations. It is necessary first to determine approximately the flux in order that a suitable value of permeability may be assumed. On the other hand, the ampere-turns required to produce a certain flux in a certain circuit can be determined at once because the flux density is known and the corresponding permeability can be taken from tables or curves for the material concerned (§ 82).

The reluctance of a composite magnetic circuit consisting of parts of lengths $l_1, l_2 \ldots$; cross-sections $a_1, a_2 \ldots$; and permeabilities $\mu_1, \mu_2 \ldots$ is given by—

$$S = \frac{l_1}{a_1\mu_1} + \frac{l_2}{a_2\mu_2} + \ldots$$

Knowing that the M.M.F. is $4\pi IT / 10$ (§ 42) we have the flux, Φ, given by—

Flux, Φ = M.M.F. / S (§ 41)

$$= \frac{4\pi IT / 10}{\left(\frac{l_1}{a_1\mu_1} + \frac{l_2}{a_2\mu_2} + \ldots\right)}.$$

As the practical problem is generally to determine the ampere-turns, IT, required to produce stated flux, this formula may be put in the form—

$$\text{Ampere-turns,} \quad IT = \frac{10}{4\pi}\Phi\left(\frac{l_1}{a_1\mu_1} + \frac{l_2}{a_2\mu_2} + \ldots\right)$$
$$= 0{\cdot}8\,\Phi\left(\frac{l_1}{a_1\mu_1} + \frac{l_2}{a_2\mu_2} + \ldots\right).$$

Note.—It is usual in practice to plot curves between B and $\frac{10H}{4\pi}$ (*i.e.* the ampere-turns per cm. length, for $\frac{10H}{4\pi} = \frac{10}{4\pi} \cdot \frac{4\pi IT}{10l} = IT/l$). From such curves (Fig. 13, § 81) it is possible to read off at once the ampere-turns required per cm. length of the material concerned, to produce a flux density B in that material.

In most cases a magnetic circuit consists mainly of iron or special steel with an air-gap; as *e.g.* in a motor or generator, where the circuit runs from the north pole of the magnet, across the air-gap, through the iron core of the armature, across the air-gap again to the south pole of the magnet, and thence back to the starting-point through the yoke. The air-gap greatly increases the reluctance, and is therefore reduced to as small dimensions as may be practicable. Some lines of force will inevitably pass from pole to pole without going through the armature core, and will therefore produce no useful effect; these constitute 'magnetic leakage.'

Ohm's Law for A.C. Circuits.

44. Resistance, Reactance, and Impedance.—Ohm's Law as stated in § 17 is only applicable when the resistance, electromotive force and current are unvarying. The law can be applied to all direct-current circuits if both internal and external resistance be taken into account (§ 21) and if allowance be made for back-E.M.F., where present (§ 28), but it can rarely be applied to alternating current circuits in its simple form, because the effective resistance (called the "impedance"; see below) to current flow in an A.C. circuit is generally greater than the ohmic resistance of the circuit.

The resistance of a conductor in ohms is an inherent property of the material, and is independent of the direction of the current and of its variations; but when dealing with alternating currents another factor comes in, called 'reactance,' which has the effect of apparently increasing the resistance—so that Ohm's Law as stated in § 17 requires to be modified. In explaining the term 'induction' in § 35 the fact is brought out that, where the value of the current in a conductor is alternating, an E.M.F. is induced, and that this E.M.F. tends constantly to oppose the current which brought it into being, and so to reduce its value; this property may be compared in its effects with inertia in ordinary matter. With a steady continuous current there is no such action. This opposing E.M.F. differs in phase from the current inducing it, so that it has the effect not only of reducing that current in amount but also of altering its phase in relation to the main or 'impressed' pressure wave. A reference back to § 11 and § 12*a* may help to explain matters. The dotted line in that illustration shows the sine wave of an alternating current, produced by the impressed E.M.F. shown in the full curve. At the moment the current wave is at a crest, whether positive or negative, the rate of change of its instantaneous value is practically nil, and therefore the change of field strength produced by it is nil, so no E.M.F. of self-induction is being generated. If, therefore, the wave of induced counter-E.M.F. were plotted, it would be on the zero line at each crest of the current wave. On the contrary, at the moment when the current wave is crossing the zero line its rate of change, and consequently that of the field produced also, is at the maximum; hence at these points the wave of counter-E.M.F. would be at its crest. Furthermore, as this E.M.F. opposes the current producing it, it will be rising towards a positive maximum when the current is falling towards zero, and descending towards zero when the current is rising to a negative maximum.

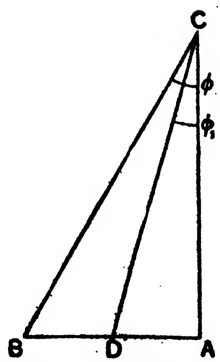

FIG. 10.—Graphical diagram of alternating E.M.F. and resistance.

(ii) A graphical representation will help to make the matter clearer. In the right-angled triangle ABC (Fig. 10) AC represents the E.M.F. required to send the current through the ohmic resistance of the circuit, and AB represents the E.M.F. required to send the current against the self-induction or reactance of the circuit. Then CB will represent, on the same scale, the total E.M.F. which must be applied, in order to produce the given current against the total 'impedance,' or apparent resistance, of the circuit. The angle ϕ is the angle of lag of the current behind the E.M.F.

Similarly, by altering the scale, the three sides will represent true or apparent resistance, since the resistance is the E.M.F. divided by the current in the circuit. On this basis AC represents the ohmic resistance of the circuit and AB represents the reactance, or apparent resistance due to self-induction; consequently BC represents, on the same scale, the total 'impedance' or apparent resultant resistance of the circuit, which will take the place of R in Ohm's Law. Whether the sides of the triangle represent volts or ohms, we have that $BC = \sqrt{(AB^2 + AC^2)}$. When dealing with resistance values this may be expressed—

$$\text{Impedance} = \sqrt{\text{resistance}^2 + \text{reactance}^2}.$$

The value of the reactance (expressed in ohms) is $2\pi fL$, where f is the number of periods per second, or the frequency and L is the coefficient of self-inductance expressed in henries; the value of L is worked out in the case of transmission lines in §§ 299 and 302, where the formula will be found. In practice, inductance is generally expressed in millihenries = 1 / 1 000 of a henry (mH).*

For a circuit containing only resistance and inductance Ohm's Law becomes—

$$I = \frac{E}{\sqrt{[R^2 + (2\pi fL)^2]}}.$$

If there is also capacity in circuit an additional term is required in the denominator of the fraction, as explained in § 46.

In some cases, *e.g.* where rapid variation of the field current of a motor or dynamo is required for purposes of speed or voltage control, it is necessary to take into account the fact that the current in an inductive circuit does not instantly assume the steady value corresponding to the applied voltage. If a constant D.C. voltage E be applied to a circuit of constant resistance R ohms and constant inductance L henries, the value (in amperes) of the current t seconds after closing the circuit is: $I = \frac{E}{R}(1 - \epsilon^{-ut})$; where ϵ = the base of natural logarithms = 2·718 approx.; and $u = R / L = 1 /$ (the 'time constant' of the circuit). The '*time constant*' $= L / R$, and is the time required for ut to become unity; the current then $= (E / R)(1 - \epsilon^{-1}) = (E / R)[1 - (1 / 2{\cdot}718)] = (E / R)(1 - 0{\cdot}368) = 0{\cdot}632\, E / R$ or 63·2 % of the steady current E / R.

Similarly, the time constant of a circuit containing a capacity C farads in series with a resistance R ohms is RC seconds, and is the time required for the voltage and charge of the condenser to reach 63·2 % of their steady values.

The greater the time constant of a circuit the longer it takes for steady conditions to be reached after applying an E.M.F. or changing the applied E.M.F.

45. Choking Coils.—It will be seen from the expression for impedance in the preceding paragraph that a circuit may have

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* *See* definition in Table 1, p. 4.

high impedance (*i.e.* high effective resistance) to alternating current though the ohmic resistance is very low. This is a fact of the highest practical importance. In a circuit of high impedance but low resistance, *i.e.* in a circuit which is practically all reactance: (i) There will be high voltage drop (given by $2\pi fLI$ (§ 44) if R be taken as zero) but very little dissipation of energy because the current is practically 90° out of phase with the voltage; *see also* § 37. (ii) Little opposition is offered to the flow of direct current, which is obstructed only by ohmic resistance and is unaffected by reactance. (iii) Less opposition is offered to the flow of low-frequency A.C. than to that of high-frequency A.C. because the reactance ($2\pi fL$) increases in proportion to the frequency. These three facts all find application in practice, as explained below.

A 'choking coil' consists of a winding of relatively low ohmic resistance with an iron core, which causes the inductance and therefore the reactance of the winding to be high. The reactance of the coil may be varied by altering the extent to which the core is inserted within the winding. Such a choking coil may be used instead of a ballast resistance in series with arc lamps (§ 595, Vol. 2) or, in general, it may be used to reduce the effective voltage in any A.C. circuit practically without loss of energy. The actual dissipation of energy is given by I^2R (§ 49), hence R should be kept as low as possible. Another application of choke coils is to obstruct high-frequency discharges (as in lightning protection, § 346). For this purpose the coil is connected in series with the line carrying the normal current (D.C. or A.C. of commercial frequency). In order that it may cause only low-pressure drop its resistance and (in A.C. service) its reactance are kept low. This is done by using only a few turns of large wire without an iron core. Though the reactance is very low when $f = 50$ or 100 cycles per sec., as in commercial supply, it is very high at the high frequencies of lightning and similar surges, hence the latter find it easier to jump an air gap (provided for the purpose) and flow to earth than to penetrate the choking coil and reach the circuit which this coil protects.

46. Capacity and Condensance.—Capacity in a circuit is that property in virtue of which a charge of electricity can be stored up in it in the form of electrostatic stress. Thus such a stress exists between the two coatings of a charged Leyden jar or the two plates of a charged condenser, and when either is discharged a capacity current flows momentarily. A condenser may be compared to an air-vessel on the delivery pipe of a hydraulic ram, storing up some of the energy of each stroke at the moment and then delivering it back to the column of water out of phase with the ram stroke; at each cycle a certain charge of water enters and compresses the air and then is driven out again.

The capacity of a condenser, whatever the form of the latter, varies directly with the effective surface of the plates or electrodes, and the specific inductive capacity of the dielectric, and inversely with the thickness of dielectric between the plates. The *permittivity, specific inductive capacity* or *dielectric constant* ϵ of the dielectric is the ratio of the capacity of a condenser using this dielectric to that of the same condenser with air as dielectric. Values of ϵ for various substances are given in Table 7, § 73.

From primitive use in the laboratory, the condenser evolved into a useful adjunct for telegraph and telephone lines; and then, as A.C. power circuits developed, uses were found for it in heavy engineering. A valuable paper * on this subject summarises the most important uses of condensers for electric power circuits as follows :—

(*a*) Power factor improvement.
(*b*) Surge reduction.
(*c*) H.-T. line tapping.
(*d*) Carrier current.
(*e*) Arc-suppression.
(*f*) Radio-interference suppression.
(*g*) All-electric radio apparatus.

Of these, (*a*)-(*f*) involve the direct connection of condensers to electric power circuits; while (*g*) includes their application in apparatus connected to such circuits, but usually with only an indirect connection of the condensers to the power circuit. These various applications imply, in general, at least different forms of condenser; and to some extent also different types of condensers as well—using these two terms to distinguish mere differences in physical form or shape from radical constructional differences of a more basic nature. Further, of the above applications, (*a*) (*b*) (*c*) and (*d*) are necessarily from their nature applications to A.C. circuits: while (*e*) and (*f*) may involve use on either A.C. or D.C. circuits; and (*g*) is almost exclusively D.C. as far as the voltage applied to the condenser is concerned.

The original Leyden jar has been replaced by condensers constructed for the most part with either mica or vacuum-impregnated paper. Mica is only available in sheets of restricted size (except in compound forms, § 74, II.) but paper can be used in rolls of any length.

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* Some applications of condensers to electric power circuits. P. R. Coursey. Paper read before the Inst. of Eng. Inspection, Oct., 1931.

(ii) The parallel wires of an overhead transmission line have a certain capacity, depending on their geometrical arrangement (§§ 304-306), and so have the conductors in a cable (§ 311). In these cases the 'charging current,' which is leading 90° in advance of the impressed E.M.F., may be of considerable importance, as will be explained in due course; the capacity in a cable or line may be likened to a very high resistance in *parallel* with the resistance and the reactance of the conductor, in that it does not appreciably affect the total impedance.

Where, however, capacity is in *series* with resistance (either alone or with reactance also) it must be taken into account (§ 480, Vol. 2). If resistance and capacity alone are present, the effect of the leading capacity current is to cause the resultant current to lead, instead of to lag behind, the E.M.F.; *i.e.* the result is exactly the opposite of induction. In Fig. 10, § 44, this would be shown by drawing AB, now the 'capacity reactance' or condensance, still at right angles, but in the opposite sense; and the angle ϕ would be on the opposite side of AC. If both inductive reactance and capacity reactance are in series with resistance they are in direct opposition (180° apart), and as both are expressed in ohms their difference is taken by vectorial or algebraic addition. In Fig. 10, after setting off the inductive reactance, AB, the capacity reactance would be set *back* from B along BA to a point D; and the line DC would then represent the net impedance; and angle ϕ_1 would then be the angle of phase difference, either lagging (as shown) or leading if the capacity preponderated and D were on the other side of A. In symbols the impedance is expressed as

$$\sqrt{R^2 + \left[2\pi fL - \frac{1}{2\pi fC}\right]^2},$$

the quantity $1 / 2\pi fC$ is the capacity reactance where C, the capacity, is expressed in 'farads.' Ordinarily capacities are expressed, for greater convenience, in 'micro-farads' or millionths of a farad (μF); an example is given in § 480, Vol. 2, in connection with the use of condensers for electric lighting circuits. If the two reactances exactly balance, the current will be in phase with the E.M.F. and the impedance will be the same as the resistance; this gives the conditions necessary for resonance or syntony in the circuit, which may cause an almost unlimited rise of pressure if the ohmic resistance is low enough.

47. Resonance or Syntony.—A combination of inductance and capacity in series has a definite rate of electrical oscillation or frequency of its own, and, if L and C have such a relation that this natural frequency coincides with that of the E.M.F., the E.M.F. rises just as the pendulum increases its swing if struck synchronously. Thus, consider a circuit consisting of a non-inductive resistance R of 5 Ω, an inductance L of 0·5 H, and a capacity C of 5·1 μF, all in series, with an E.M.F. of 100 V impressed on it, and ascertain at what frequency it will be resonant. This condition of 'critical frequency' is found when the inductance and capacity just balance, *i.e.* when $2\pi fL - 1/2\pi fC = 0$. This equation must be solved for f. Substituting the above values for L and C and expressing C in farads, the equation becomes $2\pi f \times 0{\cdot}5 - (1/2\pi f \times 0{\cdot}000\,005\,1) = 0$, from which $f =$ 100 periods per sec. Put in another way, the time interval between the crests of successive waves, or natural frequency, is $2\pi\sqrt{LC}$, which here equals $6{\cdot}28 \times \sqrt{0{\cdot}000\,002\,55}$ or 0·01 sec. giving 100 periods. The wave-length, that is the distance between the crests of successive waves, or between points of equal intensity of electric stress, is equal to the velocity of propagation multiplied by the time interval. Taking the velocity of propagation as equal to the velocity of light, the wave-length here will be $300\,000\,000 \times 0{\cdot}01$ or 3 000 000 m.

As the two reactances balance at the critical frequency, the current will be simply E/R or $100/5 = 20$ A, and it will be seen that if it were possible to reduce the ohmic resistance to zero,* the current (and therefore the pressure rise also) would be infinite. In the example chosen, the pressure across the condenser (which might be an underground cable) would be $I/2\pi fC = 6\,280$ V, and the pressure across the inductance would be $I \times 2\pi fL$, giving the same figure. (*See also* § 350.)

The above is a case of resonance of the fundamental frequency of 100 periods found for this circuit; but as the wave of an alternator is not a true sine wave, but contains superposed odd harmonics, these latter may also give rise to the phenomenon, and indeed do so more often in practice. What is, however, a danger to be guarded against in electrical engineering becomes a

* Ohmic resistance reduces the peak value of current or voltage in cases of electrical resonance, just as friction reduces the amplitude of mechanical resonance.

most valuable aid to the utilisation of high-frequency currents in wireless telegraphy and medical treatment; and it has even been proposed to utilise resonance in the transmission of power to extreme distances up to 1 000 miles by means of 'half-wave' and 'quarter-wave' systems (§ 318).

POWER AND WORK.

48. Current and Power; Watts.—The practical unit of electrical power (*i.e.* the rate of doing work) is the watt, of which the accepted definition is given in § 3, p. 46; if a pressure of 100 V, applied to the terminals of any apparatus, causes a current of 2 A to flow in it, then the power used in that apparatus is 200 W, and by Ohm's Law the resistance of the conductor carrying the current will be 50 Ω.

1 watt = 0·001 34 H.P. = 3·41 British thermal units (B.Th.U.) per hour = 0·73 ft.-lb. per sec. = 44·24 ft.-lbs. per min.

Note.—A British thermal unit is the quantity of heat required to raise 1 lb. of water 1° F. It is equal to 0·252 kg.-cal. A kg.-cal. or 'great calorie' is the quantity of heat required to raise 1 kg. of water 1° C. A 'therm' is 100 000 B.Th.U.

49. I^2R Watts.—As a general rule, when dealing with the power utilised or expended in heat in any circuit or apparatus, the power is more conveniently obtained by the derived formula (§ 17) Watts = I^2R, which in the above case gives us 4 × 50 or 200 W as before. This is the *rate* at which energy is being dissipated in the conductor, and while part of it will raise the temperature, part will be radiated away. Although the terms are synonymous, it is the custom to confine the use of the phrase I^2R to energy wasted uselessly in any piece of apparatus or in a line, while calling the power usefully employed $I \times E$ or IE. Confusion between power utilised and power lost in transmission is a fruitful source of misunderstanding, and a simple example may serve to remove this. Suppose two conductors to have a difference of potential of 100 V between them, which is maintained by a generator under all conditions: from terminals on these main conductors two wires, each having a resistance of 0·5 Ω, are led to an electric heater having a resistance of 9 Ω. The total resistance in this external circuit will therefore be 10 Ω, and, by Ohm's Law, the current will be 10 A. The total power in the circuit will be EI = 100 V × 10 A = 1 000 W or 1 kW. The power lost in the connecting wires is 10^2 × 1 or 100 W, and 10 V are lost in them. The power usefully employed is therefore 90 V × 10 A = 900 W, which brings the total up to 1 kW. This, however, is all dependent on the initial assumption that the generator *constantly maintains* 100 V pressure at the point where the circuit under consideration begins. If it is sufficiently powerful, and is driven by a suitable engine, this will be the case. But although designed to give 100 V pressure, the generator may be incapable of an output of 1 kW. For example, the source of power may be 50 small secondary cells, giving a pressure of 100 V on open circuit. If now the internal resistance of the battery has a value of 1 Ω, the total resistance in the complete circuit becomes 11 Ω, and *by no possibility* can more than 100 / 11 or, say, 9 A flow in it. The example given in § 21 will help to make this clear.

50. Kilowatts.—For convenience, the term kilowatt (kW) is used for 1 000 W in dealing with power on a large scale :—

1 kW = 1 000 W = 1·34 H.P. = 737 ft.-lbs. per sec.* = 56·86 B.Th.U. per min. = 7 040 torevs.†

746 W = 0·746 kW = 1 H.P. = 550 ft.-lbs. per sec. = 5 250 torevs = 42·4 B.Th.U. per min. = 2·28 lbs. water per hr., raised from 60° F. and evaporated at 212° F.

The output of a generator is expressed in kilowatts; thus a generator marked 100 V, 50 A would have an output of 100 × 50 / 1 000 = 5 kW. It is useful to remember that 1 kW supplied to a motor will generally produce about 1 brake horse-power at the pulley; in large motors the B.H.P. is somewhat higher in proportion.

51. Electrical Horse-power.—It has been often noticed that civil engineers, even those high up in the profession, are not clear on the significance of the International horse-power; *i.e.* they believe the *value* of the H.P. to differ according to where it occurs in a chain of conversions, instead of its being always equivalent to energy expended at the rate of 550 ft.-lbs. per sec. It may

* This is, strictly speaking, only true at sea-level and latitude 50°. Elsewhere the weight of a mass of 1 lb. varies. Consequently a string of decimals of a kilowatt, etc., is seldom accurate, apart from errors of instruments and other disturbing causes.

† *See El. Rev.*, Vol. 107, p. 917. 1 torev = 2π ft.-lb. per min. = 0·000 190 4 h.p., *i.e.* the power transmitted by a torque of 1 ft.-lb. at 1 r.p.m.

therefore not be amiss to give two examples employing the constants in the preceding paragraphs, on the basis of an original 1 H.P., premising that the efficiencies assumed would only apply to much larger plant.

First, a turbine utilising 330 lbs. of water per min. under a head of 100 ft. giving 33 000 ft.-lbs. per min., or 1 theoretical (or water) horse-power. Then the turbine, if it has an efficiency of 75 %, will give 0·75 B.H.P. (brake horse-power). If this is used to drive a dynamo with an efficiency of 90 % the latter will then give out 0·675 E.H.P. (electrical horse-power) or say 500 watts. Continuing the chain, this power is employed to drive a motor with an efficiency of motor and transmission of 85 %; the motor will then give out 0·575 B.H.P. This motor drives a pump with an efficiency of 70 %, which will deliver 0·4 H.P. to the column of water. Thus the overall efficiency of the whole chain is $0·75 \times 0·9 \times 0·85 \times 0·7 = 0·4$ or 40 %, and the whole of the original water could be pumped back up 40 feet of its original fall while 13 200 ft.-lbs. per min. would be recovered from 33 000.

A similar example can be given in steam practice. It will be seen from the constants in § 50 that 1 H.P. is equivalent to 42·4 B.Th.U. per min. The heat contained in 8 or 9 lbs. of coal burnt in 1 min. would be generated at this rate. Owing to the low thermal efficiency of a steam engine, coupled with the losses in the boiler, the indicated horse-power in the engine cylinder would be about 0·22 I.H.P. and the crank shaft would give about 0·2 B.H.P. The generator driven by this would give out 0·18 E.H.P. (134 watts) and if this power were expended entirely in heat it would produce 7·6 B.Th.U. per min. out of the original 42·4 with an overall efficiency of 18 %.

The Continental or metric horse-power is slightly different, being 75 kg.-m. per sec., equal to 736 W. The late Professor Silvanus Thompson advocated the international kilowatt as a preferable unit of power, to replace the horse-power entirely. In rating rivers for power purposes (§ 209 (iii)) this has been internationally agreed upon.

52. Energy; Kilowatt-hour; Unit.—The kilowatt-hour (kWh) is the practical commercial unit of electrical energy or work performed, and is still often called a '*Board of Trade Unit*' (*B.T.U.*), or simply a 'unit,' when dealing with the consumption of energy in an installation; the term 'Kelvin' is also used, and has official sanction, but has not found much favour as yet:—

1 kWh or B.T.U. = 1 000 volt-ampere-hours or watt-hours
= 1·34 H.P.-hours = 2 656 400 ft.-lbs. = 3 412 B.Th.U.
= 22·7 lbs. of water raised from 62° to 212° F. = 3·1 lbs. water raised from 60° F. and evaporated at 212° F.

Obviously either 1 kW for 10 hours or 5 kW for 2 hours will give 10 units.

In physical work, the *Calorie* (or calory) is used in preference to the B.Th.U. The B.Th.U. is the quantity of heat required to raise 1 lb. of water at its point of maximum density 1° F., and is equal to 252 calories ; the normal calorie being 'the quantity of heat required to raise 1 grm. of water through 1° C. at 15° C.' * Both these units involve the varying specific heat of water, while the mass of the pound also varies (*see* footnote on p. 2). In connection with recent investigations into the physical properties of steam, it has been suggested that the 'great calorie' (of 1 000 calories) should be constituted a true and invariable international heat unit, based (like all such units) on the simple relations of force, mass and acceleration. By adopting the value—

1 great calorie = 1/860 or 0·001 163 of a kWh,

which will be found to agree with the value given above both in kWh and B.Th.U., a unit is evolved free from variables and ambiguity.

53. **Horse-power-hour.**—It will be convenient here to give also the equivalents of the practical mechanical unit of work, the horse-power hour:—

1 H.P.-hour = 0·746 kWh = 1 980 000 ft.-lbs. = 2 545 B.Th.U.
= 17 lbs. of water raised from 62° to 212° F. = 2·28 lbs. of water raised from 60° F. and evaporated at 212° F.

In calculating the capacity of storage reservoirs for water-power the relations in this and the previous paragraph will be found very useful (*see* example at the end of § 239).

54. **Measurement of Power and Work.**—Watts are the product of current and pressure, and, as the pressure of an installation is usually fixed within narrow limits, the product of this fixed or standard pressure and the amperes will (*in a D.C. circuit*) give the power in the circuit in watts at any one time. If the mean power over any given period is found, *i.e.* the product of the standard pressure and the mean current, then this multiplied by the time will give the work done in watt-hours. This may obviously be expressed also as the product of the standard pressure and the ampere-hours.

Most of the domestic supply 'meters' on continuous current circuits are in fact integrating ampere-hour meters calibrated in

* *Dict. of Applied Physics*, art. 'Calorie.' There are several slightly differing named calories, according to the initial temperature taken.

B.O.T. units (§ 114). In alternating current installations integrating watt-hour meters are, however, always used (§ 115).

Watt-hours divided by 1 000 give kilowatt-hours or 'units' (B.T.U.).

55. Power in Alternating Current Supply.—Where the supply is alternating current the product of volts and amperes does not necessarily give the power in the circuit, as the waves of pressure and current may be, and generally are to some extent, out of phase with one another (§§ 11, 12*a*). In this case the average power in watts is less than the product of R.M.S. amperes by R.M.S. volts, or the voltamperes (VA). The ratio of watts to voltamperes is called the power factor. When the waves of current and voltage are both sine-shaped the power factor is equal to the cosine of the angle of phase difference ($\cos \phi$) between current and voltage. If the current lags on the voltage in phase, the power factor is said to be lagging, and if the phase of the current is leading, then likewise the power factor is said to be leading. It is necessary clearly to grasp the distinction between the true average power (watts) in an A.C. circuit and the product of volts by amperes. The power is measured by a wattmeter, and the voltamperes by an ammeter and voltmeter. The power factor of a lighting or heating load is approximately unity. In industrial power loads supplied from an A.C. system the power factor may vary from unity to 0·6 lagging (§ 157).

56. True and Apparent Power; Power Factor.—Fig. 1, § 11, is a diagram showing the wave form of an alternating electromotive force, and the consequent wave of current in a circuit. In explaining this diagram in §§ 11, 12*a*, 37 it was stated that these two waves do not always coincide, or are not always 'in phase' with one another; consequently the power is not always the product of the pressure and current as shown by a voltmeter and an ammeter. If the instantaneous values of current and pressure be taken at any moment their product will be the power at that moment; but this will be no guide either to the power a fraction of a second later or to its integrated value during the whole period. If in the case of Fig. 1 a single curve is made, on the same scale, to represent the product from moment to moment of the instantaneous values of current and pressure, this resultant curve will evidently represent the actual power at each instant. Now so long as the two waves are both positive, or above the zero line, or both negative, or below it, the algebraic result must be positive and power will be flowing into the circuit; when either wave is on the zero line the power product must for the instant be nil, and the resultant curve must be crossing the zero line also; while for so long as one wave is positive and the other negative the resulting power must be negative (*see also* Fig. 9, § 37)—*i.e.* power is going back momentarily into the generator from the circuit, just as in the old single-acting Willans engine the power consumed in compressing air below the piston on the down stroke was delivered back to the crank on the return stroke. The resulting power curve, P, chain-dotted in Fig. 11, is a cosine curve, and it will be found to differ from those of which it is the product, as it will complete one period during each *half* period of the supply; and the areas above and below the datum line may be equal (Fig. 9, § 37) or may vary until the negative component vanishes (Fig. 8, § 37). The shaded portion of the curve below the datum line represents power momentarily returning to the circuit. The amplitude of the cosine power curve is half the product of the amplitudes of the constituent sine curves; its axis is removed above the axis of the constituents by an amount which is half of the product of the amplitude of the constituents multiplied by the cosine of the angle, ϕ, of their phase difference. In the figure the current is 1 / 12 of a period or 30° out of phase with the E.M.F. (*i.e.* $\phi = 30°$), the maximum value of the current I_m corresponding to 50 A, and that of the pressure E_m to 110 V (instantaneous values). If on these scales the products of the simultaneous values are taken throughout a whole period, the power curve can be plotted from these products as shown. Its amplitude will be $110 \times 50 / 2 = 2\ 750$ and its axis will be at a point $\frac{1}{2} \times 110 \times 50 \times \cos 30° = 2\ 380$ above the principal axis. The maximum instantaneous positive value of the power will be 4 760 W at the peak of the wave. The net power delivered to the circuit will be the *difference* between the areas of the two parts of the curve above and below the zero line.

(ii) From this several facts will now be obvious. In the first place, if the waves of current and pressure are exactly coincident in phase (Fig. 8, § 37), the product must always be positive except at the moment it touches zero; the circuit is then said to have a power factor of unity. Secondly, if the waves are in quadrature or 90° out of phase (Fig. 9, § 37), the power put into the circuit during one quarter-period returns to the generator during the next quarter, so that no power is actually delivered at all, despite the fact that the volts and amperes as shown on the measuring instruments may be at a maximum; the circuit then has a power factor of zero, although the *instantaneous* values of the power, and the consequent mechanical stresses, may be very great. Thirdly, in cases intermediate between these extremes, the actual power is greater or less according to the extent to which the current is out of phase with the pressure, as will be seen if a series of curves is constructed on the above lines; and the power

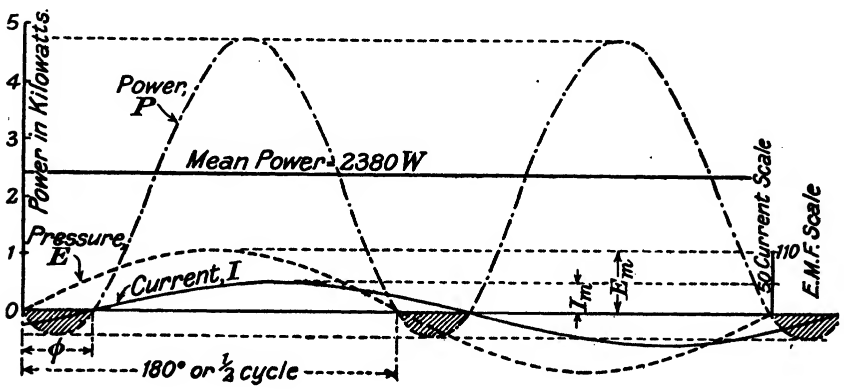

FIG. 11.—Pressure, current, and power curves.

factor varies accordingly. If the waves are out of phase by any particular fraction of a period (expressed as an angle, in degrees, in relation to the cycle of 360°), then the product of the volts and amperes as indicated on the measuring instruments gives the 'apparent power' in volt-amperes or kilo-volt amperes (kVA); and in order to find the true power this product must be multiplied by a number called the 'power factor' (P.F.), which is the cosine of the angle of phase difference, commonly called cos ϕ (*see also* §§ 109-111).* Conversely, to find the apparent power, the true power must be divided by the P.F. In practice the P.F. may be anywhere from 0·5 to unity, though generally in the neighbourhood

* Referring to Fig. 10 (§ 44), the power factor of the circuit represented by *ABC* is : $\cos\phi = AC / CB$ = Resistance / Impedance. If the circuit contains only resistance R and inductance L, the impedance $= \sqrt{[R^2 + (2\pi fL)^2]}$. Then

$$\cos\phi = R / \sqrt{[R^2 + (2\pi fL)^2]} = 1 \Big/ \sqrt{\left[1 + \frac{(2\pi fL)^2}{R^2}\right]},$$

which is sometimes a useful relation.

of 0·8. Non-inductive apparatus, such as glow-lamps, gives a P.F. of unity, *i.e.* the current and pressure are 'in phase' with one another *; in transformers, motors, and other apparatus having an inductive magnetic circuit, the current and pressure are to a greater or less extent 'out of phase,' resulting in a P.F. less than unity, which varies according to the load for the time being. This remark applies also to circuits having capacity (§ 46), except that the current is then in advance of, instead of behind, the E.M.F. This is more fully dealt with in connection with transmission of power (§ 304 and Chapter 14).

(iii) Returning to the power curve in Fig. 11, its average value can be proved to be $\frac{1}{2}E_mI_m \cos\phi$ or 110 × 50 × 0·866 / 2 = 2 380 W. That this is so can also be found by using the R.M.S. values instead of the maxima. As shown on instruments, the E.M.F. will be $110 / \sqrt{2}$ = 77·7 V and the current $50 / \sqrt{2}$ = 35·35 A. In this particular case the phase difference between E and I is 30° and the P.F. is therefore cos 30° or 0·866, so that the power will be 77·7 × 35·35 × 0·866 = 2 380 W. This alternative method of consideration amounts to pointing out that $\sqrt{2} \times \sqrt{2} / 2$ = unity. (*See also* § 157.)

By way of example, suppose on an alternating current supply there are 50 lamps, taking 100 W each, or 5 kW at 110 V; the current will then be 45·5 A, as the load is non-inductive and the waves of pressure and current will rise and fall together. The P.F. is therefore unity and the consumption will be 5 units per hour. If on the same supply there is a motor, also consuming 5 units an hour, and therefore also taking 5 true kilowatts, but having a P.F. of 0·8, then the *apparent* power taken by the motor will not be 5 kW but 5 / 0·8 or 6·25 kVA. Therefore the current will be 6·25 / 110 or 56·9 A, instead of 45·5, and the wires must be of larger size accordingly. The power factor 0·8 is the cosine of 36°, so this will be the value of ϕ, the angle of phase difference, on the assumption that the waves are sine waves.

(iv) The average value of the product of two sine waves 90° out of phase with one another is zero, and this is almost the case with the pressure and current in the primary coil of a transformer on 'open circuit,' *i.e.* with no current flowing in the secondary coil (§ 37). Although the full pressure is on the primary coil, and is

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* It should be noted that the fact that current and pressure waves are in phase is not alone sufficient to make the power factor unity; the waves must also be similar, *i.e.* the resistance must be constant. Even if the inductive effect of the control-magnet coils of an A.C. arc be eliminated, so that the pressure and current waves are in phase, the current wave is distorted by the varying resistance of the arc and the power factor is less than unity (§ 156).

causing a current to flow which fully magnetises the iron core on which the coils are wound, the power used is extremely small, *viz.* only what is used in heating up the wires and in magnetising and demagnetising the iron at each cycle (*i.e.* hysteresis, § 34). The balance is returned to the circuit, at each half-cycle, as shown in the shaded part of Fig. 11. If a current is taken from the secondary coil, and increased in amount, the two waves tend to coincide, and the power factor rises; but it never reaches unity in a transformer.

57. Energy Stored in Magnetic and Electrostatic Fields.—The energy stored in a *magnetic field* of density H lines per sq. cm. is $H^2 / 8\pi$ ergs per cu. cm. of the field. A more convenient form of this expression for the case of a solenoid of IT ampere-turns linked with a total flux of Φ lines, is: Energy stored in magnetic field $= \Phi IT / 20$ ergs $= \frac{1}{2}LI^2 \times 10^7$ ergs, where L = self-induction of coil, in henries. The energy thus stored is expended in a vicious arc at the contacts if an inductive circuit be interrupted suddenly. Another striking example of energy so stored may be seen in the case of a shunt motor; on opening the main switch the kinetic energy of the armature is expended in generating a current which flows through the field coils, and the machine is soon stopped by this 'electrodynamic braking.' If the field winding is relatively powerful or 'heavy,' the energy stored in it will cause the armature to make a few revolutions in the reverse direction after it has come to rest for the first time.

The energy stored in a *condenser* of capacity C farads when charged to a potential difference of V volts is: $\frac{1}{2}CV^2 \times 10^7$ ergs.

The above assumes a constant field or a constant state of charge of the condenser. If the field is produced by a sinusoidal current the energy stored during one quarter-cycle is $\frac{1}{2}LI_m{}^2 \times 10^7$ ergs where I_m = max. value of current. Similarly, if the condenser be charged by sinusoidal E.M.F., the energy stored during one-quarter cycle $= \frac{1}{2}CV_m{}^2 \times 10^7$ ergs, where V_m = max. value of applied pressure.

(1 joule = 10^7 ergs = 0·735 ft.-lb.)

58. Bibliography.—At the end of each chapter in this book there will be found a short list of textbooks which the authors can recommend as being useful for further study. These lists are not offered as being complete, but every effort has been made to present a useful and impartial selection. As regards papers read before institutions and societies, it would be impracticable to give a complete bibliography, and the authors have therefore decided to mention in the bibliographical lists only those papers which have been read before the Institution of Electrical Engineers (London). The *Journal* of the Institution is, or should be, in the possession of most readers of this book. Valuable references to papers and articles in other publications are to be found in *Science Abstracts*.

The books mentioned below deal with broad subjects or give data of more or less general applicability in all branches of electrical engineering. The bibliographies appended to later chapters include publications bearing directly on the subject-matter of the respective chapters.

STANDARDISATION REPORTS, etc.

Reports of the Committee on Electrical Standards (Cambridge University Press).

Clauses relating to definitions in I.E.E. Wiring Rules (Spon.); H.O. Electricity Regulations for Factories and Workshops; and H.O. Regulations as to Installation and Use of Electricity in Mines (Stationery Office).

(1) *I.E.C. Publications.*

No. 27.—International Symbols. Part 1: Letter Symbols.

No. 35.—International Symbols. Part 2: Graphical Symbols for Heavy Current Systems.

No. 42.—International Symbols. Part 3: Graphical Symbols for Weak Current Systems.

No. 77.—Voltages for New Systems and Installations.

(2) *British Standard Specifications.*

No. 108.—Graphical Symbols for Electrical Purposes (under revision; *see* No. 447).

No. 204.—Terms and Definitions used in connection with Telegraphs and Telephones.

No. 205.—Terms used in Electrical Engineering; addendum 1927; under revision.

No. 233.—Terms used in Illumination and Photometry, Glossary of.

No. 308.—Engineering Drawing Office Practice.

No. 350.—Conversion Tables (inches to mm. and mm. to inches).

No. 423.—Letter Symbols for use in Electrotechnics.

No. 447.—Graphical Symbols for use in connection with Interior Electrical Installations.

GENERAL ELECTRICAL TEXTBOOKS.

Elementary Lessons in Electricity and Magnetism. S. P. Thompson (Macmillan).

Practical Electricity. W. E. Ayrton and T. Mather (Cassell).

Electricity and Magnetism. R. T. Glazebrook (Cambridge University Press).

Technical Electricity. H. T. Davidge and R. W. Hutchinson (University Press).
Electrical Engineering. A. Thomalen. Translation by G. W. O. Howe (Arnold).
Electrical Engineering. C. V. Christie (McGraw-Hill).
Continuous Current Electrical Engineering. W. T. Maccall (University Tutorial Press).
Theory of Alternating Currents. A. Russell. 2 vols. (Camb. University Press).
Vectors for Electrical Engineers. E. Mallett (Chapman & Hall).
Theory of A.C. Wave Forms. P. Kemp (Chapman & Hall).
Alternating Current Electricity and its Applications to Industry. 2 vols. W. H. Timbie and H. H. Higbie (Wiley).
Electricity: Its Production and Applications. R. E. Neale (Pitman).

Mathematics and Physics.

Mathematics for Engineers. W. N. Rose. 2 vols. (Chapman & Hall).
Metric System for Engineers. C. B. Clapham (Chapman & Hall).
Whittaker's Arithmetic of Electrical Engineering (Pitman).
Arithmetic of Magnetism and Electricity. R. Gunn (Blackie).
Arithmetic of Electrical Measurements. Hobbs (Murby).
Textbook of Practical Physics. W. Watson (Longmans).

Pocket Books, etc.

Whittaker's Electrical Engineer's Pocket Book. Edited by R. E. Neale (Pitman).
Standard Handbook for Electrical Engineers. F. F. Fowle (McGraw-Hill).
American Handbook for Electrical Engineers. H. Pender (Wiley).
Electrical Engineers' Diary (Davis).
Practical Electrician's Pocket Book ("Electrical Trading and Electricity," London).
Mechanical World Electrical Pocket Book (Emmott).
Kempe's Engineer's Year-book. (Crosby Lockwood).
Mechanical Engineer's Pocket Book. W. Kent (Wiley).
Mechanical Engineer's Pocket Book. D. K. Clark and H. H. P. Powles (Crosby Lockwood).
Whittaker's Mechanical Engineer's Pocket Book (Pitman).

Directories, etc.

Electrician Electrical Trades Directory (Benn Bros.).
Electrician Annual Tables of Electricity Undertakings (Benn).
Universal Electrical Directory (Electrical Review).
Garcke's Manual of Electrical Undertakings (Electrical Press).
Central Station Tables (Practical Electrician's Pocket Book; Electrical Trading and Electricity).

I.E.E. Papers.

What is Electricity?, Prof. Thornton. Vol. 65, p. 674.
Electricity in the Service of Man, S. Z. de Ferranti. Vol. 67, p. 125.
How Electricity Does Things, Ll. B. Atkinson. Vol. 67, p. 937.
Electrical Standardisation, P. Good. Vol. 64, p. 495; Vol. 65, p. 136; Vol. 66, p. 132; Vol. 67, p. 196; Vol. 69, p. 404.

CHAPTER 2

MATERIALS.

59. (1) Materials and Research; (2) Classification by Conductivity; Conductors and Insulators.

(1) *Research.*—The importance of research to the electrical and allied industries cannot be overstated. The largest firms in the country are in a position to finance their own laboratories, reaping their own reward; but there are also a number of 'Research Associations' working for the general good of the community. These are financed mainly from voluntary contributions of component firms; but they have also received substantial assistance from the State, and it is to be hoped that such help will be continued steadily and on a generous basis for, as administered by the Department of Industrial and Scientific Research, money invested in research brings in a handsome return. Of the Research Associations directly affecting the electrical industry, the British Electrical and Allied Industries Research Association is, of course, the leader. Others deal with scientific instruments, rubber, refractories, collieries, iron and steel (two), cast iron, and non-ferrous metals. Up to 1933 annual savings amounting to not less than £1 000 000 had accrued from work costing £80 000 in all, carried out by the B.E.R.A. Year by year further savings are effected, and similar results have been obtained by other Research Associations.

(2) *Classification.*—The materials used in electrical engineering may easily and conveniently be divided into the two main groups, 'conductors' and 'insulators.' There is no such thing as a perfect insulator, for all substances conduct electricity to a greater or less extent, but the difference in resistivity between 'conductors' and 'insulators' is so enormous that there is no possible ambiguity in this classification. Thus slate, which is a relatively poor insulator, has a specific resistance of about 100 megohms/cm.-cube, whilst that of a high-resistance alloy may be 120 microhms/cm.-cube; the ratio between these values is $8{\cdot}3 \times 10^{11} : 1$. The ratio

between the specific resistances of the worst and best conductors is much smaller under all ordinary conditions, *e.g.* the specific resistance of nichrome is 110 microhms/cm.-cube at 0° C., or about seventy times that of copper at the same temperature.

In addition, however, to the main division between conductors and insulators it is convenient to discriminate between good and bad conductors. This may be done by reserving the term 'conductor' for high-conductivity materials such as copper and aluminium or, in general, for materials used where conductivity is desirable and resistance is objectionable; and by applying the term 'resistance materials' to high-resistance alloys and other materials which are used deliberately to dissipate energy, as in motor starters and heating elements. There is no clear boundary between conductors and resistance materials as thus defined. For instance, steel has a sufficiently high resistance to justify its use as a resistance material, yet it is sometimes used as a conductor where great mechanical strength is required. Similarly liquid solutions (electrolytes) of metal salts and acids are necessarily used as conductors in batteries and electrolytic deposition, but they are used as resistance materials in some types of motor starters and controllers.

Taking the resistance of copper, the principal 'conductor,' as 1·0, that of 'resistance alloys' is from 12 to 70, and that of 'insulators' is many thousands of millions.

Constants of conductors and resistance materials are given in Table 6 (p. 82), and of insulating materials in Table 7 (p. 96).

60. Classification by Other Physical Properties.—Though conductivity and insulation are two of the most important properties of materials used in electrical installations, there are other physical properties which must be considered, *e.g.*:—

(*a*) Mechanical Properties, such as ductility, strength, modulus of elasticity, etc., which determine the applicability of the material from the constructional point of view. These properties have specially to be considered where very fine wires are concerned (*e.g.* lamp filaments); where stresses are severe (*e.g.* in high-speed rotors, transmission line spans, etc.); and where relatively weak material (such as porcelain) used for insulation, is subjected to severe mechanical stress.

The *density* of a material is principally of importance in regard to the estimation of the weights of parts. These factors are useful—

Weight per cu. ft., in lb. = 62·43 × density.
Weight per cu. in., in lb. = 0·036 × density.
Weight per cu. cm., in grm. = density.

(*b*) Thermal Characteristics.—The *temperature coefficient of expansion* of a material is important where exact dimensions have to be maintained (as in certain instruments); where expansion and contraction vary the stresses between points which are fixed mechanically (as in long rigid conductors or transmission line spans); where differences in expansion may crack joints, etc. (as in lamp bulbs, composite insulators, etc.); and in liquids where convection currents contribute to natural cooling (as in oil-immersed transformers). The *specific heat* of a material is important where absorption or storage of heat is concerned, low specific heat being desirable where minimum absorption and rapid heating are required, and high specific heat being desirable for maximum storage of heat. *Thermal conductivity* is important in determining the rating of machinery and the efficiency of furnaces, etc.; it should be high where unavoidable heat losses have to be dissipated as rapidly as possible (*e.g.* through the insulation of machine windings), but it should be low where heat losses have to be reduced (as from electric furnaces). The *melting-point* of a material determines the maximum temperature at which it can be operated in solid form, and this is of practical importance in connection with lamp filaments, refractory bricks, etc., but the imiting temperature at which conductors can be operated is generally the maximum temperature at which their insulation can be operated without deterioration (§ 80).

(*c*) Magnetic Properties.—The magnetic properties of iron and certain special iron alloys (§ 82) are essential to commercial electrical machines and transformers. With the exception of the iron group there are no magnetic materials of commercial importance, but *see* 'mumetal' in § 82. Non-magnetic materials are definitely required where self-induction and magnetic leakage are to be avoided. Unfortunately there is no magnetic insulator; 'non-magnetic' materials are those which have no higher permeability (§ 43) than air.

(*d*) Electrical Properties other than Conductivity.—The conductivity (or resistivity) of a 'conductor' (§ 59) is its only electrical property of practical importance. On the other hand, the resistivity of insulators is relatively unimportant and generally indeterminate (§ 71). The insulation resistance of a winding or network (§§ 4, 281) is generally determined by moisture or by conducting particles; the resistivity of the insulation itself is so high that, in the absence of such foreign influences, break-down occurs by puncture when the electrostatic stress exceeds the *dielectric strength* of the material (§ 72).

The capacity of any condenser increases in direct proportion to the *permittivity* (§ 46) of the dielectric. The conductors of insulated cables act, with regard to each other and to earth, as the electrodes of condensers in which the insulating material is the dielectric; the higher the specific inductive capacity or permittivity of the insulating material, the greater the quantity of electricity required to charge the cable and, therefore, the heavier the charging current (§ 311). The different specific inductive capacities or permittivities of various insulating materials (Table 7) makes it possible to control the potential gradient in a 'graded insulation' (§§ 79, 289).

The reversal of electrostatic stress in any insulation subjected to alternating P.D. involves *dielectric hysteresis* (analogous to magnetic hysteresis, § 34); the energy thus expended in the dielectric heats the latter and may represent an appreciable loss (§ 312).

(*e*) Chemical Properties.—*Purity and homogeneity* are desirable in most electrical materials; for example, small traces of impurity increase greatly the resistance of copper and the conductivity of the cast metal is lower than that of rolled copper. Homogeneity in insulating materials makes for uniformity in dielectric strength; air films are particularly to be avoided (§ 79).

Resistance to moisture and corrosion (*atmospheric or chemical*) is generally a desirable and often an essential characteristic.

According to the relative importance of the above-mentioned properties in individual applications, electrical materials can be classified in any number of groups. For our purpose it is convenient to adopt the general classification: Conductors, resistance materials, insulating materials, magnetic and non-magnetic materials, and refractories. Data bearing on other characteristics are given where of special interest.

61. Temperature Coefficient of Resistance.—The specific resistance (§ 18) of any material is a constant for any specified temperature, but varies with temperature. The resistance of copper and most other conductors increases with temperature, *i.e.* the temperature coefficient of resistance is positive. Constantan and other useful alloys have practically constant resistance within wide limits of temperature, *i.e.* they have zero (or nearly zero) temperature coefficient of resistance. The resistance of carbon, of electrolytes, and of india-rubber and other dielectrics (§ 71) decreases as the temperature rises, *i.e.* the temperature coefficient of resistance is negative. The positive temperature coefficient of, say, iron may be used to compensate for the negative coefficient of the electrolyte in electrolytic ampere-hour meters (§ 114).

In general, the resistance of a conductor varies with temperature according to the law

$$R_t = R_0(1 + at), \quad . \quad . \quad . \quad . \quad (1)$$

where R_t, R_0 are the resistances at temperatures $t°$ and 0° C. and a is the *temperature coefficient of resistance* per 1° C.* This simple relation holds good only for a limited range of temperature, say 100° C. The resistance at temperature t is expressed in terms of the resistance at 0° C. If the resistance be R'_t at some other temperature t' we have: $R'_t = R_0(1 + at')$. Dividing this equation by equation (1), we have—

$$\frac{R_t'}{R_t} = \frac{1 + at'}{1 + at} = 1 + \frac{a(t' - t)}{1 + at},$$

whence
$$R_t' = R_t\left[1 + \frac{a}{1 + at} \cdot (t' - t)\right].$$

* The temperature coefficient per 1° F. = $\frac{5}{9}$ × the coefficient per 1° C.

This means that the resistance at a temperature t' can be calculated directly from the resistance at a temperature t (without reference to the resistance at 0° C.), by using the formula—

$$R_{t'} = R_t[1 + \beta(t' - t)] \quad . \quad . \quad . \quad . \quad (2)$$

in which $$\beta = a/(1 + at) = 1 \Big/ \left(\frac{1}{a} + t\right).$$

In other words, if a be the temperature coefficient of resistance for equation (1), which is based on resistance at 0° C., then β is the temperature coefficient of resistance for equation (2), in which the basic resistance is that at $t°$ C.

For copper, $a = 0{\cdot}004\,265$ at 0° C.; and $\beta = 1 / (234{\cdot}5 + t) = 1 / (234{\cdot}5 + 20) = 0{\cdot}003\,93$ at 20° C. If the resistance R_{20} at 20° C. be known we could calculate the resistance R_0 at 0° C. from: $R_{20} = R_0\,(1 + {\cdot}004\,265 \times 20) = 1{\cdot}085\,3\,R_0$; and the resistance R_{30} at 30° C. from: $R_{30} = R_0\,(1 + {\cdot}004\,265 \times 30) = 1{\cdot}128\,R_0$, but it is simpler to work from: $R_{30} = R_{20}\,(1 + {\cdot}003\,93 \times 10) = 1{\cdot}039\,3\,R_{20}$. The result obtained is the same by both methods.

For copper circuits a simple and easily remembered formula is

$$\frac{R_1}{R_2} = \frac{234{\cdot}5 + t_1}{234{\cdot}5 + t_2},$$

where R_1 and R_2 are respectively the resistances corresponding to the Centigrade temperatures t_1 and t_2. Thus the resistance of a copper circuit is proportional to a kind of absolute temperature found by adding 234·5 to the Centigrade temperature.

The variation of resistance of a conductor with temperature may be utilised to determine the temperature of the conductor (§ 122).

Conductor Materials (*see* Table 6, pp. 82-85).

62. Copper.—Copper is by far the most extensively used electrical conductor, combining, as it does, high electrical conductivity with excellent mechanical properties and relative immunity from oxidation and corrosion under service conditions. Electrolytic copper is practically pure. The smallest traces of impurities enormously increase the resistance of the metal. Hard drawn wire is used for overhead conductors (§ 307), due to its superior tensile strength; for most other purposes the softer, annealed wire (§ 280) is used, this having 2 or 3 °/ₒ lower resistance. Rolled bars are used where large sections are concerned. Copper castings are liable to be unsound. Copper gauze brushes are still used on low voltage, heavy current dynamos for electroplating, etc.*

* Sparking and wear on the commutator may be reduced by soaking the brushes periodically in a mixture of vaseline and finest graphite; this treatment is permissible only for low voltage machines (10-15 V).

The *international standard of resistance for copper*, as laid down by I.E.C. Publication No. 28, is based on the following values:—

Standard Annealed Copper at 20° C. (68° F.).

(i) Resistance of a wire 1 metre long and of uniform section 1 sq. mm. = 1 / 58 Ω = 0·017 241 Ω (= *volume resistivity*, § 18).

(ii) Density, 8·89 grm. per cu. cm.

(iii) 'Constant mass' temperature coefficient of resistance, 0·003 93 per degree Centigrade.

(iv) Resistance of uniform wire 1 metre long, weighing 1 grm. = 0·153 28 Ω (= *mass resistivity*, § 18).

(ii) It is stipulated that the *conductivity of commercial annealed copper* be expressed as a percentage, at 20° C., of that of standard annealed copper. The temperature t° C., at which measurements are made, must be within ± 10° C. of 20° C., *i.e.* between 10° C. and 30° C. Then if R be the resistance at t° C. of a copper wire L metres long weighing m grm., the *percentage conductivity of the copper* is—

$$100 \times \frac{0{\cdot}153\,28}{(Rm/l^2) + 0{\cdot}000\,6\,(20 - t)} \quad . \quad . \quad \text{(I)}$$

Data, consistent with those above, adopted by the B.S.I., are as follows:—

Standard Annealed Copper at 60° F. (15·6° C.).

Weight = 555·11 lbs. per cu. ft.

Specific gravity = 8·892.

$$\text{Weight per yard} = \frac{\text{area in sq. in.}}{0{\cdot}000\,012\,352\,75}\ \text{grains.}$$

$$= 11{\cdot}564 \times (\text{area in sq. in.})\ \text{lbs., approx.}$$

$$\text{Resistance per yard (annealed)} = \frac{0{\cdot}000\,024\,007\,9}{\text{area in sq. in.}}\ \Omega.$$

$$\text{,,} \quad \text{,,} \quad \text{(hard drawn)} = \frac{0{\cdot}000\,024\,728}{\text{area in sq. in.}}\ \Omega\text{, approx.}$$

Resistance per 1 000 yds. (annealed) = n / W Ω; where

W = weight of wire in grains per yard; and

n = 1 943 for plain standard annealed copper

= 1 982 for tinned wire from 0·007 in. to 0·036 in. dia. inclusive

= 1 962 for tinned wire exceeding 0·036 in. dia.

Coefficient of linear expansion = 0·000 009 44 per 1° F.

= 0·000 017 per 1° C.

(iii) The *temperature coefficient of resistance* of standard annealed copper is 0·004 26 at 0° C. and 0·003 93 at 20° C. (§ 61).*

* For a temperature rise of 50° C., which is not uncommon in practice, the resistance at 0° C. must be multiplied by 1 + (50 × 0·004 26) = 1·213. This shows the futility of expressing commercial electrical quantities to within 1 in 1 000; only when all relevant conditions are stated can there be any justification for such expression.

The coefficient decreases with the percentage conductivity of the copper (as expressed at (I) above); down to 90 % conductivity the temperature coefficient of resistance of copper of p % conductivity may be taken as $(p / 100) \times$ the temperature coefficient of standard annealed copper at the same temperature.

B. Welbourn * gives the following values for the *modulus of elasticity of hard-drawn copper strands*:—

20 000 000	lbs. per	sq.	in. for	7-strand	cable.	
17 500 000	,,	,,	,,	19-	,,	,,
15 500 000	,,	,,	,,	37-	,,	,,

63. Aluminium.—Aluminium is often used in place of copper for bus-bars and overhead transmission lines and, less frequently, for insulated cables and windings. It is much lighter than copper (the ratio of the densities being 1 : 3·42), and its electrical conductivity and mechanical strength are lower than those of copper in about equal ratios, so that, for equal electrical conductivities, aluminium and copper conductors are of nearly equal strength. The wind pressure and weight of snow are, however, greater on an aluminium line than on a copper line of equal conductivity because (the specific conductivity of aluminium being about 61 % that of copper), the aluminium line is of 65 % greater cross-section and 28 % greater diameter than the equivalent copper line. The relative weight of electrically equivalent conductors is: aluminium 0·48, copper 1·0, so that the bare metals are about equally economical when the price of aluminium is 2·08 times that of copper. Additional information on the use of aluminium for overhead lines is given in §§ 308, 331.

The larger diameter of the conductor renders insulated aluminium cables much more costly than copper cables of equal conductivity; on the other hand, the larger diameter with aluminium reduces dielectric stress and corona loss at the surface of high-voltage conductors.

Aluminium was used instead of copper in the armature and field windings of motors, generators, etc., and in transformers built in Germany during the Great War, and it has been claimed that such machines compete in efficiency and price with copper-wound machines. Aluminium is, however, at an obvious disadvantage wherever the space for windings is limited.

* *Jour. I.E.E.*, Vol. 56, p. 53.

The thin film of oxide which forms on the surface of aluminium makes soldering a matter of some difficulty and uncertainty. Mechanical joints (bolts, clamps, twisted sleeves, etc.) are used extensively, and welded joints have been used in aluminium windings. (*See also* § 383.)

The use of aluminium in lightning arresters and rectifiers is mentioned in §§ 346, 417, Vol. 2, respectively.

(ii) Steel-cored aluminium cables are dealt with in § 917 (Vol. 3). The following * is an interesting comparison between these, plain aluminium, and a new light aluminium alloy called 'Almelec.'

'Almelec' contains small percentages of magnesium and silicon so proportioned that the alloy can be subjected to a hardening process akin to that of steel, its mechanical properties being obtained by the combined effect of hammering during the drawing operation and heat treatment. The physical constants are: density, 2·5 grm. / cu. cm.; breaking strain, 35 kg. / sq. mm.; elongation before rupture, 6 to 8 %; modulus of elasticity, 6·45 kg. / sq. mm.; coefficient of expansion, 23×10^{-6}; resistivity at 15° C. in microhm centimetres, 3·1; and temperature coefficient of resistance, 0·0038. As compared with other conductors, it is claimed that (1) its mechanical resistance is 1·5 times higher, and its weight 46 % less, than that of copper; (2) its mechanical resistance is twice as great as that of aluminium for an increase of weight of only 8 %; (3) compared with a 7-strand aluminium-steel cable, its mechanical resistance is 12 % greater with 30 % less weight; (4) compared with a similar 37-strand cable, these figures are 4 % less and 30 % less. If these data are borne out in practice, and no compensating disadvantages appear, almelec will enable lines to be erected with longer spans than lines of copper, with reduced cost of masts. The alloy can be used in conjunction with steel in cables and is suggested as likely to find employment for very high voltage lines in rural distribution.

64. Iron and Steel as Conductors.—The magnetic properties of iron and steel are discussed in §§ 81-84. The resistivity of steel is about six or eight times that of copper, so that steel is used as a conductor only when: (i) mechanical strength is specially important; or (ii) so large a cross-section is required, for other reasons than for conductivity, that steel is more economical than copper (§ 309).

(i) All steel and steel-cored copper or aluminium-stranded wires are used for very long spans in *overhead lines* (§§ 309, 331), and tinned or galvanised small steel wires are often used with copper for strength in *small flexible wires and cables.*

(ii) Low-carbon steel is used for *conductor-rails* in traction circuits (§ 901, Vol. 3). The British Standard method of specifying the resistance of such rails (B.S.I. Report No. 68) is to state the resistance in microhms at 60° F. (15·6° C.) of a rail of the same material as the conductor rail in question, having a length of

* From E. Dusaugey; *see El. Rev.*, Vol. 101, p. 272.

1 yd. and a weight of 100 lbs. As thus specified, the resistance of flat-bottom conductor rails now in use ranges from 15 to 19·5 microhms (mean 18 microhms) per 100-lbs. yard; whilst that of specially hard T rails ranges from 19·8 to 20·5 microhms (mean 20·2 microhms) per 100-lbs. yard. For chemical analyses, and conversion formulæ and tables reference should be made to B.S.I. Report No. 68.

Reference to § 902, Vol. 3, will show that the special steels used for traction work have much higher resistance than carbon steels; thus manganese steel for points, etc., has 3½ times the resistance of carbon steel.

Iron pipes are sometimes used as *bus-bars*, and steel is fairly satisfactory for *slip rings*.

Iron wires, used in Germany during the war to replace copper, have been proposed for normal use in *small domestic installations* where the section of copper required for mechanical strength is greater than would be needed for conductivity alone. It is possible that stainless iron or steel may find an application in this field. Galvanised iron wire has, for a similar reason, been found economical in *overhead lines* supplying small rural loads (§ 331.)

Wherever iron or steel is used as a conductor the possible importance of skin-effect (§§ 38, 309) should be considered.

The specific resistance of *grey cast iron* is roughly ten times that of steel and seventy times that of copper; for this reason, no reliance should be placed upon the metal of a cast-iron joint box for carrying appreciable current.

(ii) Apart from the increase in resistance due to temperature coefficient (§ 61 and Table 6, p. 82), the resistance of iron increases greatly and suddenly at the temperature of recalescence (about 680° C.). This phenomenon is utilised in an automatic current regulator, the principle being that the iron wire (enclosed in a hydrogen-filled bulb) is brought nearly to red heat by the normal current of the circuit; an increase of current then brings the iron to the temperature of recalescence, greatly increases its resistance, and thus limits the increase of current.

Such a device is known as a *barreter tube.* In appearance it resembles an ordinary lamp 'bulb,' and its life is very great. Over its operating range a barreter passes a constant current irrespective of the voltage across its terminals. When it is inserted in series with a load, small changes in the applied voltage are absorbed in the tube, and no change in current results. Similarly, small changes in the load, resistance or back E.M.F., do not alter the current within working limits.*

These properties depend on the fact that an increase in applied voltage results in a momentary increase in the current with a consequent increase in the temperature of the filament. Due to the rapid rise of the specific resistance of iron at the

* 'Barreters,' R. L. Spiller, *El. Rev.*, Vol. 112, p. 112.

recalescence point, the resistance of the filament increases and the current then falls In a suitably designed tube, the increase in resistance is exactly proportional to the increase in applied voltage, and the current returns to its original value. The characteristics of the tube, therefore, depend upon the temperature-resistance coefficient of iron and also on the watt-temperature characteristics of the filament, which latter are influenced by the density of the atmosphere in which it operates. Hydrogen at a suitable pressure has the desired properties, and prevents the iron from rusting.

Under suitable conditions, barreters can be used either in series or in parallel. They have been used in connection with trickle charging (§ 432, 5th ed.); for radio valves; and for controlling the temperature in electric furnaces, etc.; but they are more suitable for controlling small than large currents.

65. Other Metallic Conductors.—The notes on these are necessarily brief and, for convenient reference, the metals are arranged alphabetically.

Bismuth.—When bismuth is placed in a magnetic field, the electrical resistance of the metal increases, nearly in proportion to the field strength. A spiral coil of bismuth wire wound non-inductively, calibrated by reference to a magnetic standard, and used in conjunction with a Wheatstone bridge, is sometimes used to measure field strengths (§ 121). It is unsuitable for alternating fields due to time lag in the changes of resistance.

Brass for casting generally contains 66 °/。 copper and 34 °/。 zinc. Sound castings are obtained more easily than in copper. The alloy is cheaper than copper and is used for various current-carrying parts in which the cross-section is determined by mechanical rather than electrical considerations.

Bronze.—Silicon bronze and phosphor bronze wires are used for long spans in overhead conductors (§ 331). Silicon bronze consists of copper and up to 5 °/。 of silicon, and a typical phosphor bronze (*q.v.* below) contains Cu, 92·5; Sn, 7; P, 0·5. Constants for both types of bronze are given in Table 49, § 331.

Cadmium-copper.—Alloys containing up to 1·1 °/。 cadmium give wires which are stiffer, harder, and of higher tensile strength than hard-drawn copper (Table 49, § 331). The annealing temperature is raised, 1·1 °/。 cadmium wires softening only slightly at 260° C.

Lead.—This metal is used for sheathing various types of insulated wires and cables, particularly where moisture is to be excluded. The addition of about 3 °/。 tin increases the tensile strength 50 °/。. Lead is also used in bimetal fuse wire and for interconnecting the plates and cells of accumulator batteries.

Mercury.—This metal is made the basis of the international definition of the ohm (§ 3). It is used for making and breaking contact in many types of apparatus, but is suitable only for weak currents and low voltages, and should be used *in vacuo* or protected from air by a layer of oil to avoid oxidation. It is also used in certain electricity meters. The use of mercury in lamps and rectifiers is mentioned in § 588 and 422, Vol. 2, respectively.

Nickel is malleable and resists corrosion. It is used for connections in heating and cooking apparatus, for supports in glow lamps, and for sparking plug electrodes. It is a constituent of many important resistance-alloys (§ 67) and valuable magnetic alloys (§ 82). Its use in alkaline accumulators (Edison, etc.) is dealt with in §§ 434, 434 *a*, 939. The high specific resistance and low temperature coefficient of the non-magnetic nickel-iron alloys make them useful for resistance grids of maximum capacity and minimum bulk, especially in such applications as starters on tramway cars. A copper-nickel alloy (Ferry, Table 6) useful for motor starters and controllers has an almost negligible temperature coefficient. Up to the maximum temperature allowed by the B.S.I., *viz.* 300° C., this wire does not deteriorate or alter in any way; it does not rust or get brittle, or perish with age or exposure, and is not affected by sea water or subject to corrosion.

Nickel Steels offer a wide range of valuable properties. High-tensile steels (3 °/₀ Ni) are used for large dynamo frames and high-speed rotors. For sparking-plug electrodes 22 °/₀ Ni steel is suitable. The 25 °/₀ Ni steel is non-magnetic (§ 84). Invar is 36 °/₀ Ni steel and has practically zero temperature coefficient of expansion. As a substitute for platinum leading-in wires for lamps, etc., there is used platinite (46 °/₀ Ni steel) or a 38 °/₀ Ni steel wire copper-coated.

Phosphor-bronze and *gun metal* are used for brushes and bearings; and the former for nuts and bolts and occasionally for overhead lines on long spans. It is worthy of note that the cables used for crossing the Thames at Dagenham consist of seven cadmium-copper wires (§§ 65, 331, 909) surrounded by 84 phosphor-bronze wires of 0·085 6 in. diam., the latter being chosen for their strength and resistance to corrosion. This wire has also many purely mechanical uses, *e.g.* for pulling cables through conduits. Again, it is used for springs and contacts, see Table 6 (§ 66) and §§ 331, 335. (See also *Bronze*, above.)

Phosphor-tin and *phosphor-copper* are also made, chiefly for alloying castings.

Platinum was formerly used for the leading-in wires of glow lamps and for contact pieces, but its price has become prohibitive; *see* Nickel Steels and Tungsten.

Selenium.—When suitably annealed, selenium assumes a crystalline form, and has then the curious property that its electrical conductivity varies (roughly) as the square root of the intensity of illumination upon the specimen. Different workers advise different methods of preparing the material, and quote widely different values for the electrical resistance, light sensitivity, and time lag in response. The conductivity may increase 100-200 times or more when the material is taken from a dark room into sunlight; some specimens increase in resistance when taken from dark to light, but the change in resistance of such 'light negative' material is generally very small. The time lag in the changes of resistance under varying illumination may be reduced by suitable treatment of the material, and selenium cells have been used to control flashing buoys, and in the electrical transmission of pictures; also in devices for enabling the blind to read by sound, and in the recording and reproduction of sound for 'talking (cinema) pictures.' Photo-electric cells (§ 420 *a*, Vol. 2) have no time lag and can be incorporated easily in thermionic amplifying and control arrangements.

It is reported (*El. Rev.*, Vol. 89, p. 717) that synthetic antimonite may be used as a substitute for selenium, it having no appreciable lag in responding to variations in light.

Silver has higher conductivity than copper, but is too costly for general use. It is used for special contacts unless a more refractory metal is required, *e.g.* platinum or tungsten.

Tin demands special notice, owing to its increasing use in the electrical industry: in the U.S.A. alone, some 350 tons were used in one year for cable-sheathing and some 400 tons for solder by one telephone company; while for tinning copper it is estimated that the world's annual consumption is about 2 500 tons.

For cable-sheathing, in order to prevent the inter-crystalline cracking of the lead when subject to vibration, an addition of about 3 % of tin is often made. A ternary alloy developed by the British Non-Ferrous Metals Research Association for the same purpose contains 1·5 % tin and 0·25 % cadmium. These alloys have a higher strength and fatigue range than pure lead, and under certain conditions a better resistance to corrosion (§ 553).

The use of tin and its alloys and combinations for fuses is dealt with in § 342. At joints, tin is often used to assist in making a good contact, whether by clamping or soldering. Solders used for jointing the sheathing of lead-sheathed cables are richer in tin than the standard in Table 6 (§ 66), containing 35 to 40 % of tin, and the plumber's 'wiped joint' is used. For joining up copper conductors, similarly constituted core solders are used, commonly containing up to 50 % of tin. Resin-cored solder is used for all indoor and plant connections, and acid-cored for outdoor line connections, where the acid spray produced during soldering has no harmful effect. It has recently been found possible to solder glass and porcelain with the same solder.* For general information on solder see *Solder*, Bulletin No. 2, International Tin Research and Development Council.

The tinning of copper wires prevents injurious interaction of the copper and the rubber insulation. Among other important uses of the metal (in small quantities, however) may be mentioned tinfoil for condensers and the spraying of tin on to insulators for reducing corona discharge.

Tungsten is now the standard material for the filaments of glow lamps (§ 583, Vol. 2), and thermionic valves (§ 418, Vol. 2), and is used for sparking points and contact pieces. Its refractory nature makes the manufacture of the metal difficult. The ore is reduced to tungsten powder which is compressed into blocks, and sintered by the passage of a heavy current. By swaging, rolling, and repeated drawing the sintered rods can be reduced to wire of 1 mil diameter. The initial stages of mechanical working have to be conducted at temperatures between 1 000° and 1 500° C., but as working proceeds the ductility increases and the temperature may be reduced. The tensile strength of drawn tungsten wire from 1 to 5 mils in diameter is from 290 to 200 tons per sq. in.

Tungsten steels are used for permanent magnets (§ 83).

Zinc is used to galvanise steel cores and armouring wires as a protection against rusting. It was used in place of copper in windings and cables in Germany during the war, but was found difficult to handle due to its brittleness. The electrical conductivity is less than half that of aluminium and little more than one-fourth that of copper.

66. Carbon and Graphite.—Carbon is used for electrical purposes in its amorphous form (lampblack, charcoal, gas-retort carbon, petroleum-coke, etc.; sp. gr. 1·6 to 2·0) and in its crystalline form (graphite, sp. gr. 2·3). One or more varieties of the amorphous form are ground finely, mixed with tar or pitch as binder, moulded under pressure and baked out of contact with air in order to obtain dense and strong amorphous carbon for use as electrodes in *arc lamps* or *electric furnaces*. By heat treatment in an electric furnace, the electrodes may be 'graphitised.'

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* *Bulletin*, Dec. 4, 1933, of the International Tin Research and Development Council.

Table 6.—*Approximate Constants of Electrical Conductors and Resistance Materials.* (*Compiled from Various Sources.*)

CONVERSION FACTORS.

Resistance per in.-cube = 0·394 × resistance per cm.-cube.
Ohms per mil.-ft. = 6·02 × microhms per cm.-cube.
Temperature coefficient per 1° F. = $\frac{5}{9}$ × temperature coefficient per 1° C.
Temperature in °F. = (°C × $\frac{9}{5}$) + 32°.

Material.	Composition, State, etc. For key see Note at foot of Table.	Specific Gravity.	Specific Resistance Microhms Per cm.-cube at 20° C.	Temperature Coefficient of Resistance Per 1° C.	Tensile Strength. Tons / Sq. In.	Modulus of Elasticity Million Lbs. per Sq. In.	Temperature Coefficient of Linear Expansion Per 1° C.	Melting-Point °C.	Specific Heat 0°-100° C.	*See also* §
Aluminium	Cast, soft	2·68	2·8	0·003 5	—	—	0·000 024	655	0·212	63, 308, 331
"	Rolled or drawn	2·71	2·9	0·003 5	11½-15	9·8				
Antimony	—	6·6	40·0	—	—	—	—	630	0·051	127
Bismuth	—	9·8	116·0	0·004 2	—	—	—	269	0·030	65
Cadmium	—	8·6	10·8	0·004 2	—	—	—	—	—	65
Carbon	Graphite	1·9-2·3	400-1 200	*minus* 0·000 6- to 0·001 2	—	—	—	3 450	0·19-0·20	66
"	Moulded electrodes	1·5-2·0	3 500-7 500							
Chromium	—	6·5-6·7	2·6 × 10^{-6} ohm. cm.	—	—	—	—	1 520-1 616	0·08-0·1	83, 994
Cobalt	—	8·77	10·4	0·003 3	—	—	—	1 488	0·1030	82, 83
Copper	Annealed	8·89	1·72	0·003 9	14	—	0·000 017	1 084	0·094	62, 307, 331
"	Hard drawn	8·93	1·77	0·003 9	21-30	15-16				
Gold	—	19·3	2·47	0·003 8	17	13·7	0·000 014	1 063	0·031	127, 988 994
Iridium	—	22·4	5·3	—	—	—	—	2 290	0·032	122
Iron, pure	(*See also* cast iron and steel)	7·8	9-10	0·006 2	30-40	26·3	0·000 012	1 500-1 530	0·116	64, 81
Lead	(*See also* solder)	11·4	21·0	0·004 1	1¼	2·5	0·000 030	327	0·030	65
Magnesium	—	1·7	4·4	0·003 8	—	—	0·000 032	632	0·246	67
Mercury	—	13·6	96·0	0·000 9	—	—	—	− 38·8	0·033	65
Molybdenum	—	8·5	4·5	0·005	—	—	—	2 500	—	636, 979
Nickel	Commercial	8·85	10·5	0·004	35	29·3	0·000 013	1 450	0·109	65, 67
Palladium	—	—	10·9	0·003 5	—	—	—	—	—	—
Platinum	—	21·5	11·8	0·003 8	21	24	0·000 009	1 710	0·032	65, 122
Silver	—	10·5	1·6	0·004	19	9·8	0·000 019	960	0·056	65
Tantalum	—	16·6	15·0	0·003 3	—	—	0·000 007	2 910	0·036	583, 979
Thallium	—	11·9	1·90	0·004	2	—	—	301	0·033	—
Tin	—	7·3	11·5	0·004 6	27½	6·8	0·000 022	232	0·0534	65

TABLE 6 (*continued*).

Tungsten	—	18·8	4·7-5·0 annealed 5·8-6·2 drawn		0· 005	200-290 wires 5 to 1 mil. dia.	—	0· 000 004	3 300	0·034	65
Zinc	—	7·2	6·2		0· 004	10-13	12·3	0· 000 029	419	0·095	65
Zirconium	—	4·2	4·2		0· 005	—	—	—	1 700	—	85, 979
Cast iron	'No-Mag' (1*a*)	—	140		0· 000 9	—	—	—	—	—	84
,, ,,	Ordinary	7·2	75-100		0· 001 9	5-13	—	—	—	—	64
,, ,,	Malleable	—	23-33		—	—	—	—	—	—	—
Manganese steel	1·0-1·3 % C ; 11-13 % Mn	7·85	70		0· 001 4	65	—	0· 000 018	—	—	84
Silicon steel	3½ % Si	7·7	50-60		—	30-35	—	—	—	—	331
Nickel steel	4½ % Ni	—	30		—	39	28·5	—	—	—	65, 82, 84
Carbon steel	Conductor rails, etc. ; up to 0·4 % carbon	7·8	10-14		0· 004-0· 005	30-60	29·5	0· 000 012	1 350	—	64
,, ,,	High carbon	—	15-45		0· 002-0· 004	55-100	—	0· 000 010	—	—	64, 309, 331
Almelec	Al(98·5%), Mg and Si	2·5	3·1		0·003 8	22	—	0·000 023	—	—	63 (ii)
				At °C.							
Kanthal Al	Co—Cr—Al—Fe (8*n*)	7·1	145	15	0· 000 089 between 20 and 1100°C.	—	—	0· 000 022 3 (20-1 400° C.) 0· 000 017 4 (20 -1 000°C.)	1 660	—	—
Kanthal A		7·15	139	15				0· 000 018 6 (20-1 300° C.) 0· 000 016 8 (20-1 000° C.)	Below 1 600	—	—
Kanthal D		7·25	135	15				0· 000 017 7 (20-1 100° C.) 0· 000 015 9 (20-1 000° C.)	Below 1 660	—	—
Invar	63·8Fe ; 36Ni ; 0·2 C (3*d*)	—	—	—	—	—	—	$1{\cdot}2 \times 10^{-6}$	1 497	—	—
Nichrome II		8·02	110	24	0· 000 16	—	—	—	—	—	122
Nickel chromium	80 °/o Ni ; 20 °/o Cr	—	107	—	—	—	—	—	—	—	—
Calido	Ni—Cr—Fe (2*b*)	8·15	103	—	0· 000 36	—	—	—	1 530	—	—
Manganese-copper	30Mn + 70Cu	—	101	—	0· 000 04	—	—	—	—	—	—
No. 525 nickel-chrome	(3*c*)	8·15	100	24	0· 000 37	—	—	—	—	—	—
Nichrome	Ni—Cr—Fe (3*b*)	8·15	100	24	0· 000 44	—	—	—	1 538	—	122

Table 6 (*continued*).

Material.	Composition, State, etc. For key see Note at foot of Table.	Specific Gravity.	Specific Resistance Microhms Per cm.-cube.	At °C.	Temperature Coefficient of Resistance Per 1° C.	Tensile Strength. Tons / Sq. In.	Modulus of Elasticity. Million Lbs. per Sq. In.	Temperature Coefficient of Linear Expansion Per 1° C.	Melting-Point °C.	Specific Heat 0°-100° C.	See also §
Rayo	Ni—Cr—Fe (2*d*)	8·05	95·7	—	0· 000 18	—	—	—	1 530	—	—
Kromore	(3*b*) nickel-chromium alloys	8·9	95	24	0· 000 18	—	—	—	—	—	—
Chronic	(4*b*) nickel-chromium alloys	8·28	93·5	15	0· 000 42	47	—	—	1 400	—	—
Comet	(2*ce*) nickel-chromium alloys	8·15	87	—	0· 000 7	—	—	—	1 510	—	—
Superior	Nickel-steel	8·1-8·2	87	—	0· 000 8	—	—	—	—	0· 117	—
No. 193 alloy	Nickel steel (3*c*)	8·14	87	24	0· 000 72	—	—	—	—	—	—
Climax	(5)	—	87	—	0· 000 54	—	—	—	—	—	—
Beacon	(6)	8·13	85	—	0· 000 7	—	—	—	—	—	—
Ferrozoid	Nickel steel (4*c*)	8·28	84	15	0· 000 76	42·4	—	0· 000 007	1 490	—	—
Kruppin	,, ,,	8·10	84	15	0· 000 63	—	—	—	—	0· 012 (?)	—
Phenix	,, ,, (2*c*)	8·10	83	—	0· 001 1	—	—	—	1 510	—	—
Resista	5 % Mn; 15 % Ni; 80 % Fe(9)	—	80-84	—	0· 001 092	—	—	—	—	—	—
Rheostene	—	—	69	—	0· 001 04	—	—	—	—	—	—
SB alloy	(5)	—	53	—	—	—	—	—	—	—	—
Ferno	(6)	8·88	50	—	near nil	—	—	—	—	—	—
Constantan; Eureka	40-45 % Ni; 60-55 % Cu (*efgh*)	8·88	49	15	0· 000 01	—	—	—	—	0· 095-0· 105	—
Advance	Ni—Cu (3*g*)	8·9	49	24	0· 000 018	—	—	—	—	—	—
Ideal	Ni—Cu (2*efg*)	8·9	49	15	0· 000 005	—	—	—	1 210	—	—
Hecnum	— (7)	—	48	—	0· 000 041	61-66	—	—	over 1 260	—	—
Ferry	Ni—Cu (4*cf*)	8·99	47·2	15	0· 000 022	39	—	0· 000 014 6	1 250	—	—
Therlo	Cu—Mn—Al (3*j*)	8·15	46·7	24	0· 000 006	—	—	—	—	—	—
Lucero	Ni—Cu (2*c*)	8·9	46·5	—	0· 000 7	—	—	—	1 350	—	—
Rheotan	—	8·5	45	—	0· 000 41	—	—	—	—	0· 093	—
Nickelin	68Cu; 32Ni	8·2-9·5	43	—	—	—	—	—	—	0·08-0·10	—
Monel metal	67Ni; 28Cu; 5Fe, etc. (*k*)	—	42	15	0· 001 9	—	26	—	1 370	—	—
Tarnac; Manganin	84-55Cu; 4-41Ni; 12-1Mn (4*fl*)	8·9-8·5	40-50	15	0· 000 02-0· 000 04	—	—	—	910	0· 097-0· 105	—
Manganin	84Cu; 12Mn; 4Ni	—	42	—	—	—	—	—	—	—	—
BB alloy	Nickel silver (4)	8·98	40·2	15	0· 000 21	34·8	—	0· 000 015 7	—	—	—
Zodiac	,, ,, (4*f*)	8·97	36	15	0· 000 23	37·8	—	0· 000 015 9	—	—	—
German silver	60Cu; 15Ni; 25Zn (*g*)	8·5	20-35	15	0· 000 3-0· 000 6	30	—	—	—	0· 094-0· 096	—

TABLE 6 (*continued*).

Argentan	—	—	28·7	15	0·000 39	—	—	—	—	—	—
Platinoid	German silver + 0·1 % W	9·0	35-45	15	0·000 23	—	—	—	—	—	—
,,	60Cu; 25Zn; 14Ni; 1 to 2W		41	—	—	—	—	—	—	—	—
Ferro-nickel	—	—	27-36	24	0·002 2	—	—	—	—	—	—
Nickel-silver	52-80Cu; 10-35Zn; 5-30Ni (4)	8·93-8·8	29-18	15	0·000 27-0·000 76	30-29½	—	0·000 016-0·000 018	—	—	—
Platinum-silver	66-33 % Pt (*m*)	Up to 17·8	29 25	15	0·000 31-0·000 33	—	—	—	—	—	—
Cupro-nickel	(4*c*)	8·88	26·4	15	0·000 285	23	—	—	—	—	—
Platinum-rhodium	90Pt; 10Rh (*e*)	20·6	21·3	15	0·001 5	—	—	—	—	—	—
Edina	(6)	7·8	21	—	0·009	—	—	—	—	—	—
Magno-nickel	Ni—Mn (2*k*)	8·8	20	—	0·002	—	—	—	1 400	—	—
Platinum-iridium	80Pt; 20Ir (*em*)	—	32·5	15	0·002	—	—	—	—	—	—
Bronze	88Cu; 12Sn	8·7	17·7	15	−0·000 5	40	17·5	—	—	0·09 (ca.)	—
Aluminium bronze	97Cu; 3Al	—	8·97	15	0·000 9	—	—	—	—	—	—
Phosphor bronze	92½Cu; 7Sn; 0·5P	8·7-8·9	7-8	—	0·002-0·004	20-65	15	0·000 018	—	—	331, 335
Gun metal (Admiralty)	88Cu; 2Zn; 10Sn	8·8	—	—	—	—	—	—	1 010	—	—
Brass	66-90Cu; 34-10Zn	8·4-8·7	7-3½	15	0·001 5-0·002	10-24	13·7	0·000 019	—	0·092	—
Silicon bronze	—	—	3·9-1·8	—	0·001 8	49-28	—	0·000 018	—	—	329, 331, 335
Solder	67-68Pb; 33-30Sn; 0·2Sb	9·4-9·6	19·20	—	—	3-3½	—	0·000 026	240-225	0·04	—
Solder*	100Pb; 0Sn	11·34	21·8	—	—	0·89	—	—	327	—	—
	70Pb; 30Sn	9·48	18·1	—	—	2·66	—	—	183-257	—	—
	60Pb; 40Sn	9·34	16·9	—	—	2·75	—	—	183-238	—	—
	50Pb; 50Sn	8·91	15·6	—	—	2·75	—	—	183-212	—	—
	37Pb; 63Sn	8·42	14·5	—	—	3·35	—	—	183	—	—
	0Pb; 100Sn	7·31	12·4	—	—	0·94	—	—	232	—	—

* These data are based on figures given in *Solder*, Bull. No. 2, International Tin Research and Development Council.

Note.—The data concerning proprietary materials are mainly as given by the makers (or calculated therefrom). The *reference numbers* in the Table apply to the subjoined list of makers or suppliers, and the *reference letters* to the list of typical applications for the various materials :—

(1) Ferranti, Ltd., Hollinwood.
(2) Electrical Alloy Co., U.S.A.
(3) Driver, Drennan & Cooper, Ltd., Manchester.
(4) H. Wiggin & Co., Ltd., Birmingham.
(5) Driver Harris Wire Co., U.S.A.
(6) Bruntons, Musselburgh.
(7) A. E. Heckford, Birmingham.
(8) A. B. Kanthal, Hallstahammar, Sweden (Hall & Pickles, Ltd., Manchester).
(9) Hadfields, Ltd., Sheffield.

(*a*) Switch or transformer covers, cable boxes, resistance grids, etc.
(*b*) Heating elements and rheostats for high temperatures.
(*c*) Resistances to be worked up to about 250° C.
(*d*) Permanent working at 1 000°-1 100° C.
(*e*) Thermo-couples.
(*f*) Shunts; and resistances to 'swamp' the temperature coefficient of copper, etc.
(*g*) Resistances to be worked near atmospheric temperature.

(*h*) Thermo-E.M.F. against copper 0·004 6 V per 100° C.
(*j*) Thermo-E.M.F. against copper 0·3 microvolt per 1° C.
(*k*) Contact points, sparking plug electrodes, etc.
(*l*) Thermo-E.M.F. against copper 2 to 2½ microvolts per 1° C.
(*m*) Hot wires of measuring instruments.
(*n*) Furnaces up to 1 300° C.

Carbon brushes for electrical machinery are made by a similar process; the principal types are as follows:—

Amorphous carbon brushes, to which a small percentage of graphite is sometimes added to reduce friction, are generally hard enough to wear the micas level with the commutator bars, and are therefore suitable where micas are not 'undercut.' The coefficient of friction is usually between 0·22 and 0·29; the permissible current density 35 to 40 A per sq. in.; and the specific resistance 1 300 to 2 500 microhms per in.-cube.

Graphitised brushes are made from a mixture containing more or less graphite, and the amorphous carbon is converted to the graphitic form by heating in an electric furnace. These brushes are relatively soft and it may be necessary to under-cut the micas. The coefficient of friction is usually between 0·20 and 0·25; the permissible current density 55 to 60 A per sq. in.; and the specific resistance 600 to 1 200 microhms per in.-cube.

Graphite brushes, made from graphite with a small proportion of binder, are very soft and should be used with under-cut micas. The coefficient of friction is low, from 0·12 to 0·17; the permissible current density from 60 to 65 A per sq. in.; and the specific resistance from 600 to 1 000 microhms per in.-cube.

Metal-graphite brushes contain a proportion of powdered metal (generally copper) which increases the conductivity. This type of brush is suitable only for slip rings or low-voltage commutators (up to 100 V). The coefficient of friction is from 0·18 to 0·20; and the permissible current density is from 60 to 100 A per sq. in. on commutators (50 °/₀ higher on slip rings), according to the proportion of metal in the brush. For electroplating dynamos (up to 10 or 12 V) metal-graphite brushes are available with specific resistance as low as 7 microhms per in.-cube; other brushes, containing less copper, range from 100 to 500 microhms per in.-cube.

(ii) Other uses of carbon are for glow lamp filaments, arcing tips, and rheostats. *Carbon filament glow lamps* are still used where their energy consumption is of secondary importance or where (as in radiator lamps) it is actually requisite. *Carbon arcing tips* are used to break circuit in switchgear, because they are damaged but slightly by arcing and are easily renewed (§ 365). The critical voltage required to maintain an arc between carbon electrodes is higher than that required between metal electrodes (say 35-40 V compared with 12-15 V). For this reason, and because of its very high melting-point, and the relatively low electrical conductivity of the carbon arc (compared with the metallic arc), carbon is more effective than metals as a material for the arcing contacts of switchgear, provided that its mechanical weakness does not prevent its being used. Carbon powder, granules, and plates are used for *rheostats* of various types; the resistance being variable within wide limits by changing the mechanical pressure applied to the material. A line drawn with a 'lead' pencil on a piece of ground glass can be used as a high resistance (of the megohm order).

(iii) Carbon differs from most metallic conductors in that it has a *negative temperature coefficient of resistance* (Table 6). Except where carbon is used as a resistance material, this negative temperature coefficient is advantageous; for instance, the resistance of carbon-furnace electrodes may be 50 °/₀ lower at the working temperature than at atmospheric temperature.

67. Resistance Materials.—Conductors of high resistance are used where it is actually desired to dissipate electrical energy as heat, *e.g.* in starting and regulating apparatus for motors (Chapter 29), in heating and cooking apparatus (Chapter 26), and so forth. In such cases it is usual to speak of the high-resistance conductors as 'resistances,' and to say that they are used as 'resistance coils,' 'resistance elements,' or 'heating elements.' Table 6 gives the properties of many conductors and resistance materials.

The British Standard specification for metallic resistance materials (B.S.I. Report, No. 115, 1924, under revision at the time of writing) divides these materials into five classes:—

(A) For use when a low temperature coefficient is required at temperatures not exceeding 60° C. (as in standard resistances and sub-standard instruments). The permissible temperature coefficient is ± 0·000 02 per 1° C., within the range 10° to 60° C.

(B) For use when the temperature coefficient may vary more than in Class (A) and at temperatures not exceeding 200° C. (as in instruments other than sub-standard). The permissible temperature coefficient is ± 0·000 04 per 1° C. within the range 10° to 100° C.

(C) For use when the temperature coefficient may vary over a wide range and at temperatures not exceeding 300° C.

(D) For use at high temperatures not exceeding 700° C. (as in heating apparatus).

(E) For use at high temperatures not exceeding 1 000° C. (as in heating apparatus).

In classes (C), (D), (E) the temperature coefficient is to be stated by the supplier who must also declare, for all classes, the thermal E.M.F. of the material against copper at 0° and 100° C.

The resistance, R, of any conductor is given by: $R = \rho l/A$ (§ 18). The resistivity or specific resistance, ρ, is a constant of the material employed, but any number of values can be given to the length, l, and cross-section, A, to obtain the desired value for R. The resistance must be designed with reference to the current to be carried, for the energy dissipated as heat is I^2R watts (§ 49), and this causes a temperature rise which is greater the smaller the radiating surface of the wire. Though the total resistance required may be the same, it is necessary to use a larger wire or strip for a heavier current and a greater length is then required to provide the desired resistance. It does not follow that material of higher specific resistance is better than one of lower specific resistance for a particular purpose. The amount of energy to be dissipated and the permissible temperature rise may be such that it is more convenient or more economical to use the material of lower specific resistance. Tables of current-carrying capacity for wires of various materials and sizes, for specified temperature-rises, are applicable only to a particular set of cooling facilities. In practice, it is generally necessary to find by experiment the best material, dimensions, and arrangement of resistances, for the purpose concerned.

As shown by Table 6, *nickel* is an ingredient of many important resistance materials; alloyed with chromium it furnishes wires which can be operated indefinitely at red heat in air without becoming brittle or seriously oxidised. Backer * claims to have discovered a *magnesium alloy* suitable for use in heating apparatus and electrical machinery when insulated only by an oxide film produced by boiling the metal in water. *See also* nickel in § 65 and core and screening materials in § 82.

Glow lamps are sometimes used as resistances, particularly when charging small accumulators from lighting supply.

Mixtures of *carbon dust and carborundum* and prepared blocks of similar composition are used between lightning arresters and earth, and between generator neutrals and earth to limit the current flowing (§§ 346, 354).

Silit consists of a mixture of silicon carbide and silicon, or of silicon carbide alone (*see also* carborundum, § 85). It has been used considerably on the Continent for electric heating elements. The material is supplied in the form of tubes or rods and can be turned or cut to shape. The resistance at 1 000° C. is said to be about one-third of that at atmospheric temperature, but to be nearly constant between 1 000 and 1 400° C. Silit is unaffected by heating to 1 400° C. in air.

Liquid resistances are discussed in § 68 and Chapter 29.

68. Electrolytes.—Electrolytes are conductors of electricity which are chemically decomposed by the passage of direct current †; generally they are liquids as in primary and secondary batteries (§§ 127 and 431) and electroplating vats, etc. (§ 994, Vol. 3), but at high temperatures, electrolytic conduction and

* *El. Ind. and Invest.*, March 30, 1921, p. 395.

† Some electrolytes are decomposed appreciably by alternating current, but, in general, the chemical effect of one half-cycle is undone by the next half-cycle of current at all commercial supply frequencies, and provided that there is no rectifying action (§ 417 *et seq.*, Vol. 2).

decomposition occur in many refractory materials (furnace linings, glass etc.) which are insulators when cold. Most liquid electrolytes are aqueous solutions of acids, akalis, and salts, and in these solutions the dissolved substances are decomposed or dissociated into components known as ions, which act as carriers of electricity. In very dilute solutions the dissociation is nearly complete, and the conductivity of the electrolyte is proportional to the concentration.

It is characteristic of electrolytes that their specific resistance decreases rapidly as the temperature rises, the temperature coefficient for aqueous solutions of metallic salts and of acids being usually between $-1.5\ \%$ and $-4\ \%$ per 1° C.

(ii) Liquid resistances, as used for motor control (§ 739, Vol. 3), a load for generators on test (§ 1021, Vol. 3), or for 'dimming' lights in theatres, consist of electrolytes into which dip metal electrodes; by varying the submerged area of electrodes or tho distance between them, the resistance in circuit may be altered within wide limits. The electrolytes most used for such purposes are solutions of common salt, sodium carbonate, and sulphuric acid.

69. Water.—Pure water is an insulator, but practically all substances are to some extent soluble in water, and ordinary 'tap water' and water present in hygroscopic materials as 'moisture' are relatively good (electrolytic) conductors due to the substances dissolved in them.* Water from town mains is sufficiently conducting to be used as a resistance in water-jet lightning arresters (§ 346), and as an artificial load for high-voltage generators.†

Many of the most used insulating materials are highly hygroscopic, and moisture is probably the commonest cause of insulation break-downs (§§ 71, 72). It reduces both the specific resistance and the dielectric strength of insulating materials and, in conjunction with dust and dirt, it is responsible for much trouble from surface leakage. Where surface leakage is liable to occur, the form and finish of the surface should be such as to offer

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* For conductivity curves, *see* 'Examination of Water by Electrical Methods,' by Digby, *Jour. I.E.E.*, Vol. 45, p. 541.

† 'Artificial Load for Testing Electrical Generators,' by Morcom and Morris, *Jour. I.E.E.*, Vol. 41, p. 137.

minimum lodgment for dust. Moisture increases the power losses in dielectrics, but its influence on the risk of break-down is of primary importance. (*See also* §§ 74, 77.)

Insulating Materials.

70. Characteristic Properties of Dielectrics.—The properties which determine the suitability of a material for use as a dielectric (§ 4) are: (i) its resistivity or specific resistance, § 71; (ii) its dielectric strength or break-down voltage, § 72; (iii) its permittivity, § 60 (*d*); and (iv) its dielectric hysteresis (§§ 60 (*d*), 312). In addition to these electrical criteria, there must be considered the mechanical properties of the material, and its ability to withstand moisture, chemical attack, heat, or other conditions of the proposed service.

Unfortunately, the electrical properties of insulating materials vary widely with many factors, including: Dimensions of test-piece; R.M.S. value, wave form, and frequency of test voltage; temperature and moisture of test-piece; and mechanical pressure on test-piece. The data given in Table 7 have been compiled from many sources, and may be taken as typical values, but as will appear from §§ 71, 72, the range of values is necessarily wide and a high factor of safety must always be provided in electrical insulation to allow for the effect of moisture, heat, and mechanical stress, and for abnormal electrical stress due to pressure surges (§ 345), or to burrs, sharp edges, etc., the small radius of curvature of which produces intense local stress (§§ 78, 288).

71. Resistivity or Specific Resistance of Insulating Materials: Leakage Current.—It is one of the requirements of an insulating material that its resistivity or specific resistance should be high (§ 59) so that the 'leakage current' through the insulation may be small. The actual value of the specific resistance is reduced greatly by the presence of moisture (§ 69) and decreases rapidly with temperature rise. For these reasons the specific resistance of dried specimens tested under laboratory conditions bears no definite relation to the 'insulation resistance' of complete machines, cables, wiring installations, and the like under service conditions. Apart from variations in the specific resistance, it is rarely possible to calculate the effective cross-section of the leakage path offered by the insulation, hence it is usual to take these factors into account by measuring the resultant insulation resistance under service conditions; thence the leakage current may be calculated by applying Ohm's Law (§ 17, and Chapter 40). Insulation resistance measurements are of little value (except as regards ascertaining that the resistance does not fall below a prescribed limit, § 1018, Vol. 3), unless all the conditions of test are specified in detail. The quantity of moisture absorbed by such materials as fibre or pressboard varies with the duration of exposure and natural drying (without applied heat) may extend over a period of months, the insulation resistance meanwhile rising to 10 or 100 or more times that of the damp material.

The reduction in specific resistance of an insulating material with rise of temperature is often compensated for to some extent by moisture being expelled as the temperature rises. It is therefore difficult to obtain consistent data, and it would be unwise to base any predictions upon calculations unsupported by confirmatory tests made under service conditions. From data published by various investigators it appears that the decrease in specific resistance between 20° C. and 30° C. is from 15 to 25 °/₀ for mica; about 30 °/₀ for rubber; about 50 °/₀ for guttapercha; and from 60 to 70 °/₀ for cellulose, fibre, glass, and porcelain. At a temperature of 70° to 80° C. the specific resistance of cellulose, fibre, porcelain, and moulded compositions may be from $\frac{1}{100}$ to $\frac{1}{300}$ of the value at 20° C. The yet greater decrease in insulation resistance at temperatures in the neighbourhood of 500° to 1 000° C. is of great importance in relation to the insulation of sparking plugs, heating elements, and electric furnaces.

Low insulation resistance permits appreciable leakage current to flow through the insulation; the I^2R watts (§ 49) thus dissipated, together with the heating produced by dielectric hysteresis (§ 60 (*d*)), cause the temperature of the insulation to rise. This results in a decrease of insulation resistance, and an increase of leakage current and heating. In extreme cases the insulation is broken down by the combined effect of heat and electrolytic action and, in any case, the losses in the dielectric are objectionable in that they raise the power factor of the charging current; this is of practical importance where cables are concerned (§ 312).

In general, the insulation resistance of a dielectric in service is the resultant of the volume resistivity (determining the leakage through the body) and the surface resistivity (determining the leakage over the surface of the material). Surface leakage may need special consideration at terminal bushings and the like. The special case of the static condenser is interesting; * the insulation resistance is measured by the application of a steady D.C. potential and affords an indication of the degree of dryness of the dielectric, when comparing condensers of the same type, using the same dielectric. For proper comparative purposes the 'ohm-farad' value of the condenser may be determined; this is the product of the measured insulation resistance of the condenser in megohms by its capacity in microfarads. Numerically, Megohms × Microfarads = Ohms × Farads, so that the 'megohm-microfarad' insulation factor may be called the 'ohm-farad' factor of the dielectric. It is, or should be, a factor independent of the form in which the condenser is made up, *i.e.* it is a specific property of the dielectric, and it is a useful guide to the state of the latter unless the surface leakage of the terminals and similar parts is excessive. Values given by Coursey (*loc. cit.*) are as follows:—

Nature of dielectric.	*Average Ohm-farad value.*†
Mica dielectric	5 000 to 20 000
Waxed paper dielectric, using 'wood' base papers	250 to 1 000
Waxed paper dielectric, using ordinary 'linen-rag' base papers . .	1 000 to 5 000
Waxed paper dielectric, using superfine 'linen-rag' papers . . .	5 000 to 15 000
Oil impregnated paper dielectric, using good quality 'linen-rag' base papers	3 000 to 15 000
Oil impregnated paper dielectric, using special quality 'linen-rag' papers	10 000 to 50 000

These figures apply to a standard temperature of 15° C. and to insulation resistance values measured after 1 min. of electrification. The ohm-farad value decreases rapidly with increasing temperature. Also, owing to the time taken by the charge to flow fully into the interior of the dielectric, the measured insulation resistance is, say, 20 % higher at the end of 2 mins. than at the end of 1 min. The ohm-farad value for 1-min. electrification is, however, convenient for comparative purposes.

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* Some applications of condensers to electric power circuits. P. R. Coursey, *Inst. of Eng. Inspection,* Oct., 1931.

† Condensers giving lower values may still be satisfactory in practice, but if the ohm-farad value is very low the cause may lie in damp or imperfectly impregnated dielectric.

71a. Dielectric Power Factor.—The presence of absorption and losses in a dielectric results in the current curve leading the voltage curve by less than 90° when the dielectric is subjected to A.C. potential. The condenser itself then absorbs a certain amount of energy, and the ratio of this loss to the total hVA in the condenser circuit is the power factor of the condenser. Values given by Coursey (*supra*) are:

Large radio-frequency mica condensers	0·000 2
Small „ „ wax-impregnated paper condensers	0·005 to 0·007
Oil-immersed paper condensers, radio-frequency . .	0·001 5 to 0·002
„ „ „ low-frequency . . .	0·003 to 0·004

The efficiency of condensers ranges from 99·3 % for the poorest commercial condensers to at least 99·98 % for large radio-frequency condensers (*see also* § 312).

72. Dielectric Strength: Break-down Voltage.—Though break-down of insulation may be caused by leakage current (§ 71), it is generally caused by the dielectric stress exceeding the 'dielectric strength' of the material. Both the dielectric stress or pressure gradient and the dielectric strength are expressed in terms of potential difference per unit thickness. The dielectric strength of thin materials such as paper, mica, insulating tape, and pressboard is expressed in volts per mil or volts per mm., whilst that of porcelain, slate, air, etc., is more conveniently expressed in volts per cm. Unfortunately, the dielectric strength is not directly proportional to the thickness of the dielectric but is relatively greater for thin sheets or plates; thus the break-down voltage of a 1-inch plate is much less than 1 000 times that of a sheet 1-mil thick. This lack of proportionality is due partly to the electrostatic field not being uniform and partly to the inability of heat to escape rapidly from the central portions of thick dielectrics; the outer skin surface is also probably a factor of importance in paper and similar materials.

There are wide variations between the values of dielectric strength determined by different observers, these being explained by the fact that the dielectric strength varies with the following factors:—

(*a*) The structure, homogeneity and quality of the sample.

(*b*) The uniformity or otherwise of the electrostatic field, as determined by the size and shape of the electrodes, and by the thickness and shape of the sample.

(*c*) The thickness of the sample, as explained above.

(*d*) The wave form of the test voltage, and the rate and duration of application of voltage.

(*e*) The moisture content of the specimen.

(*f*) The heat capacity of the electrodes.

It is the *maximum* voltage which causes break-down to occur and the relation between this and the R.M.S. voltage varies with the crest factor (§ 30) of the voltage wave. In X-ray work it is convenient to measure the very high voltages employed by reference to the length of spark gap (in air) which is broken down, and this demands a knowledge of the dielectric strength of air in terms of peak voltage (§ 78), but for machines, cables, etc., it is more convenient to express the dielectric strength in terms of R.M.S. voltage, a sinusoidal test-wave being assumed. The wave form has also an influence on the manner in which the dielectric is stressed and fatigued, so that, for example, a D.C. pressure is less severe on a dielectric than is an A.C. pressure of the same maximum value; this is important in relation to D.C. pressure tests on cables (§ 1027 *et seq.*, Vol. 3), but for ordinary operating voltages it may be assumed that D.C. induces the same dielectric stresses as sinusoidal A.C. of the same maximum value (§ 298).

Rapid increase and *prolonged application* of voltage favour break-down, hence it is usual to specify both of these factors, a reasonable rate of increase being 1 000 V per min. when approaching the test pressure or anticipated break-down voltage, and the standard time of application being 1 min.

Moisture reduces greatly the dielectric strength of all hygroscopic insulating materials, and every precaution must be taken to exclude it by impregnating and sheathing fibrous materials. The effect of moisture on oil is mentioned in § 77.

With *increasing temperature* the dielectric strength of all insulating materials decreases; this effect may be masked by the recovery of dielectric strength due to the drying hygroscopic material, or it may be accentuated by the formation of water and acid products at higher temperatures (as where certain condensation products (§ 74, VIII*a*) are used).

From an extensive series of tests by W. S. Flight * it appears that typical values for the reduction in break-down voltages at 100° C. compared with those at 30° C. are:—

For mica, and mica-papers and -cloths	5 to 15 %
For paper fullerboard, and wood	15 ,, 30 % †
For varnished papers and varnished cloths	40 ,, 50 %
For untreated fibre, micarta, and moulded compositions which liberate moisture when heated	60 ,, 80 %

The factors determining dielectric strength are so numerous, and of such great but variable importance, that the adequacy of particular constructions can be determined only by break-down tests under, as nearly as possible, the actual conditions of service.

At the Annual Convention of the American Institute of Electrical Engineers in 1922 (*see Jour. Amer. I.E.E.*, Vol. 41, p. 973) Steinmetz stated that there appeared to be no such thing as a definite break-down voltage or break-down

* *Jour. I.E.E.*, Vol. 60, p. 218.

† Sometimes the dielectric strength is greater at 100° C. due to drying-out.

gradient in solid insulation. A solid insulator appears to be, at least in many cases, a third-class or pyro-electric conductor. On the application of a gradually increasing voltage, the current increases at first in proportion to the voltage, then more rapidly until a certain maximum voltage is reached; at this point the current 'runs away' and rises to the short circuit current of the voltage supply, which generally means the destruction of the 'insulation' (now a conductor) by heat and the elimination of all that can be seen. If, however, for any reason, the amount of energy which can be concentrated on the conducting portion of the dielectric is limited, the disruptive strength of the latter remains unimpared. This may explain why in some cases (*e.g.* in a cable with high ratio of external to internal diameter) part of the insulation can be stressed above the so-called break-down point without changing the insulation. Peaslee (*ibid.*, p. 975) supported this view and stated that the so-called puncture voltage was really the voltage at which, with given material and spacing, the overall volt-ampere characteristic of the path from the conductor to the sheath became negative. This possibility of over-stressing without break-down may be compared with the formation of corona discharge round a conductor in air. In the zone of the discharge the air has become a conductor and the effective diameter of the conductor, as regards distribution of electrical stress in the dielectric, has been increased; complete break-down does not occur until the potential gradient at the surface of the corona exceeds the dielectric strength of the surrounding layer of air.

73. Classification of Insulating Materials.—In practice, the selection of an insulating material for a particular application generally resolves itself into a compromise between the desirable mechanical and electrical characteristics; it is seldom possible to obtain in one material the ideal mechanical and electrical properties, to say nothing of thermal, chemical, and other properties. According to the characteristics which are most important in specific applications, insulating materials may be classified in many different ways. In the following paragraphs they are discussed under the broad headings: Solid Insulators (§ 74); Moulded Insulating Materials (§ 75); Insulating Paints, Varnishes, etc. (§ 76); Liquid Insulators (§ 77); Air as an Insulator (§ 78). Table 7 gives the constants of a number of insulating materials, many of them referred to in succeeding paragraphs.

74. Solid Insulators.—The term 'solid insulators' includes rigid, natural, and artificial materials, such as slate, glass, and porcelain, which are generally used in more or less massive form; and flexible materials, such as mica, rubber, and manufactured fibrous product (papers and textiles), which are used for wrappings or coverings and for other applications where flexibility is required. Waxes, compounds, gums, and resins may fairly be considered as solid insulators, though they are liquid under some

TABLE 7.—*Approximate Constants of Insulating Materials.* (*Compiled from Various Sources.*) [SEE NOTE ON OPPOSITE PAGE.]

Material.	Specific Gravity.	Megohms per cm. cube (at about 15°-20° C.).	Breakdown Volts per mil (at about 15°-20° C.).	Specific Inductive Capacity ε.	Material Uninjured by Temperatures up to (about) °C.	*See also* §
Asbestos	3·0	16×10^4	100-110	—	1 000	74, IX*a*
Bakelite products	1·3-1·9	$(0·2\text{-}40)\times10^6$	250-500	2·5-5·0	125 with sawdust 200 ,, asbestos 250 pure	74, VIII*a*
,, special	—	20×10^9	500-800	—		
Basalt	3·0	—	140	—	1 200	74, II*d*
Bitumen, pure	1·0-1·8	—	30-50	2·7	90	74, V*a*
,, vulcanised	1·2	2×10^9	300-350	4·0	43	74, V*a*
Cambric, cotton or silk, varnished: 50 mils	—	$(300\text{-}500)\times10^6$	400-500	4·0-6·0	95	74, IX*d*
5 mils	—	$(300\text{-}500)\times10^6$	800-1 200	4·0-6·0	95	74, IX*d*
Celluloid	1·4	$(2\text{-}7)\times10^4$	350-500	1·2-2·7	75	—
Ebonite (vulcanite)	1·2	$(2\text{-}1\,000)\times10^9$	750-1 000	2·0-3·5	80	74, IV*d*
Erinoid	1·3	$(2\text{-}100)\times10^3$	150-200	—	75	74, VIII*e*
Fibre, vulcanised	1·4	100-5 000	200-400	4·5	200-300	74, IX*d*
Formite, fibre filled	1·4	—	250-500	—	175	74, VIII*c*
,, heat resisting	2·0	—	100-150	—	260-315	74, VIII*c*
Galalith	1·3	$(10\text{-}20)\times10^3$	150-210	—	75	74, VIII*d*
Glass, crown, plate, window	2·5	$(10\text{-}20)\times10^6$	250-350	5·0-8·0	—	74, II*a*
,, flint, lead	3·2-4·5	—	125-150	5·5-9·0	—	74, II*a*
,, special condenser	—	—	1 250	8·5	—	—
,, special conducting	—	500	—	—	—	—
Glyptal micanite	2·64	—	620	5·2	—	74, III*d*
Guttapercha	0·98	$(1\text{-}400)\times10^6$	200-500	2·5-4·5	—	74, IV*e*
Jute, impregnated	—	—	20-40	3·4	—	74, IX*d*
Leatheroid, plain	—	—	350-420	—	90	74, IX*c*
,, varnished	—	—	400-500	—	95	74, IX*c*
Marble	2·5-2·8	500-5 000	50-150	8·3	—	74, I*b*
Mica	2·8-3·2	$(10\text{-}200)\times10^9$	1 500-5 000	5·0-8·0	115	74, III*a*
Mica-cloth or -paper	1·2-1·9	—	300-600	—	—	74, III*c*
Micanite	2·54	—	500-1 000	4·5	80-115	74, III*b*
Micarta, Paxolin	1·2-1·4	—	300-500	—	95	74, IX*c*
Paper, plain	0·7-1·0	$(5\text{-}100)\times10^4$	150-300	2·0-2·5	90	74, IX*c*
,, varnished	—	$(300\text{-}500)\times10^6$	400-1 000	2·5-4·0	95	74, IX*c*
Paraffin wax	0·9	$(3\text{-}5)\times10^{12}$	300	2·0-2·3	—	74, VI*a*
Pitch	1·1	—	50	1·8	—	75, I*b*
Plaskon	1·43	—	300-400	5·0-6·0	—	74, VIII*b*
Porcelain, wet process	2·3-2·4	$(1\text{-}1\,000)\times10^6$	200-300	4·4-6·0	1 300 (special)	74, II*c*
,, dry process	2·0-2·3	—	100	—	—	74, II*c*
Pressboard, plain	—	10 000	200-350	—	90	74, IX*c*
,, varnished	—	—	250-400	—	95	74, IX*c*
,, oiled	—	—	700-900	—	95	74, IX*c*
Quartz, silica	2·2-2·7	$(1\text{-}2)\times10^8$	—	3·5-4·5	1 100-1 200	74, II*b*
Resin	1·1	5×10^{10}	280	2·6	—	74, VII
Rubber, plain	0·9-1·0	$(10\text{-}15)\times10^9$	400-700	2·0-2·5	—	74, IV*a*
,, vulcanised	1·3-1·8	$(1\text{-}10)\times10^9$	300-600	3·0-5·0	—	74, IV*a*
Shellac	—	$(2\text{-}10)\times10^9$	40	2·75-3·0	—	75, II*b*
Siluminite, Grade 2	2·0	$4·3\times10^6$	48	—	200	74, IX*aa*
,, Grade 4	—	$(1\text{-}3·4)\times10^6$	—	—	100	
Slate	2·5-3·0	100-50 000	20-40	6·5-7·4	—	74, I*a*
Sulphur	1·9	$(4\text{-}100)\times10^9$	—	3·0-4·0	—	—
Varnish, oil	—	—	800-1 000	—	—	76
Wood, plain, dry	0·4-1·3	$(1\text{-}50)\times10^6$	10-15	2·5-7·0	90	74, IX*b*
,, impregnated	—	—	50-150	—	95	74, IX*b*
Benzine	0·88	1400	—	2·4	—	—
Castor oil	0·97	—	—	4·8	—	—
Petroleum	0·85-0·9	—	160-170	2·0	—	77 (1)
Turpentine	0·87	—	240	2·2	—	—
Air, atmospheric pressure	—	Infinite	95-100	1·0	—	78
,, at 10 atmos.	—	,,	600	—	—	78

conditions of temperature and in some methods or stages of application. Moulded insulating materials are solid in their service condition but an essential feature of these materials (§ 75) is their initial plasticity or 'mouldability.' As to the economic use of waste and scrap material of these solid insulators, see § 75.

I. Stones.—(*a*) *Slate* is used extensively for the panels of low-voltage switchgear, etc. There are frequently metallic veins in the material, hence all live parts should be insulated by micanite washers and bushes or equivalent means. The front and edges are generally enamelled. Treatment with oil counteracts the hygroscopic nature of the material. Inferior slate contains hard spots and is liable to flaking.

(*b*) *Marble*, when polished, provides a handsome mounting for switchgear and instruments but is liable to contain conducting veins, hence live parts should be insulated (*see* (*a*)).

(*c*) *Steatite* (*Soapstone*) is the massive form of talc, a silicate of magnesia. Pieces to be used as insulators in heating and cooking apparatus, arc lamps, sparking plugs, etc., may be machined from the natural mineral, or the latter may be pulverised, mixed with a cement, and moulded to form. After kilning the steatite is extremely hard, less brittle than porcelain, but porous. A glaze may be applied to exclude moisture. The specific resistance falls rapidly above 300° C.

(*d*) *Concrete* cannot be relied upon for insulation except where low voltages are concerned. It is, however, useful in cellular switchboards (§ 378) as a 'non-conducting' structural material for partitions, etc., the actual insulation being provided by porcelain. Protective reactance coils (§ 340) are sometimes encased in concrete.

II. Vitreous Materials.—(*a*) *Glass* varies widely in electrical properties according to its chemical composition. It is impervious to moisture and the transparency of the material facilitates inspection. The principal disadvantages are its brittleness and its high temperature coefficient of expansion. Where used, glass should be annealed. The specific resistance decreases rapidly above about 200° C. Glass is an electrolytic conductor (§ 68), and there is considerable surface leakage over those glasses which are attacked by moisture.

(*b*) *Quartz* (*Silica*) has practically zero temperature coefficient of expansion and is, therefore, not cracked by wide and sudden variations of temperature. This property makes it useful for pyrometer-sheaths, supports for heating elements, special lamp bulbs (Chapter 25), sparking plugs, etc. It is also largely used for sheathing high-voltage induction coils and for high-frequency

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Note to Table 7.

The data in this table must be regarded as only approximate; where exact values are of importance, special tests must be made because the electrical properties of all materials vary widely with the sample and with the conditions of testing. To facilitate comparison, the break-down voltage of specimens of the thicknesses commonly used in practice have been reduced to V/mil by simple proportion. Actually, the break-down voltage does not vary directly with thickness (§ 72) but the values per mil when multiplied by the thickness actually employed will give approximately the break-down voltage of the latter; a large factor of safety must be allowed (§ 72). Arithmetically (but *not* electrically, § 72): 1 V/mil = 39·4 V/mm.; 1 V/mm. = 0·025 4 V/mil.

wireless transmission work.* Fusing at a temperature of about 1750° C., it has great stability under wide changes of high temperature, so that a tube may contain a cold liquid or gas and be surrounded by one at high temperature or *vice versa.* Other properties are resistance to acids, high transmission of light generally and of ultra-violet rays in particular, and high electrical resistance; this last is about 10 °/₀ higher than that of the best porcelain, being 900 megohms per cu. cm.; but the specific resistance decreases rapidly above 400° C. Quartz is less brittle than porcelain and is sometimes used on the moving parts of oil switches. Due to its refractory nature quartz is difficult to work, and this is the chief hindrance to its more general utilisation. Pure quartz produces a transparent, colourless glass, while quartzite gives a translucent white glass, which, however, is quite as valuable for electrical purposes as the more costly clear form, despite the existence of occluded water. In manufacture, a carbon electrode is embedded in the quartz and the crystalline formation is broken up so that a fused semi-liquid is produced, which can be drawn into rods or tubes or blown by compressed air into moulds.

(c) *Porcelain* for electrical purposes should be vitreous throughout and a 0·5 °/₀ alcoholic solution of fuchsin dye should not penetrate into broken test-pieces, even when the latter are immersed for 24 hrs. under a pressure of 2 000 lbs. per sq. in.† Porcelain is not so brittle as glass, and the special qualities now used for transmission line insulators have a low temperature coefficient of expansion and are able to withstand indefinitely alternate immersion in boiling and freezing water. Other applications include the support and insulation of conductors, contact-pieces, terminals, etc., on switchboards and in all kinds of apparatus and accessories. The compression strength of porcelain is high, but the material should not be subjected to tension. Pieces of relatively complex form can be moulded, but the material cannot be worked after firing. Porcelain resists chemical attack and may be exposed to high temperatures, but the specific resistance decreases rapidly above 200° C.

Porcelain is made from kaolin (china clay) and felspar as main ingredients. The details of composition and manufacture of special qualities are carefully-guarded secrets. A certain amount of useful information on the subject has, however, been published by a manufacturer in the U.S.A.‡ Mr. Lapp considers that the failure of porcelain insulators comes from within the material itself, and not (as generally supposed) from external effects due to the expansion or contraction of the cement or steel parts. He points out that 'a thousand pieces of burned porcelain may contain literally hundreds of different grades'. The fundamental process of manufacture is that: the clays, flint and feldspar, all in very fine powder form, are mixed with water, making what is called 'slip'; this slip for best product is ground in flint pebble mills, then filtered under pressure to eliminate the bulk of water, leaving a stiff mud which is kneaded in what is called a pugmill. The clay, softened by the kneading, is expressed from the mill by means of a screw or spiral pusher. Perfect kneading is of the utmost importance for reducing voids and the water-space content, which latter is of the order of 40 to 45 °/₀ at first; the ground slip is loaded with dissolved air and bubbles of air of minute size, and is to some

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* *El. Rev.*, Vol. 110, p. 36.

† Standard porosity test for porcelain insulators for high-tension lines (B.S.S. 137).

‡ 'Physical Research Methods in the Study of Dielectric Materials,' John S. Lapp (Lapp Insulator Co., Inc., Le Roy, N.Y.). National Electric Light Assoc., U.S.A.

extent laminated by the action of the kneading knives. To get rid of the evil effects of these conditions, two processes have been evolved: (1) a fundamental vacuum process covers the method of passing all the clay slip through apparatus, subjecting it to a sufficiently high vacuum to boil the liquid slip at moderate temperature to eliminate the air, and (2) another new and basic process covers the method of kneading or mixing the clay from the filter cake so that as the clay passes through the mill, it is treated back and forth *across* the axis of the stream instead of *along* the axis of flow. This eliminates torsional strains or stream lines from the clay. Porosity, considered by this research worker to be the main cause of failure, is thus avoided, even as regards those 'micropores' so small that they cannot be filled with a liquid in any reasonable time of soaking. The paper should be studied in full. Dry moulded porcelain is apt to be porous.

After a preliminary drying the pieces are fired at 1 200°-1 300° C. The glaze is of the same general composition as the porcelain, but is a more fusible mixture and therefore melts to form a glass-like film on the surface. Though the glaze has considerable dielectric strength and does 'seal' pores it should not be taken as reducing in the slightest degree the necessity for a vitreous structure throughout the porcelain. The glaze should be regarded simply as a self-cleaning, dirt- and weather-resisting 'finish.'

(*d*) *Basalt.*—Insulators of fused basalt are extensively used in France, in place of porcelain, mainly for electric railway work. There are many varieties of basalt, all of igneous origin, some naturally vitreous, others compact or crypto-crystalline, others, again, finely or coarsely crystalline. The mineral is composed of plagioclase felspar, augite, olivine and magnetite or titaniferous iron. The approximate constitution of that used for moulded insulators is 55Si; 12Al; $22Fe_xO_y$ with small amounts of lime, soda, potash and magnesia.* While difficult to work in its natural state, it can be fused at 2 300° F., and then cast in moulds, after which a lengthy annealing process restores it from the brittle state to its normal original condition. The coefficient of expansion is so near to that of iron that iron parts can be incorporated in the molten basalt before solidification, thus obviating cementing; or metal can be screwed into the moulding. The dielectric strength of annealed basalt is 35 kV per $\frac{1}{4}$ in. thickness; the tensile strength $18\frac{3}{4}$ tons / sq. in., and the compression strength $18\frac{1}{4}$ tons / sq. in. Tests made on a number of anchorage insulators, in Paris, with a frequency of 42 cycles, showed a first flash-over at from 27 to 30 kV, arcing beginning at 32 to 37 kV. Each insulator was then immersed in oil and subjected to four consecutive piercing tests in rapid succession, the E.M.F. being gradually built up until puncture occurred; the second similar test being begun immediately after the first piercing and the third and fourth similarly. In nearly every case, the second puncture required a *higher* E.M.F. than the first, or the third than the second, showing that after being pierced the basalt immediately re-solidifies at that point. For resistance to lightning discharges, this property is of the greatest value. The average piercing values of the four tests were 32, 35, 33 and 33 kV. The further advantages claimed for fused basalt are its high dielectric strength; total absence of hygroscopicity; the possibility of incorporating stalks, hoods, etc., in the insulator; resistance to atmospheric conditions and acids; capacity for being moulded into any shape; greater tensile and compressive strength; and, finally, cheapness.

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* 'The Insulating Properties of Fused Basalt.' *El. Rev.*, Vol. 98, p. 862.

III. Mica and Mica Products.—(*a*) *Mica* is a mineral consisting of silicates of aluminium, potassium, and magnesium, with certain impurities, of which iron oxide is electrically the most objectionable. Amber (Canadian) mica is soft and is recommended for use between commutator bars. White and ruby micas (Indian) are harder and of higher dielectric strength; they are recommended for sparking plugs and condensers. Spotted mica is suitable for use in electric heaters. All varieties of mica are characterised by their laminated structure; the plates can be split and resplit almost indefinitely. Sheets 1 mil thick should not crack when wrapped round a lead pencil. In use, the sheets should be clamped, or otherwise subjected to mechanical pressure, in a direction perpendicular to the plane of cleavage. Mica is disintegrated by oil; it is also disintegrated at temperatures above 500° C. (as reached in heating elements, etc.) unless it is subject to compression. Of all flexible insulating materials mica is the most resistant to high temperatures; mica insulated windings have operated without deterioration at 200° C., but a lower working temperature is desirable (§ 80).

Mica sheets 12 ins. square are now rarely found. Sheets 2 ins. × 1½ ins. are about the smallest size of any commercial value; these cost a few pence per lb., whereas the largest selected sheets may cost more than £1 per lb. In such applications as sparking plugs it is possible to build up pure mica insulation by superimposition of small sheets, and in other applications it is sometimes possible to use larger sheets with the joints staggered in consecutive layers. Generally, however, it is more satisfactory to use one or other of the mica products mentioned below.

(*b*) *Micanite*.—The best micanite sheets are built up from mica splittings, about 1 mil thick and 2 or 3 sq. ins. in area, cemented together with shellac or similar binder and consolidated by heat and mechanical pressure. Though the maximum dielectric strength of micanite is lower than that of mica, there is less variation in the dielectric strength of the manufactured product, due to metallic inclusions in the mica being distributed throughout the micanite. *Moulding micanite* softens at about 95° C. and can then be pressed into shape for commutator end rings, slot linings, etc. A harder *commutator micanite* with less than 5 °/₀ of a binder which does not soften at 95° C. is made for use between commutator bars and in other places where flat sheets are required. *Flexible micanite* is made with a flexible binder (generally containing some oil) and is flexible at all temperatures; it is used to insulate windings. *Heat-resisting micanite*, made with water-glass (sodium silicate) as binder can be used at temperatures up to 500° C. without injury; it is suitable only for low voltages (say, 250 V) and must be kept dry. (*See also* § 75.)

According to requirements, various grades of micanite are obtainable in sheets up to 3 ft. square and in thicknesses from 5 mils to ⅛ in. or more.

(*c*) *Mica Papers, -Cloths, etc.*, consist of one or more layers of mica splittings supported on one or both sides by Japanese or other special paper, silk, or cloth, to which it is attached by a quick-drying copal or shellac varnish. Micanite-cloth is stronger than micanite-paper; so also is micanite-silk, with the further advantage that it is thinner and more flexible than cloth. In all three cases the dielectric strength is practically that of the mica alone. *Micafolium* (micarta folium or mica-paper) can be built up into tubes, etc., and is used extensively to insulate high-voltage windings. Thick tubes and shields are sometimes built up from micanite and impregnated paper. *Micarta* is *not* a mica product, *see* section 9 (*c*).

(*d*) *Glyptal Mica*.—The synthetic resinous product known as 'Glyptal' has been developed in America and described by Mr. L. F. Barringer.* It is used for

* *Gen. El. Rev.*, Vol. 29, p. 757, and Vol. 32, p. 530.

bonding or cementing mica flakes into fabrics similar to those described above; but the results are claimed to be superior. Originally made in rigid form, over 1½ million commutators have been constructed with glyptal-mica insulation; and recently a highly flexible form has been produced. This flexible mica can be wrapped around sharp bends of small radius without loosening or displacing the flakes, and it remains flexible under service conditions; it is used between high-voltage and low-voltage coils and also as a pad between core and coils in transformers; for the end-windings of high-voltage railway armatures; at cross-overs; and under terminals of field-coils, pole insulation, etc. In addition, Glyptal-pasted mica is being used for composite insulation, in the making of slot or cell insulation for D.C. motors, where it is stated that it ensures closer adherence to the coils, with no springing back due to gradually developing brittleness, and no cracking or breaking in service. A series of competitive physical tests, against three other similar mica compositions in common use, included: wrapping on a small mandrel, both before and after baking at 200° C.; immersing for 48 hrs. in water at 25° C.; immersing for 48 hrs. in mineral oil at 100° C. While all the other three compositions were distorted or broken up, the Glyptal-pasted mica was not. As the average of all the tests, taking 100 as a perfect standard, Glyptal mica gave a result of 94 as against 78, 72 and 56 for the other samples. (*See also* § 74, VIII (*f*).)

IV. Rubber and Rubber Products.—(*a*) *Rubber*, a complex compound of carbon and hydrogen, is the coagulated latex of certain trees and vines. Synthetic rubber can be made, but is, at present, more costly and less satisfactory than the natural product. Para rubber is generally considered to be the best for electrical work. Pure rubber strip is used to protect copper from the sulphur in vulcanised rubber (§§ 283, 285) but, as pure rubber is hygroscopic and oxidises rapidly, it may not be exposed to air.

(*b*) *Vulcanised Rubber* (V.I.R.).—When mixed with 5 °/₀ or less of sulphur and heated to 150°-160° C., rubber is *vulcanised* and in this form it is tough, elastic, non-hygroscopic, and less affected than pure rubber by heat. Vulcanised rubber is the standard insulating material for low voltage cables (§ 283). Even the vulcanised product is deteriorated by light, air, ozone (§ 287), oil, and grease; and it deteriorates in service if heated above 50° C.

As used to insulate conductors, V.I.R. contains from 30 to 60 °/₀ of pure rubber, according to the requirements to be met, together with litharge (up to 10 °/₀ or so), whiting (up to 25 or 30 °/₀), zinc oxide (from 20 to 50 °/₀), and colouring materials as required. The relative proportions of the inorganic ingredients vary widely according to the practice of individual makers or the specifications of purchasers. The general effect of these ingredients is to toughen the product and facilitate vulcanisation. It is remarkable that rubber can carry 50 °/₀ or more of mineral matter without losing its characteristic elasticity.

(*c*) *Tough Rubber Compound* (C.T.S.) is a 'mechanical' rubber and should be regarded primarily as protection against rough-usage, corrosion, etc., though it has, of course, some insulating value as well (§ 283).

(*d*) *Ebonite, Vulcanite or Hard Rubber* is vulcanised rubber containing from 30 to 50 % of sulphur and subjected to prolonged curing at 150° C. The material is hard and brittle; can be machined and polished; softens between 60° and 100° C. and can then be moulded into simple shapes. It is much used in instruments, telephone parts, etc. Sheets are made in moulds faced with metal foil to obtain a planished surface; sufficient of the metal enters the ebonite to reduce the surface insulation of the latter. The original surface should therefore be removed where surface leakage is to be avoided. When exposed to sunlight or ultra-violet rays the surface of ebonite undergoes decomposition and surface leakage ensues. Ebonite-mounted resistance boxes, etc., should be kept away from sunlight, and the surface should be washed occasionally with distilled water. Ebonite is not suitable for immersion in oil.

The mechanical and heat-resisting properties of ebonite can be improved by the addition of certain mineral ingredients to the mixture before curing; the dielectric strength is lowered however. *Stabilit* is a proprietary composition of this type. The use of ebonite as a sheath for insulated conductors is mentioned in § 551, Vol. 2.

(*e*) *Guttapercha* is similar to, but chemically distinct from, rubber. It is inferior to rubber as an insulator and oxidises in air; it softens about 65° C. It is unaffected by water and its main use is in the insulation of submarine cables.

V. Bitumen.—(*a*) *Bitumen or Asphalt* is a natural product (mineral pitch) consisting of a complex mixture of hydrocarbons with more or less inorganic matter. The best crude material is in the Trinidad Lake deposit, and is a semi-fluid material which softens and melts between 80° and 100° C. Refined bitumen is used in the manufacture of certain insulating varnishes, impregnating compounds, and joint box compounds. It is also used round cables which are laid solid (§ 290). No form of bitumen should be exposed to oil.

(*b*) *Vulcanised Bitumen* is made by a process similar to the vulcanising of rubber (IV (*b*)) and is used to insulate cables. It is brittle at low atmospheric temperatures and softens at about 38° C.; for other properties *see* § 287.

(*c*) *Elaterite* (*Elastic Bitumen or Mineral Caoutchouc*) is a soft grade of asphalt.

(*d*) *Gilsonite* is a hard grade of asphalt which melts at about 135° C.

VI. Waxes and Compounds.—These are used to fill joint boxes, instrument transformer cases, terminal boxes, etc., and to impregnate absorbent coverings of wires and windings to exclude air and moisture, and contribute to the insulation strength. The waxes used include beeswax, ceresine, montan, and paraffin wax; and the composition of compounds varies widely with the needs of individual cases. Soft wax (ozokerite, etc., § 283), melting at 50°-70° C., is used to finish cotton-braided wires. Mixtures of bitumen and pitch with various waxes yield hard, tough compounds for joint boxes, etc., and can be obtained with melting-points from 65° to 150° C. as required. *Chatterton compound* consists of guttapercha, tar, and resin, and is very elastic.

Paraffin Wax is often used to render wood acid-proof, and to render wood and paper non-hygroscopic; applied to the edges of rolled oiled tape, it excludes moisture. As a filling for instrument transformers, etc., this wax has the advantage of being a good insulator which fills all crevices and is normally solid; in the event of undue heating in service, the wax melts and then circulates (like oil) thus improving the cooling facilities.

VII. Resins. Natural resins (new or fossilised) are oxidised exudations from certain trees or insects thereon. *Shellac* is refined lac in flake form, and is used in the preparation of various varnishes and in making micanite and similar products. *Copal* is another natural resin; its applications are similar to those of shellac. (*See also* §§ 74 (viii), 76.)

VIII. Synthetic Products.—(*a*) *Bakelite* is the trade name of a series of 'condensation products' or 'synthetic resins' developed by the researches of Dr. Baekeland, from whom they take their name. 'Bakelite-A' is formed by the action of phenol (carbolic acid) on formaldehyde at a temperature below 100° C. This product is used as a varnish or to impregnate paper, etc., or it is mixed with porous 'fillers' to form moulding compounds (§ 75). After application for one or other of these purposes, the resin is converted to 'Bakelite-C' by heating under a pressure of 100-150 lbs. per sq. in. at a temperature between 150° and 200° C. according to the makers' instructions for the particular application concerned. 'Bakelite-C' is an amber-coloured solid with good mechanical and electrical properties; it is unaffected by water, oils, and all but strong acids and strong alkalis; it is not softened by heat but chars at from 250° to 300° C. 'Bakelite-B' is an intermediate product which is sometimes preferable to the A-product for use in moulding compositions.

Bakelite, converted to the C-form after application or moulding, is suitable for use where a solid, inflexible (but relatively tough) sheath or filling is to be produced by surface treatment or impregnation respectively. Small parts can be made of bakelite alone, but for most purposes it is sufficient and cheaper to use a composition (§ 75). The final 'condensation' (to form C) liberates water which should be removed by vacuum-drying in the case of coils.

The rapidly increasing use of Bakelite in various forms is principally due to the fact that it can be machined as well as moulded.

(*b*) *Plaskon.*—This is a synthetic resin developed at the Mellon Institute of Industrial Research in the U.S.A. Its properties, as given in a report of that Institute, are as follows:—

Specific gravity, 1·43. Modulus of rupture, 10 000-14 000 lb. / sq. in. Tensile strength, 4 000-6 000 lb. / sq. in. Compressive strength, 25 000 to 30 000 lb. / sq. in. Impact strength (Sharpe), 0·7-1·2 ft.-lb. Dielectric constant (25° C.), 5-6. Dielectric strength to puncture, 300-400 V per mil. Water absorption (20° C.; 1 / 8 in. section), 0·07 to 0·66 °/₀ in 24 hrs. Hardness (Mohr scale), 3·0-3·5. Hardness (scleroscope), 80-95. It can be machined, bored, re-surfaced and polished. It is unaffected by alcohol, acetone, oil or other common solvents; is moderately resistant to cold dilute acids, but not to hot or concentrated acids; and while quite resistant to cold dilute alkalis, it also resists very dilute hot alkalis such as soap, borax and cleaners. Moulding is said to be easily performed, and the speed of 'cure' is high, so that rapid low-cost mass fabrication is possible. The base shade is one of neutral translucency, permitting pigmenting to give all colours of any intensity, either opaque or translucent, as well as mottled or striated effects, the surface being hard and lustrous.

(*c*) *Formite* is a British-made phenol-formaldehyde product used in the preparation of moulding powders (§ 75).

(*d*) *Galalith* is a dried-milk product which can be moulded or bent but is hygroscopic. Insoluble casein is treated with formaldehyde and subjected to mechanical pressure.

(*e*) *Erinoid* is also made by the action of formaldehyde on milk proteins. It can be machined and softens in boiling water. Its electrical properties are similar to those of red fibre, but it is less hygroscopic than the latter.

(*f*) *Glyptal.*—This product of the research laboratories of the General Electric Company of America is made from glycerine and phthalic anhydride. It is a pale yellow transparent resin which changes from a fusible and soluble state to a relatively infusible and insoluble state when heated to 210° C. It is soluble in acetone, and a mixture of acetone, benzole and denatured alcohol is used as solvent in making glyptal varnish.

Glyptal is claimed to be superior to phenol-formaldehyde resins in flexibility, ability to bond mica (§ 74, III (*d*)) and resistance to arcing and discharge. Arcing or spark discharge on the surface of material bonded with phenol-formaldehyde is apt to produce an electrically-conducting 'track' of carbon, but this does not occur with glyptal. When cured by heat, glyptal becomes leathery; under no circumstances does it become hard or brittle. Its adherence to smooth and slippery surfaces contributes to its utility as a bond for mica. Volume and surface resistivities of glyptal micanite have been found * respectively to be two and three times those of shellac micanite.

An article (*loc. cit.*) on glyptal in relation to other synthetic resins contains the following useful tabulation:—

Class of Resin.	Name.	Makers.
Phenol-formaldehyde	Bakelite, Condensite, Redmanol	U.S.A.
	Fabrolite	B.T.-H. Co., Ltd., Coventry
	Elo	Birkby's Ltd., Liversedge
	Formite	Damard Lacquer Co., Birmingham
	Formapex	Ioco. R. and W. Co., Glasgow
	Mouldensite	Mouldensite Ltd., Darley Dale
Urea-formaldehyde	Pollopas	Dr. Pollak, Vienna
Phenol-formaldehyde and natural rosin linseed oil, etc.	Albertol	K. Albert, Biebrich, Rhineland
Glycerine-phthalic anhydride	Glyptal	B.T.-H. Co., Ltd., Rugby

Other classifications of plastics are mentioned in § 75.

IX.—Fibrous Materials and Products.—(*a*) *Asbestos* is used in insulating tapes, sheets, and varnishes where resistance to heat is required. It is highly absorbent and can be impregnated satisfactorily with materials of higher dielectric strength than itself. Mechanically, it is weak. Resistance nets are woven with warps of spun asbestos and wefts of suitable resistance wire. Where used as a fireproof braiding asbestos should be varnished to prevent it acting as a 'wick' for oil, if there is any risk of the latter being present. Asbestos is used in heat-resisting moulding compositions (§ 75). A wet paste of asbestos protects the insulation of conductors when welding joints in the latter. Lagging for thermal storages, etc., may contain asbestos as an ingredient. Asbestos is attacked by acids and alkalis.

(*aa*) *Siluminite.*—This is an asbestos product capable of being moulded in a multitude of forms, and made in several grades (Table 7 *supra*) according to the

* H. Warren, *Electrician*, Vol. 98, p. 286.

purpose for which it is to be used. It is practically non-hygroscopic, has great mechanical strength—asbestos having very little—and is unaffected by moderately high temperatures. The uses of the material include fuse carriers, insulators for tubular heaters, motor-starter face plates, arc shields and chutes, telegraph and telephone insulators, and many others.

(*b*) *Wood*, when dried and impregnated with oil, is used as a tank lining in oil-immersed switchgear to prevent arcs from coming into contact with the metal. Maple is useful for such work. Wood impregnated with paraffin wax is acid-resisting and moisture-proof. Hard-wood rods are used as handles for operating arrester charging and opening isolating links.

(*c*) *Paper*, though highly hygroscopic, is used in many applications on account of its flexibility and good dielectric properties. Dry paper, wrapped loosely, is used to insulate the conductors of dry-core (air-space) telephone cables ; a lead sheath is used to exclude moisture, and the advantage of the dry paper insulation is that the inductive capacity of the cable is kept low and attenuation and distortion of speech currents are reduced. In cables for lighting and power service substantial thicknesses of paper are required (§ 280), and the paper is impregnated to increase its dielectric strength and to exclude air films (§ 79). Rosin oil is the principal ingredient of the impregnating compound used where the paper is to remain flexible ; the compound must not be so fluid as to drain out of the paper. Non-drying impregnating materials are displaced by moisture, hence a sheathing of lead or vulcanised bitumen is necessary (§ 287). Paper which is to be used as insulation exposed to air may be impregnated with a drying varnish or bakelite.

Manilla paper is generally considered to be the best for electrical purposes, but there are many papers now available for the special requirements of various applications. Japanese papers are used in mica-paper tapes. Papers made from cotton and linen rags are used in condensers. Wood-pulp papers are highly absorbent but mechanically weak.

Paper may be impregnated with oils before or after its application to conductors. Thin strong paper coated with successive layers of flexible-drying varnish is used in instrument and machine windings and in condensers ; this material is often called oiled paper. Paper soaked in paraffin wax is used in condensers ; the wax cracks if bent.

Micarta consists of paper which is dried, covered with insulating varnish, and built into sheets, tubes or rods ; heat and mechanical tension or pressure are applied to consolidate the successive layers and, when cold, the product can be machined. *Bakelised micarta or paxolin* is made by using liquid bakelite (instead of shellac, copal, etc.), which is subsequently converted to the C-form (see VIII *a*). Micarta with shellac as binder softens at about 80° C. ; bakelised micarta can be used at 100°-110° C. or, if asbestos paper be employed, up to 180° or 200° C. Paxolin can be used in oil ; its toughness is a valuable property ; this material is often used in preference to wood or vulcanised fibre.

Paper Boards, Fibre, etc. Some of the materials coming under this heading are produced by paper-making processes, whilst others (using similar raw materials) are subjected to chemical, mechanical, and thermal treatment which first reduces the cellulose to a more or less gelatinous condition and then consolidates the whole to a horn-like material showing little or no trace of fibrous structure.

Presspahn, Pressboard, or Fullerboard is a paper made, in thickness up to ½ in., from hemp, rags, wood-pulp or mixtures of these. It is highly absorbent and is oil-impregnated for use in transformers, oiled or varnished for use in air, or impregnated in the same way as coils. *Leatheroid, fibroid, fish paper or tarpon* *paper* is made in thickness up to $\frac{1}{8}$ in., from cotton rags subjected to chemical treatment. It is a tough, horny material of higher dielectric strength than pressboard. It is unaffected by grease or oil and is much used between windings, for slot and core insulation, etc. If required, it may be impregnated, varnished, or waxed. *Whalebone paper, horn fibre, and red rope paper* are practically identical materials; they are made like leatheroid, but from a hemp base, and are used for similar purposes. Their dielectric strength is lower than that of leatheroid. *Vulcanised fibre* is made in many varieties, most of which bear trade names and are made by secret processes. In all cases the basic ingredient is some form of cellulose which is treated chemically to obtain a horn-like structure. Mineral ingredients are added for colouring or other desired physical properties. Vulcanised fibre is highly hygroscopic and swells when moistened without, however, such disintegration as is liable to occur in boards which are built up layer by layer. Vulcanised fibre is sold in sheets, rods and tubes, and can be machined; it may be waxed or varnished to exclude moisture. It is insoluble in water or oil, and is charred by strong acids or high heat. Fibre containing asbestos is disintegrated very slowly by fire.

Gummoid, as made on the Continent, is variously described as a hard paper or moulded insulating material with an asbestos base.

(*d*) *Textile Materials* used for insulating purposes include cotton, linen, jute, and silk. The uses of woven asbestos have already been mentioned (Section IX (*a*)). *Cotton and silk* are used in one or two layers for the covering of bell wire and flexibles (§ 285), the actual insulation being provided by one or two layers of rubber next to the conductor. Cotton-covered bell wire is waxed to exclude moisture and to provide a good finish. Cotton or silk is used as the sole insulation on small wires for instruments, small motors, etc.; generally, it is advisable to dry and varnish or impregnate the winding to exclude moisture and to reinforce the insulation provided by the fibrous material. *Artificial cellulose silk* is an efficient and economical substitute for real silk in the insulation of small wires for fan armatures, instruments, etc.; when dissolved it forms a highly insulating varnish. Cellulose acetate from which artificial silk is made is non-inflammable. The spun thread is thicker than real silk, but its insulating properties under vary ing conditions of temperature and humidity are more than proportionately higher. This material and tests upon it are described by W. R. Kennedy, *El. Rev.*, Vol. 87, p. 836.

Jute is used as insulation on cables, being then impregnated like paper and for the same reasons. It is also used as a filler between the cores of multi-core cables, and as a bedding and covering for armouring. *Hemp* is used as a core for stranded cables and as a packing for insulator pins.

Oiled (or varnished) Tape or Cloth consists of cotton, silk, duck, canvas, etc., prepared by repeated dipping in oxidised linseed oil or a special varnish, each coat being baked before the next is applied. Such materials owe their dielectric strength mainly to the oil or varnish. They are non-hygroscopic, strong, and flexible and are used extensively as wrappings for individual conductors, for coils, and between windings. "Empire" cloths and paper belong to this class. Untreated tapes may be dried and impregnated, after application, with varnish, compound, or bakelite. Yellow oiled cloth is treated with oil alone; black oiled cloth is treated with a mixture of oil and asphaltic matter and has slightly higher dielectric strength. These materials are more flexible than paper and much less hygroscopic. Varnished (or oiled) cambric forms an excellent dielectric for high voltage cables, particularly where great flexibility is required; the cambric should be served, as wound, with a non-drying compound to exclude moisture and air (§ 79). The oiled fabric is unaffected by oil.

Rubbered Linen Tape (coated on one side with rubber) is useful in insulating machine windings.

Adhesive or Friction Tape is coated with a tacky compound which gradually 'sets' when exposed to air. Though it has considerable insulation value, this material should *not* be counted as part of the insulation, but should be regarded merely as holding in place the rubber tape, etc., which forms the true insulation.

(*e*) *Bakelite Laminated Material.*—Laminated materials impregnated with synthetic resin may have a paper, fabric or asbestos base, and vary widely in properties according to the purposes for which they are intended. The following data are given, by Bakelite Ltd., London, S.W. 1, as typical for paper laminated sheet intended for electrical insulation:—

	High Grade for H.T. Insulation.	Ordinary for L.T. Insulation.	Special for Tropical and H.F. Insulation.
Tensile strength 1 000 lb./sq. in.	13-15	15-19	7·8-9·2
Shear strength, 1 000 lb./sq. in.	10-12	15-17	9-11
Specific gravity	1·31	1·38	1·33
Resistivity: Megohms/cu. cm.	10^7-10^8	10^6-10^7	10^8
,, Megohms/sq. cm.	10^6-10^7	10^5-10^6	10^7
Dielectric strength:			
Volts/mil, at 20° C.	400-600	350-450	400-700
,, at 90° C.	200-400	120-200	300-600
Dielectric constant	5·4-5·7	5·7-6·3	4·2-4·5
Moisture absorption:			
1/32 in. thick	0·9 %	3·5 %	0·25 %
1/8 in. thick	0·4 %	1·1 %	0·09 %

Materials of this class offer a valuable combination of mechanical strength and dielectric properties, *viz.*: About 90 % of the strength of aluminium with only about half its weight; greater strength and dimensional accuracy than porcelain; greater uniformity than mica; chemical permanence superior to rubber; more resistant to heat than shellac, and more resistant to water than fibre.

75. Moulded Insulation Materials.—This heading includes a great variety of materials (mostly mixtures) which can be moulded in a die to produce pieces accurate in dimensions and requiring little or no machining. Heat and mechanical pressure have usually to be applied during the moulding process, and these convert the raw materials (by physical or chemical changes or both) into a homogeneous mass. There are also cold-moulding preparations which set like cement. The electrical properties of moulded insulators vary widely with the composition. The principal applications of these materials are where identically similar parts are required in sufficient numbers to justify the cost of the dies. The more intricate the pieces, the greater the saving by moulding, once the cost of the dies is covered. The exact compositions of preparations for moulding are trade secrets, but the ordinary engineer is concerned only with the general nature and applications of the materials. The design of dies and the manipulation of mixtures to meet specified requirements are matters for specialists. The important point to be remembered is that one-piece moulded insulators frequently replace many loose components and reduce assembly work to a minimum; metal inserts can be placed in the die and thus become mechanically one with the insulation.

All moulding compositions consist essentially of a 'filler' and a 'binder,' together with such special additions as colouring ingredients. According to the type of binder employed, the compositions may conveniently be classified as: (I) Cold-moulding compositions, using an asphaltic solution or a water cement as binder. It may be necessary to heat the moulded pieces to dry them or to set the binder. (II) Hot-moulding compositions, using (*a*) shellac, rubber, or other bond which melts or softens when heated and sets on cooling; or (*b*) synthetic resins which are mouldable whilst in their primary or secondary form but are converted by heat to a rigid solid. It has been pointed out * that large amounts of scrap and waste insulating material, including mica, are used on the Continent for making up moulded insulation at a cost with which manufacturers using only new material cannot compete. The scrap is pulverised in an automatic mill, then bonded with synthetic resins of the Bakelite class (§ 74, VIII), and used especially for very large moulded parts, such as low-voltage transformer bushings and wall bushes. It is stated that, after suitable treatment to ensure a perfect mixture, the homogeneous mass is as good as most of the material on the market, from which it is indistinguishable and which it undersells. The whole process can be done by automatic machinery, except making and filling the moulds.

I. Cold-moulding Compositions.—(*a*) *Portland Cement* may be used as binder with asbestos as filler for simple pieces which are required to stand high temperatures (400° C.). The material is naturally hygroscopic but may be waterproofed. *Lime-silica cement* and asbestos is claimed to withstand temperatures up to 650° C. without serious deterioration. *Sodium silicate* (*water glass*) gives a hygroscopic product of low mechanical and electrical strength, but one which resists heat well.

* 'Waste Insulating Materials,' A. A. C. Dickson, *Elec. Rev.*, Vol. III, p. 814.

(*b*) *Pitch or Asphalt* is dissolved in an appropriate solvent, mixed with wood, fibre, asbestos, sand, etc., and heated (after moulding) to expel the solvent. Intricate shapes can be made with a good finish, but the product is not suitable for machining; it will stand about 300° C., and is non-absorbent.

Compositions of type (*a*) are of low dielectric strength (20-50 V per mil) and are useful for shields and mountings to withstand heat rather than electrical stress. Compositions of type (*b*) are of higher dielectric strength (75-150 V per mil), and are suitable for actual insulation up to 500 or 600 V. Hot-moulded compositions are better electrically and mechanically, but the most refractory of them cannot be used above about 300° C.

II. Hot-moulding Compositions.—(*a*) *Rubber*, mixed with sulphur and various fillers, can be moulded under heat and pressure, and then converted to ebonite (§ 74, IV (*d*)) but the applicability of the latter in this connection is limited, because it begins to soften about 60° C. The dielectric strength is high, say 400 V per mil.

(*b*) *Shellac* as binder for mica produces the valuable material micanite (§ 74, III (*b*)) which can be moulded into simple shapes. Shellac can be used as binder for many other fillers, but its utility is limited by its softening between 65° and 90° C. Shellac and cotton fibre or similar material gives a good finish and high dielectric strength (say 200-300 V per mil.) and is suitable for use in sheltered situations.

(*c*) *Synthetic Resins*, etc. (§ 74, VIII, IX) find some of their most important applications in the preparation of moulding compounds. Sawdust, fibre, asbestos mica, slate, etc., are used as fillers according to the properties desired. In the Bakelite series, the makers of the primary condensation product frequently mix this with appropriate fillers, convert the resin to the B-form (§ 74, VIII (*a*)), and grind the product to form a moulding powder which is supplied to licensed moulders. The powder is reduced to about one-fourth of its 'loose' volume when compressed in the hot moulds at from 500 to 2 000 lbs. per sq. in., and 150°-200° C., according to the makers' instructions. The final product (with the resin in the C-form) is accurate within good machine-shop limits, say ± 2 mils, and has a valuable combination of properties. With cotton, hemp, sawdust, or similar filling, a machinable product is obtained which will withstand temperatures up to 150° C. and has a dielectric strength between 250 and 500 V per mil, according to its composition. Heat-resisting fillers, such as asbestos, sand, etc., yield non-absorbent products, which are almost or quite unaffected by acids, alkalis, and hot oil; these products are unsuitable for machining, withstand temperatures up to 250° or 300° C., and have dielectric strengths from 100 to 150 V per mil.

B.S.S. No 488 (1933) deals with 'Moulded Insulating Materials for Accessories for General Electrical Installations.'

Materials.—The materials are classified on the basis of deformation temperature and four grades are covered, corresponding to good quality synthetic resin (deforming temperature above 140° C.), medium quality synthetic resin (100° C.), loaded hard-rubber (70° C.), and non-loaded hard-rubber (55° C.) respectively. The mechanical and electrical properties are defined by means of limits, and appendices deal with the details of the tests for these properties and for the conditioning of the specimens before test. There are a number of significant omissions from the Specification, but there appear to be good reasons for these. Copies may be obtained from the Publications Department, British Standards Institution, 28 Victoria Street, S.W. 1, price 2s. 2d. post free. (*El. Rev.*, Vol. 112, p. 762.)

Dunton and Caress (*Jour. I.E.E.*, Vol. 79, No. 478) give a classification of plastics according to their applications, taking as the crucial factor the maximum temperature which the materials will withstand. W. Blakey (*El. Rev.*, Vol. 121, p. 275) gives a useful classification according to chemical composition, together with physical properties and typical applications; and the same author (*El. Rev.*, Vol. 122, p. 83) gives electrical properties and applications of all the main types of plastics.

76. Insulating Paints, Varnishes, etc.—Though paints enamels, and varnishes are liquid when applied to the parts or material to be insulated, it is the dry material left by evaporation of the solvent, or the solid matter formed by combined oxidation and drying, which constitutes the actual insulation. Liquid compounds which set by evaporation of solvent or by chemical changes caused by heat (§ 74, VIII (*a*)) can be used for deep penetration or complete impregnation, but materials which depend upon oxidation for their solidification can only be used on surfaces or for tapes, etc. (§ 74, IX (*d*)). At one end of the scale there are non-drying compounds (resin oil, etc.) used to impregnate paper cables, and at the other end there are the enamels which dry as a tough, flexible coat which is sufficient insulation for wires to be used in low-voltage instrument coils, bells, etc. Vacuum impregnation is essential for most windings for use in the tropics or monsoon countries, especially for fan motor windings. Asphaltic material may be used to produce a black varnish, or the varnish may contain no colouring matter, in which case it produces a colourless, yellow or brown coat according to the gum or oil which forms the residual constituent.

Air-drying Spirit Varnishes, used for finishing or for quick repair work, consist of a gum or resin in a solvent which evaporates quickly when exposed to air. The coating dries in 1 hr. or less, but is relatively brittle and not able to stand heat and vibration without cracking. *Air-drying oil varnishes* take longer to dry (12-24 hrs.) but produce a much tougher and more flexible coat. *Baking oil varnishes* need stoving for from 3 to 9 hrs. at a temperature of 80°-100° C. and yield a hard, tough coat of maximum mechanical and electrical strength. *Synthetic resin varnishes* are converted to the C-form (§ 74, VIII (*a*)) by stoving for several hours at about 150° C., the coils treated being then set solid in a mass of rigid insulation. A final drying *in vacuo* is needed to remove water liberated by the condensation process. *Acid-proof paints* should be regarded as finishing materials, affording protection against acid fumes but of no electrical insulating value.

The general precautions to be observed when using insulating varnishes are: (i) To dry thoroughly the material to be varnished.

This is done by stoving; the dried coil, etc., may then be coated by brushing or dipping, but vacuum impregnation is preferable where applicable. (ii) The varnish itself must be dry, clean, and of the right consistency; the viscosity affects the penetration and adherence obtained. Evaporation of solvent must be made good at frequent intervals, a hygrometer and thermometer being used to check the consistency. The density of an average insulating varnish decreases or increases about 0·3 to 0·35 °/₀ per 5° C. rise or fall from 15° C. (See I.E.E. paper in Bibliography, § 87.)

A good oil varnish is practically proof against acid, oil, and moisture. A valuable effect of impregnating windings is to increase the heat conductivity of the insulation as a whole.

77. Liquid Insulators.—The only insulators which are liquid during normal service are oil and carbon tetrachloride. As generally employed the purpose of such insulators is to assist in removing heat (as in transformers) or to quench arcs (as in switches and fuses). The dielectric strength of oil is higher than that of air (§ 78), but the main reasons for its use are as stated. Due to its convection currents, oil is more effective than a solid filling in removing heat, within the range of thermal conductivities of the insulating materials available.

(1) *Transformer and Switch Oil.*—(*See also* § 403, Vol. II.) Mineral, animal, and vegetable oils are all good insulators, of practically equal value when pure and dry, but mineral oils have the advantage of being practically immune from oxidation and the development of acidity in service; also, they are less subject to sludging and carbonisation by heat. Resin oil has been mentioned favourably in Germany for use in transformers because it forms no tar deposits; it is, however, quickly carbonised by arcs if used in switchgear. The oils employed almost universally for transformers and switchgear are petroleum distillates. The particular grade employed is called *transil oil.* Specifications * vary somewhat, but properties commonly demanded *in the oil as delivered* † are: An unmixed, clear, refined product of sp. gr. between 0·85 and 0·90 at 20° C. Viscosity (Redwood), say, between 100 and 200 secs. at 20° C., and between 60 and 75 secs. at 50° C. Practically free from moisture, sand, fibres, etc.* Free from alkali and sulphur. Acid content not more than 0·02 °/₀ expressed as H_2SO_4 (often 'no trace of acid' is specified). Setting-point (cold test) not above − 15° C. for switch oils, and not above − 4° C. for transformer oils. Flash-point not below 145° C. for transformer oil, and 160° C. for switch oil. The loss by evaporation when heated for 6 hrs. at 100° C. should not exceed 0·5 °/₀; no deposit should form, and no acidity should be developed during this heating. Tests for sludging (which should not occur) involve bubbling air through oil at, say, 110° C. for two or three days.

* See B.S.S. No. 148; 'Insulating Oils for Electrical Purposes.'

† The oil must be filtered and dried before use as explained below.

Though a specification of this nature ensures that a suitable oil is obtained, the influence of the various clauses is not so definite as might be expected. The viscosity of the oil affects the rate of cooling of transformers and, naturally, the viscosity at the normal working temperature should be considered; the viscosity at atmospheric temperature is of little practical importance. It is doubtful whether viscosity, within the range of practical values, has appreciable influence on the speed of quenching arcs at switch contacts. There must be no risk of a switch oil congealing at low atmospheric temperatures, but stiff oil in a cold transformer is of little importance, provided that the viscosity becomes correct as the transformer heats up. The flash-point test is useful only as excluding oils with highly volatile constituents. The maximum temperature in service is always far below the flash-point (§ 80) except at submerged arcs, where burning cannot occur; if arcing occurs in contact with air the oil will ignite whatever its flash-point. A small loss by evaporation, on heating, is desirable, but the rate of loss naturally becomes much smaller as evaporation proceeds. In modern transformers volatile matter can escape only slowly, if at all, from the tank; oil-switch tanks are provided with pipe-vents to free air.

Sludging in transformer oil forms deposits which clog the circulating passages, and reduce the rate of heat-transmission from transformer to oil and from oil to tank. The deposits are oxidation products and have an acid reaction; their formation appears to be hastened by a catalytic action on the part of copper. Forced circulation of oil prevents the sludge from settling; periodic filtration is desirable. Russian oils contain less tar and give less trouble from sludge than do American oils.

It is useless to specify voltage break-down tests for oil as delivered, because oil delivered in bulk inevitably contains fibrous and other foreign matter and some moisture (up to, say, 0·1 %). Recent research * indicates that break-down tests on oils with needle points or point and plate electrodes do not indicate the quality of oil as regards wetness or dirt, and therefore give a fictitious consistency of results. After filtration and drying, a good transformer or switch oil should not break-down below 20 000 V when tested on a 0·15 in. gap between spheres of ½ in. diameter submerged at least 2 ins. Filtration and drying may be effected by forcing the oil through a filter-press containing sheets of absorbent paper.

The break-down of oils appears to be due generally to fibrous particles forming chains between the electrodes under the influence of the intense electrostatic field. The remarkable effect of a trace of moisture in reducing the dielectric strength of oil (1 part of water in 10 000 of oil may halve the break-down voltage) is explained by the moisture being absorbed by the fibrous particles. If oil be cleansed by a colloid or membrane filter its break-down voltage, on a 0·15 in. gap between ½ in. spheres, may be 65 000-90 000 V or higher.

(2) *Carbon Tetrachloride* is incombustible and comparable with mineral oil as an insulator. It has been tried as a substitute for mineral oil in oil switches, but is subject to serious disadvantages, *viz.*: (1) It evaporates at atmospheric temperatures. This may be prevented by a layer of glycerine, but the latter is a conductor and is liable to get on the insulators; also, glycerine corrodes copper. (2) It corrodes copper, but protection can be obtained (except at the contact faces) by tinning. (3) It has no lubricating value. (4) It is about twice as heavy as mineral oil (sp. gr. 1·6 compared with 0·87). (5) It has anæsthetic effects, is detrimental to health, and dissolves rubber.

* See communication from B.E.R.A., 'Research on Insulating Oils,' *El. Rev.*, Vol. 89, p. 687.

Carbon tetrachloride boils at 76° C. and freezes at – 27° C. Its only advantage for switchgear appears to be its incombustibility, and this is outweighed by its many disadvantages. A liquid described as "of tetrachloride type" is used as a filling for certain high tension fuses.

(3) *Pyranol.*—This is a synthetic liquid insulator, developed in America.* It is claimed that it not only has all the advantages of mineral oil as an insulating and cooling medium for electric equipment, but in addition is non-inflammable and non-explosive. There are a number of forms for different purposes, all being synthetic organic dielectrics of varying physical and electrical properties, and all having a high dielectric constant. The colour is water-white; burning-point, none; viscosity (Saybolt), 40 secs. (37·8° C.); pour-point (A.S.T.M.) *minus* 30° C.; and dielectric constant or permittivity, 5. The liquid is a solvent for some materials ordinarily used in transformers and other apparatus, which must therefore be specially designed; it is claimed that the higher cost is justified by the elimination of fire and explosion hazards. Condensers can be made physically smaller per microfarad by its use. There is no sludging on exposure to heat or air, as the liquid is chemically stable and resists oxidation. It is said to demulsify, or separate from water, more than twice as rapidly as does mineral oil, and the moisture rises to the surface, from which it may be evaporated. The viscosity and freezing-point can be varied to suit the conditions without affecting other qualities. Subjected to an arc, hydrochloric acid is given off and must be absorbed or removed.

78. Air as an Insulator.—Wherever it is applicable as insulation, air has the advantage that it needs no preparation or maintenance. Should a voltage break-down occur the full insulation is restored by fresh air directly the discharge ceases, unless the ionised air cannot escape—in which case the insulation may be low for some time. Though air itself costs nothing, a structural support has to be provided to hold conductors apart in air, and porcelain or equivalent insulators have to be provided between the conductors and their supports; these insulators are electrically in parallel with the air between the conductors. Again, though air is a 'self-mending' insulator, a break-down may result in injury to the conductors by arcing, or in the establishment of pressure surges (§ 349) which damage the insulation of machine windings, etc., at other points, in the system.

The dielectric strength of compressed air is considerably higher than that of air at atmospheric pressure, and compressed air has therefore been used in E.H.T. condensers and instruments, mainly for experimental purposes.

There is a fairly definite relation between the maximum value of an alternating voltage and the length of air-gap across which sparking occurs between stated electrodes. This affords convenient method of measuring very high pressures, and tables have been prepared by various investigators to show the voltages corresponding to various sparking distances. For a given voltage the spark gap is

* *Gen. El. Rev.*, Vol. 35, p. 577.

greater between needle points than between spherical electrodes (roughly four times as great between needles as between spheres of 6 ins. diameter for pressures between 40 000 and 80 000 V, R.M.S.). The break-down voltage increases about 0·25 °/₀ per 1 mm. rise in barometric pressure, and decreases about 0·35 °/₀ per 1° C. rise in temperature; the humidity and amount of dust in the air also affect the break-down voltage very considerably. In X-ray work and insulation tests the crest voltage (§ 30) is important and tables are available * showing the peak voltage corresponding to various gap lengths. For industrial purposes, where sinusoidal waves are used, it is more convenient to use tables showing the R.M.S. voltages for various gap lengths.† With spheres 1 ft. or more in diameter the break-down voltage becomes *roughly* proportional to the gap length and is about 20 000 V per cm. for gaps from 2-5 cm., and about 16 000 V per cm. for gaps from 10 to 15 cm. (R.M.S. values). These figures are for general guidance only; see B.S.I. tables (*loc. cit.*) for complete data.

It is necessary to distinguish carefully between the true dielectric strength of air in volts per cm. when subject to a uniform electrostatic stress, and the break-down voltage for a particular gap. The relation between applied P.D. and maximum dielectric stress is easily calculated where spherical electrodes are used; Russell ‡ gives the formula $R_{max.} = (V/x)f$; where $R_{max.}$ = maximum electric stress in volts per cm.; V = P.D. between spheres; x = minimum distance between spheres, in cm.; f = a correction factor varying with x/a, where a = radius of each sphere, in cm. Tables of values for f are given *loc. cit.* With infinitely large spheres $(x/a = 0)$ $f = 1$; for $x/a = 0·3$, 0·5, 0·7, 1·0, and 1·5, $f = 1·10$ 1·17, 1·25, 1·36, and 1·56 respectively. Russell ‡ finds that the maximum stress between spherical electrodes in air at the moment of break-down is, in maximum (*not* R.M.S.) kilovolts per cm., $R_{max.} = 27·4 + 14·1/\sqrt{a}$, for values of a (= radius of sphere in cm.) from 0·25 cm. to 25 cm. and at 25° C. and 760 mm. barometer. The corresponding maximum (*not* R.M.S.) sparking voltage is calculated from: $V = R_{max.}(x/f)$. This indicates that, *at atmospheric pressure*, the dielectric strength of air is about 27 500 V (max.) per cm., the other term in the expression for $R_{max.}$ being a correction for the effects of currents of electrified air and vanishing when a is very large.

As regards *compressed air*, Watson § finds that the dielectric strength of air at 17° C. is approximately (20 + 25·6 P) kV per cm. (maximum, *not* R.M.S. volts), where P = air pressure in atmospheres absolute. This formula is purely empirical, but is sufficiently accurate for all pressures between 3 and 15 atmos. absolute. Air at 200 lbs. per sq. in. gauge pressure (14·6 atmos. absolute) has a dielectric strength of about 395 kV per cm. (1 000 V per mil), which is about ten times the dielectric strength of air at atmospheric pressure (between 1 in. spheres), and equal to that of micanite.

79. Effect of Air Films in Layered Insulation.

—Air films afford an opportunity for hygroscopic insulating materials to

* See *X-Rays* by Kaye (Longmans).

† A table of sparking distances for sphere spark gaps from 10 000-400 000 V (R.M.S.) is given in B.S.I. Report 137.

‡ *Phil. Mag.*, 6, Vol. 2, p. 258; *Jour. I.E.E.*, Vol. 40, p. 6; *Electric Cables and Networks* (Constable), p. 243.

§ *Jour. I.E.E.*, Vol. 43, p. 113.

become damp; also, the dielectric strength of air at atmospheric pressure is lower than that of solid and impregnating insulating materials. The most serious result, however, of air films between layers of paper, micanite, etc., in insulation subjected to high voltage, is the uneven voltage gradient thus established. The layers of solid insulation and air amount to condensers in series, and the total voltage across the insulation as a whole is divided between the layers in proportion to their thickness and in inverse proportion to their specific inductive capacities or permittivities (§ 46). The specific inductive capacity of air being lower than that of solid dielectrics (Table 7), the voltage across an air film is higher than that across an equal thickness of the solid dielectric and may be sufficient to cause break-down; even if break-down does not occur at once the air is ionised, and the solid dielectric is deteriorated by the ozone and nitrous oxides formed.

Example.—Suppose that two 2 mm. sheets of micanite with a 0·1 mm. air film between them be subjected to a P.D. of 6 600 V. Let the P.D. across the micanite be v_m and that across the air be v_a. Denoting the corresponding thicknesses by t_m, t_a; and the specific inductive capacities by k_m, k_a respectively, $v_m : v = (t_m / k_m) : (t_a / k_a)$. Now $k_a = 1{\cdot}0$ and $k_m = 6$ (say). Hence, $v_m : v_a = (4/6) : (0{\cdot}1/1)$; whence $v_m = v_a \times 4 / 0{\cdot}6 = 6{\cdot}7\, v_a$. But $v_m + v_a = 6\,600$ V; therefore $6{\cdot}7\, v_a + v_a = 6\,600$ and $v_a = 6\,600 / 7{\cdot}7 = 860$ V. A P.D. of 860 V across a 0·1 mm. film corresponds to 86 000 V per cm., which stress is two or three times the dielectric strength of air at normal pressure (§ 78). The air film will therefore break down, and the heat from this discharge will soon cause the micanite to fail.

Due to the excessive stress otherwise placed upon air between layers of paper or fibres of cotton, silk, etc., such materials must be impregnated when used as high-tension insulation, apart from the equally important consideration of excluding moisture.

80. Temperature Limits for Insulating Materials.—As stated in §§ 71, 72, the specific resistance and dielectric strength of all insulating materials decrease rapidly when the temperature is raised. Also, organic insulating materials suffer permanent injury (by charring, becoming brittle, etc.) if heated above a quite moderate temperature (usually in the neighbourhood of 100°-130° C.* For these reasons it is necessary to avoid overheating

* Charring temperatures of insulating materials quoted by Messrs. Pinchin, Johnson & Co. Ltd. are (in °C.): Cambric, shellacked 160°, untreated 168°; oiled duck, 170°-175°; drilling, untreated, 175°; leather, oiled, 182°; silk, oiled, 200°, untreated, 220°; surgical brand cotton, 230°; glazed pressboard, 240°-250°; fine linen, 250°.

such materials both during manufacture and in service. If charring occurs the material is converted more or less completely to carbon which is a conductor. Refractory insulating materials used in heaters and the like have necessarily to be exposed to high temperatures, and the approximate limits have been stated in preceding sections relating to the materials concerned. The I.E.C. Rules for Electrical Machinery (Publication No. 34) stipulate that the highest observable temperatures in the machinery covered by these rules * shall not exceed for—cotton, paper, or silk, 80° C. when not impregnated, and 95° C. when impregnated or immersed in oil; enamelled wire, 95° C.; mica, asbestos, glass, porcelain, micanite, and similar compositions, 115° C. The proposed temperature limit for oil, measured by thermometer, is 90° C. (*See also* § 136.)

80a. Hydrogen-Cooling of Electrical Machinery.—There has always been difficulty in getting rid of the internally-generated (I^2R and iron-loss) heat of a large generator or motor (§ 671) on load. In this connection § 136 (Standard Rating for electrical machinery) and § 670 (British Standard Types and Ratings for electric motors) may be referred to. Formerly, cooling was effected only by the circulation of air over the surfaces and through ducts in the parts concerned (§§ 146, 356, 670 (2)), but hydrogen offers important advantages. The machine is enclosed by a gas-tight casing filled with hydrogen at a pressure kept slightly above atmospheric, to prevent ingress of air which might result in the formation of an explosive mixture. The function of the hydrogen is to transfer heat from the core and windings to the casing whence it dissipated to the surrounding atmosphere. If necessary, the atmospheric cooling surface may be increased by ribs on the casing or by a radiator in circuit with the latter. In any case, the hydrogen is circulated in a closed space to prevent loss of gas. The following notes † are useful:

The density of hydrogen is about 7 °/₀ that of air, hence windage losses are reduced to 10 °/₀ of their air-value in an atmosphere consisting of 97 °/₀ hydrogen. The thermal conductivity of hydrogen is about 7 times that of air, and in passing

* *i.e.* rotating machines of which the terminal pressure does not exceed 5 000 V or of which the rated output does not exceed 750 kVA, or of which the stator cores do not exceed 50 cm. axial length, and all transformers which are not water-cooled.

† *El. Industries*, Vol. 36, p. 1300, from *Power*, Vol. 80, p. 362.

over a hot surface, hydrogen removes 30 % more heat than air for a given temperature drop. All of these characteristics increase the permissible rating of a machine of given size, or reduce the size of machine for given output. Quieter running is secured, and the requisite gas-tight shell makes the machine inherently suitable for outdoor installation. From experience now available, unusually long life with remarkably low inspection and maintenance cost is predicted for hydrogen cooled machines. The risk of explosion has been exaggerated. A mixture of air and hydrogen will not explode if it contains less than 9·5 % or more than 74 % of hydrogen by volume. The shell is first filled with CO_2, which is then replaced by hydrogen kept under slight pressure to ensure that leakage is outward. The cost of make-up hydrogen for a 15 000 kVA synchronous condenser is about 5d. a day. If an explosion should occur, a partial vacuum results from the almost immediate condensation of the steam formed; tests indicate that, even with the most explosive mixture, the maximum pressure reached is 50 lbs. per sq. in., and that only momentarily. Motor-driven exciters are used with hydrogen-cooled machines to avoid the cost and complication involved by providing for brush inspection of direct-connected machines. Usually, hydrogen-cooled synchronous condensers effect 12 to 15 % reduction in losses at full-load, and 45 % at no-load, compared with air-cooled units; in low-speed frequency changers, the saving is 10 % at full-load and 30 % at no-load. The above remarks apply to relatively low speed salient-pole machines. Different problems arise in the hydrogen-cooling of turbo-generators. Several orders have been placed for these machines, but it will be several years before operating data becomes available.

The advantages of hydrogen over air as a cooling medium are its lower density, greatly reducing windage losses, and giving an increase in efficiency of about 1 %; higher thermal conductivity, facilitating the removal of heat; higher heat convection; practical absence of damage to insulation from corona discharge; and the prevention of fire, to which air-cooled machines are obviously prone.

Magnetic Materials and Non-magnetic Steels.

81. Magnetisation Curve and Cycle.—A solenoid of IT/l ampere-turns per cm. (§§ 42, 43) produces within itself a magnetic field $H = (4\pi/10) \times (IT/l)$ lines per sq. cm. but if the solenoid have a magnetic core, the magnetic induction, B, therein is greater than the magnetising field, H, in the ratio $B/H = \mu$, the permeability of the core material (§ 43). Referring to Fig. 12 the induction rises comparatively slowly from O to a while the initial resistance of the steel to magnetisation is being overcome. From a to A the induction increases rapidly as the field H increases, the permeability being high. Beyond A the effect of magnetic saturation becomes evident, and at C the steel is practically saturated, further increase in the magnetising field producing only the same additional induction as would be produced with an air core. Within the practical range of magnetising forces, however, the permeability is high—of the order 1 000 at flux densities about 10 000 lines per sq. cm., in the case of those grades of iron and steel which are used as cores for electromagnets, armatures, transformers, etc. For such applications high permeability and low hysteresis and eddy current losses (§§ 34, 39) are primary requirements. In permanent magnets, however, the principal requirements are: (i) a high saturation density (*OC′*, Fig. 12); (ii) a high remanent magnetism (*OD*, Fig. 12) when the magnetising force is removed; and (iii) a high coercive force (*OE*, Fig. 12),

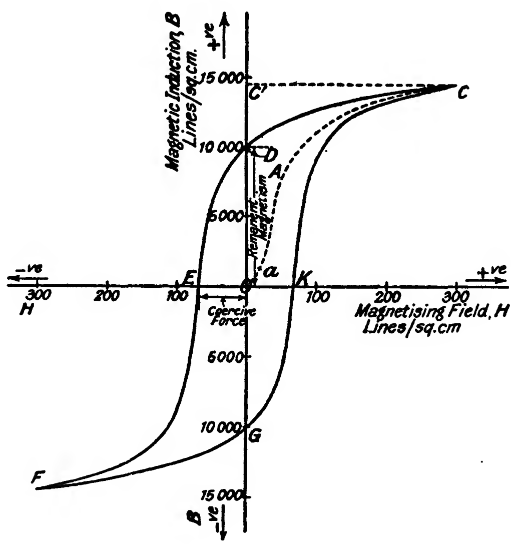

FIG. 12.—Magnetisation curve and cycle.

this being the *negative* magnetising force required to neutralise the remanent magnetism *OD* and thus a measure of the tenacity with which the material holds this remanent magnetism. If the negative magnetising force be increased beyond the value *OE*, the steel is re-magnetised (in the opposite polarity) and ultimately reaches a saturation point *F* corresponding to *C*. On again reducing the magnetising force there is left remanent magnetism *OG* ($\doteq$ *OD*) to remove which the coercive force *OK* (= *OE*) must be applied. Beyond *K* positive magnetisation occurs along the curve *KC* and *not* along *OAC*. The latter curve is followed only during the initial magnetisation from the non-magnetised state represented by O; to retrace OAC, we should have to remove the negative magnetising force at such a point on the curve EF that the remanent magnetism was zero (instead of OG). The complete curve $CEFKC$ is the 'hysteresis loop' for the material and the area enclosed by this loop represents the energy expended in overcoming hysteresis during one complete cycle of magnetisation. The loop shown in Fig. 12 refers to Firth's permanent magnet steel. The area of the loop is large, *i.e.* the hysteresis loss is high, but this is inevitably so where a permanent magnet is concerned and is, indeed, an index of merit, for the desirable qualities are high remanence and high coercive force, both of which involve a wide loop.

Where iron or steel is to be used as the core of an electromagnet, armature, transformer, etc., the desirable qualities include high permeability and a small hysteresis loop.

The succeeding paragraphs deal briefly with core materials, permanent magnet steels, and non-magnetic irons and steels. Typical magnetisation curves for irons and steels and for nickel and cobalt (the only two non-ferrous materials possessing any high degree of magnetic susceptibility) are given in Fig. 13. Permeability values may be obtained for any particular value of induction, B, by dividing the latter by the corresponding value of H. A scale of ampere-turns per cm. is added below the H-scale, this being more convenient for purposes of design (§ 43).

82. Core and Screening Materials.—Broadly speaking, maximum physical hardness coincides with the best magnetic qualities (high remanence and coercivity) in permanent magnets whilst physical softness is associated with high saturation density, high permeability and low hysteresis loss, these being desirable characteristics in iron which is to be used in electromagnets (including armature and transformer cores, etc.). For the frames of D.C. motors and dynamos, which serve also as the magnetic yoke between the field poles, cast iron or cast steel is generally employed. Cast steel has the advantage of being mechanically and magnetically superior to cast iron; also, it is magnetically equal to or better than wrought iron and is more convenient for the constructional purposes concerned. A 3 % nickel steel is sometimes used for the frames and rotors of large dynamos on account of its excellent mechanical properties. In the rotating field systems of high-speed turbine-driven machines the mechanical stresses are such that rolled steel plates offer advantages compared with forgings (§ 145).

Where the magnetic field is alternating—as in armatures, transformers and the field-systems of A.C. motors—it is necessary to subdivide the core into thin sheets in order to reduce the eddy current loss (§ 39). For the same reason it is desirable that the electrical resistance of the metal should be high. The dimensions of such cores have a large influence on the overall dimensions and cost of the machine or transformer and, in order to reduce them, high permeability and high saturation density are required. The shape of the curves in Fig. 13 is such that a small vertical distance between them involves a large increase in ampere-turns per cm. in order to reach a given flux density in the inferior material.

(ii) For many years sheets of Swedish charcoal iron were the best material available for cores; these have a maximum permeability, 3 000; a hysteresis loss about 1·8 W per kg. * ($B_{max.}$ 10 000 gauss); and an electrical resistance, 10 microhms per cm. cube. It has been found, however, that a small percentage of aluminium or silicon greatly increases the permeability and reduces the hysteresis loss of iron. The authors are indebted to Messrs. J. Lysaght, Ltd., and J. Sankey & Sons, Ltd., for permission to reproduce the curves in Fig. 13, relating to their special electrical steels 'Lohys,' 'Special Lohys,' and 'Medium Resistance' dynamo steels, and 'Stalloy' which is a high resistance silicon steel used mainly in transformers. The total hysteresis plus eddy loss in 20 mil sheets of these materials at $B_{max.}$ = 10 000 gauss, 50 cycles per sec. is approximately 3·5 W per kg. for Lohys (sp. gr. 7·8); 2·9 W per kg. for Special Lohys (sp. gr. 7·8); 2·5 W per kg. for Medium Resistance Steel (sp. gr. 7·75); and 1·75 W per kg. for Stalloy (sp. gr. 7·5). The maximum permeability of 4 °/₀ silicon steel is nearly 8 000, and an important advantage of this material is that the 'ageing' is negative, *i.e.* the losses actually decrease during years of service.

An iron alloy containing 35 °/₀ of cobalt has a saturation density about 25 °/₀ higher than that of iron, but this alloy is prohibitively expensive at present; for hard cobalt steel *see* § 83.

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* 1 watt per kg. = 1 550 ergs per cu. cm. per cycle, at 50 cycles per sec. (nearly).

(iii) Electrolytic (carbon-free) iron melted *in vacuo* has a maximum permeability ranging from 20 000, up to 40 000, or higher, according to the degree of purity, a hysteresis loss about 0·5 W per kg. ($B_{max.}$ 10 000 gauss, 50 cycles per sec.), and an electrical resistance about 10 microhms per cm. cube. Swedish iron similarly treated is deprived of its carbon and gives nearly as good results.

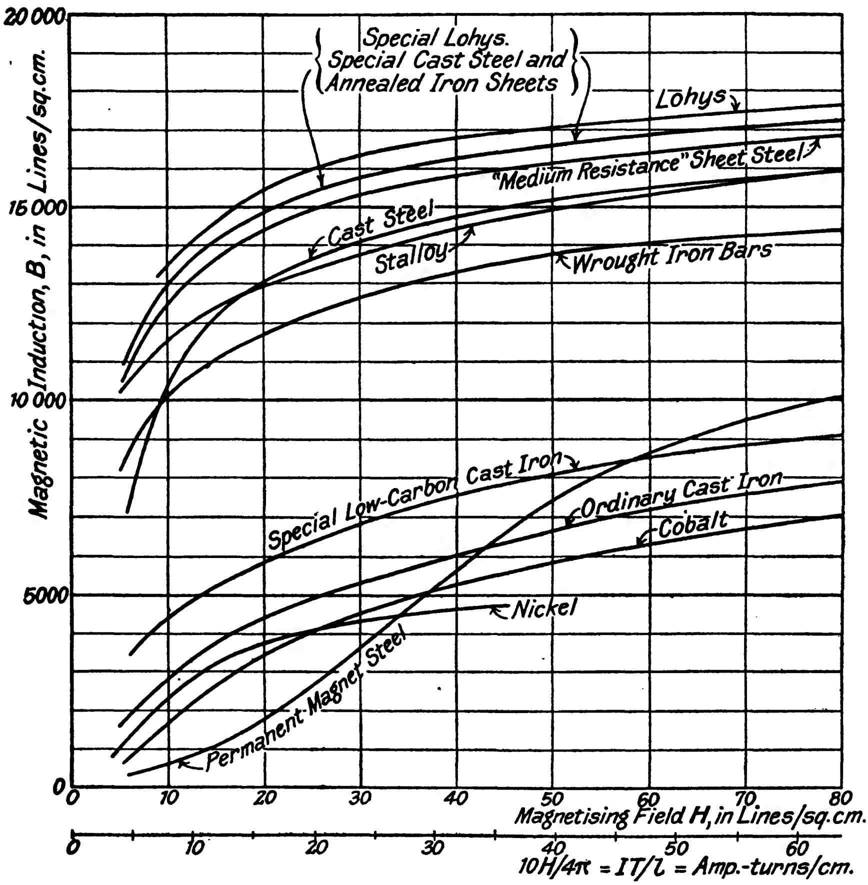

FIG. 13.—Magnetisation curves for various materials (*see also* Fig. 13A).

Yensen's tests on vacuum-melted 3·4 °/₀ silicon alloy show this material to have maximum permeability between 60 000 and 70 000; hysteresis loss about 0·2 W per kg. ($B_{max.}$ 10 000 gauss, 50 cycles); and electrical resistance nearly 50 microhms per cm. cube. There are obvious practical difficulties in melting large quantities of metal *in vacuo*, but the use of this class of material is likely to extend.

Large quantities of powdered iron are used as a substitute for hard iron wire in the cores of 'loading' coils for telephone circuits, where the requirements are constant permeability and small loss by hysteresis and eddy currents. Electrolytic iron is ground to pass a sieve with 100-200 meshes per inch, rolled with flake zinc (which is then removed), insulated with shellac, and compressed at 100 tons per sq. in. to produce blocks nearly as dense as iron and with a tensile strength of ¼ to ½ ton per sq. in. A permeability of 50 to 150 is obtained in the range H = 25 to

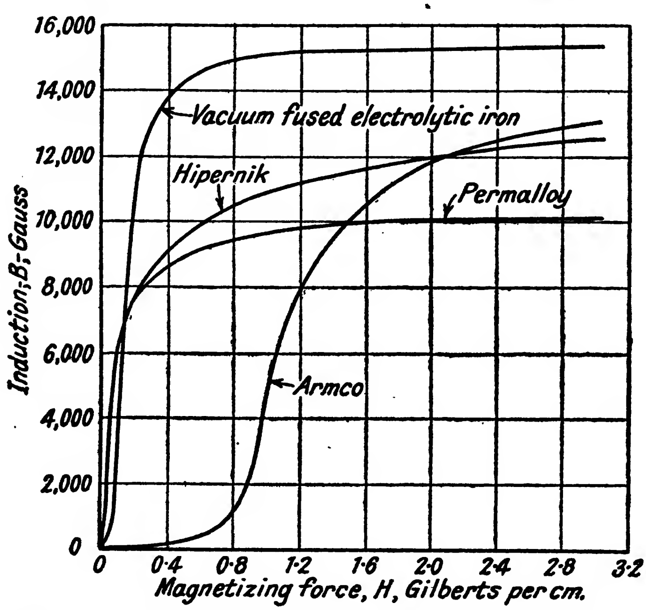

FIG. 13*a*.—Magnetisation curves for various materials (*see also* Fig. 13. *Note*—1 gilbert per cm. = 0·796 amp.-turns / cm.; and 1 gauss = 1 line per sq. cm.).

50 gauss (*cf.* Fig. 13), the permeability of particular samples being nearly constant over a considerable range of flux density. The eddy losses are low, due to the iron being electrically discontinuous.

(iv) A paper by Yensen * casts deserved ridicule on the comparison of modern alloys, in the matter of permeability, with 'iron' —'x times more magnetic than iron,' etc.; pointing out that in the last 40 or 50 years iron itself has advanced from a maximum permeability of 2 000 (1885) to 10 000 (1910) and 40 000 (1924). The investigations of this writer at the Research laboratories of

* 'What is the Magnetic Permeability of Iron.' T. D. Yensen, *Jour. Franklin Inst.*, Oct., 1928, p. 503.

the Westinghouse Co., in Pittsburg, and of other workers in the same field, are referred to in the paper quoted. It is pointed out that the initial bend of the ordinary *B–H* curve has generally been considered an inherent characteristic of iron; but that the purer the metal is made, the less pronounced does the bend become, so that possibly it may disappear altogether in a perfect crystal. Curves (B–H) are given, comparing (*a*) vacuum-fused electrolytic iron, (*b*) permalloy, (*c*) hipernik and (*d*) armco iron. The last-named, stated to be 'the purest commercial grade of iron available,' is used for comparison 'because of its excellent magnetic properties, particularly at high inductions, for which the permeability approaches that for vacuum-fused electrolytic iron'; but at low values of *H* it barely appears on the curve, see Fig. 13*a*. These newer alloys may now be considered. Incidentally, the presence of nitrogen, as well as of oxygen and carbon, is thought to be noxious.

(v) *Nickel-Iron Alloys.*—The magnetic properties of nickel-iron alloys are important and present striking contrasts. They are presented in a brochure * which includes information summarised below and supplemented by particulars from other sources as noted:

Diversity of Properties.—The permeability of pure iron is reduced by additions of nickel exceeding 10 °/₀ until, with about 30 °/₀ Ni, the alloys are non-magnetic. Further additions give a range of alloys, with 35-80 °/₀ Ni, which—after suitable treatment—have very high permeability and small hysteresis loop; they are, in fact, the magnetically 'softest' materials commercially available. Alloys containing aluminium as well as nickel are, however, magnetically 'hard' and form permanent magnets of great strength (§ 83).

Non-Magnetic Alloys (about 30 °/₀ Ni).—The actual percentage of nickel required depends on the impurities, particularly carbon. With only 0·2-0·3 °/₀ C, the nickel necessary for a non-magnetic product is reduced from 30 to 25 °/₀. This non-magnetic alloy is tough, strong, highly ductile and corrosion-resisting.

High Permeability Alloys (35-80 °/₀ Ni): Permalloy; Mumetal.—The name *Permalloy* covers a series of nickel-iron alloys which have remarkable magnetic properties after suitable heat treatment. The alloy of this type originally recommended by the Western Electric Co. (America) contained 78·5 °/₀ Ni, 21·5 °/₀ Fe, and required heating to 900° C. for 1 hr. and cooling slowly, followed by reheating to 600° C. and cooling at a prescribed rate. Research has developed from the original alloys 'A' and 'B' a material known as 'Permalloy C,' greatly superior to the original forms except in the one matter of the maximum flux density obtainable.† Table 7*a* gives the properties of the new alloy.

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* *The Magnetic Properties of the Nickel-Iron Alloys*, Mond Nickel Co., Ltd., London. An extensive bibliography of other literature on the subject is appended.

† 'Permalloy.' International Standard Electric Corporation Bulletin.

Permalloy C is made with a single heat treatment in a high-frequency furnace (§ 639). The low hysteresis loss and high permeability enable the errors in moving-iron ammeters and voltmeters (§ 101) for both D.C. and A.C. to be reduced to negligible proportions, thus competing with the cheaper moving-coil instruments (§§ 96, 101). For moving-coil milli-ammeters and voltmeters also it is useful, the trouble due to stray magnetic fields being eliminated by the use of shielding covers of the alloy; this applies also to dynamometer-type wattmeters, in which also the alloy may with advantage be used in the magnetic circuit. The special feature of 'perminvar' (mentioned further below) is an initial permeability which is constant over a limited range of applied field strength, while the hysteresis loss at low flux densities is extremely small; in other respects, however, perminvar is considered inferior to permalloy 'C' in the applications mentioned above, which take advantage of the high initial permeability of the latter.

Mumetal is another high-permeability nickel-iron alloy (patented by the Telegraph Construction and Maintenance Co., London) containing about 6 °/ₒ Cu to stabilise the alloy and facilitate heat treatment. This material is mentioned briefly

TABLE 7*a*.—*Characteristics of Permalloy and some other Magnetic Materials.*

	Permalloy B.	Permalloy C.	Silicon Steel.	Magnetic Iron.
Initial permeability (at 200 p.p.s.) μ_0 .	2 200	6 000	400	250
Maximum permeability, $\mu_{max.}$ . . .	10 000	100 000	6 500	5 000
Magnetising force at $\mu_{max.}$ (gauss) . .	0·5	0·035	0·75	1·2
Maximum flux density $B_{max.}$ (lines per sq. cm.)	16 000	9 000	16 000	20 000
Remanence from $B_{max.}$ (lines per sq. cm.) .	9 000	4 500	9 000	9 000
Coercive force from $B_{max.}$ (gauss) . .	0·5	0·035	0·6	0·8
Hysteresis loss for B = 5 000 (ergs per c.c. per cycle)	300	50	550	1 000
Resistivity (microhms per cu. cm.) . .	45	55	55	10

in § 979 (7) in relation to its production by the high-frequency furnace and its application to inductively-loaded signalling cables. In submarine cables, the copper core is surrounded by an annular ring of the alloy, the added inductance overcoming the unfavourable transmission characteristics caused by the capacity of the circuit, so that cables of more than five times the carrying capacity of the older type are now in use. Instead of this 'continuous loading,' which is necessary for constructional purposes in deep-sea cables, land telephone lines have similar loading by means of 'Pupin coils' spaced equally along the line, with similar effects. While a typical composition is 74 °/ₒ Ni, 20 °/ₒ Fe, 5·3 °/ₒ Cu, 0·7 °/ₒ Mn, the range of alloys of this class extends from 75 to 50 °/ₒ Ni and from 20 to 25 °/ₒ Fe. In addition to copper and manganese, there are often small quantities of cobalt, tungsten, chromium, silicon, vanadium, titanium, molybdenum or aluminium, according to the properties required.*

Cold working of the method, before annealing, increases the maximum permeability of mumetal, to obtain which the magnetising field is applied parallel to the direction of rolling. Some of the alloys develop extraordinary properties (*e.g.*

* *The Engineer*, May 15, 1927, p. 521.

permeabilities up to 600 000) when heat-treated in a magnetic field. In general, the distinctive characteristics of high permeability nickel-iron alloys can only be realised by strict adherence to the workers' instructions, and the permeability curve generally shows a very pronounced peak (up to 80 000 or 100 000 or higher) over a narrow range of weak magnetising forces (usually in the neighbourhood of $H = 0{\cdot}05$ oersted), the permeability falling rapidly at higher values of H, becoming about equal to that of silicon steel for $H = 0{\cdot}8$ oersted.

Table 7b (Mond Nickel Co., *loc. cit.*) compares the magnetic properties of mumetal with those of other magnetic materials.

Hipernik is a 50 °/₀ Ni-iron alloy of somewhat lower maximum permeability than permalloy but higher maximum induction (Fig. 13*a*).

TABLE 7*b*.—*Characteristics of Mumetal and some other Magnetic Materials.*

	Mumetal.*	Radiometal.*	Silico-Iron.	Armco Iron.
Electrical resistivity in microhms per cu. cm.	42	55	55-56	10
Permeability, initial .	10 000-30 000	2 000	200-400	250
Permeability, maximum .	60 000-100 000	10 000-15 000	6 500-7 000	5 000
Magnetising force in oersteds for μ maximum .	0·025-0·04	0·3-0·4	0·75-1·0	1·2
Maximum flux density in gauss	8 000-9 000	15 600	16 500	20 000
Magnetising force in oersteds for B maximum = 10 000 gauss . .	—	2-2·5	3-5	—
Coercive force in oersteds for B maximum = 5 000 gauss	0·03	0·4-0·5	0·6	0·8
Hysteresis loss in ergs per cu. cm. per cycle for B maximum = 5 000 gauss	40-60	350	550	1 000
Total loss in watts per lb. for B = 10 000 gauss . (*Frequency* 50 *cycles. Sheet metal* 28 *s.w.g.*)	—	0·45	0·7	—
Specific gravity . .	8·6	8·3	7·5	7·8

Nickel-Iron Alloy Powder.—In the manufacture of loading coils for communication circuits, and in radio tuning coils and high-sensitivity electromagnetic devices it is often an advantage to use nickel-iron alloys in the form of powder. The powder or dust is prepared by physical or chemical means, and is generally mixed with a binder and perhaps inert spacing material before being pressed into shape. The permeability of such a powder core is often less than 100 or even less than 10, though the initial permeability of the alloy may be as high as 20 000; the reason for using the alloy then lies in the low hysteresis loss which is specially important in high frequency work.

Isoperm Alloys.—These are nickel iron alloys subjected to special heat treatment and very heavy cold working (92-95 °/₀ reduction in thickness), the effect of

* By courtesy of The Telegraph Construction and Maintenance Co., Ltd.

which is practically to eliminate hysteresis. The initial permeability of the alloys is, however, low, often less than 100.

Invar.—This 36 °/₀ Ni-iron alloy is used in delicate relays where rapid make and break is important; also, in precision pendulums. In common with all the Ni-Fe alloys between 35 and 80 °/₀ Ni, it has very low hysteresis loss. *Perminvar*, consisting of iron, nickel and cobalt, is so named from the constancy of its permeability at low field strength; this property is restricted to field strengths up to about 4 gauss with initial permeabilities about 400, and is not to be confused with the very high permeability of permalloy. The hysteresis loop of perminvar is negligible and this, combined with its high electrical resistance and the constant permeability over a certain range (resulting in the inductance of coils not varying with current), makes the alloy valuable in high-frequency applications.

(vi) *Uses of High-Permeability Nickel-Iron Alloys.*—The high permeability at low field strengths and the low losses of these alloys makes them valuable for the cores of current transformers for precision instruments and meters; the ratio and phase errors of the transformers are exceedingly small. The alloys are also used for the magnetic shielding of sensitive instruments and cathode ray tubes. The electrical and magnetic properties of the different alloys vary so widely that the workers' advice should be sought. For example, the 50 °/₀ Ni alloy combines high resistivity and high permeability; the 30 °/₀ Ni alloy combines high resistivity and low permeability; and the 78 °/₀ Ni alloy has low resistivity and high permeability. The high saturation value, high electrical resistance and high permeability of the 50 °/₀ Ni alloy at high field strengths make this material and its modifications useful for cores of radio transformers and chokes. High-permeability, low-hysteresis nickel iron alloys are useful for tuning coils by varying their inductance as the core is inserted or withdrawn. Nickel-iron alloys are also used for the cores of relays and similar devices.

In mumetal the hysteresis effect is small (Table 7*b*), and its substitution for iron in A.C. circuits (such as transformer cores) would therefore reduce eddy current losses; but unfortunately the saturation-point is soon reached (at 9 000 lines/sq. cm.), so that it is only for instrument transformers and the like, where the cost of material is secondary, that it is suitable.* For this work the core can be reduced to a fraction of its former size, when made with silicon-iron, without sacrificing efficiency. 'The easy magnetisation of such a core ensures a low phase angle and, owing to the fact that core losses for any given induction are a fraction of those of so-called transformer irons, ratio errors can be reduced to a degree previously unattainable. Added to this is the fact that mumetal is constant in character, none of the ageing of the magnetic properties observed in some irons having been noticed' (Randall, *loc. cit.*). The alloy is also used for the audio-frequency intervalve transformers of radio receiving sets; for electro-magnetic measuring

* 'A Useful Instrument Alloy,' W. F. Randall, *Elec. Rev.*, Jan. 13, 1933, p. 42.

instruments, both A.C. and D.C.; and for sensitive relays and cut-outs, where the rapid response to magnetic changes is valuable. Finally, shields of mumetal only $\frac{1}{20}$ in. thick can reduce the intensity of field inside to 0·1 per cent. of its outside value, where previously a shield 20 or 30 times as thick was needed (*loc. cit.*).

(vii) *Magnetostriction.*—The phenomenon of 'magnetostriction,' *i.e.* change of dimensions on magnetisation, occurs to a more or less considerable extent in most nickel-iron alloys, excepting the 30 °/ₒ Ni and 80-85 °/ₒ Ni alloys. It is very pronounced in the ranges 10-25 °/ₒ Ni and 35-55 °/ₒ Ni. A rod of magnetostrictive metal resonates when it is subjected to a magnetic field of frequency equal to its own natural frequency of longitudinal vibration; this is applied in high-frequency standardisation and control. Magnetostriction can also be utilised in marine soundings.*

'Permalloy' is the generic name applied to nickel-iron alloys containing about 78½ °/ₒ Ni and 21½ °/ₒ Fe. These alloys possess remarkable magnetic properties; they will certainly be of importance in electrical communication (telegraphy, etc.) and may find application in heavy engineering. When properly heat-treated, permalloy 'A' has an 'initial permeability' (*i.e.* permeability at zero field, by extrapolation) as high as 13 000. Permalloy 'A, although it has a saturation value B = 11 000 gauss (approx.), comparable with that of iron, approaches saturation in the earth's field. The area of the hysteresis loop with $B_{max.}$ = 5 000 gauss is one-sixteenth of that for soft iron. For B = 4 000 to 6 000 gauss the permeability is 80 000 to 90 000, which is very much higher than the value for silicon steel (§ 82). For further information, see *Jour. Franklin Inst.*, Vol. 195, p. 621.

83. Permanent Magnet Steels.—As explained in § 81 two of the main requirements in a permanent magnet steel are high remanence and high coercivity; in addition the magnet should not be weakened appreciably by 'ageing' when exposed to vibration, temperature variations, etc. High-carbon steel (1 to 1½ °/ₒ carbon) can be used for permanent magnets, best results being obtained when the metal is so quenched as to yield the finest grain and greatest mechanical hardness; a remanence of 8 500 gauss and a coercivity of 50 can be obtained. Alloy steels are now available which give far better magnets than plain carbon

* 'Magnetostriction Echo Depth Recorder,' A. B. Wood and F. D. Smith, *Jour. I.E.E.*, Vol. 76, p. 550. *See also* Magnetostriction,' W. Alexander and J. Swaffield, *Beama Journal*, Vol. 41, p. 99.

steel, but in the alloys there are many factors determining the magnetic qualities, and it does not follow that the latter are best when the metal is in its hardest state.

Most of the permanent magnet steels on the market are tungsten alloys containing from 5½ to 6½ °/₀ tungsten; 0·55 to 0·7 °/₀ carbon; 0·3 to 0·5 °/₀ manganese; 0·1 to 0·15 °/₀ silicon; and traces of phosphorus and sulphur. When quenched at 825°-850° C. such steel has a remanence of 9 000 to 11 000 gauss and a coercivity of 60 to 70 gauss. Chromium steel containing about 2 °/₀ chromium and 0·85 °/₀ carbon gives about the same coercivity as tungsten steels, but the remanence is lower (9 000-9 500). Honda's cobalt steel, containing 35 °/₀ cobalt, 7 to 9 °/₀ tungsten, and 0·5 °/₀ carbon, can be made to give a coercivity of 180-200. Hadfield's 'Permanite,' also a cobalt steel, is claimed to have a remanence of 11 200 and a coercivity of 120 gauss.

(ii) *Nickel-Alloy Permanent Magnets.**—A typical composition of the simplest nickel-aluminium steel for permanent magnets shows Ni 25 °/₀, Al 13 °/₀, but later alloys also contain cobalt, *e.g. Alnico* contains Ni 20 °/₀, Al 10 °/₀, Co 10 °/₀. These alloys are relatively cheap and they offer much higher magnetic energy per unit volume or weight than any of the older magnet steels. Table 7*c* compares the magnetic properties of various materials and shows that while the coercive force of the nickel alloys is very high, the remanence is lower than that of certain older types of steel. Magnets of the newer materials are therefore generally of greater cross-section for a given result but can be used in much shorter lengths. The alloys are highly stable in service even when exposed to heat and shock. An important application is in loud speakers. Another is in permanent magnet chucks which hold or release work when a handle is turned so that pole pieces in the chuck either form extensions of the magnets or short-circuit them and act as keepers. The properties of the Ni-Al-Co alloys are also admirably adapted to the construction of small permanent magnet electric generators for speedometers, miners' electric lamps, aircraft radio generators, and the like. Many uses for them arise in instrument work, and they may be applicable to fractional-H.P. motors. Automatic traffic signals and train control also offer opportunities for powerful permanent magnets.

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* Abridged from *The Magnetic Properties of the Nickel-Iron Alloys*, Mond Nickel Co., Ltd., London.

All permanent magnets should be 'aged' by heating them to 100° C. for 24-48 hrs. and subjecting them to vibration. The extent and rate of ageing in service depends considerably upon the form of the magnet.*

84. Non-Magnetic Steels.—Iron loses its magnetic properties completely when (and whilst) heated to the temperature of recalescence (about 680° C.) or higher. This is important in connection with the use of lifting magnets (§ 806, Vol. 3) and in the magnetic determination of the correct temperature for hardening carbon steel (§ 122). A somewhat similar phenomenon is observable in 25 °/ₒ nickel steel (§ 82) which is normally non-magnetic, but which becomes magnetic when cooled to – 40° C. and

TABLE 7c.—*Permanent Magnet Steels.*

Material.	Remanence (Gauss).	Coercive Force (Oersteds).	Br × Hc.	BH max.
1 % carbon steel .	9 000	55	500 000	200 000
6 % tungsten steel .	11 000	70	770 000	300 000
3 % chromium steel .	9 000	65	600 000	250 000
15 % Co/10 % Cr steel	8 600	170	1 000 000	630 000
36 % cobalt steel .	9 800	260	3 300 000	1 100 000
Ni-Al steel (A) . .	6 000	500	3 600 000	1 300 000
Ni-Al steel (B) . .	8 200	510	4 200 000	1 750 000
New Honda steel † .	7 000	840	6 000 000	—

then remains magnetic until heated to 600° C. Steels which are non-magnetic at atmospheric temperature are useful for structural purposes where the mechanical strength of steel is desired without the disturbing effects which would be caused in the neighbourhood if magnetic material were employed. About 16 % or less of manganese (according to the amount of carbon present) produces a non-magnetic steel, the electrical resistance of which is about five times that of iron. Hadfield's manganese steel containing 13 % manganese, 1·3 % carbon, and 0·3 % silicon is practically non-magnetic, and is used near magnetic compasses and in other similar applications; the metal is practically unmachinable and,

* 'Permanent Magnets in Theory and Practice,' by S. Evershed, *Jour. I.E.E.*, Vol. 58, pp. 780 *et seq.* (Part I), and Vol. 63, pp. 725, 817 (Part II), is a classic treatment of the subject.

† Said (*loc. cit.*) to contain 15-36 % Co, 10-25 % Ni, 8-25 % Ti, with or without small quantities of aluminium.

indeed, owes its principal applications (to special trackwork, rock-crushers, etc.) to its remarkable toughness and strength.

A non-magnetic cast iron 'No-Mag' (Dawson-Ferranti patent application 33290/20) is recommended for use in resistance grids, switch, and transformer covers, and general structural components in which eddy currents are to be avoided. This material resembles ordinary cast iron except that it is tougher, more malleable, and of higher electrical resistance (140 microhms per cm. cube); its permeability is 1·02-1·03.

Refractory Materials and Timber Preservatives.

85. Refractory Materials.—Information concerning the heat-resisting properties of porcelain, asbestos-compositions, and other materials which are used primarily as electrical insulators, is given in earlier paragraphs. The materials here considered are those used as supports for the hot wires of heating apparatus, as linings for electric furnaces, and in other applications where resistance to heat is a primary consideration. Another requirement is low thermal conductivity, in order that heat losses may be reduced. At their working temperature, most refractory bricks, etc., become relatively good electrolytic conductors (§ 68), hence they must not be subjected to high P.D. Mechanical strength and low temperature coefficient of expansion are desirable from the constructional point of view. Chemical inertness, particularly resistance to oxidation, is essential.

Under suitable conditions the electric furnace can be made to melt practically all materials, hence it is correspondingly difficult to obtain refractories able to resist for a reasonable period the high temperatures attained, the chemical action of the charge, and the scouring action of the molten metal; no known material will stand up to these conditions indefinitely. The mechanical strength of all refractories is low at high temperatures and the melting (or flowing) temperature is reduced by 10 to 15 °/ₒ by the application of a load of 50 lb. per sq. in. Conditions are much less severe in furnaces for the common non-ferrous metals, because not only are the melting-points of the latter lower than that of steel, but also there is not, in simple melting, the severe slag action which is inevitable in steel refining.

Refractory materials may be calcined, ground, mixed with binder, and then either formed into bricks, or rammed to form a solid hearth or lining. The initial drying and heating must be conducted slowly and uniformly. Moisture in refractories containing lime is apt to cause slaking. Freezing is disastrous to most refractories.

Refractories with a *basic* reaction are: alundum, bauxite, carborundum, dolomite, magnesite, and zirconite; those with an *acid* reaction are silica and kieselguhr; and those which are *neutral* are chromite and fireclay. Brief notes on these materials are appended:—

Alundum (artificial corundum) is made by fusing and refining bauxite in the electric furnace. Its thermal conductivity is about 20 % higher than that of silica. Linear coefficient of expansion 8×10^{-6} per 1° C. Specific resistance 9×10^{6} Ω per cm. cube at 20° C.; 190 Ω per cm. cube at 1 600° C. Strong at high temperatures, less liable than silica to spall or splinter. Used in heating and cooking apparatus and for furnace roofs. Weakened by lime and magnesia vapours. Melting-point, 2 000°-2 100° C.

Bauxite Brick consists of calcined alumina with fireclay bond, fired at the highest attainable temperature in order to complete shrinkage. Melting-point 1 550°-1 800° C. according to quality.

Carborundum (silicon carbide or crystolon) is useful for furnace roofs, due to its refractory nature, its strength at high temperatures, its high thermal conductivity (more than twice that of silica), and its low coefficient of expansion (lower than that of silica). It can be used at temperatures exceeding 1 800° C. So-called *carbon bricks* consist of carborundum.

Chromite Brick containing about 40 % chromium oxide together with alumina. silica, and iron oxide is attacked by molten steel and weakens about 1 550° C, Melting-point about 2 100° C.

Dolomite consists of limestone with a high percentage of magnesia. When calcined and mixed with tar it is used for rammed hearths of steel furnaces. If exposed to moisture the lime slakes; for this reason dolomite bricks are rarely used.

Fireclay is a generic term applied to clays which melt about 1 550-1 750° C. The principal constituents are 25-35 % of alumina and 50-60 % of silica. *Firebricks* made from burnt fireclay, with raw clay as bond, are not suitable for exposure to the full heat of electric furnaces, but are useful as heat insulation. Specific heat, 0·22-0·30 at temperatures from 500°-1 500° C.; weight, 130 lbs. per cu. ft.; crushing strength 1 300 lbs. per sq. in. at 1 350° C., softens about 1 550° C. Thermal conductivity, 10-15 B.Th.U. per sq. ft. per 1° F. per hr. for 1 in. thickness.

Kieselguhr (diatomaceous earth) contains up to 95 % silica and consists of the shells of diatoms. Due to the innumerable air pockets (of microscopic proportions) in the material—whether used as a loose powder or in the form of bricks—the thermal conductivity is very low (from 1 to 2 B.Th.U. per sq. ft. per 1° F. per hr. for 1 in. thickness, *i.e.* about one-tenth that of solid silica). Kieselguhr is useful for lagging, and can be used in building and lining high temperature furnaces. Owing to the enclosed air, the apparent sp. gr. is about 1·0. Melting-point about 1 610° C.

Magnesite is used with tar for rammed hearths, etc., or calcined magnesite

(85 °/₀ to 94 °/₀ magnesium oxide) is moulded without bond to form bricks which are fired at or above 1 700° C. to complete their shrinkage. Pure magnesia melts at about 2 800° C. and magnesite brick at 2 165° C. Magnesite is much used for the hearths and walls of steel furnaces and in furnaces for melting aluminium and its alloys, bronze, bearing metals, lead, and copper. *Magnesite bricks* expand greatly with temperature ($\frac{3}{16}$ in. per ft. should be allowed at expansion joints), and though the melting-point is high the bricks are weak at a much lower temperature. Crushing strength 65 lbs. per sq. in. at 1 650° C.; weight 164 lbs. per cu. ft.; thermal conductivity 15-20 B.Th.U. per sq. ft. per 1° F. per hr. for 1 in. thickness.

Silica Bricks (Dinas bricks) are made from sharp quartzite with 2 °/₀ lime as bond; the bricks should be at least 96 °/₀ silica. They are strong at high temperatures but spall if subjected to sudden temperature changes. They are used for furnace roofs and as lining in furnaces for melting bronze, copper, or silver. Silica is liable to attack by fluxes. Specific heat 0·22-0·30 between 500 and 1 000° C.; weight 100-110 lbs. per cu. ft.; crushing strength 1 850 lbs. per sq. in. at 1 350° C. and over 75 lbs. per sq. in. at 1 500° C.; thermal conductivity 5-10 B.Th.U. per sq. ft. per 1° F. per hr. for 1 in. thickness. Melting-point 1 700° C. *Ganister brick* is made from siliceous rock containing about 10 °/₀ of clay and requiring no other bond. *Pure silica* (quartz) flows at 1 750° C. and is used in heating and cooking apparatus, etc. (§ 74, II (*b*)).

Zirconia, which is now available in commercial quantities, is exceptionally refractory (melting-point, 2 600°-3 000° C.) and may be used with tar for rammed linings or in the form of bricks. Though dearer than magnesite, the maintenance costs are low because zirconia is very resistant to slags and metals, is mechanically strong, and has low expansion and low thermal conductivity. The specific heat is 0·14-0·18 from 500°-1 500° C. Zirconia bricks withstand 1 800° C. satisfactorily; iron oxide, as impurity, lowers the melting-point.

Refractory cements are generally of the same composition as the mixture from which the bricks are baked. A paste of asbestos (2 parts) and water glass (3 parts) mixed with water is useful in repairing refractories exposed to moderate temperatures.

86. Preservative Processes for Timber.—Wood impregnated with paraffin wax is acid-resisting and moisture-proof, but this treatment is too expensive for use in the wholesale preservation of timber (particularly poles for overhead lines, § 323) which is to be exposed to weather or buried in the ground. The preservative processes applicable in such cases may require extensive plant for the injection of antiseptic solution under pressure, or penetration may be secured by more or less prolonged immersion in open tanks. Among the pressure processes are creosoting by the old method or the modern Rüping and Rütger processes. A large number of the patent solutions have been introduced for open-tank processes.

Creosote is the preservative most used for poles in this country. To facilitate penetration small radial holes may be forced (*not* drilled) in the butt. It is advisable to impregnate the whole pole and not merely the butt. There is a certain settlement and oozing out of the creosote in service; after a time there is about one-third the original weight of creosote in the butt and a less proportion in the upper parts. Weight for weight, creosote is estimated to have about twice the antiseptic effect of copper sulphate at one-fiftieth the cost for materials. With deep penetration the oil is fairly resistant to attack by white ants. Injection of about 10 lbs. of creosote per cu. ft. of timber is recommended for poles, and the wood should not be cut or drilled after creosoting, as the heavier fractions of the oil lie near the surface.

Kyanising is a low-pressure process, seasoned timber being steeped for days or weeks in a weak solution of mercury chloride (corrosive sublimate). The solution does not penetrate deeply, and the weight of salt absorbed is given as about 0·01 lb. per sq. ft. of surface for fir. The preservative is said to be leached out by rain, and may then contaminate drinking water, but the process has been used extensively on the Continent. Kyanised timber can be painted.

Aczol is a mixture of copper or zinc ammoniates with an antiseptic acid containing phenols and naphthalenes. Its action is to cement together the surface layers of wood fibres and tissues, and is claimed to be as effective as creosoting, and to cost about 2½d. per cu. ft. for pole timber.

The Powell *saccharine* process employs by-products of sugar-refining which are said to form an approximation to amorphous wood in the interstices of the timber treated. Wood is appreciably strengthened by the treatment, and, by inclusion of arsenic in the solution, becomes resistant to white ants. The process is used fairly extensively in Australia, New Zealand, and India. Treated timber is clean, dry, and can be painted.

Solignum has proved useful within the authors' experience when merely painted on. *Microsol* consists of sulphates of copper, soda, and lime. *Bellit* consists mainly of sodium fluorite. There are many other materials and processes which cannot be dealt with here. Treatment by simple metallic salts is not in high favour in this country.

The 'Cobra' process employs a paste composed of 15 °/₀ sodium dinitrophenate and 85 °/₀ of sodium fluoride, which is injected either into growing trees or cut poles by a portable instrument on the lines of the 'grease-gun.' The holes so made are plugged, and the surface is brushed over with 'celoid'—creosote and a mixture of naphthylamine and dinitrochlorbenzole. The process is claimed to have a definite superiority over kyanising and other processes.

An exhaustive treatment of the nature of decay in wood, and of preservative materials and processes, is given by A. J. Wallis-Tayler in the Royal Society of Arts *Journal*, Vol. 62, pp. 286 *et seq.* A valuable monograph on the antiseptic treatment of timber is given by R. S. Pearson in *Indian Forest Records*, 3, Part 2, and a bibliography is given therein.

Data concerning the life of timber, treated and untreated, are given in § 323.

87. Bibliography (*see* explanatory note, § 58).

STANDARDISATION REPORTS, ETC.

(1) *I.E.C. Publications.*

No. 28. International Standard of Resistance for Copper.

No. 34. Rules for Electrical Machinery.

(2) *B.S. Specifications (Titles abbreviated).*

No. 7. Insulated Annealed Copper Conductors for Electric Power and Light (with addenda).

68. Specifying Resist. of Steel Rails.
107. Sections for Magnet Steel.
115. Metallic Resistance Materials.
119. Baking Oil Insltg. Varnish.
125. Hard-drawn Copper Conductors.
128. Bare Annealed Copper Wire.
134. Steel Poles for Telegraph, &c., Lines.
137. Porcelain Insulators for Power Lines.
139. Red Fir Poles.
144. Creosote for Timber.
148. Insulating Oils.
156. Enamelled Copper Wire.
160. Slate Slabs.
198. Electrolytic Copper.
216. Vulcanised Fibre.
219. Soft Solders.
223. Performance of Bushing Insltrs.
231. Pressboard.
234. Ebonite.
316. Synthetic-Resin Varnish-Paper.
384. Phosphor Bronze Wire.
406. Testing Permanent Magnets.
419. Varnished Cloth.
443. Testing Zn on Galv. Wires.
444. Dead-Soft Copper.
445. Copper Commutator Bars.
474. Synthetic Resins.
488. Moulded Insulating Material.
514. Insltg. Varnish (Bitumen Type).
518. Medium-Hard Copper.
547. Synthetic-Resin Bonded-Paper.
626. Micanite for Commutators.
633. Cotton Tapes and Webbing.
634. Air-Drying Insltg. Varnish.
688. Bituminous Filling Compounds.
697. Rubber Gloves.
698. Papers (Unvarnished).
729. Testing Zn on Galv. Artls.
737. Non-Ign. and Self-Exting Boards.
738. Non-Ign. and Self-Exting Prop. of Solid Insul. Matls.

See also Specifications for Rating of Electrical Machinery in § 152; and for railway materials, Chapter 35, Bibliography.

Books.

Industrial Chemistry. E. R. Riegel (Reinhold Publishing Corp.).
Theory of Dielectrics. A. Schwaiger and R. W. Sorensen (John Wiley).
Impregnated Paper Insulation. J. W. Whitehead (John Wiley).
Asbestos. A. L. Summers (Pitman).
Electrical Insulation. W. S. Flight (Pitman).
Special Steels. T. H. Burnham (Pitman).
Magnetic Induction in Iron and other Metals. J. A. Ewing ('Electrician').
Industrial Chemistry. H. K. Benson (Macmillan).
Insulation and Design of Electrical Windings. A. P. M. Fleming and R. Johnson (Longmans).
Mechanical Technology. G. F. Charnock (Constable).
Copper for Bus Bars (Copper Development Assocn., London).

I.E.E. Papers.

Properties and Characteristics of Insulating Materials, R. T. Fleming. Vol. 60, p. 58.
Effect of Heat on the Electric Strength of Some Commercial Insulating Materials, W. S. Flight. Vol. 60, p. 218.
The Testing of Materials used in the Manufacture of Electrical Equipment, C. Dawson. Vol. 61, p. 59.
Permanent Magnets and the Relation of their Properties to the Constitution of Magnet Steels, E. A. Watson. Vol. 61, p. 641.
The X-ray Examination of Materials, A. G. Warren. Vol. 61, p. 949.
The Electrical Conductivity of Light Aluminium Alloys and Copper Conductors, Prof. E. Wilson. Vol. 63, p. 1108.

Insulating Oils, A. R. Everest. Vol. 65, p. 686.
Insulating Oils for High-Voltage Cables, T. N. Riley and T. R. Scott. Vol. 66, p. 805.
Electrical Insulating Papers for the Manufacture of Power Cables, T. N. Riley and T. R. Scott. Vol. 67, p. 946.
The Testing of Porcelain Insulators, B. L. Goodlet. Vol. 67, p. 1 177.
Magnetic Characteristics of Nickel-Iron Alloys with Alternating Magnetizing Forces, E. Hughes. Vol. 79, p. 213.
Plastics for Use in Electrical Engineering, A. R. Dunton and A. Caress. Vol. 79, p. 463.
A Record of Recent Progress towards the Correlation of the Chemical Composition, the Physical Constitution, and the Electrical Properties, of Solid Dielectric Materials, W. Jackson. Vol. 79, p. 565.
Nickel-Iron Alloys of High Permeability, with special reference to Mumetal, W. F. Randall. Vol. 80, p. 647.
The Effect of Change of Temperature on the Strength of Permanent Magnets, with special reference to Modern Magnet Steels, A. C. Whiffin. Vol. 81, p. 727.
Recent Developments in Magnetic Materials, C. E. Webb. Vol. 82, p. 303.

B.E.R.A. PAPERS PRINTED IN I.E.E. JOURNAL.

Properties and Uses of Micas. Vol. 60, p. 339.
Directions for the Study of Pressboard. Vol. 61, p. 486.
Directions for the Study of Vulcanised Fibre. Vol. 61, p. 954.
Directions for the Study of Electrical Insulating Papers (unvarnished) for Purposes other than Cables. Vol. 61, p. 982.
Directions for the Study of Varnish Paper, Fabric-Boards and Tubes. Vol. 62, p. 160.
Directions for the Study of Varnished Cotton Cloth. Vol. 62, p. 173.
Directions for the Study of Electrical Insulating Varnishes, Paints and Enamel Paints. Vol. 62, p. 936.
Directions for the Study of Non-Ignitable and Self-Extinguishing Boards and Mouldings. Vol. 63, p. 51.
Directions for the Study of Unvarnished Textile Fabrics. Vol. 63, p. 133.
Directions for the Study of Micanite. Vol. 67, p. 1 243.
Report on Researches on the Chemical and Physical Properties of Insulating Oils. Vol. 61, p. 661.
Tentative Directions for the Determination of the Electrical Strength of Solid Dielectrics. Vol. 64, p. 165.
A Critical Resumé of Recent Work in Dielectrics. Vol. 64, p. 1 152.
Thermal Transference in Transformer Oils. Vol. 67, p. 527.
The Effect of Added Impurities on the Breakdown Voltage of Insulating Oils. Vol. 67, p. 750.
The Thermal Resistivity of Solid Dielectrics. Vol. 68, p. 1 313.
The Dielectric Properties of Varnished Cloth at Low Voltage-Gradients, L. Hartshorn. Vol. 70, p. 417.
The Dielectric Properties of Varnished Cloth at High Voltage-Gradients, L. Hartshorn and E. Rushton. Vol. 75, p. 631.
The Dielectric Properties of Paper, L. Hartshorn and W. H. Ward Vol. 77, p. 723.
Directions for the Study of Hard Composite Dielectrics (Mouldings, Sheet and the like). Vol. 81, p. 553.

CHAPTER 3.

INSTRUMENTS AND MEASUREMENTS.

88. Measurements Required.—In order to know what is happening in an electrical circuit it is necessary to measure the quantities, current, pressure, power, frequency, etc., relating to the current itself. Also by utilising properties of the electric current or variations in electrical quantities produced by other than electrical causes it is possible to measure the latter; for instance, the resistance of a conductor varies with temperature and may be used to measure temperature (§§ 61, 122). Instruments for measuring electrical quantities, and electrical instruments for measuring other than electrical quantities, are described in this chapter, mainly as regards the principles upon which they operate and the facts bearing upon their use. For details of construction reference must be made to books devoted to this subject (§ 125).

89. Types of Instruments.—An electric current can be measured by any of the effects which it produces, and, in so far as the effects of direct and alternating current are different, some instruments can be used only for direct current and others only for alternating current measurements. In general—

(*a*) Any 'polarised' instrument the direction of deflection (or other action) of which reverses with the direction of the current is unsuitable for alternating currents unless, as in the oscillograph (§ 118), the instrument is capable of following the alternations completely and accurately. Polarised instruments can be arranged with a centre-zero scale so as to read in either direction without reconnection.

(*b*) Instruments in which the effect varies with the square of applied current or P.D., are unaffected by alternations in these quantities (except as regards hysteresis and eddy current effects, §§ 34, 39, 100, 101*b*) and can therefore be used in A.C. circuits. They cannot be arranged as centre-zero instruments.

(*c*) Instruments which depend upon alternation of current for their action (*e.g.* induction ammeters, § 102) cannot be used on D.C. circuits.

The effects of the electric current on which its measurement may be based, and the main types of instruments utilising these effects are as follows:—

(i) *Electro-Chemical.*—The electrolytic effect of a direct current is made the basis of the international definition of the ampere (§ 3). It cannot be used to measure an alternating current because the electrolytic effect of one half-cycle is reversed and neutralised more or less completely by the ensuing, reversed half-cycle (see, however, § 415 *et seq.*, Vol. 2). Neither can the electrolytic effect be used to measure the instantaneous value of a varying direct current. The amount of electro-chemical action produced varies with the *quantity* of electricity (§ 28), hence this effect is used to measure ampere-hours (§ 114) or, on the assumption of an unvarying current (§ 3), amperes indirectly.

(ii) *Thermal.*—The heating effect of an electric current varies with the square of the current (§ 49), and is therefore the same for A.C. as for D.C. The expansion of a fine wire traversed by the current to be measured is made to produce a convenient deflection by means of a mechanical or optical magnifying system (§ 99). Alternatively the heating of a special resistance element may be measured by a thermo-couple built permanently in the circuit of a moving coil instrument (§ 99).

(iii) *Electromagnetic.*—Instruments of this type are used for practically all ordinary commercial measurements. A current-carrying conductor establishes round itself a magnetic field (§ 32) which can be used: (*a*) to attract or displace a permanent magnet (as in certain galvanometers, § 96) or a piece of soft iron (as in 'moving iron' instruments, § 100); (*b*) to react with the field of a permanent magnet (as in 'moving coil' instruments, § 101 *a*) or with the field of a second current-carrying conductor (as in dynamometer instruments, § 101 *b*); or (*c*), if alternating, to induce currents in a second conductor and then to react with the field of the latter (as in induction instruments, § 102). The general principle employed is that of attraction or repulsion between fixed and moving parts, one of which is a current-carrying conductor (usually wound in the form of a coil in order to multiply its effect, § 42). The moving part—whether a permanent magnet, soft iron, or a coil of wire—tends to deflect against the control of a constant magnetic field, a spring, or the force of gravity as the case may be. The deflection or the controlling force required to prevent deflection of the moving system is a measure of the quantity under investigation. Polarised electromagnetic instruments, *i.e.* those employing permanent magnets, cannot be used for A.C. measurements (excepting oscillographs, § 118, and vibration galvanometers, § 96), but moving (soft) iron instruments and dynamometer instruments can be used on A.C. circuits. Induction instruments cannot be used on D.C. circuits.

Moving iron and moving coil instruments will withstand much greater overload than hot-wire instruments. The hot wire of the latter is necessarily relatively thin and worked at high temperature, and the heating varies with the square of the current; on overload the hot wire is liable to be melted sooner than a protective fuse-wire in series with it.

(iv) *Electrostatic.*—The electrostatic attraction between two metallic vanes connected between points at different potential may be used to measure this P.D. The only current flowing in the instrument circuit is the extremely small charging current (§ 46) required to charge the condenser formed by the vanes of the instrument; this may be neglected for all practical purposes. Electrostatic instruments are equally suitable for measuring continuous or alternating pressures. They can be used to measure current (D.C. or A.C.) indirectly by measuring the P.D. across a non-inductive resistance traversed by the current in question (§ 107*c*); for economic reasons, however, the P.D. across resistance in the main circuit must be kept low and electrostatic instruments are not suitable for the measurement of small P.D.'s. The principal uses of electrostatic instruments are for pressure measurements in laboratory work, and in high-tension circuits (§ 103). Electrostatic instruments depending upon the repulsion between similarly charged vanes are used to indicate whether conductors are 'live' (§ 104). In damp places leakage current affects the reading of any electrostatic instrument.

(v) *Dielectric Break-down.*—The break-down of a dielectric is determined by the *maximum* P.D. to which it is subjected (§ 72) and the length of gap across which sparking occurs between suitable electrodes (§ 105) forms a measure of crest voltage and hence of R.M.S. voltage if the crest factor (§ 30) of the wave be known. This method is equally applicable to continuous and alternating pressures, but is only suitable for extra high voltages.

90. Control and Damping.—In thermal, electromagnetic and electrostatic instruments a 'deflecting' force is exerted upon a pivoted (or suspended, etc.) 'movement,' deflection of which is resisted by gravity, a spring, or some other 'controlling' force. In some types of laboratory instrument there is an advantage in varying the control (say by varying the torsion of a spring) so as to hold the movement over a zero index mark. The measure of the control force is then a measure of the electrical quantity tending to deflect the movement. For all practical purposes it is much more convenient to use a deflecting instrument, the pointer of which moves over a calibrated scale (§ 91) and comes to rest when the control force is equal and opposite to the deflecting force. If the deflecting force be varied suddenly, by a sudden change in the quantity measured, the momentum of the movement will tend to carry the latter beyond the new position of equilibrium, *i.e.* the pointer will tend to overshoot the correct deflection and oscillate before coming to rest. This may be prevented by applying a retarding force which retards the motion of the movement, but which diminishes as the movement comes to rest and is then zero. Such a 'damping' force is provided by the movement of a vane in a dashpot chamber, the walls of which it just clears; by the motion of a vane, or the 'movement' itself, in oil; or by the eddy currents induced in a brake disc moving between the poles of a permanent magnet. Solid friction, such as produced by a brake band, may *not* be used for damping because it exerts a force when the movement is stationary and thus affects the deflection.

(ii) A commercial instrument is said to be 'dead beat' when the oscillations die away rapidly. If the damping be increased till there is no overshooting, the instrument is then strictly 'aperiodic'; further increase of damping makes the instrument 'sluggish,' *i.e.* the pointer crawls slowly to the steady deflection. Oscillographs must be exactly aperiodic or 'critically damped,' but in ordinary indicating instruments a slight degree of overshooting is useful as indicating that there is no abnormal friction. Recording instruments must be aperiodic. Sluggishness produced by over-damping is useful where it is desired to obtain an average reading of a quantity which is fluctuating too slowly for the movement to take up a mean position by its own inertia.

(iii) Gravity-controlled instruments must be levelled before use, and, since the control force varies with the sine of the angle of deflection in this type, the scale is cramped near the zero. Spring-controlled instruments can and should be balanced so that they can be used without levelling; the control exerted by the spring varies uniformly with the deflection and this tends to produce an even scale (§ 91). On the other hand, the spring can, if desired, be 'set up' so that the pointer does not move until a predetermined value of current, etc., is reached; the suppressed portion of the scale may be as much as 0·7 of the maximum reading, the whole scale length being then available for the remaining 0·3 of the maximum (*e.g.* the instrument might indicate 70 to 100 V only). Control springs are used to carry current into moving windings.

Air vane damping is generally employed in moving iron instruments, and eddy current damping in hot wire instruments, moving coil instruments, and supply meters. The time taken for the pointer of an indicating instrument to come to rest should not exceed (0·4 × total length of scale, in inches) seconds.

91. Scales.—When the pointer of any instrument is at rest at any point on its scale the control force is in equilibrium with the deflecting force on the movement *in the position concerned.* By varying the control (§ 90) or the manner in which the deflecting force on the movement varies with the position of the latter, any desired gradation of scale divisions can be obtained within a wide range. For general testing purposes a uniformly divided scale is desirable, but for switchboard service a scale which is open between the usual working limits and contracted elsewhere facilitates observation. Though an open scale contributes to accuracy of reading it has no relation to accuracy of indication (§ 92). The 'effective range' of an ammeter, voltmeter or wattmeter scale is assumed to extend from the maximum scale value down to 10 °/ₒ of the latter if the scale be nearly uniform and down to 25 °/ₒ if the scale be greatly contracted near zero; if the scale be partially suppressed (§ 90) the whole actual range is effective.

The value of each scale division should be 1, 2, or 5 of the units measured or a decimal multiple or sub-multiple of these numbers. The angle subtended by 1 scale division should be at least 0·5° in sub-standard and portable first-grade instruments (§ 92) and at least 1° in other instruments; *see also* B.S.I. Report No. 89 (1937).

In order that it may all be visible at once, an edge-type scale must not subtend more than 80°. Until recently disc-type moving-iron and moving-coil instruments have been built with scales subtending about 85°. By modifying the mechanical details and placing the scale arc on a diameter of the disc a scale length equal to the diameter of the instrument can be obtained, subtending about 125°. In the Record 'Cirscale' moving-coil instruments (§ 101*a*) the scale subtends 300°-330°.

92. **Instrument Accuracy and Errors.**—Two grades of instruments are recognised in British Standard Specification No. 89, 1937: Sub-standard grade, used for checking other instruments, and First Grade for switchboard and portable duty. The limits of allowable error for *Sub-standard instruments* are expressed as percentages of the maximum scale value and vary according to the type of instrument. The smallest limit is 0·2 °/₀ for a single range moving coil voltmeter and the limit increases to 0·5 °/₀ for ammeters, wattmeters and voltmeters used with a voltage transformer. There is a special grade for an electrodynamic wattmeter for which the maximum error is to be 0·25 °/₀. The limits of error for *First Grade instruments* are expressed as a percentage of the maximum scale value for indications in the upper half of the effective range, and as a percentage of the indication for readings in the lower half. The allowable errors so defined vary from 0·5 to 1·25 °/₀ in the upper half of the range for all but thermal and rectifier instruments and from 1·0 to 2·5 °/₀ in the lower half. The provisions of the Specification are complicated and cannot be summarised, and this Specification must be consulted for exact particulars of the limits of error allowable for instruments of any particular grade and type.

The limit of error for *power factor meters* is 2° of angle over a range of power factors of 0·5 to 1, at rated voltage, and for currents exceeding one-fifth of the rated current for polyphase instruments and one-third of the rated current for single phase instruments. A variation of the voltage of 10 °/₀ shall not change the indication by more than 0·5°.

Two classes of *frequency meters* are recognised, short and long range. For high accuracy short-range instruments, the maximum error is 0·1 °/₀; and it is specified that a change of voltage of

± 10 % or a change of temperature of ± 10° C. shall not change the indication by more than 0·05 cycle. For long range frequency meters the limit of error is 1 % of the mean scale reading.

Temperature Variation.—The maximum percentage change in indication for a temperature change of ± 1° C. for instruments of various grades and types is as follows:—

	Sub-standard.	First Grade.
Voltmeter . . .	0·03	0·1
Ammeter . . .	0·10	0·2
Milli-voltmeter 50-74 mV	0·15	0·3
,, over 75 mV	0·10	0·2
Wattmeter . . .	0·05	0·15

External Magnetic Fields.—Unless specially marked the maximum indication of an instrument permanently fixed in any position must not change by more than 1½ % if of the permanent magnet type, or 3 % if of any other type when the instrument is exposed to a field of 5 c.g.s. units in any direction.

Frequency Variation.—For sub-standard instruments a wattmeter shall not have its indication changed by more than 0·2 % or an ammeter or voltmeter by more than 0·25 % for a 20 % change of frequency. For First Grade ammeters, voltmeters and wattmeters the change in indication shall not exceed 0·4 % for a 5 % frequency change.

Power Factor.—The change in indication due to variation of power factor from unity to 0·5 shall not exceed 0·5 % for a Sub-standard or 1·5 % for a First Grade wattmeter.

93. Recording Instruments.—A graphic recording instrument is essentially an indicating instrument, all the movements of the pointer of which are recorded on paper, either by the pointer itself being used as a pen or by its being used as a type-bar as explained below. The paper is calibrated, in one direction by divisions equal to those of the instrument scale and in the other direction by equally spaced divisions which form a measure of time. The chart may be circular and rotated once in 24 hrs. (or other convenient time) or it may be in the form of a long band which is wound from one drum to another at a speed of say 1 in. per hr. (up to 1 in. per sec. if required). The chart is generally driven by clockwork and the error in its driving should not exceed 5 min. in 24 hrs. (about 0·35 °/$_o$).

In most cases the pointer is used as a pen. The displacements depending upon the quantity measured are then along the arc of a circle of radius equal to the length of the pointer. The chart movement (proportional to time) is linear in the band-type but angular in the disc-type of record; the latter type in particular is difficult to interpret because the time interval which corresponds to 1 in. circumferential displacement of the chart at 2-in. radius is represented by 2 ins. at 4-in. radius, and so on. Various methods are available by which a pointer, turning as usual about a centre, can be made to record its position with regard to a fixed straight line perpendicular to the line of advance of the paper. The curve thus traced has rectangular axes of co-ordinates. In one system the pointer normally swings clear of the paper, and an inked ribbon is placed between the two. At predetermined intervals an electromagnetic device presses the pointer on to the ribbon and thus records the deflection by a dot on the paper. The record obtained is as good as a continuous record for most practical purposes, with the important advantage that the instrument is free from the friction which exists between pen and paper in a pen-recorder. Also, by using a polychrome ribbon or a printing wheel bearing different numbers, distinctive records for a number of circuits can be made on a single chart.

94. Power and Power Consumption of Instruments.—The ratio of torque for full-scale deflection to weight of moving system is a convenient measure of the mechanical power of an instrument. This ratio should be reasonably high in order that the effect of pivot friction may be negligible, but an unduly high torque: weight ratio may be obtained at the cost of high expenditure of electrical energy in the instrument or of cutting down the weight of the movement below the limit of reasonable mechanical strength. The torque of indicating instruments should be not less than 0·05 cm.-grm. per grm. weight of moving system in portable instruments, and not less than 0·15 cm.-grm per grm. in switchboard instruments. In recording instruments pen friction is much greater than pivot friction.

Table 8, based on a more detailed one by Edgcumbe,* shows

* *Industrial Electrical Measuring Instruments* (Pitman), p. 109.

typical values of volt-amperes for full-scale deflection of switchboard indicating instruments. Graphic recording instruments generally consume from 2 to 3 times the power required by the corresponding indicating instruments.

Energy dissipated in the instrument itself may produce error by the heating which it causes (§ 92). Again, the volt-ampere load which may be placed on the secondary of an instrument transformer is strictly limited (§ 108). Not all the power expenditure involved by an instrument may be expended in the indicator itself; for instance, a shunted D.C. ammeter in a 500 A circuit involves, at 0·075 V maximum shunt P.D. (§ 107), a power loss of $500 \times 0 \cdot 075 = 37 \cdot 5$ W, but if 0·05 A goes through the instrument and 499·95 A through the shunt, the power expended in the instrument (including its leads) is

$$0 \cdot 05 \times 0 \cdot 075 = 0 \cdot 003\ 75 \text{ W}.$$

TABLE 8.—*Volt-Amperes for Full-Scale Deflection of Indicating Instruments (Switchboard Types).*

Type of Instrument.	Ammeter.	Voltmeter.
Indicating Ammeters and Voltmeters :—		
Moving iron, 6″ or 8″ dial	0·5 to 3	7 to 15
,, ,, large sector or edgewise	4 to 8	10 to 20
Moving-coil (permanent magnet) all sizes	Amps. × 0·05 to 0·1	Volts × 0·005 to 0·02
Dynamometer, 6″ or 8″ dial	3 to 6	7 to 15
Hot wire, 6″ or 8″ dial	Amps. × 0·2 to 0·4	Volts × 0·1 to 0·2
Induction, 6″ or 8″ dial	3 to 7	7 to 20
Indicating Wattmeters :—	Current circuit	Pressure circuit
Induction	0·5 to 3	5 to 8
Dynamometer	3 to 6	2 to 5

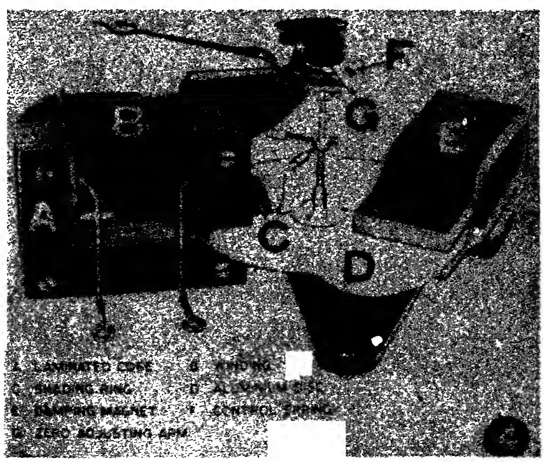
95. Standard Measurements; the Potentiometer. — For ordinary current and pressure measurements of high accuracy, the instrument known as the potentiometer is generally used.

(1) *The D.C. Potentiometer.*—The principle of this instrument is as follows: A wire of very uniform size is divided up into a number of lengths of exactly equal resistance, all in series, of which one length called the slide wire is stretched over a calibrated scale divided into 1 000 parts. A steady current from a secondary battery traverses the whole wire, and this

Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF 'SUPERSCALE' MOVING COIL INSTRUMENT.

The moving coil, B, wound on an aluminium frame swings in the magnetic field due to the permanent magnet A. The pivots are internal and work in jewels held in place by the grub screws F. The movement is controlled by a hair spring attached to the zero adjustor J. The evenly divided scale is mounted on the supports L, and the movement of the pointer is limited by stops M. The sensitivity can be varied by means of an adjustable magnetic shunt H, and the whole mechanism is insulated from the case by insulators at K.

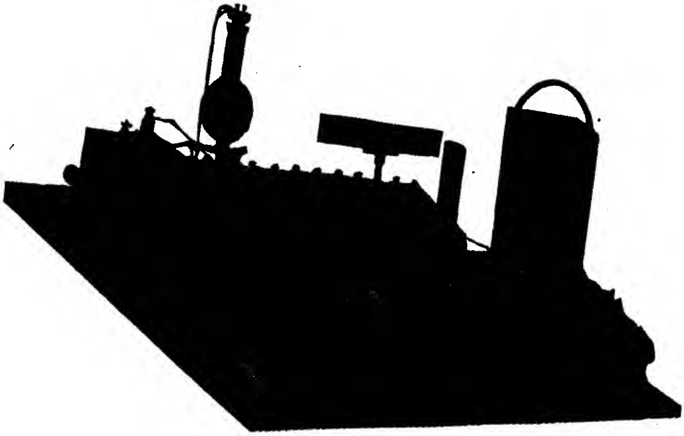


Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF INDUCTION-TYPE AMMETER.

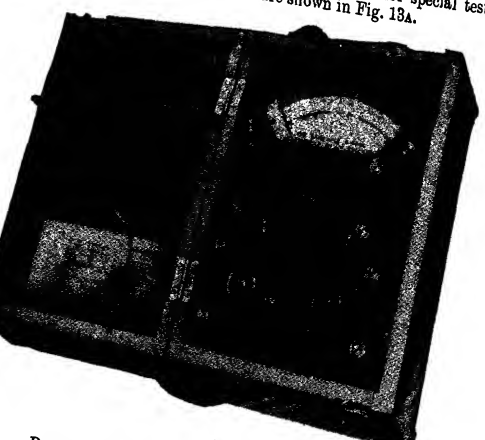
The electro-magnet A with laminated core is energised by the current to be measured which passes through the winding B, and half the resulting flux is 'lagged' by a copper ring C. The two fluxes, thus displaced in phase, in passing through the aluminium disc D induce a current in it and consequently a torque which carries the pointer over the scale in opposition to the spiral spring F. The magnet E makes the motion 'dead-beat' and the special shape of the disc D causes the scale, which would otherwise be quadratic, to become practically even throughout the working range.

[*To face p.* 144.



Complete Potentiometer Set. *Crompton & Co., Ltd.*

The set comprises a Crompton potentiometer; a reflecting galvanometer, lamp, stand, and scale; standard cells; accumulator cells; a volt box of suitable range for the pressures to be measured; a series of standard resistances for the range of currents to be measured; and a few accessories for special tests. The internal connections of the potentiometer are shown in Fig. 13A.



Cambridge & Paul Instr. Co., Ltd.

Portable Testing Set for D.C. Measurements.

The 'Unipivot' galvanometer used in this set eliminates troublesome adjustment and accurate levelling. It makes possible the measurement of pressures from 0·000 1 to 600 V; insulation resistances from 20 000 ohms to 1 000 megohms at 500 V; currents from 1 μA to 120 A (or any value with external shunt); and resistances from 10 microhms to 10 ohms, or, with Wheatstone bridge, up to 1 100 000 ohms. The set comprises a micro-ammeter, a universal shunt, series resistance coils, selecting and reversing switches, and standard shunts. Its uses include checking meters; measuring voltage, current, and power; measuring low or high resistances; and locating faults.

[*To face p.* 145.

current is adjusted by means of resistance coils until there is a fall of potential of exactly $\frac{1}{10}$ of a volt over the slide wire and each of the other corresponding lengths. This is secured by putting the E.M.F. of a standard cell (§ 128) in opposition to the fall of potential on the slide wire, over a length of the latter nominally equivalent to the pressure of the standard cell, and adjusting the resistance in circuit with the secondary cells until a galvanometer shows that the two opposing pressures are actually balanced. The instrument being thus calibrated ready for use, the standard cell is disconnected. Utilising the principle of Ohm's Law, if the current to be measured is made to pass through a known standard resistance (§ 20), the drop in pressure therein will be a measure of the current; this drop in pressure is then determined by indirect comparison with the pressure of a standard

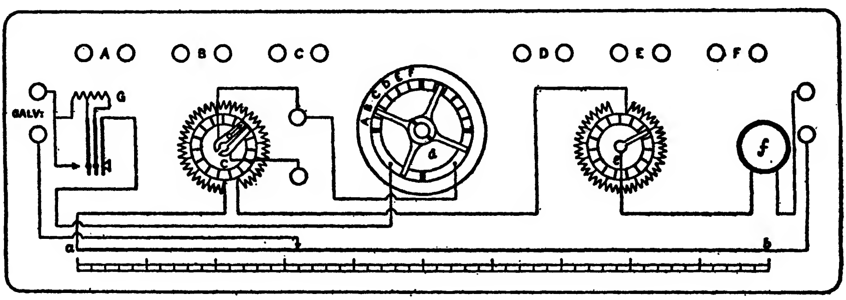


FIG. 13*b*.—Internal connections of Crompton potentiometer (see also Plate opp.).

cell on the slide wire of the instrument. The two pressures are made to oppose each other and exactly balanced, when the galvanometer will show no deflexion. The standard resistances are designed generally so as to give direct readings on the instrument, so that a current of 1, 10, 100, or 1 000 A allows in each case a drop of potential of $\frac{1}{10}$ volt in the standard resistance, this being also the drop of potential in each section of the potentiometer. The actual resistance is a trifle more than is required; auxiliary terminals are then fixed a short way from the main terminals, so that the resistance between them is exactly the required sub-multiple. The usual values are 0·001 Ω to carry 1 500 A; 0·01 Ω to carry 150 A; 0·1 Ω to carry 15 A; with a drop of 1·5 V over the whole instrument consisting of fourteen equal coils and the slide wire. The larger sizes often consist of water-cooled manganin tubes, as clean tap-water led in by a rubber tube does not affect the resistance.

In Fig. 13B *ab* is the slide wire; *c* the set of equal potentiometer coils in series with it; *d* the double pole switch connecting the six pairs of terminals *A*-*F* in succession to the slide contacts; *e*, *f* are the resistance coils and rheostat respectively; and *G* is the galvanometer key. All the moving contacts are under glass and the coils and the scale wire are inside the box. The pair of terminals *A* is assigned permanently to the standard cell in order to prevent confusion in working. Fine fuses are inserted at all the terminals except those for the galvanometer to save the instrument coils in case of accidental connection to high voltage. The two terminals to the right of the potentiometer coil switch *c* are used in testing the equality of the series of potentiometer coils. The resistance of the scale wire between 0 and 100 is the same as that of each potentiometer coil, but the scale is extended to 105 so that readings can be taken a little beyond the 100 mark without having to move the potentiometer coil switch.

(ii) Many forms of potentiometer are on the market to meet the needs of various classes of commercial testing work. In all these forms as much use as possible is made of direct-reading switch dials and arms. The slide wire itself may be mounted on a marble cylinder and traversed by a rotating contact arm which carries a direct indicating scale. In one form of potentiometer, the slide wire is entirely eliminated by a suitable arrangement of high resistance coils and dial switches. In yet another form a reasonably close 'balance' is obtained in the manner described above, and the deflection on the specially graduated galvanometer scale then indicates what must be added to the switch readings to obtain the unknown P.D. With this deflection-type of potentiometer, direct readings are generally obtainable to 0·001 V; null- or balance-type potentiometers for commercial work generally give direct readings to 0·000 1 V (or to 0·000 01 V on reduced range); and special precision instruments permit readings to be taken, by estimation between direct readings, to within 1 microvolt, *i.e.* one-millionth of a volt.

(iii) When a pressure is to be determined a definite proportion of that pressure (obtained from a standardised pressure-reducing coil, potential divider, or 'volt box') is similarly compared with the pressure of the standard cell. The volt box consists simply of a large coil of fine wire, wound non-inductively (§ 35 *end*), the terminals of which are connected across the full pressure to be measured. As shown in § 24, there will be an even potential gradient along this wire; and secondary terminals are connected at intermediate points to give exact sub-multiples of the total pressure.* The terminals used in any case are selected so as to give an actual pressure of 1·5 V or less. Thus, for measuring a pressure of 1 000 V, a volt box of 100 000 Ω could be used; then the fall over 100 Ω of this would be one-thousandth of the total, or 1 V only, which would be carried to the potentiometer.

(iv) When a resistance is to be measured a current of suitable amperage is passed through it, and the values of this current and the resulting drop of pressure in the resistance are measured as explained; then $R = E / I$. Considerable trouble is often experienced, especially in damp climates, owing to leakage from one circuit to another over the ebonite insulation, which is affected both by light and moisture in the air (§ 74, IV (*d*)); this leakage may be quite appreciable in comparison with the currents in the instrument.

(2) *A.C. Potentiometers.*—The potentiometer principle can be adapted for the measurement of alternating voltages. The potentiometer circuit carries a current of the correct value and the instrument must include some device whereby a fraction of the voltage drop in it can be adjusted to be equal in magnitude to, and in exact phase coincidence with, the voltage to be measured. The correct value of the current in an A.C. potentiometer is set by means of a dynamometer ammeter which is first calibrated by using the instrument in a D.C. supply circuit from an accumulator and adjusting against a standard cell in the usual way. A vibration galvanometer (§ 96) is used as a null indicator.

(ii) In the Drysdale potentiometer the A.C. supply for the slide wire circuit is derived from a phase shifting transformer whereby

* The principle that the P.D. across any fraction of a volt box is the same fraction of the total P.D. across the latter, holds good only if no current flows through the shunt circuit (§ 107) between the points tapped. For example, the current flowing through a 100 Ω volt box connected across 100 V supply will be 1 A (§ 17) and the P.D. across 1 Ω of the box will be 100 V × 1 Ω / 100 Ω = 1 V (§ 24). If this P.D. be measured by an electrostatic instrument (which passes no current, §§ 89, 103) or by a potentiometer (which is adjusted to balance the P.D. between the points of measurement, and then neither adds to nor subtracts from the current in the volt box), it will be found to be 1 V. If, however, 1 Ω of the volt box between two points *AB* be shunted by a measuring instrument of 1 Ω resistance, the effective resistance between *A* and *B* is halved, and the total resistance of the volt-box circuit is reduced to 99½ Ω. The current through the volt box is then 100 / 99½ = 1· 005 A and the P.D. between the points *AB* is 1· 005 × 0·5 = 0· 502 5 V instead of the original 1 V. Thus a volt box provides uniform potential gradient only so long as no current is shunted from (or added to) part of the volt box. *See also* § 107 (*c*).

the phase of the slide wire current can be continuously varied, without alteration of its magnitude. The adjustment for the measurement of an unknown alternating voltage consists in varying both the magnitude and the phase of the fraction of the total volt drop in the potentiometer circuit till this coincides in phase and magnitude with the unknown voltage as indicated by the vibration galvanometer. The phase of the potentiometer drop is indicated on an angular scale of the phase shifting transformer, so that, if a second correlated voltage is measured, the phase difference of the two voltages is known. Thus it is possible to measure the magnitudes of the current and voltage in an A.C. circuit, and also the phase difference between them.

(iii) In the Gall Co-ordinate potentiometer there are two distinct circuits carrying equal currents in accurate phase quadrature. The unknown voltage supply is connected to both circuits, and the tapping points are adjusted till the resultant of the two fractions of the voltage drops is equal to and coincident in phase with this unknown voltage. As two components of the unknown voltage in phase quadrature are known, the magnitude and phase of the voltage can be calculated; the magnitude being the square root of the sum of the squares of the two components given by the two potentiometer components.

(iv) The A.C. potentiometer made by the Cambridge Instrument Company is Campbell's modification of Larsen's original arrangement, this modification enabling the in-phase and quadrature components of an alternating voltage to be read directly. The in-phase component is read on a resistance unit and the quad-phase on an inductometer. (The resistance unit may also be used separately as a D.C. potentiometer, while the inductometer can be used for A.C. 'bridge' work.) Currents down to a few microamperes and pressures down to 10 microvolts in-phase and 2 microvolts quad-phase can be measured to an accuracy of at least 1 part in 1 000 at frequencies up to 1 000 cycles per second. The inductometer is independent of frequency up to 2 000 cycles per second and the accuracy of adjustment is to 1 part in 10 000.

Due to the fact that in an A.C. potentiometer the reference to the standard cell is indirect and through the medium of an indicating instrument its inherent accuracy is inferior to the D.C. type. It is, however, a valuable instrument for research and for the accurate determination of phase angles between alternating quantities.

96. Galvanometers.—The name galvanometer is applied to a variety of instruments, the purpose of which is to detect weak currents. The relation between deflection and current strength varies with the mechanical and electrical characteristics of the instrument and its circuit, but if the 'law' of the instrument be known quantitative measurements of current, P.D., resistance, etc., can be made.

(i) *Fixed Coil Galvanometers.*—The current to be measured is passed through a fixed coil the field of which deflects a permanent magnet against the torsion of a suspending fibre or against the control exerted by the earth's magnetic field. If the magnet be attached to the back of a small mirror its deflection is greatly magnified by the movement over a distant scale of a spot of light reflected by the mirror.

In the *tangent galvanometer* a horizontal magnetic needle carried by a vertical pivot is placed at the centre of a circular coil the plane of which is vertical and coincident with the direction of the earth's field. When current passes round the coil the needle is deflected through an angle θ and the current in amperes = $K \tan \theta$, where K is the 'constant' of the galvanometer. If the coil be turned about a vertical axis in the same direction as the deflection of the needle it will overtake the latter, and if the angle through which *the coil* has been turned is a, when its plane is again coincident with the needle, the value of the current is $K^1 . \sin a$, K^1 being a different 'constant.'

The *linesman's detector*, used principally for indicating current when identifying or testing the continuity of circuits (§§ 120*a* and 1037), has a pivoted magnetic needle which is deflected when current flows through an adjacent fixed coil. Two windings are generally provided, one of many turns of fine wire and about 100 Ω resistance for currents of a few milliamperes, and one of a few turns of thick wire (about 0·2 Ω) for heavy currents—up to 150 A if the coil be shunted (§ 107). This instrument may be used for rough comparisons of currents, but a testing set (§ 106) should preferably be used.

(ii) *Moving-Coil Galvanometers.*—The D'Arsonval galvanometer is the prototype of moving coil, permanent magnet voltmeters, and ammeters (§ 101) from which it differs only in having a fibre suspension instead of pivots for the moving coil and a reflecting mirror instead of a pointer to magnify the deflection. By eliminating the soft iron core inside the moving coil, replacing the latter by a single conductor of silvered glass or quartz, and reducing to a minimum the length of air gap, we arrive at the *Einthoven string galvanometer*. When current passes through the 'string' the latter is deflected (§ 33); the deflection is magnified by a microscope and recorded photographically. A small fraction of one-millionth of an ampere can be measured. Replacing the magnetic poles by plate electrodes at known potential, and the current carrying fibre by a fibre connected to a source of potential under investigation, the instrument becomes the *string electrometer*.

An ordinary moving-coil galvanometer is essentially a D.C. instrument (§ 89*a*), but if provision be made to vary the tension of the suspension, the natural frequency of the moving system can be made to coincide with the frequency of alternating current used in A.C. bridge measurements (§ 120), etc. Thus arranged, the instrument is a *vibration galvanometer*. Its coil vibrates in resonance (§ 47) when traversed by A.C. of the frequency for which it is adjusted, and when the band of light, so produced on its scale, is reduced to a steady spot it is known that no current is flowing through the instrument, *i.e.* balance has been obtained in the case of a bridge measurement.

(iii) *Ballistic Galvanometers.*—Either a moving needle or a moving-coil galvanometer may be used ballistically if its damping (§ 90) be small, and its time of vibration not less than, say, 10 secs. The principle used is that when the whole of a transitory current flows through the galvanometer before the moving system has time to move appreciably, the subsequent deflection depends upon the *quantity* (§ 28) of current which has passed. The instrument must be calibrated experimentally and its principal use is in determining magnetic flux or flux density by measuring the quantity of electricity induced in a 'search coil' when the latter is rotated in or withdrawn from the field in question (§§ 36, 121).

97. Commercial Measurements.—For the ordinary measurements of commercial electric supply an accuracy of about 99 °/$_\circ$ is generally quite sufficient (§ 92), and self-contained instruments are employed.

For the measurement of current and pressure 'ammeters' and 'voltmeters' are used respectively (§ 98). These may be either plain, indicating-dial instruments, showing the reading at any particular instant, or recorders, marking the current or pressure continuously on a revolving chart, divided up into hours (§ 93).

For measuring low or medium resistance the 'Wheatstone bridge' (§ 120) in one form or another is ordinarily used, while for very high resistances (especially insulation resistances) ohmmeters calibrated to read direct in megohms are employed, each instrument having its own magneto-generator for supplying the testing current (§ 119).

For measuring ampere-hours integrating 'ampere-hour meters' are used, having a clock mechanism and a train of dial wheels, in conjunction with current-measuring coils (§ 114). Electrolytic meters are also used for this purpose (§§ 28, 114).

'Watt-meters' (§ 109) contain a pressure-measuring coil and a current-measuring coil, so arranged with regard to one another that the indicating needle shows the product in watts. They may either indicate the power at the moment or record it continuously on a chart marked out in hours.

Watt-hour meters (§ 115) integrate the total work and record the result on a series of dials. Usually they are calibrated directly in Board of Trade units (kWh). The term 'meter,' as ordinarily used, includes this class of meter, as used to measure the value of the electric supply to buildings (§ 270)—corresponding, except for its greater accuracy, to the gas meter—as well as ampere-hour meters (§ 114).

D.C. supply meters generally *measure* ampere-hours (Ah) but *record* in units (kWh) on the assumption that the 'declared pressure' is constant; in the Electricity Commissioners' Regulations for ensuring a constant supply this is called 'the electrical quantity contained in the supply' as distinct from 'the amount of energy supplied' through a watt-hour (Wh) meter.

Other instruments used for commercial measurements are dealt with in §§ 111-123 inclusive. (*See also* index.)

98. Ammeters and Voltmeters; General.—Since the current flowing through a non-inductive resistance is proportional to the P.D. across the latter (§ 17) it follows that theoretically any current-measuring instrument can also be used to measure voltage. The only distinction between the two cases is that a voltage-measuring instrument for connection between two poles or phases of supply must be of high resistance to limit the current flowing and so restrict the expenditure of power within the instrument (§ 94), whilst any instrument used to measure the current flow in supply conductors must be of low resistance in order to reduce the I^2R losses (§ 49) in the instrument if the latter is connected in series with the main circuit or in order that it may be operated by a low-P.D., low-loss shunt (§ 107*a*). The high resistance of the voltmeter may be secured by connecting a suitable resistance in series with it, the instrument proper being identical with an ammeter except as regards the marking of the scale. By varying the resistance in series with the instrument, the range may be altered (§ 107*d*). Electrostatic instruments are not convenient or economical for current measurements (§ 89 iv). Hot wire instruments are generally shunted when used for current measurements (§ 99), and a shunted ammeter can be designed for the same small operating current which is alone economically permissible in a circuit connected across the mains. In other words, a shunted hot-wire ammeter may be identical with a hot-wire voltmeter, but when used for voltage measurement it must be connected in series with a suitable resistance (*see* Ex. § 107*d*). For the same reasons, a shunted moving-coil permanent magnet ammeter can be used as a voltmeter without change of winding (*see* Ex., *loc. cit.;* also § 106). Moving-iron instruments are not suitable for alternative use as ammeters or voltmeters, and are generally designed to suit the range of current or voltage in which they are required to measure. Thus, for practical reasons, there are considerable differences between the constructions of moving-iron ammeters and voltmeters. In a moving-coil ammeter or voltmeter there need be only 0·3 to 1 ampere-turn which can be provided by the same winding and an equally small current in both cases.

In A.C. circuits it is generally the R.M.S. value of current or voltage which is to be measured (§ 29), hence not every type of instrument can be used (§ 89). For special purposes crest voltage (§§ 30, 105) must be measured, or the complete wave of current or voltage must be traced (§ 118). An ammeter should be used in every important circuit; the current consumption alone is sufficient general indication of power consumption if the voltage be constant (as it generally is), and in A.C. circuits, if the power factor be reasonably constant (*see also* §§ 110, 114). The use of shunts and instrument transformers is discussed in §§ 107, 108.

99. Hot-wire Ammeters and Voltmeters.—The expansion of a fine wire due to heat developed by the current to be measured (§§ 89 ii, 98) is used to move an indicating pointer. Instead of measuring the actual expansion, the sag of the hot-wire (which is much greater than the expansion which causes it) is magnified by the yet greater sag in a tie wire between a fixed point and the centre of the hot wire. The latter is necessarily very fine and is easily burnt out; the principal use of the instrument is in the test room. Hot-wire instruments are unaffected by stray fields and can be used for either D.C. or A.C. of any frequency or wave form. The zero is liable to 'creep'; temperature errors may be serious; and the P.D. across the instrument or its shunt must be at least 0·2 V, *i.e.* the power loss in a hot-wire ammeter is about three times that in a moving-coil instrument (Table 8, § 94).

The *Duddell thermo-ammeter* is a combined thermal and electromagnetic instrument especially suitable for measuring currents from a few amperes down to a few milliamperes at high frequencies. The current to be measured is passed through a heating element of wire or platinised mica which is mounted below a bismuth-antimony thermo-couple (§ 122) connected in the circuit of a low resistance moving coil, permanent magnet instrument (§ 101). This instrument combines independence of wave form and frequency with the high sensitivity obtainable by using a powerful permanent magnet, whilst avoiding the mechanical difficulties of the ordinary hot-wire instrument (*see also* § 118).

100. Moving Iron Ammeters and Voltmeters.—The differences between ammeters and voltmeters of this type are noted in § 98. The general principle of both instruments is the same. A suitably shaped piece of soft iron is drawn into a coil through which is passed the current to be measured; or the iron may be moved from a weaker to a stronger part of the field so produced; or the moving iron may be repelled from a stationary piece of iron magnetised by the same field. In any case the moving iron is attached to the spindle carrying the pointer, and its movement takes place against the control of a spring or gravity (§ 90). According to the shape and disposition of the iron, the variation of deflection with current may be altered within wide limits.* So long as the iron is unsaturated the flux produced in it varies with the current in the magnetising coil (§§ 42, 81), hence the deflecting force on the iron (varying with flux × current) is proportional to the square of the current. The instrument is therefore inherently suitable for A.C. measurements (§ 89 *b*). Due to hysteresis in the iron (§§ 34, 81) there is a tendency for the instrument to read high on descending values. Again, the winding of

* If the scale be logarithmic (like that of a slide rule) overloads of 100 % or so can be read with sufficient accuracy whilst retaining an open scale within the normal range.

a voltmeter of this type is necessarily inductive (§ 98), and unless the inductance can be 'swamped' by plenty of non-inductive resistance (§ 44) the impedance of the instrument circuit, and therefore the calibration of the instrument, varies with frequency. It is claimed for the latest moving iron instruments that the error is less than 1 °/ₒ whether D.C. or A.C. of 50 or 100 cycles per sec. be used. In the absence of suitable guarantees, moving-iron instruments should be calibrated with A.C. of the frequency and wave form on which they are to be used.

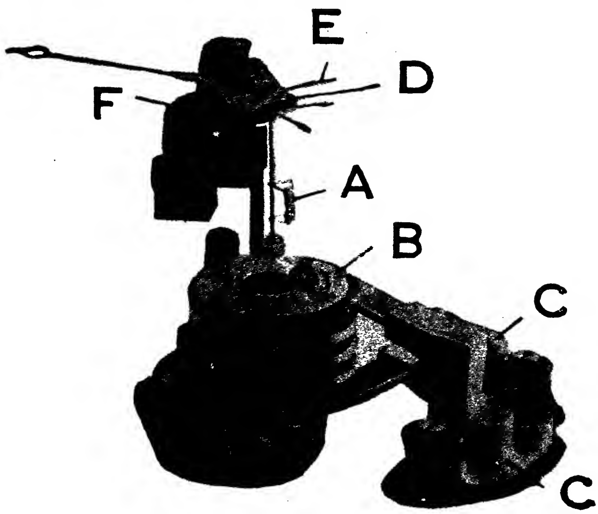
(ii) The Dransfield 3-phase voltmeter is a moving-iron instrument with two coils. The latter have one common terminal and the other ends of the coils are connected through inductance and resistance respectively to the second and third terminals of the instrument. The instrument serves the double function of (*a*) measuring the voltage of a 3-phase system, and (*b*) indicating incorrect connections or phase rotation, or failure of h.t. or l.t. fuses in the circuits of the 3-phase instrument transformer (or two single-phase transformers) which serves the voltmeter itself and also P.F. indicators, watt-meters, etc. Normally the instrument indicates the 3-phase voltage, but its scale is marked with lettered lines to one or other of which the pointer falls back in event of wrong connections or blown h.t. or l.t. fuse in the instrument transformer circuit.

101. Moving-coil Ammeters and Voltmeters.—There are two main types of instruments to be considered under this heading, *viz.* :—

(*a*) Moving-coil, permanent magnet instruments; and
(*b*) Moving-coil, dynamometer type instruments.

The two types have many points of similarity but also important differences (*see also* §§ 89 iii, 94).

(*a*) *Moving-coil, Permanent Magnet Instruments*, commonly called 'moving-coil instruments' for brevity, consist essentially of a fine wire coil so pivoted that it can swing in the intense magnetic field produced in a narrow air gap between a permanent magnet and a soft iron core. The latter is commonly cylindrical, and coaxial with the spindle of the moving coil which has a small clearance between the core inside it and the cylindrically-bored pole shoes of the magnet outside it. The permanent magnet and core are stationary, and the moving-coil is deflected against the



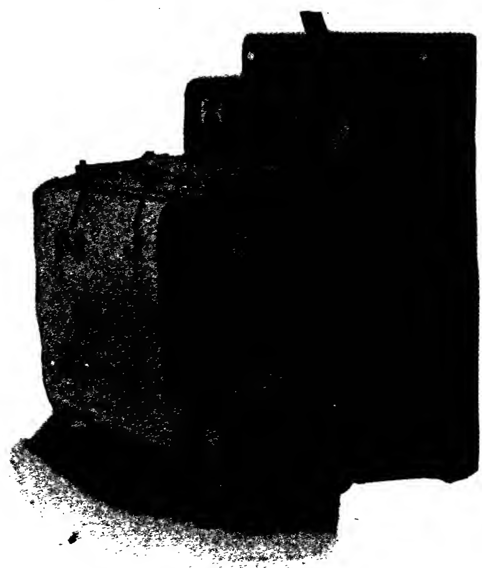
Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF 'SUPERSCALE' MOVING IRON AMMETER FOR 100 A
(Moving element withdrawn from coil for clearness).

The current flows from the terminals C round the copper winding and thus magnetises a fixed piece of iron attached to the regulating lever B. This piece of iron repels another small iron A attached to the pointer spindle, and the movement of the latter is opposed by the spiral spring D, attached to the zero-adjusting lever E. The motion is rendered 'dead-beat' by a pneumatic damper F. Owing to the quality and shape of the iron used, the hysteresis is negligible and the indications with A.C. and D.C. are practically identical.

WORKING PARTS OF THE 'INK-WELL' GRAPHIC RECORDER.

The inking member consists of a capillary tube S, which carries the ink from a fixed central reservoir on to the chart N. The clock K draws the chart at a constant speed of, say 1 in. per hour, by means of the toothed wheel J from the spool H on to the roller L. D is the clock winding lever and Z the zero adjustor. In this instrument the supply of ink is unlimited and the friction between pen and paper is negligible.



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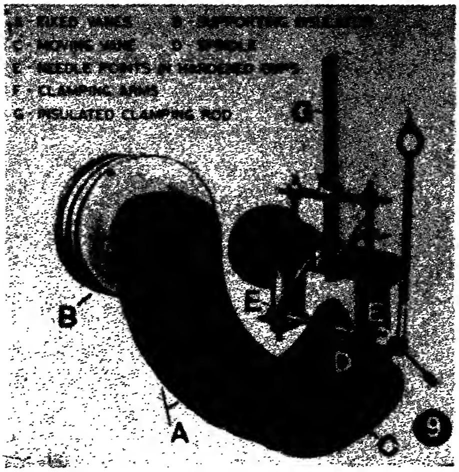
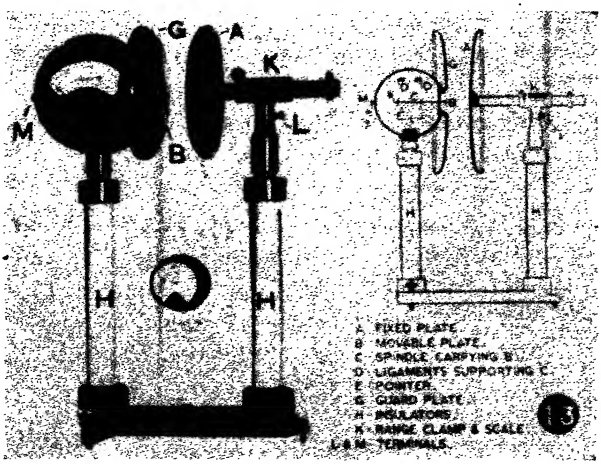


Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF H.T. ELECTROSTATIC VOLTMETER.

The moving vane C is attracted by the fixed vane A, the motion being opposed by a spiral spring. The movement is rendered 'dead-beat' by a pneumatic damper, which has been removed for the sake of clearness. The spindle D has needle points in hardened cups at E. The insulated clamping rod G works in conjunction with the clamping arms F, and the whole is carried by the insulator B. These voltmeters are used direct up to 7 000 V and through series condensers for higher voltages.



Everett, Edgcumbe & Co., Ltd.

WORKING PARTS OF E.H.T. ELECTROSTATIC VOLTMETER (ABRAHAM TYPE).

A movable plate B, within a guard-plate G, is attracted by the fixed plate A, and so carries the pointer over the scale, the movement being damped by a pneumatic device. The spindle C is supported by ligaments D. The instrument is mounted on insulators H; the terminals are at L and M; and K is a range clamp and scale. These instruments are constructed for all pressures up to 300 000 V, and, owing to the absence of any solid or liquid-dielectric (*e.g.* oil), the readings are independent both of frequency and of wave form. All projections are carefully rounded off so as to avoid 'brushing.'

[*To face p.* 155.

control of spiral springs which serve to carry current into the coil. The deflecting force is produced by the current-carrying conductors of the coil and the magnetic field in the air gap (§ 35, footnote). The field in the narrow annular gap is radial and practically uniform, hence the deflecting force is nearly proportional to the current. This being so, and the controlling force exerted by the springs being nearly proportional to the deflection, it follows that the scale is practically uniform in this type of instrument. In the Record 'Cirscale' instruments the same principle is employed, but the construction is modified to increase the scale length. A C-shaped magnet is used, and one pole is provided with two circular-plate extensions between which projects a single similar plate attached to the other pole. There are thus obtained two narrow air gaps between the circular plates, and the moving-coil is pivoted on the line of centres of the interleaved pole plates. The central plate is 'necked' so that the moving-coil can turn through 300° or even 330°.

The moving-coil can accommodate a considerable number of turns of fine wire and the field is very strong, hence the instrument is highly sensitive and the power consumption is low (§ 94). For currents exceeding $\frac{1}{4}$ A or so, ammeters of this type must be shunted (§§ 98, 107). Damping is provided by eddy currents induced in the aluminium 'former' on which the coil is wound. The direction of the deflecting force reverses with the direction of the current, hence these instruments are suitable only for D.C. measurements (see, however, vibration galvanometers, § 96, ii). The intensity of field in the narrow air gap is such that stray fields (§ 92, ii) are of negligible effect. When the instrument is used as a voltmeter the influence of temperature can be eliminated by making the series resistance (§ 98) of manganin or other wire with zero temperature coefficient. In the case of the ammeter no appreciable 'swamping' resistance can be used (the shunt P.D. being limited to 75 mV, § 107*a*), and it is inadvisable to use a copper shunt because the temperatures of shunt and moving-coil may differ considerably. (*See also* § 118.)

(*b*) *Moving-coil, dynamometer-type instruments*, generally called 'dynamometer instruments,' differ from the permanent magnet type in that the stationary field is produced by a pair of coils embracing and connected in series with the moving-coil. The field is no longer constant but varies with the current (or voltage) measured, hence the deflecting force varies with the square of the current and the instrument is equally suitable for D.C. or A.C. measurements, provided that there are no constructional parts in which eddy currents (§ 39) can be induced. The coils have no iron cores, hence the field is relatively weak (§§ 42, 43), and large coils must be used to obtain adequate working forces.* Because the working fields are weak, stray fields introduce serious errors unless the instrument is built astatically (§ 92). The scale is not uniform but, like all square-law scales, crowded at its lower end. In ammeters of this type the main current can generally be taken through the fixed coils, but 5 A is about the maximum for the moving-coil which is therefore generally shunted. If the whole instrument be shunted the field of the fixed coils is reduced unnecessarily. In voltmeters the same current flows through both windings. Because of the many turns required to obtain suitable field strength the pressure drop in dynamometer ammeters is high (§ 94). Ammeters and voltmeters of this type are rarely used outside laboratories.

The *Kelvin ampere balance*, used for current measurements in standardisation tests, has a balance beam carrying a coil at each end. These coils lie between pairs of fixed coils and all the coils are electrically in series. The connections are such that both sets of coils tend to tilt the beam in the same direction and balance is restored by adjusting weights. The deflecting force which is thus 'weighed' is proportional to the square of the current through the coils.

101a. Rectifier Instruments.—Rectifier instruments are now extensively used for the measurement of alternating currents and voltages. A rectifier instrument comprises a copper oxide rectifier and a moving-coil indicator. A copper oxide rectifier unit, which is described in detail in § 417, Vol. 2, is a cold static device comprising a disc of oxidised copper clamped between two discs of lead, which possesses unilateral conductance over a wide range of currents. If such a unit be interposed in an A.C. circuit, it will suppress alternate halves of the current waves. Rectifier units used for A.C. measurements are assembled in a circuit similar to that shown in Fig. 142, Vol. 2, so that both positive

* This objection is overcome, but at the cost of other difficulties and complications, by iron-cored dynamometer-type ammeters, voltmeters, and watt-meters (§ 109).

and negative waves of current pass through the moving-coil indicating instrument in the same direction. The current in the indicator is thus graphically represented as shown in Fig. 2, § 13. The torque developed by a rectified current in a moving-coil instrument is proportional to its average value, so that a rectifier instrument used in an A.C. circuit must be scaled to indicate 1·11 times the value which would be indicated by a direct current, because the R.M.S. value of an A.C. is 1·11 times its average value, § 30. The ratio of R.M.S. to average value, known as the form factor, varies with the shape of the current wave, and if this wave shape be distorted the form factor may be greater or less than 1·11, and the instrument will indicate R.M.S. values incorrectly.

The impedance of a rectifier voltmeter comprises that of the series resistance and that of the rectifier unit. The resistance of a rectifier unit varies with the current it carries, increasing as the current diminishes. If the series resistance is high, relative to that of the rectifier, the instrument current will always be approximately proportional to the voltage. The scale of a high range rectifier voltmeter is therefore uniform. For low voltage ranges the scale tends to be contracted near the zero point. At an applied pressure of about 0·4 V a copper oxide unit loses its rectifying property and forward and reverse resistances become approximately equal. Rectifier millivoltmeters are not therefore available.

In rectifier ammeters the current to be measured is transformed by a self-contained current transformer, the instrument current for full scale deflection being of the order of 50 mA. Due to the variable resistance of the rectifier units, a rectifier ammeter cannot be shunted across its terminals without alteration of the scale shape.

102. Induction Ammeters and Voltmeters.—These instruments depend upon transformer action and will therefore only read in AC circuits, and their fundamental characteristic depends upon the production of two alternating magnetic fields displaced both in space and in phase. A pivoted disc is cut by both fields, and the operating torque on the disc can be considered as being due to the interaction of one of the fields on the spatially unsymmetrical eddy currents induced in the disc by the second field (§ 39). The torque is proportional to the product of the magnitudes of the fields and the sine of the angle of phase difference between them. Induction instruments may be considered as analogous to those of the dynamometer type, the current in the moving element being conveyed by induction or transformer action instead of by conduction through ligaments. There are two methods of producing the component magnetic fields. In the shaded pole type of instrument one half of each pole of the electromagnet is encircled by a copper band, and the result of the currents induced in the band is to cause a phase lag of the flux threading it. In the transformer type of instrument the lagging component of the magnetic field is produced by a secondary winding in which current is induced by the main winding by transformer action.

Induction instruments are rugged and simple, and they can easily be provided with long scales (say 330°). They are admirable for switchboard service, but not for general testing work because the torque varies with frequency and wave form. In voltmeters the effect of frequency is less marked than in ammeters because the change in impedance (§ 44) of the inductive circuit of the former compensates to some extent for the change in torque. Error due to stray fields is not likely to be serious, but the temperature error (§ 92) is considerable due to change in resistance of the parts in which the eddy currents are induced.

103. Electrostatic Voltmeters.—The force of electrostatic attraction between plates or vanes at different potential is proportional to the square of the P.D. between them, but is so small that, for low and medium voltages, the mechanical construction of an electrostatic voltmeter must be so delicate that the instrument is not suitable for commercial service. With higher voltages, however, the operating forces become so great that a relatively robust construction can be employed. Also, at such voltages, the insulation problem is simpler in electrostatic voltmeters than in other types. For low-voltage measurements a number of vanes are mounted one below the other on a common spindle and attracted by an equal number of pairs of fixed plates or 'cells.' The P.D. to be measured is connected between the vanes and the fixed cells. Since the deflecting force varies with the square of the voltage the instrument is equally applicable to D.C. and A.C. circuits (§ 89 *b*). The indications are independent of temperature, frequency, wave form, and stray magnetic fields, but error is introduced by stray electrostatic fields, unless the instrument is suitably screened.

For high-voltage measurements (from 10 000 to 200 000 V) the attraction between two parallel plates is sufficient to operate the indicating mechanism. One plate consists of a large stationary disc, the other of a smaller disc surrounded by a 'guard ring' which is of the same outside diameter as the fixed disc; the object of this arrangement is to secure a uniform field between the fixed and moving discs. The range of measurement may be increased by increasing the distance between the discs. (*See also* § 107*c*.) If the plates be submerged in oil the range and sensitivity are increased, because the operating force increases with the specific inductive capacity (§ 46) of the dielectric, and the dielectric strength of oil is greater than that of air, hence higher voltages may be used or, alternatively, a smaller gap (giving greater sensitivity) may be used for a given voltage. For laboratory measurements up to 250 000 V compressed nitrogen (§ 78) at a pressure of 10-12 atmospheres has been used as dielectric in electrostatic instruments. In all cases a high resistance should be connected in series with the instrument to limit the current flow in event of flash-over; otherwise the instrument may be destroyed before the protective fuses melt. Series resistance has no effect on the indication of an electrostatic voltmeter, because there is no appreciable current flow (§ 89 iv). The fact that no current flows through these instruments is of economic importance where high voltages are concerned, because even 10 mA corresponds to 1 kW at 100 000 V (unity P.F.).

See also current measurement by electrostatic voltmeter (§ 89 iv); charge indicators (§ 104); leakage indicators (§ 553, Vol. 2; § 1037, Vol. 3); and electrostatic oscillographs (§ 118).

104. Electrostatic Charge Indicators.—These are essentially electrostatic voltmeters (§ 103) without pointer or scale. The moving vane has a red spot or line which is normally hidden, but which shows behind a sighting aperture when the indicator is applied to a 'live' conductor. A calibrated electrostatic voltmeter could be used for the purpose (with the advantage of actually measuring the P.D. between conductors or between conductor and earth), but simple uncalibrated devices can be made strong, cheap, and easily portable. For use in detecting live wires, want of continuity, leakage, etc., in D.C. or A.C. systems at from 80 to 700 V between conductors or to earth, there is on the market a device about the size and shape of a lead pencil. A metal point and casing at opposite ends of the device are connected respectively (in series with a high internal resistance) to a fixed electrode and an adjacent flexible vane; the latter is attracted and shows a warning signal when there is a P.D. between the terminals. For high-voltage circuits a testing point connected to a combination of fixed and moving vanes (mounted on an insulating handle) is brought into contact with the conductor to be tested; if the latter be live the vanes are charged similarly and the moving vane is repelled. Another device depends upon the attraction of a balanced vane by a live high-voltage conductor; this device can be used without making electrical contact with the conductor. Yet another detector, depending on a different principle (static sparking) is described in *El. Rev.*, Vol. 90, p. 752.

104*a*. **Klydonograph.**—The klydonograph records the polarity and measures the magnitude of voltage surges on transmission systems by photographing the Lichtenberg figures produced by electrodes connected to the line conductors. The original Lichtenberg figures were produced by discharging a Leyden jar through a needle point on to a plate of insulating material, which was then dusted with a mixture of red lead and flowers of sulphur. The sulphur adhered to the positively, and the red lead to the negatively, charged areas of the plate. A positive discharge on to the plate resulted in the formation of a yellow patch with radiating streamers; and a negative discharge caused the retention of a smaller, well-defined red disc without streamers. The klydonograph works on the same principle, but a permanent record is obtained, more conveniently and accurately, by using a photographic plate resting on an earthed electrode, the recording electrode being a disc placed on the emulsion and connected to the line. The figure produced by a surge has a distinctive form, according to the polarity, and the diameter of the figure is a measure of the crest voltage. The size of the figures for given voltage increases as the air pressure is reduced.

The apparatus can be arranged for continuous recording on a daylight-loading roll film, and it is calibrated by applying surges of known voltage. The calibrations for the positive and negative figures are different. Normally, the record is independent of the steepness of the wave front, but by taking the direct record in conjunction with that of a record instrument shunted across a high impedance in an auxiliary circuit, the steepness of the wave front can be deduced.* Important advantages of the klydonograph are its rapidity of action compared with sphere gaps, and its simplicity compared with cathode ray oscillographs.

105. Spark Gap Voltmeters.—With given electrodes and dielectric, there is a definite relation between voltage and the length of gap that it will break down. On reducing the gap length until the first spark passes, the value of the voltage can be read from a calibration table (§ 78) or curve, or a pointer moving with the adjustable electrode may indicate the voltage on a graduated scale. The break-down depends upon the *maximum* value of the voltage (§§ 30, 72)—hence the name ' crest voltmeters '—but if the wave form be sinusoidal or of other known form the instrument can be calibrated in R.M.S. values. For insulation tests (§ 30) and in X-ray work, however, it is the peak value of the voltage wave which is to be measured. The use of spark gap voltmeters is limited to high pressures (say over 10 kV); D.C. or A.C. pressures can be measured, but the calibration is different in the two cases.

Air is generally used as dielectric between the electrodes because it is self-repairing and is of lower dielectric strength than oil (*i.e.* greater sensitivity is obtained, the gap for given P.D. being greater). Ionisation of air, produced by sparking or by an electric arc, reduces the dielectric strength, hence a spark gap voltmeter must not be used near an arc lamp, and the gap length across which the *first* spark passes must be taken as determining the voltage. Up to 30 000 V needle electrodes should be used (these work at greater gap lengths for given voltage), but for higher pressure spherical electrodes give results which are less affected by frequency, wave form, and atmospheric conditions. The diameter of the spheres must be large enough to prevent corona or brush discharge preceding the spark, otherwise the air is ionised and the relation between gap length and voltage becomes quite erratic. A table of R.M.S. voltages from 10 to 400 kV and

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* For further information on the characteristics and applications of these instruments, see *El. World*, 83, p. 769; *El. Rev.*, 94, p. 770; *Jour. Amer. I.E.E.*, 44, p. 1094; 46, p. 459; *Siemens Zeits.*, 9, p. 368, with a full bibliography; *Jour. I.E.E.*, 68, p. 1476; *E.T.Z.*, 54, p. 627.

corresponding gap lengths between spheres from 62·5 mm. to 500 mm. diameter is given, together with particulars of corrections required, in B.S.I. Report No. 137.

Crest voltages can be determined, often more conveniently and generally with at least equal accuracy, by an oscillograph or by the point-by-point method (§ 118).

106. Testing Sets.—There are a number of useful portable testing sets on the market which are both accurate and handy. They may be used either for checking other instruments or for making measurements where no others are provided. Typical sets have two moving-coil millivoltmeters (§ 101) generally reading from zero to 150, the scale reading being multiplied by one or other of several factors according to the range employed. This type of instrument is suitable only for D.C. measurements. A single moving-coil instrument can be used for both pressure and current measurements (§ 98), but it is more convenient to have two instruments as this simplifies connections and makes possible simultaneous readings of pressure and current, and thus calculation of D.C. power (§§ 50, 54).

For volt measurements the case contains a subdivided resistance coil (§ 95), of about 60 000 Ω resistance, which can be connected across the pressure to be measured. There is a positive terminal V + attached to one end of the coil, and negative terminals V −, for 1·5, 15, 150, and 600 V, respectively, attached to suitable points on the resistance coil, so that the pressure can be read off directly.

For current measurements, standard resistances (§§ 20, 95) are connected in series into the circuit (*not* across it) and the drop in pressure across the resistance is actually measured, as explained in § 95; the usual ranges are 1·5, 15, 150, and 600 A, and the instrument reads directly in amperes in the three lower ranges. The flexible connecting leads supplied with these instruments, or others of exactly the same resistance, must be used for current measurements; otherwise the readings will be incorrect.

Resistance measurements can sometimes be made conveniently by noting corresponding values of P.D. and current, but the ohmeter in one of many forms is often preferable; both methods are dealt with below in § 119; in other cases the testing set includes a Wheatstone bridge (§ 120).

Similar testing sets with hot wire or electrostatic instruments could be used for D.C. or A.C. measurements, but these instruments are not suitable for portable service (§§ 99, 103). Methods of measuring A.C. power are described in §§ 109, 110.

107. Extending the Range of Instruments: Shunts and Potential Dividers.—The current which can safely be passed through an ammeter of other than the moving iron type (§ 100) is generally limited to a few amperes and sometimes to a fraction of 1 A. Much heavier currents (up to, say, 20 000 A) can be measured by passing through the instrument a definite fraction of the total current; this fraction is obtained by a shunt, or, in the case of A.C., by a current transformer (§ 108). The scale is calibrated in main-current values, unless the instrument is to be used with different shunts, in which case the indication must always be multiplied by the appropriate factor.

Similarly, the range of a voltmeter can be extended almost indefinitely by applying to the instrument a definite fraction of the total P.D. (obtained by a volt box, § 95, or a potential transformer, § 108), or by connecting a suitable resistance in series with the instrument. Condensers can be used with electrostatic instruments as explained below.

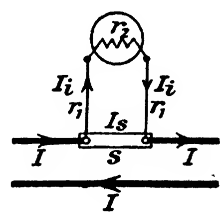

FIG. 14.—Shunted ammeter.

(*a*) *Shunts.*—Referring to Fig. 14, if an ammeter of resistance r_2 Ω be connected, by two leads each of resistance r_1 Ω, to the terminals of a 'shunt' of resistance s Ω, the pressure drop in the instrument circuit equals that in the shunt. Denoting the total resistance of the instrument circuit by $R = 2r_1 + r_2$, we have: Pressure drop in instrument circuit $= I_iR$ (§ 24) $= I_ss$ (the pressure drop in the shunt). Therefore $I_s = I_iR / s$. The 'multiplying power' of the shunt (= main current / instrument current) $= I / I_i = (I_i + I_s) / I_i = \left(I_i + \frac{I_iR}{s}\right) / I_i = 1 + \frac{R}{s} =$ say, n. Hence, if the multiplying power is to be n (generally 10 or a decimal multiple thereof): $\frac{R}{s} = n - 1$ and $s = \frac{R}{(n-1)}$, *i.e.* the resistance of the shunt must be $\frac{1}{(n-1)}$ times the resistance of the instrument (including its leads).

In order that the multiplying power of the shunt may not vary R and s must be constant or they must vary always in the same ratio. If both branches consisted only of copper, the ratio R/s would be constant if the temperature of shunt and instrument were always the same; this cannot be guaranteed, hence it is usual to make the shunt of manganin and to 'swamp' the copper in the instrument circuit by using as much manganin as possible in this branch (§§ 92 i, 98).

The actual resistance, s, of the shunt should be low in order that the energy dissipated in it ($I_s^2 s$ watts, § 49) may be low. The pressure drop, $I_s s$, must, however, be sufficient to operate the instrument satisfactorily, and British Standard values for this drop (at rated current) are: 0·075 V for first- and second-grade indicating instruments (§ 92); 0·2 V for recording instruments; and either 0·000 5 or 0·001 V per scale division for indicating sub-standard instruments, of the moving-coil, permanent magnet type (§ 101a) in each case. For instruments of other types the P.D. across the shunt at rated current may not exceed 1 V. The total resistance of the leads in series with the instrument across the shunt should not exceed 0·05 Ω for portable instruments and 0·025 Ω for switchboard instruments at 20° C. The material and construction of the shunt and instrument leads should be such that alteration in instrument indication, due to thermoelectric E.M.F. (§§ 122b, 129) does not exceed 0·25 %. The temperature rise of a shunt when carrying rated current for 2 hrs. should not exceed 80° C. Best ventilation for laminated shunts is generally obtained by mounting with the terminals in line horizontally and the plane of the plates vertical. (*See also* B.S.I. Reports 89 and 90; and 'Multiple-Unit Shunts for the Measurement of Very Heavy Currents,' by M. B. Field, *Jour. I.E.E.*, Vol. 58, p. 661.)

(b) *Magnetic Shunts* are used in some supply meters and in some moving-coil indicating instruments as a means of adjusting the active magnetic field and so providing for fine adjustment of the 'law' of the instrument. A piece of soft iron of relatively small section bridges the main air gap more or less completely, and thus provides a shunt path for some of the magnetic flux.

(c) *Potential Dividers.*—(i) *Volt Box.*—The principle of the 'volt box' has already been explained in § 95. As there noted, the uniform potential gradient in a uniform, non-inductive resistance connected across the voltage to be measured, is not disturbed if an electrostatic instrument be connected across part of the resistance; neither is the gradient disturbed appreciably if an instrument be used which is of very high resistance, compared with the section of the volt box across which it is connected. In any case the total resistance of the volt box must be high, otherwise the power consumption therein becomes excessive. This method of extending the range of a voltmeter is applicable to both D.C. and A.C. instruments, but in practice series resistance (see (*d*) below) is generally used for D.C. voltmeters and potential transformers (§ 108) for A.C. instruments.

(ii) *Condensers.*—The range of an electrostatic voltmeter (§ 103) can be extended by connecting a condenser in series with the instrument. The P.D. applied to two condensers connected in series is divided between these in *inverse* proportion to the capacities of the condensers; hence if the P.D. across an electrostatic instrument is to be made a small fraction of the total P.D. the instrument must be connected in series with a condenser the capacity of which is much smaller than that of the electrostatic instrument. This is a matter of practical difficulty, because the capacity of the instrument is very small and changes with the position of the vanes. An alternative method is to connect several relatively large condensers in series across the mains and to connect the electrostatic instrument in parallel with one of these. This arrangement is the electrostatic equivalent of the volt box and the small capacity of the instrument does not affect appreciably the potential gradient in the chain of condensers across part of which it is connected. Even the smallest leakage currents make the readings vary with frequency.

(*d*) *Series Resistance.*—As explained in § 98, any ammeter can—subject to certain practical considerations—be used as a voltmeter by connecting a suitable resistance in series with it. The range of the instrument can be increased by increasing the series resistance.

Example.—Suppose that, in Fig. 14, $r_1 = 0{\cdot}025\ \Omega$ and $r_2 = 1{\cdot}5\ \Omega$, and that the instrument gives full scale deflection when the shunt P.D. $= 0{\cdot}\,075$ V. Then: Current through instrument for full scale deflection $= 0{\cdot}\,075 / (2 \times {\cdot}025 + 1{\cdot}5) = 0{\cdot}\,075 / 1{\cdot}55 = 0{\cdot}\,048\,5$ A. If this instrument is to be used as a voltmeter measuring up to v volts it must be connected in series with a resistance R such that $v / (R + 1{\cdot}5) = 0{\cdot}\,048\,5$. If $v = 220$ V, we have: $220 / (R + 1{\cdot}5) = 0{\cdot}\,048\,5$, whence $R = 4\,534{\cdot}6\ \Omega$.

An ammeter of resistance $r\ \Omega$ reading i amperes per scale division will read 1 V per scale division when connected in series with a resistance $R = (1 - ir) / i$ ohms.

Hot wire, moving iron, and moving-coil voltmeters (§§ 99-101) are operated by a current which is proportional to the voltage to be measured. The full scale deflection corresponds to a particular value of this current, and in order to extend the voltage range it is only necessary to connect in series with the instrument such a non-inductive resistance that the higher voltage sends the full-scale current through the combined resistance of the instrument and series resistance. The range of the voltmeter is multiplied by n if the instrument be used in series with a resistance $= (n - 1)$ times its own resistance.

Electrostatic voltmeters, however, depend upon the potential of the vanes (§ 103), and this is unaffected by series resistance,* hence the range of these instruments *cannot* be increased by series resistance (*see*, however, § *c* (ii) above).

108. Instrument (Voltage and Current) Transformers.—Instrument transformers are used with A.C. indicating, recording, and integrating measuring instruments and with relays and automatic devices of various descriptions when the main current is too heavy and/or the main pressure too high to allow direct connection between the instrument, etc., and the main circuit They are applicable only to A.C. circuits. The transformer windings are electrically distinct (auto-transformers (§ 396, Vol. 2) may *not* be used), the primary being connected with the main circuit and the secondary with the instrument, etc. Instruments used with current or potential transformers should be calibrated with them, the scale being marked to show the main circuit values of current, voltage, power, etc. The use of these transformers permits instruments to be lighter in mechanical construction and electrical insulation than would otherwise be possible; accuracy and safety are enhanced, and a standard type of instrument can be used for measurements over a very wide range. About 600 A and 750 V are the extreme limits for direct-connected ammeters and voltmeters (excepting electrostatic instruments, § 103). By the use of instrument transformers high voltage is excluded from

* There being no current flow, there is no pressure drop in the series resistance.

the instrument circuits,* and the main current (and its field and eddy currents induced thereby) is kept away from the instrument. For example, a low-pressure wattmeter can be used with current and potential transformers to measure power in a high-voltage circuit.

(ii) In current transformers a low-resistance primary winding of one or a few turns is connected in series with the main circuit, and a secondary winding with a greater number of turns supplies a correspondingly reduced current to the instrument circuit. The secondary may be threaded directly on to the main circuit conductor itself which then forms, in effect, a single turn primary. If the secondary circuit is to be opened whilst the main current is flowing, the secondary terminals of the transformer should first be short-circuited, otherwise a dangerous P.D. may be produced between them when the circuit is opened.

(iii) Voltage transformers are step-down transformers, the secondary winding consisting of a few turns whilst the primary is a high-resistance winding of many turns connected between the main-circuit conductors.

The ratio of an instrument transformer is the ratio of the number of primary to secondary turns and is expressed by stating the corresponding values of primary and secondary current or pressure as the case may be. Thus a 5 000 / 5 current transformer is one rated for 5 000 A primary, and 5 A secondary current; and a 6 600 / 110 potential transformer is one which yields 110 V secondary voltage when connected to 6 600 V supply.

The percentage difference between the actual and normal ratios of primary to secondary quantities in terms of the normal ratio is known as the ratio error. The angle of phase difference between the primary and secondary quantities is known as the phase error, leading or lagging according to the phase of the secondary output.

The output of an instrument transformer is known as the

* If the main circuit is at high potential, the insulation problem is transferred from the instrument to the instrument transformer where it is more easily dealt with but still remains of vital importance. By earthing the secondary circuit danger of shock is eliminated, but serious interruption of service may result if the transformer insulation fails. The insulation difficulty is particularly great in potential transformers the primary winding of which, consisting of many turns of fine wire, is subjected to the full P.D. between phases. Potential transformers constitute one of the weakest features in a modern h.t. installation.

burden, and is expressed in volt amperes when the primary voltage or current has its rated full-load value. Thus a voltage transformer delivering 0·5 A at 110 V, has a burden of 55 VA. Again, if the secondary voltage of a current transformer at half the rated full load is 1 V, 2·5 A, this would become 2 V, 5 A at full load, and the burden would be stated as 10 VA. The burden of an instrument transformer depends upon the impedance of the secondary circuit, and can be stated in ohms, but the standard conventional method is in VA at the full-rated current or voltage. The actual physical secondary circuit, instruments and connecting leads of an instrument transformer is sometimes termed the burden.

In a voltage transformer ratio and phase errors are governed by the same principles as determine the regulation of power transformers (§ 392, Vol. 2) and are due inherently to internal voltage drop set up by the transformer impedance. These errors therefore increase as the secondary output is increased. The errors of a current transformer are due to the fact that a fraction of the primary current is used to magnetise the core and is not transformed. This fraction, for a given value of the primary current, increases as the impedance of the secondary circuit increases, since a higher secondary voltage is required, with a proportional increase of the core flux. Current transformer errors can therefore be reduced by making the secondary impedance as small as possible.

The untransformed fraction of the primary current of a current transformer required to produce a given secondary voltage depends upon the permeability of the core (§ 43). The accuracy of current transformers has of late years been vastly increased by the use of nickel iron alloys which have high permeability at low flux densities (§ 82).

When the current from a current transformer energises a wattmeter, the phase error of the transformer will modify the phase difference of the current and voltage in the instrument, and will give rise to an error depending on the power factor of the circuit. This error, expressed as a percentage, is equal to $a \tan \phi$, where $\cos \phi$ is the power factor, and a the phase error in centi-radians (57·3 centi-radians $= 1°$). Phase errors of instrument transformers do not affect current or voltage measurements.

Due to the effect of secondary impedance (burden) on the errors of instrument transformers, the advice of the makers should be sought in the design of an instrument transformer for the instruments it will have to supply.

Standard ratings and classes of instrument transformers with the corresponding limits of ratio and phase error are given in B.S.S. No. 81, 1936. The usual secondary voltage of a voltage transformer is 110, and the full load current of a current transformer is 5 A, although 1·0 and 0·5 A secondaries are sometimes used. For further particulars the Specification should be consulted.

British Standard *current transformers* (B.S.S. No. 81) are wound to give 5 A secondary current with rated primary current, there being 23 standard ratios from 5 / 5 to 5 000 / 5 A. The two standard sizes of current transformers have rated outputs of 15 VA and 40 VA respectively at 50 cycles per sec. At these outputs the maximum permissible ratio error is ± 1 % and phase error 2° when the primary current is not less than one-fifth the rated value.* When selecting a current transformer one should be chosen with a primary current rating high enough to avoid destruction of the primary winding before the circuit is opened in event of short circuit, but not so high as to reduce abnormally the accuracy of measurement on normal loads.

In British Standard *voltage transformers* the secondary pressure is 110 V when rated voltage is applied to the primary, and there are 12 standard ratios ranging from 110 / 110 to 33 000 / 110 V. The three standard sizes have rated outputs of 15, 50, and 200 VA per phase. At 110 V and approximately unity P.F. in the secondary circuit the maximum permissible ratio error is 1 % and phase error ½° at rated or lower output. (*See also* B.S.S., *loc. cit.*)

Additional notes on instrument transformers are given in § 384.

108a. D.C. Measuring Transformer.—In most applications, heavy direct currents can be measured satisfactorily by means of shunts (§ 107), using a sensitive voltmeter (calibrated in amperes) to measure the P.D. across a known low resistance traversed by the current to be measured. Where very heavy direct currents are concerned, as in some electro-chemical applications, more or less difficulty is experienced in keeping within permissible limits of calibration—and temperature—error. In such cases, use may be made of a D.C. 'transformer' consisting of a ring of iron encircling, and therefore magnetised by, the conductor carrying the current to be measured. The iron ring is cut to accommodate a wound armature connected to a measuring instrument and driven by a constant-speed motor. It is claimed † that this arrangement permits a direct current of 30 000 A to be measured by the deflection of a 5 A instrument, accurately within about +0·2 to −0·8 %

* The phase error is likely to exceed 2° in single-turn primary transformers unless the primary current is at least 800 A or 1 200 A for the 15 VA or 40 VA transformer respectively.

† O. E. Nölke, *Elekt. Zeitschrift*, Vol. 57, p. 37.

without, or within + 0·2 to − 0·4 °/$_{o}$ with temperature correction. A further advantage claimed is equal applicability to the measurement of rapidly fluctuating D.C. or D.C. with superimposed A.C.

109. Wattmeters.—The majority of wattmeters are of the dynamo-meter or induction type (§§ 101 *b*, 102). The main current (or a definite fraction thereof obtained by shunt or current transformer, §§ 107, 108) is passed through the stationary coil which is of low resistance, and the main voltage (or a fraction thereof) is applied to the moving coil circuit which is of high resistance. The deflection of the instrument, against the torque of the control spring, varies with the product current × voltage, *i.e.* watts (§ 48). In order to appreciate that an instrument of this type can be used also to measure A.C. power, and to understand the conditions which must be fulfilled when so doing, it is necessary to consider the basic formulæ relating to A.C. power. This is done in § 110, and from the results there obtained it will be seen that, since a dynamometer-type wattmeter measures the mean product of pressure by current, it takes into account phase difference between the two, and it is suitable in principle for measuring A.C. power at any frequency and power factor. Actually, however, the inductance of the pressure coil causes the current in this coil (and therefore the field produced) to lag behind the applied voltage. From this cause the phase angle between the fields of the wattmeter coils is less than that between the main pressure and current,* and the instrument then tends to read 'high.' On the other hand, eddy currents induced in the fixed (current) coil cause its field to lag behind the main current, thus increasing the phase difference between the two fields of the instrument. The two sources of error compensate each other to some extent, but the extent to which this occurs depends on the characteristics of the instrument and on the main circuit P.F. If the inductance of the pressure coil be high the current in that coil will be lower than it is assumed to be, and if instrument transformers be used their ratio and phase errors (§ 108) introduce errors in power measurement. Complete investigation of the accuracy of A.C. power measurements is thus a complex problem, and the risk of error may be great if the P.F. of the load measured be lower than 0·5.

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* Assuming that the main-circuit current *lags* behind the voltage; if the main current be *leading* with regard to its voltage, inductance in the pressure coil of the wattmeter tends to make the instrument read 'low.'

(ii) The *Duddell-Mather wattmeter* is a dynamometer-type instrument designed for precision measurements. Its principal features are: (1) The elimination of all unnecessary metal to prevent the induction of eddy currents. (2) For the same reason the fixed coils are composed of insulated strands of fine wire; these can be connected in various ways to alter the range of the instrument. (3) There are two pairs of fixed coils and two pairs of moving coils arranged astatically (§ 92). (4) Readings are taken by observing on the 'torsion head' the rotation of the control spring required to bring the moving system back to the zero line. This instrument is equally suitable for D.C. and for A.C. of any frequency up to 350 cycles per sec. It can be used to measure A.C. power at very low P.F., *e.g.* the dielectric loss in cables the P.F. of which is about 0·02 (§ 312).

The remarks made in § 101*b* concerning the weak field of dynamometer-type ammeters and voltmeters apply also to wattmeters of this type. If the coils be provided with iron cores, the fields are greatly increased (§ 43) and greater working forces can be obtained. This is particularly desirable where recording instruments (§ 93) are concerned. The use of iron cores in D.C. wattmeters is subject only to the objection that hysteresis errors are introduced (§§ 34, 100), but in A.C. wattmeters the errors of the ordinary air-core dynamometer wattmeter—particularly the phase errors—would be prohibitive if the coils were simply provided with iron cores. Specially arranged *iron-cored wattmeters* have been devised by Drysdale, Sumpner, and others for use on A.C. circuits.*

(iii) *Induction wattmeters* can be used only for A.C. power measurements. The principle employed by these instruments is identical with that of induction ammeters and voltmeters (§ 102), except that the two fluxes are produced, the one by the voltage and the other by the current of the circuit. The pressure flux must lag 90° on the voltage producing it, as the sine of the angle of phase difference between the fluxes is then sin $(90 - \phi)$ or cos ϕ, and the torque is proportional to IV cos ϕ, or to the true-power, at all power factors (§ 102). These instruments are very suitable for use on switchboards.

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* For details see *Industrial Electrical Measuring Instruments*, by Edgcumbe and Ockenden (Pitman).

The measurement of 'wattless power' is discussed in §§ 110, 116.

110. Power and Energy Measurement in A.C. Circuits.—As explained in § 29, the *average* value of an alternating current or pressure is zero, and the effective value of the wave is the *root mean square* (R.M.S.) ordinate. The instantaneous power in a single-phase A.C. circuit equals the product of the corresponding instantaneous values of pressure and current, and if the pressure and current waves are not in phase the power curve is an alternating wave (§ 56). Whereas a negative (reversed) current is exactly equivalent to a positive current as regards heating (§ 29), a negative value of instantaneous power means that power is being returned to the supply circuit. It is therefore the *average* (and *not* the R.M.S.) value of the power wave which is the measure of its effective value. It can be shown that the average value of the power is given by—

(i) *Single-phase Circuits*—

Average power = R.M.S. volts × R.M.S. amperes × Power factor,

i.e. $W = EI \cos \phi$.

(ii) *Three-phase Circuits* (if symmetrical and balanced)—

Average power = $\sqrt{3}$ × R.M.S. volts between phases × R.M.S. amperes per phase × Power factor,

i.e. $W = \sqrt{3}\, EI \cos \phi$.

In a dynamometer type wattmeter (§ 109) the torque on the moving system is at every moment proportional to the instantaneous value of the power and may be negative during part of the cycle. The inertia of the moving system causes it to take up the position corresponding to the mean value of the torque and thus to indicate the average power.

(2) *A.C. Wattmeter Connections.*—The connections for a *single-phase* wattmeter are identical with those for a D.C. wattmeter. The common terminal of the pressure and current coils should be on the supply side (*see* Fig. 15). The power indicated is then greater than that supplied to the load by the amount of power expended in the current coil, but this is of little practical importance. If the pressure coil were connected on the load side of the current coil the power indicated would be greater than actually supplied to the load by the amount of power expended in the

pressure coil. This again is of little importance in commercial power measurements, but if a watt-hour meter be connected in this way, it will record continuously the energy consumption of the pressure circuit; there is necessarily an expenditure of energy in the pressure circuit so long as the instrument is connected to the supply, but this is not charged to the consumer if the meter

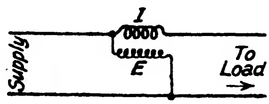


FIG. 15.—D.C. or single-phase A.C. wattmeter.

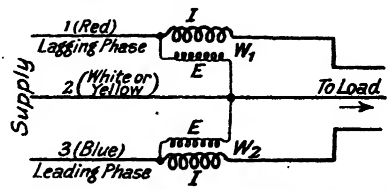


FIG. 16.—Measuring 3-phase power (balanced or unbalanced load) in 3-phase, 3-wire circuit by two wattmeters.

be connected as in Fig. 15 because the current for the pressure coil does not then pass through the current coil.

Alternative methods of measuring 3-*phase power* are represented in Figs. 16-18, the conditions applying to each being stated below the diagrams; these methods are applicable also to watt-hour meters (§ 115). The *two-wattmeter method* is applicable to balanced or unbalanced loads in 3-phase, 3-wire circuits. The current coils of two wattmeters are connected in two of the

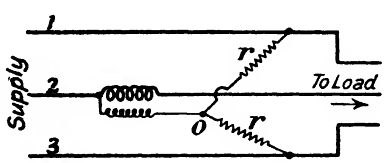


FIG. 17.—Measuring 3-phase power (balanced load) in 3-phase, 3-wire circuit by one wattmeter.

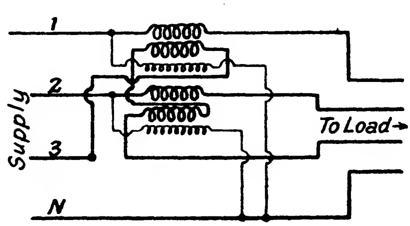


FIG. 18.—Measuring 3-phase power (balanced load) in 3-phase, 4-wire circuit by two wattmeters.

phase conductors (directly or through instrument transformers, §§ 107, 108), and the pressure coils are connected between these phases and the third phase. The total power supplied to the load is the algebraic sum of the readings of the two wattmeters.

If the line currents and line voltages are balanced $\sqrt{3}$ times the difference of the wattmeter readings is equal to the reactive component of the 3-phase volt amperes (§ 110*a*). Thus, if the instrument readings are W_1 and W_2, then the following rules apply:—

$W_1 + W_2$ is equal to the total watts in all conditions, $\sqrt{3}(W_1 - W_2)$ is equal to the reactive VA if the load is balanced. The ratio of reactive VA to watts is equal to $\tan \phi$, where ϕ is the phase difference of current and voltage.

Thus $\tan \phi = \sqrt{3}\dfrac{W_1 - W_2}{W_1 + W_2}$ for balanced loads.

Having calculated $\tan \phi$, $\cos \phi$ can be found from tables. The power factor $\cos \phi$ can be calculated direct from the formula

$$\cos \phi = \frac{m + 1}{2\sqrt{m^2 - m + 1}},$$

where $m = W_1 / W_2$.

If the power factor be less than 0·5 one wattmeter will reverse and its connections must be interchanged in order to obtain a positive reading; the *difference* between the readings of the two instruments is then the power supplied to the load.

Instead of using two independent wattmeters, two wattmeter elements may be mounted on a common spindle. The resultant deflection is then the algebraic sum of W_1 and W_2 provided that the connections are correct. Where a two-element wattmeter or watt-hour meter is used the reactive VA can be determined by reversing the voltage connections to one element.*

In a *balanced* 3-phase system the power (or energy) can be measured by a *single wattmeter* (or watt-hour meter) by connecting the current coil in one phase and the pressure coil between that phase and the neutral. This measures the power in one phase, and the total power is three times as great. If the neutral is not available an 'artificial neutral' can be obtained by connecting two resistances of suitable value as in Fig. 17; the relation between these resistances and the impedance of the pressure coil must be such that O is the true neutral point. Alternatively, the current coil may be excited by current transformers in two phases

* Where two *separate* watt-hour meters are used to measure the energy consumption of a balanced load it is possible to calculate the P.F. by the formula given above, or, if one of the instruments fails to register, it is possible to calculate what its record should be from the reading of the other meter, provided that the average P.F. is known.

connected differentially, the pressure coil being connected across these two phases.

The power in a 3-*phase, 4-wire circuit* unbalanced load can be measured by three wattmeters, each instrument having its current coil in one phase conductor and its pressure coil between that phase and neutral. If, however, the sum of the phase to neutral voltages is always zero the connections shown in Fig. 18 may be used. This arrangement resembles the 2-wattmeter method (Fig. 16), but the two pressure coils are connected to the neutral, and each of the current coils is opposed by a current coil connected in the phase which has no pressure coil.

110*a*. Reactive Measurements; 3-phase kVA and Power Factor.—It has already been explained in § 55 that the power W in an A.C. circuit is usually less than the volt amperes, VA. An important conception is that the VA can be resolved into two components, one, the watts W, and the other which is wattless and is called the reactive volt amperes. The symbol for reactive volt amperes is VAr. The relation between these components is given by the relation $VA = \sqrt{W^2 + (VAr)^2}$. As the ratio W / VA is usually equal to $\cos\phi$, $\frac{VAr}{VA} = \sin\phi$, and $\frac{VAr}{W} = \tan\phi$. Geometrically W, VAr and VA are represented by a right-angled triangle, one angle of which is ϕ. If the power factor is lagging so is the VAr. Lagging VAr are 180° geometrically displaced in phase from leading VAr. Thus leading VAr may be considered as reversed lagging VAr.

In an unbalanced 3-phase circuit, the total power can be considered as the sum of the watts due to the association of each line current with the corresponding line-to-neutral voltage. The algebraic sum of the three values of the VAr so obtained is called the 3-phase VAr. According to this definition, it should be noted, lagging VAr in one phase can be partially or completely cancelled by leading VAr in another. The square root of the sum of the squares of the total watts and the algebraic sum of the VAr in an unbalanced 3-phase circuit is called the total equivalent volt amperes. The ratio of watts to total equivalent VA is the conventional definition of power factor in an unbalanced 3-phase circuit. The total equivalent VA is always less than the sum of the three single phase VA, excepting when the circuit is balanced. The value of the 3-phase power factor given by the foregoing definition is not necessarily equal to the average of the three single-phase power factors. It can be shown theoretically to be the value given by an unbalanced load power factor meter (§ 111) if the voltages are balanced.

Reactive measurements in 3-phase circuits are of considerable importance in modern metering, since 3-phase kVA is based upon watts and VAr. It has been seen in § 110 that when a three-phase load is balanced, the VAr can be determined from the difference of the readings of two wattmeters. A simpler method is to use a single wattmeter carrying the current of one line, and energised by the voltage between the other two. $\sqrt{3}$ times the reading of the instrument gives the 3-phase VAr in a balanced load.

If the 3-phase load is unbalanced, the VAr can be measured by the 2-wattmeter method if the voltages on the instruments are arranged to lag 90° in phase on those used for power measurement, Thus, in the circuit shown in Fig. 16, if suitable phase to neutral voltages be used instead of line voltages, the sum of the instrument readings will give the 3-phase VAr, when multiplied by $\sqrt{3}$ Similarly, using line voltages instead of phase-to-neutral voltages in the circuit of Fig. 18, the sum of the readings, divided by $\sqrt{3}$ will give the 3-phase VAr. In each of these amended schemes of connection for VAr measurement, the voltages must be balanced to give the exact 90° phase shift.

The practical importance of the conception of leading and lagging VAr will be dealt with fully in Chapter 5. (*See* also § 116*a*.)

111. Power Factor Indicators or Phase Meters.—The principle generally employed in power factor indicators is that of using two magnetic fields, respectively in phase with the main current and voltage, to determine the position of a moving system the spindle of which carries a pointer moving over a scale calibrated in values of $\cos \phi$.

(i) The operation of the Everett-Edgcumbe *single-phase P.F. indicator* may be explained by reference to Fig. 19. The fixed coil I is traversed by the main current (or fed by current transformer, § 108). The moving system, which has no control (§ 90), consists of two coils AB mounted at right angles on the spindle which carries the pointer P. The coil A is in series with resistance R, and B is in series with a condenser C; an inductance may be used instead of the condenser, but it is not then possible to get so nearly 90° phase difference between the currents in the two coils. When the P.F. of the main circuit is unity the current *I* is in phase with that in *A*, therefore this coil lies parallel to the coils *I*. At zero power factor in the main circuit, the current *I* is in phase (or 180° out of phase) with the current in *B* which leads 90° with regard to the voltage *E*, hence the coil *B* sets itself parallel to the coils *II*, the pointer being then horizontal and pointing to the left if the main current be lagging, and to the right if the main current be leading. For intermediate values of P.F. the pointer takes up a position intermediate between these extremes. At unity and zero power factor the position of the pointer is independent of frequency, but the division of current between *A* and *B* varies with frequency, hence the reading at intermediate values of power factor is affected by frequency and this instrument must be calibrated for the frequency on which it is to be used.

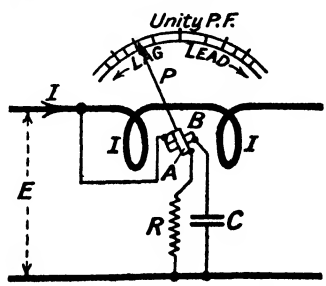


FIG. 19.—Single-phase power factor meter.

For 3-*phase systems* two different instruments are used according to whether the load is balanced or unbalanced;* the general principle of operation is, however, the same as already described. The instrument for use on *balanced* 3-phase systems embodies a fixed coil, carrying the main or transformed current of one phase, and three pressure coils attached to a pivoted spindle which carries the pointer. Each of the three coils has one end connected through a resistance to one of the phases, the other ends being joined up together to form a neutral point. Three-phase currents flowing in these coils induce a rotating field, and the system will set itself in such a position that, at the moment the

* The requirements for measuring the P.F. of a polyphase system are as follows:—

	Coils required With Balanced Load.	Coils required With Unbalanced Load.
For a 2-phase or 4-phase circuit	*Either* 2 current and 1 pressure *or* 1 current and 2 pressure.	2 current and 2 pressure.
For a 3-phase circuit . .	*Either* 3 current and 1 pressure *or* 1 current and 3 pressure.	3 current and 3 pressure.

current in the fixed coil reaches its maximum value, the field due to the moving system lies along its axis. In the instrument for *unbalanced* 3-phase loads, three fixed coils are employed, one on each phase; the moving system then takes up a position corresponding with the *average* power factor of the main circuit, while each phase can, if desired, be separately tested by means of a short-circuiting plug. Both the 'balanced' and the 'unbalanced' 3-phase P.F. indicators are unaffected by changes in voltage, temperature, frequency or wave form.

(ii) The Nalder-Lipman *moving-iron* power factor indicator for *single-phase* and for *polyphase balanced or unbalanced* loads is characterised by the fact that the moving system consists only of thin iron vanes carried by a spindle which is built up of magnetic and non-magnetic portions. Two sets of fixed coils are employed, *viz.* the 'field' coils energised by the line currents, and the 'magnetising' coils energised by the line voltage (through transformers in both cases if the load exceeds 30 A at 650 V). The 'field' (current) coils are placed with their axes parallel to each other and in separate planes. The iron vanes lie in these planes and are set at angles corresponding to the phase displacement of the currents in the phases of the main circuit (90° and 120° for the 2-phase and 3-phase instruments respectively). The 'magnetising' (pressure) coils magnetise the corresponding vanes, of the moving system periodically and in correct sequence, and the vanes are subject to the directive pulsating magnetic forces produced by the 'field' coils. For every value of main circuit P.F. there is a position of the moving system in which the latter is in equilibrium; this position is indicated by the pointer and forms a measure of the power factor. The readings are unaffected by changes in current, pressure, or temperature and, over a wide range, by changes in frequency or wave form. Since no current has to be carried into the moving system, the latter is quite free from control and the scale is a complete circle (360°). Leading and lagging power factors are indicated respectively in the right- and left-hand quadrants of the upper semi-circle and in the diametrically opposite quadrants of the lower semi-circle. The direction of current flow determines in which of two opposite quadrants the pointer stands for any particular P.F. The connections are such that the pointer is in the upper semi-circle when the power flow is forward, *i.e.* from generator to line. In inter-connecting or 'tie' lines the power flow may be in either direction.

Values of P.F. commonly found in practice are given in § 157.

Phase rotation indicators are discussed, together with *synchroscopes*, in connection with the paralleling of generators (§§ 148, 149).

112. **Frequency Meters.**—One method of determining the frequency of an A.C. supply is to use the alternations of the latter to set in vibration a number of metal reeds of known and graduated natural frequencies; that reed, the mechanical frequency of which corresponds to the frequency of the A.C. supply, is set into vigorous, resonant vibration and thus indicates the frequency in question. A number of other frequency meters utilise in one way or another the fact that the reactance of an inductance (§ 44) or the condensance of a capacity (§ 46) varies with the frequency of the current passing through them; this characteristic, which makes the accuracy of some instruments dependent upon constant frequency (*e.g.* the single-phase P.F. indicator, Fig. 19, § 111) can be used as a measure of frequency. The associated principle of electrical resonance (§ 47) is also employed.

For testing purposes a frequency meter may need a wide range of measurement (say from 15 to 100 cycles per sec. for commercial supplies), but under working conditions the periodicity of any particular A.C. supply varies but little, and an open scale with a range of a few cycles per sec. (say from 47 to 53 cycles) is required. In the absence of a frequency meter, the frequency of supply can be calculated from—

$$\text{Cycles per sec.} = \left\{\begin{array}{l}\text{Revs. per sec. of}\\ \text{alternator or } syn\text{-}\\ chronous \text{ motor.}\end{array}\right\} \times \left\{\begin{array}{l}\text{No. of } pairs \text{ of poles}\\ \text{in the alternator or}\\ \text{motor.}\end{array}\right\}$$

(ii) *Reed-type Frequency Meter.*—A number of steel springs of different natural frequencies (*i.e.* miniature tuning-forks) are mounted parallel to the core of an electromagnet which is excited from the circuit, the frequency of which is to be measured. One end of each spring is fixed and the other is bent inwards so as nearly to touch an iron disc attached to one end of the magnet core. All the reeds are thus subjected to a periodic attraction, the frequency of which is *twice* the frequency of the supply current (because each half wave produces an attraction). That reed, the natural frequency of which equals twice the frequency of the A.C., vibrates in resonance and its bent-over end appears as a radial white line; the other reeds remain nearly or quite stationary. Against each reed (or every fifth reed) there is marked on the scale the supply frequency corresponding to resonance of that reed.

It is sometimes useful to know that the range of a frequency meter of this type can be doubled by polarising the magnet (by a D.C. winding or a permanent magnet) so as to neutralise the effect of alternate half-waves of the A.C. The number of attractions on the reeds is thus halved and the frequency corresponding to the resonant reed is twice that shown by the scale.

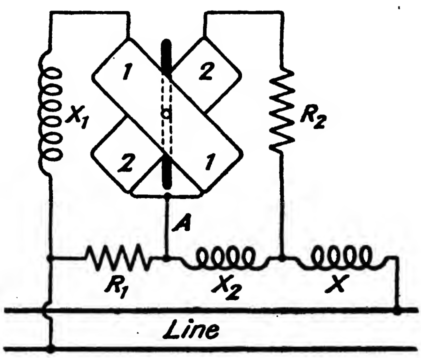


Fig. 20.—Diagram of Weston frequency meter.

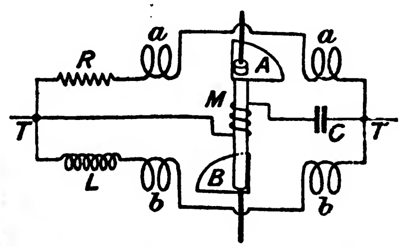


Fig. 21.—Diagram of Lipman-Nalder frequency meter.

(iii) The *Weston frequency meter* works on a different system. In this instrument there are two fixed coils each made up of two sections wound flat, of which one is slipped inside and at right angles to the other. The movable system consists of an iron needle, a pointer, and a single vane air damper, no control springs being required. The connections are shown in Fig. 20. The fixed coils are in series across the line with a reactance X_1 in series with one and a resistance R_2 in series with the other; a resistance R_1 is in parallel with the former and a reactance X_2 with the other. The whole combination is then in series with a further reactance X. The circuits as shown form a balanced Wheatstone bridge (§ 120) at normal frequency, but any change of frequency is accompanied by a corresponding shift of the resultant field of the fixed coils, which is indicated by the pointer on an open scale.

(iv) In the *British Thomson-Houston frequency meter* a curved iron core is excited by a coil connected to the A.C. supply. A moving coil is connected to a condenser and is so pivoted that it can move along the curved iron core towards or away from the fixed coil. The moving coil acts as the secondary of a transformer (the fixed coil being the primary) and it always sets itself so that its inductance, which varies with the position of the coil along the core, and the capacity of the condenser to which it is connected are in resonance (§ 47) with the supply frequency. Harmonics in the supply wave have little effect on the flux threading the moving coil, hence the instrument is practically unaffected by wave form; neither is it affected by wide variations in supply voltage. The moving coil carries a pointer which moves over a scale calibrated in frequencies. If the frequency be constant the instrument can be calibrated to measure inductances or capacities connected in the circuit of the moving coil.

(v) The *Nalder and Thompson* (*Lipman*) *frequency meter* depends on the fact that the P.F. of a circuit containing inductance and capacity varies widely with change in frequency round about the value of frequency for which the circuit is in resonance (§ 47). The P.F. of such a circuit can thus be made a measure of frequency. The instrument described is broadly similar to the Lipman P.F. meter (§ 111), but the connections are such that the position of the pointer varies with the P.F. of the magnetising circuit of the instrument itself. Referring to Fig. 21, the supply of which the frequency is to be measured is brought to the terminals *TT*, between which there are three parallel paths through the instrument. The branch *Ra* is of high resistance and low inductance, whilst the branch *Lb* is of high inductance and low resistance. The vanes *AB* on the spindle are thus subjected to magnetic fields differing practically 90° in phase. The magnetising coil *M* surrounds the spindle (which is of magnetic material between *A* and *B*), and the inductance of *M* and capacity of *C* are such that this circuit is in resonance at, say, 50 cycles per sec. At higher frequencies the inductance of *M* preponderates and the current lags behind the E.M.F. producing it. At lower frequencies the current leads with regard to the E.M.F. Thus the phase of the field produced by *M*, and

dial plate of the instrument by electric light furnished by dry cells and a glow-lamp included in the equipment. The negative thus obtained is used by the clerical department in making out the consumer's bill, and it is even suggested that a photo-print might be attached to the bill. There is nothing impracticable in this system of 'meter-reading,' but every supply engineer must decide for himself whether it is worth while employing it, under the particular conditions of supply and office organisation in the supply area concerned.

Meters are often provided with cyclometer dials, giving the indications in plain figures. In the earlier types these were apt occasionally to slip a notch and give a reading 10, 100, or 1 000 units in excess; such a mistake could only be detected by the

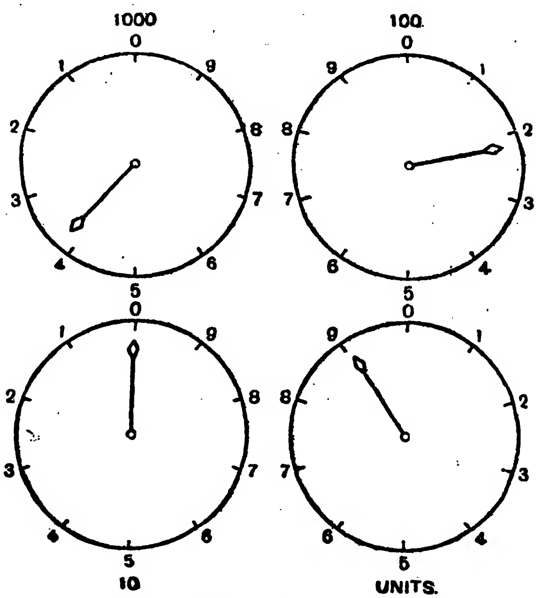
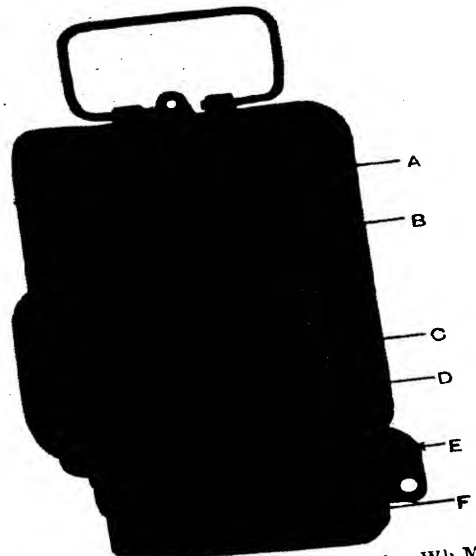


FIG. 22.—Illustrating the misleading effect of errors in the setting of hands on meter dials.

The correct reading of the dials shown is 4199.

comparison of one month's consumption with another, and not always by this method. As the actual reading of a meter is, in the absence of fraud, taken to be 'conclusive proof' of the consumption indicated, this source of error was a dangerous one. Manufacturers claim to have cured the defect, but there may still be early batches of these meters in use; the cause appears to have been due to the gear wheels being only friction-tight on the spindles; they should always be rigidly attached, so that when once accurately set they cannot alter.



(1) Metropolitan-Vickers A.C. Induction Wh Meter.

A Pinion driving register.
B Sockets for fixing register.
C Brake magnets.
D Micrometer screw for speed adjustments.
E Earthing terminal.
F Main terminals.

(2) Metropolitan-Vickers D.C. Mercury Ah Meter.

The rotor of the meter is a disc of pure copper situated in a moulded bakelite container. The permanent magnets are embedded in a block which is fitted into this container. The space round the disc is filled with pure mercury.

[*To face p.* 185.

Electrolytic meters are simple in construction, and have no moving parts and therefore no friction error; no current can pass through the electrolyte without producing its share of electrochemical action, and no current passes through the meter when the consumer's circuits are open. Periodic re-setting of the measuring chamber, etc., is required but this is a minor disadvantage. Electrolytic meters are unsatisfactory in very hot climates; they have been known, when disconnected entirely from the circuit, to record a very large consumption of energy (90 kWh in one day) owing to temperature effects at about 110° F. Any commutator-type motor meter is subject to more or less error due to variable friction and electrical resistance between brushes and commutator; automatic brush-shifting gear is often employed so that the contact surfaces used when the meter is on very light load are kept in perfect condition.

The principal features of various types of meters are mentioned in the following paragraphs; for detailed information reference must be made to special treatises (§ 125). Meter testing is discussed in § 1035, Vol. 3. As regards supply meters (§§ 114 to 116), reference should be made to B.S.S. No. 37; but a warning is necessary. The specification lays down the limits of accuracy of a meter when new, and for a limited time thereafter. Supply meters, however, are kept in use for many years, during which time wear and tear of pivots and the effects of climate, etc., are cumulative. For the purpose of official regulations, no meter can be expected to maintain its initial accuracy, especially in hot climates with noxious insects abounding; a point often overlooked by those who draw up these regulations.

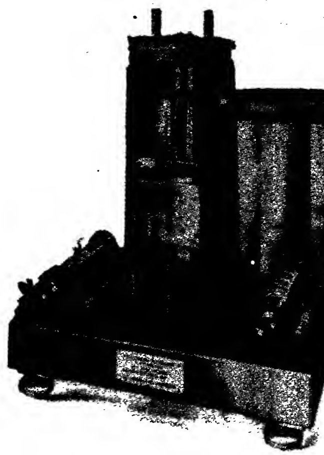
114. Ampere-hour Meters.—The quantity of electricity supplied to a circuit can be determined by a current-actuated device, time being taken into account by measuring the total effect produced. Thus in electrolytic meters the amount of electrolyte decomposed, or of metal electro-deposited, is a measure of ampere-hours whilst in a motor meter the total revolutions of the spindle form the desired measure.

(ii) *Electrolytic Meters.*—The Bastian electrolytic meter employs nickel electrodes in a solution of caustic soda, the level of which falls as the gaseous products of electrolysis escape. A layer of paraffin prevents evaporation, and the level of the electrolyte is read against a scale which is calibrated in kWh (§ 113). The pressure drop in this meter is 2 or 3 V which is prohibitive where heavy current circuits are concerned. In the Wright shunted electrolytic meter about $\frac{1}{200}$ of the main current passes through the meter and the pressure drop is 1 V or less. A solution of a mercury salt is used as electrolyte and mercury is transferred electrolytically from a reservoir of mercury (forming the anode) to an iridium cathode, whence it runs into a tube calibrated in B.O.T. units.

(iii) *Motor Meters.*—In motor meters the current to be measured passes through an armature which lies in the field of a permanent magnet. In the D.C. mercury motor meter current flows radially through a copper disc mounted on the spindle and immersed in a shallow chamber filled with mercury; a magnetic field perpendicular to the disc is produced by a permanent magnet. Alternatively, the armature is bell-shaped, current flow therein being parallel to the spindle, and the armature rotating in an intense radial field. Eddy-current braking (*cf.* damping, § 90) is provided in this, as in all other types of motor meters, and when it is necessary to compensate for the fact that the fluid friction in the mercury chamber rises more rapidly than is desired with increase of speed, this is done by using an auxiliary coil to increase the driving field.

Commutator-type meters have an armature winding similar to that of a D.C. motor with the important exception that the meter armature has no iron core. The winding may be drum-shaped or it may be flat and enclosed by an aluminium casing which reduces windage, protects the windings, and acts also as braking disc. In order that the armature may be wound with fine wire, meters of this type are generally shunted; the p.d. across the shunt is about 1 V at full load. The field is produced by permanent magnets. This type is now practically obsolete.

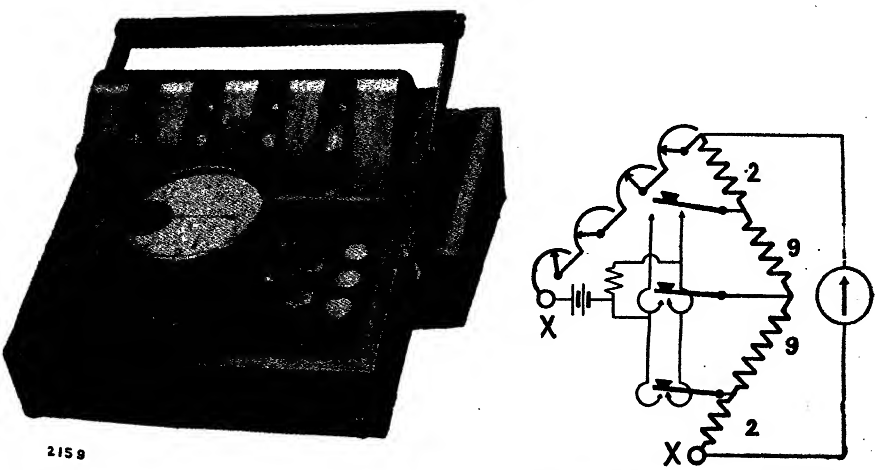
Any motor-type ampere-hour meter with permanent magnet field is reversible according to the direction of the current so that if the current is first going through the coils in one direction, as when charging a battery, and then in the opposite direction, as when discharging the battery, the instrument will show the difference between the ampere-hours passed through it in the two cases. Ampere-hour meters used in this way on electric battery vehicles (Chapter 36) to indicate the state of charge of the battery are calibrated in ampere-hours (standard dial ranges being up to



H. Tinsley & Co.

THE DRYSDALE WATTMETER.

This instrument can be calibrated on D.C., and will then read accurately on D.C., or single- or three-phase A.C. circuits. Metal parts are eliminated wherever possible, and the windings are stranded to reduce eddy currents. The two systems of the wattmeter are arranged at right angles so as to have no interaction; if desired, one system can be used with D.C. and one with A.C. For tests at very low power factor (*e.g.* on cables or condensers) the current through one set of coils can be increased, so as to magnify the deflection.

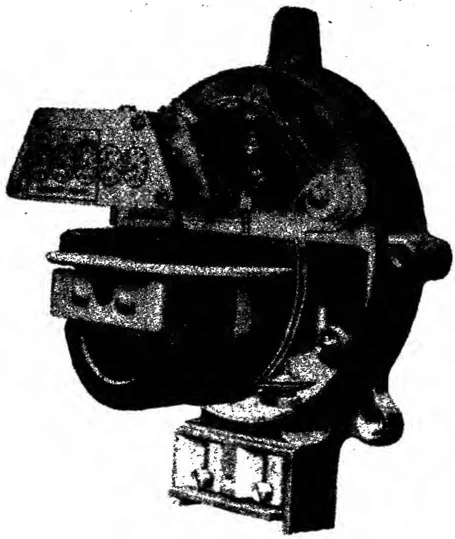


Cambridge & Paul Instr. Co., Ltd.

SELF-CONTAINED ROTARY PATTERN WHEATSTONE BRIDGE.

The set is complete with dry battery, and the only connection required is that of the unknown resistance to the terminals XX. The 'Unipivot' galvanometer requires no accurate levelling. Measurements can be made, accurate to 1 in 500, over the range 0·01 to 11 110 ohms. The rheostat arm is adjusted by rotating the drums shown. The value of the unknown resistance is obtained by multiplying the reading on the drums by the ratio employed (*i.e.* 0·1, 1 or 10 according to the key pressed).

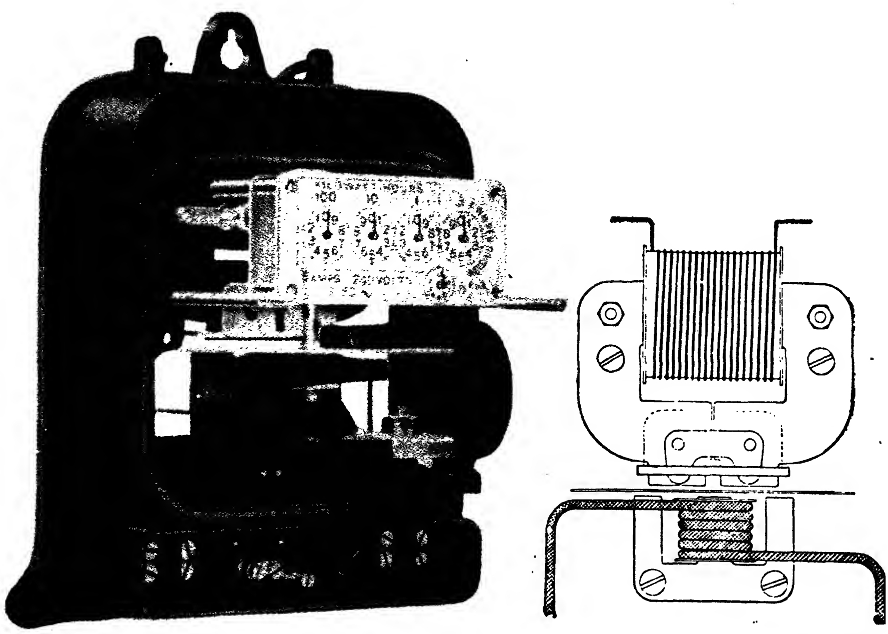
[*To face p.* 186.



Electrical Apparatus Co., Ltd.

D.C. Ampere-Hour Meter.

This meter is of the commutator motor type with the armature windings enclosed in an aluminium disc. The magnets are of cobalt steel. The meter starts at $\frac{1}{400}$ of full-load current and is accurate within 4 % at $\frac{1}{100}$ load, and within 2 % down to $\frac{1}{40}$ load. The speed is low, *viz.* 75 r.p.m. maximum; and the full load torque is 26 grm.-cm., and is uniform except at the points of commutation when it exceeds 32 grm.-cm. The pressure drop is less than 1 volt.



Ferranti, Ltd.

A.C. Watt-Hour Meter.

This meter is a single-phase instrument of the induction motor type. A shunt-wound stator is placed above, and a series-wound stator below, an aluminium rotor disc, which is braked by a permanent magnet. The principal data are: Accuracy, ± 2 % from 25 % overload to $\frac{1}{20}$ load at any P.F. down to 0·5, leading or lagging. Starts at 0·5 % of full-load watts at 1·0 P.F. Rotor speed 40 r.p.m. at full load. Full-load torque 5 grm.-cm. Shunt loss 1·5 W. For unbalanced polyphase circuits two rotor discs are mounted on one spindle, each with its own stator system.

[*To face p.* 187.

100 or 500 Ah). The pointer rotates clockwise on discharge and counter-clockwise on charge, and stands at zero when the battery is fully charged. To allow for the fact that the Ah-input on charge is necessarily greater than the Ah-output on discharge (§ 431, Vol. 2), the meter is arranged to read correctly, on discharge, but slow on charge by an amount which is adjustable up to 30 °/₀ according to the efficiency of the battery concerned.*

115. Watt-hour Meters.—The *Thomson-type watt-hour meter* is an ironless commutator-type motor, the stationary field coils of which carry the main current (or a fraction thereof) whilst the armature is connected, in series, with a suitable resistance, across the mains. The driving torque and meter speed vary with the power supplied to the load metered (*cf.* dynamometer wattmeter, § 109), a brake disc rotating between the poles of a permanent magnet. A compensating coil in series with the pressure circuit aids the field coils and produces a constant torque compensating for the (assumed) constant friction; if the meter be subject to vibration this compensating torque may cause 'creeping' (*i.e.* running on no load). This type of meter can be used for D.C. or A.C. measurements, but the mercury motor meter is more powerful and can be used on D.C. systems, whilst the induction meter is better than the Thomson type for A.C. systems.

(ii) The *mercury motor watt-hour meter* is practically identical with the ampere-hour meter of this type (§ 114) except that the field, in which the armature disc rotates, is produced by an electromagnet excited by a pressure coil. The driving torque on the disc is proportional to the product of Current × Field strength, and therefore to Current × Voltage (= Power). With a correctly designed brake the speed of the disc is similarly proportional to the power, and the total number of revolutions, *i.e.* the meter reading, is proportional to the watt-hours consumed by the load. Within normal variations of voltage, the field of the electromagnet is proportional to the supply voltage where D.C. is concerned, but to fulfil the conditions requisite for A.C. would require the use of an ironless field system. The mercury motor watt-hour meter is therefore restricted in practice to D.C. service, induction meters being generally used for A.C. supply.

* For the Electric Vehicle Committee's recommendations concerning ampere-hour meters for battery vehicles *see The Electric Vehicle*, Vol. 5, p. 35.

(iii) The principle of action of *induction watt-hour meters* is identical with that of induction wattmeters (§ 109), and, like the latter, these instruments are not applicable to D.C. measurements. In general, the meter disc is placed between the poles of one electromagnet excited by the load current and one excited by the supply pressure (instrument transformers, § 108, being used if necessary). The current winding is of low inductance, but the pressure circuit is made as inductive as possible. An auxiliary short-circuited winding on the pressure core produces some extra lag and brings the flux of the pressure magnet into quadrature with the line voltage. The torque on the meter disc is then proportional to the load (watts) supplied. A permanent magnet embracing the disc at another place produces eddy-current braking. The moving system consists only of the disc and spindle, and two meter elements can easily be placed on one spindle for measuring 3-phase energy by the two-wattmeter method (§ 110).

(iv) The Ferranti *polyphase induction meters*, Type FLY for 3-ph., 3-wire and Type FLX for 3-ph., 4-wire circuits, use a special disc with an insulated centre. This makes it possible to group the elements round a *single* revolving disc or rotor. Glass has proved to be the most suitable insulator for the centre of the disc, as it possesses the advantage of standing up to the most extreme climatic conditions without distortion. The rotor weights in the two types are 32 and 40 grammes respectively; with such light weights and a low speed of rotation, the wear on the jewel pivot is small, thus reducing one of the commonest causes of inaccuracy. In addition, the out-of-balance pull on the rotor is smaller than usual, on account of the position in which the elements are placed round the disc. The torques of these meters are high in proportion to the small rotor weights. The interference between elements is small, due to the special disc, which consists of an annulus of aluminium round the glass centre. This centre limits the eddy currents crossing the disc between elements, and consequently there is little possibility of interaction of the fluxes due to the eddy currents from one element with the torque-producing fluxes of either of the others. The shunt losses per element are 1·3 W and 1·1 W in the two types FLY and FLX respectively; the series losses per element are, up to 20 A, 0·5 W and up to 50 A, 0·9 W in both types. These meters are connected in accordance with B.S.S. No. 37 (1930); the FLY type having two driving elements and the FLX type three. The accuracy curve is very good, *viz.* within 0·5 % from 1/20 load up to 100 % overload.

(v) The *Aron (pendulum) watt-hour meter* employs two stationary solenoids, traversed by the load current, to accelerate and retard respectively two pendulums, the "bobs" of which are coils of fine wire connected, in series with each other and a suitable resistance, across the supply voltage.* The difference between the rates of oscillation of the pendulums is proportional to the power supplied, and the energy (Wh) is recorded by a train driven from the two pendulums through a differential gear. The spring driving the pendulums is wound electrically and difference between the natural periods of the pendulums is neutralised by reversing every 10 mins. the recording gear and the current through the pendulum coils. Though rather intricate and costly in construction, these meters are precision instruments; provided that the inductance of the pressure circuit is low, they can be used for A.C. measurements. The winding gear of the A.C. meter must, however, be adapted to the frequency of supply concerned.

Though theoretically independent of voltage changes, any watt-hour meter should be used on approximately the pressure for which it is designed, otherwise the torque will be unduly low (low voltage); the pressure winding will be overheated (high voltage); or the pressure flux will not be proportional to the voltage where iron cores are used.

116. Special Supply Meters.—Many instruments come under this heading, but those of general interest (§ 275) are as follows:—

(i) *Prepayment Meters.*—Any meter can be made to operate on the prepayment principle by adding to it a mechanism which closes a switch in the main circuit when a coin is inserted, and opens the circuit automatically when the amount of energy corresponding to the prepayment has been consumed. The trip gear is actuated from the recording train, and a further payment is required to restore supply after interruption.

Several types of prepayment meters are now available in which the switch is responsive not only to the registration of an energy meter but also to the rotation of an auxiliary constant speed time meter. With such a meter the consumer has to insert coins at a

* Where the load is heavy, the pendulums may carry shunted current coils, the pressure coils being then the stationary ones.

constant rate irrespective of his actual consumption of energy. The total amount which has to be prepaid in a quarter is thus a constant sum plus an amount proportional to the meter registration. This is the principle of many domestic 2-part tariffs explained in Chapter 12.

(ii) *Two-rate Meters.*—Any meter can be provided with two recording trains and a change-over device operated electromagnetically under the control of a time-switch. The consumptions recorded on the two trains are charged at different prices (§ 272).

(iii) *Summation Meters.*—These are used to measure the total energy supplied by a station or through a number of circuits. Each machine or 3-phase circuit may have its own pressure and current circuits in the meter operating on the two-wattmeter principle (§ 110), a number of such elements operating on one rotor disc and several discs being mounted on one spindle; the mechanical effects of each meter are thus added together. Alternatively, the addition may be effected on the electrical side, a current transformer in, say, the No. 1 phase of each machine or feeder being connected to a pair of bus bars which serve the current circuit of the summation meter. The latter is then an ordinary induction meter (§ 115), the pressure circuit of which is excited by the appropriate phase of the system (No. 1 phase in the case assumed).

116a. Reactive and kVAh Meters.—The integration of 3-phase VAr and VA is important in the application of the special power tariffs discussed in § 274. 3-phase VArh can be measured by two-element energy meters with the voltage connections modified as explained in § 110*a*. The dial train is usually so adjusted as to take the required multiplier into account so that the meter registers in kVArh direct. It will have been understood from § 110*a* that if a kVArh meter rotates in a forward direction for lagging VAr, it will reverse its direction for leading VAr. Reactive meters are sometimes fitted with a ratchet device to prevent reverse rotation if the power factor changes from lagging to leading.

kVAh meters are constructed in which the sum of the registrations of kWh and kVArh components are vectorially combined in such a way that the speed of the kVAh register is proportional to $\sqrt{W^2 + (VAr)^2}$. This result is obtained by means of special gearing. A second method of measuring kVAh is by means of a 3-phase energy meter excited by artificial voltages which, by means of a power factor relay and phase shifting device, are always maintained such that the meter 3-phase power factor is unity. This method is fully explained in a paper by Casson and Gray.*

The ratio of kWh to kVAh gives an average value of the power factor which is sometimes called the energy factor. Another average value can be obtained from the ratio

$$(\text{kWh})^2/\sqrt{(\text{kWh})^2 + (\text{kVArh})^2}.$$

Neither of these averages will be identical with the actual time average of the power factor if the load conditions are variable. When average power factor is used for tariff adjustments the value adopted is a matter of convention and is based upon convenience of measurement. From this point of view that based upon kWh and kVArh is the simplest.

117. Maximum Demand Indicators.—The importance of the maximum power demanded in any consumer's circuit is explained in § 260. Just as ampere-hours can be taken to be a measure of watt-hours in a constant-voltage system (§ 114), so can the maximum current be taken as a measure of the maximum power demanded. An indicating ammeter with an auxiliary pointer, carried forward by the main pointer and left at the maximum deflection of the latter, would show the actual maximum current, but it is necessary to discriminate between momentary heavy current, due to motor starting, short circuit, etc., and maximum demand sustained for such period (15-60 mins.) as to preclude accidental or transitory demands. The requisite time lag may conveniently be introduced by using the heating effect of the current.

(ii) In the Wright demand indicator a heating coil wound on one bulb of a differential thermometer drives liquid into a calibrated side tube to an extent depending on the sustained maximum current. The use of a differential thermometer eliminates the effect of the general air temperature. While it is reliable as a rule, a device operating on this principle lends itself to tampering, *e.g.* by artificial cooling, when an exceptionally heavy load is required.

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* *Jour. I.E.E.*, 1936, Vol. 78, p. 681.

(iii) Another type of maximum demand indicator operates on the thermal-storage principle and has a pointer, the deflection of which is determined by the *difference* between the heating of two bi-metal spiral springs. These springs are enclosed in capsules which are heated by resistances so connected that the difference in heating is proportional to the watts supplied in the main circuit. The maximum deflection of the pointer, during the period over which the demand is assessed, is indicated by a pilot pointer. It is claimed that this device has the same heating characteristics as the machines and cables in the supply circuit.

Another principle is to introduce heavy damping (§ 90), by glycerine or otherwise, in a current-indicating mechanism which is operated electromagnetically.

The Merz maximum demand indicator uses an auxiliary recording train and pointer to record the maximum advance of the main recording train of the meter to which it is fitted, during a predetermined period. At the end of every period (15-30 mins.), the auxiliary train is returned to zero, but its pointer is left at its maximum deflection and is not again moved forward until a higher consumption occurs during some subsequent period.

The Merz-demand indicator attachment can be used in conjunction with a kVAh meter to indicate the maximum demand in kVA (*see* § 274).

The Hill-Shotter kVA maximum demand indicator consists of an induction ammeter movement and a continuously rotating disc damped by a permanent magnet. Over a considerable range the speed is nearly proportional to the current. If this instrument be fitted with a Merz demand attachment it can be made to register the demand in kVA, although the scale of the indicator is non-uniform. An auxiliary device compensates for small voltage changes. Three such elements with a common spindle and a single register are used for a 3-phase kVA indicator. When the load is unbalanced, this type of instrument does not indicate total equivalent VA, but a quantity proportional to the square root of the sum of the squares of the single phase VA. This is greater than the value of the VA based upon $\sqrt{W^2 + (VAr)^2}$.

118. Ondographs and Oscillographs.—The wave form of alternating current, pressure, or power can (*if constant*) be plotted by the *point-by-point method* or recorded automatically by an *ondograph* which works on this method. In either case, a disc carrying a contact pin is mounted on the shaft of the supply alternator or on the shaft of a synchronous motor driven from the supply to be investigated. A stationary contact brush touches the contact pin once per revolution, and thus connects the supply momentarily to an indicating instrument which shows the instantaneous value of the current, pressure, etc., under investigation. By advancing the contact brush between readings, and taking a sufficient number of observations, the instantaneous values of the wave can be determined throughout a complete cycle. In the ondograph the brush is advanced automatically and a recording instrument records the successive instantaneous values; a complete cycle can thus be recorded in, say, $\frac{1}{2}$ min., by readings taken from about 1 000 successive cycles. To trace a pressure wave by the point-by-point or ondograph method, the indicating or recording instrument is connected across the supply mains; for a current curve it is connected across a non-inductive shunt (§ 107) in the main circuit; and for a power wave a wattmeter is used.

(ii) The *oscillograph* is a much simpler instrument than the ondograph and, having no appreciable lag, it is able to follow accurately all the variations in every cycle of an A.C. wave, thus providing a continuous indication or record and making possible examination of transient or non-periodic as well as periodic waves. A small mirror (actuated electromagnetically or by a hot wire or electrostatic instrument) deflects a spot of light proportionally to the instantaneous values of the quantity to be measured. The movements of the spot may be recorded on a falling or rotating photographic plate or film. Alternatively the oscillating spot may be focussed on a plane mirror which is itself oscillated by a cam on the shaft of a synchronous motor driven from the supply investigated. A second movement (proportional to time) is thus imparted to the spot which then falls on a screen and traces the complete wave form; retentivity of vision makes the moving spot appear as a continuous line. Photographic recording is alone suitable for the investigation of a particular series of waves, *e.g.* switching surges, etc.

(iii) The *Duddell oscillograph* uses a loop of phosphor bronze strip stretched in the narrow air gap of a permanent magnet or of an electromagnet with constant excitation. The instrument thus belongs to the moving-coil, permanent magnet class (101*a*).

At any moment current flowing up one side of the loop flows down the other side, and since both sides lie in the same magnetic field, one moves forward and the other moves backward (§ 33). A small mirror attached to the two sides of the loop is thus tilted, and the spot reflected by it is deflected through a distance proportional to the current in the strip, the sensitivity being about 300 mm. deflection per ampere at a distance of 50 cm. According to the strength of the magnetic field, the dimensions of the strips, etc., the natural period of vibration is from $\frac{1}{5000}$ to $\frac{1}{12000}$ sec.; waves up to 500 cycles per sec. or even higher frequencies can be traced, and the oscillograph can be insulated for use on 50 000 V circuits.

(iv) In the *Irwin hot-wire oscillograph* the A.C. to be investigated is passed through a loop of fine wire, and a polarising direct current, fed into the centre of the loop, flows through the two halves of the latter in parallel. The resultant current in one half of the loop is the sum of the A.C. and D.C., and in the other half is the difference of the A.C. and D.C. The difference in expansion of the two sides then varies directly with the instantaneous values of the A.C. (*not* with their squares), the D.C. being constant. This difference in expansion is used to tilt a small mirror. A compensating circuit prevents any lag in the heating of the wires. No field magnets are required, hence the instrument is much smaller than the Duddell instrument; its range of applicability is practically the same.

Either the Duddell or the Irwin oscillograph can be used to trace pressure and current waves simultaneously, a fixed mirror providing a zero line and two moving systems being connected respectively across the mains (in series with resistance) and across a non-inductive shunt in the main circuit. The Irwin oscillograph can be arranged to trace a power curve if required.

(v) Where very high pressures (up to 250 kV) are concerned, the insulation and series resistance required by current-carrying oscillographs become inconvenient or impracticable. In such cases and even at lower pressures (down to 5 kV) the *electrostatic oscillograph* offers advantages. The principle employed is identical with that of the electrostatic voltmeter (§ 103), a phosphor bronze or steel strip or strips oscillating in an electrostatic field produced between plate electrodes connected to the pressure under investigation, this motion being imparted to the mirror which reflects the indicating spot of light. Currents of 1 mA or less can be recorded by connecting the instrument across a non-inductive shunt which must, however, be of very high resistance (some megohms) in order to provide a suitable operating P.D.; such conditions arise when testing dielectrics. The electrostatic oscillograph can be used for frequencies of some thousands of cycles per sec.

(vi) The *cathode ray oscillograph* utilises the fact that a cathode ray is deflected by electrostatic or electromagnetic forces. The ray passes between two electrodes connected to the pressure under investigation, and also between field coils which impart to it a second motion proportional to time. It then falls upon a fluorescent screen where it produces a loop or polar diagram. The principal utility of this instrument is in investigating waves of very high frequency, the cathode ray having no inertia.*

119. Measurements of Resistance.—By an inversion of Ohm's Law (§ 17) $R = E / I$ or, in words, the resistance (ohms) of a conductor equals the potential difference (volts) between the ends of the latter divided by the current (amperes) which it produces. This law, which holds only when the three factors are unvarying, may be applied to the determination of resistances from voltmeter and ammeter readings. Referring to Fig. 23 the ohmic resistance of any conductor or winding, R (whether inductive or not), can be found by passing through R a steady D.C., the value of which is measured by an ammeter, A (reading I), whilst the P.D. across the terminals of the winding is measured by a voltmeter V (reading E); then $R = E / I$ ohms. The voltmeter should be of very high resistance compared with R, and it should be connected across the terminals of R; the current through V (which is included in the reading of A) is then so small as to introduce no serious error. If V were connected between B and C it would include the pressure drop in A which may be quite appreciable in comparison with

* A convenient cathode ray oscillograph requiring an anode battery of only 300 V is described, *El. Rev.*, Vol. 91, p. 783; and a low-voltage, hot-cathode oscillograph adapted for commercial production and of great sensitiveness is described in 'The Cathode Ray Oscillograph,' by A. B. Wood, *Proc. Phys. Soc. (London)*, Vol. 35, Pt. 2, p. 109.

that across R. This method is useful for measuring the resistance of machine windings.*

(ii) High resistances, such as insulation resistance, may be measured by applying say 440 V or 500 V to the resistance R in series with a moving-coil voltmeter of resistance r (Fig. 24). If V be the applied voltage and v the reading of the moving-coil voltmeter, then $R / r = (V - v) / v$, therefore $R = r(V - v) / v$ ohms.

From the relation $R = E / I$ it follows that a D.C. ammeter can be calibrated to indicate resistances in ohms if the voltage applied to the resistance be constant. This amounts to dispensing with V (Fig. 23), and calibrating A to read the values of R corresponding to various currents at constant voltage V; the calibration applies only to this voltage.† If the instruments V, A

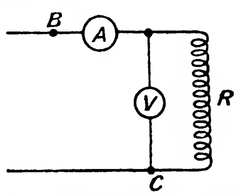

Fig. 23.—Determining resistance from ammeter and voltmeter readings.

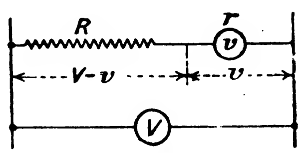

Fig. 24.—Determining resistance by voltmeter readings.

(Fig. 23) be arranged so that their pointers cross, the crossing-point varies with the ratio E / I ($= R$) and the corresponding resistance can be read on curves mounted behind the pointers (§ 91). Such a combination constitutes a true ohmmeter in that it measures resistance independently of the actual values of current and voltage.

(iii) The name *ohmmeter* is, however, generally reserved for instruments which indicate resistance values by a single pointer

* If the resistance measured between two line terminals of a 3-phase winding be R ohms, the resistance per phase is $\frac{1}{2}$ R if the winding be star-connected, and $\frac{3}{2}$ R if the winding be delta-connected.

† An interesting application of this principle is in determining the salinity of boiler feed, condensate, etc. The electrical resistance of water falls rapidly as the percentage of dissolved matter increases (§ 69) and may be taken as a measure of that percentage, provided that there is only one substance, say salt, concerned. The water to be tested flows through a tube in which are two electrodes connected in series with a milliammeter across a constant supply voltage. As thus arranged, the ammeter may be calibrated to indicate directly the salinity of the water. An ohmmeter, eliminating the effect of voltage variations, may be used for the same purpose.

and scale, the ratio of voltage to current then being taken into account in the instrument itself. Ohmmeter, Ohmer, Megger, and Omega are trade names applied to various types of direct-reading instruments for measuring resistances. These instruments are available for measuring resistances from a fraction of an ohm up to 50 or 1000 megohms on one or other of several scales, a switch determining the range. A small hand-driven magneto generator supplies the testing pressure of 200, 500, or 1 000 V. The generator is capable of giving only a minute current, but it is important that it should be a high-voltage machine in order that the insulation of conductors and apparatus in ordinary supply circuits may be tested at or above working voltage; high-voltage plant is tested by other means (Chapter 40). If there is poor insulation resistance so that

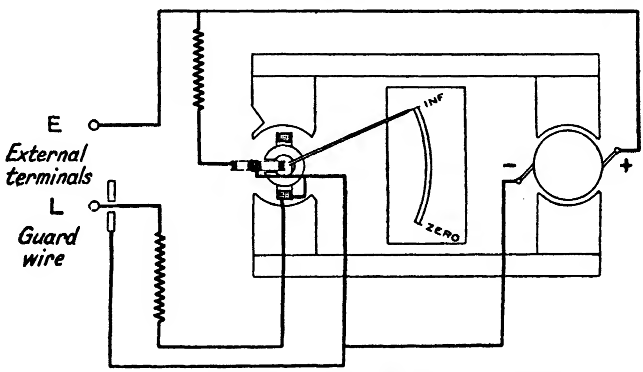

FIG. 25.—Principle of the 'Megger' testing set.

appreciable leakage current is passed, the pressure of the magneto generator immediately drops.

(iv) The illustration, Fig. 25, shows the essentials of the 'Megger' Insulation Testing Set in diagrammatic form, the gaps between the ohmmeter pole-pieces and the central iron core having been exaggerated to show the coils more clearly. The current coil is connected in series with a resistance between one of the generator terminals and the external line terminal. The pressure coil is arranged with its magnetic axis parallel to the magnetic axis of the pole-pieces when the coil is in the infinity position, as shown in the diagram. This coil in series with a suitable resistance is connected across the generator terminals.

With perfect insulation, or infinite resistance, between the external terminals, it will be evident that no current can flow in the current coil, and the pressure coil alone will control the movement, taking up the position shown in the diagram. When, however, a resistance is connected across the terminals, a current will flow in the current coil and the corresponding torque will draw the pressure coil away from the infinity position into a field of gradually increasing strength until a balance is obtained between the forces acting on the respective coils. By introducing resistances of different known values across the terminals of the instrument and marking the corresponding position of the pointer in each case, a scale calibrated in resistance can be obtained.

For the testing of the insulation resistance of conductors having appreciable capacitance it is essential that the testing pressure is maintained constant, or false readings will be given by the

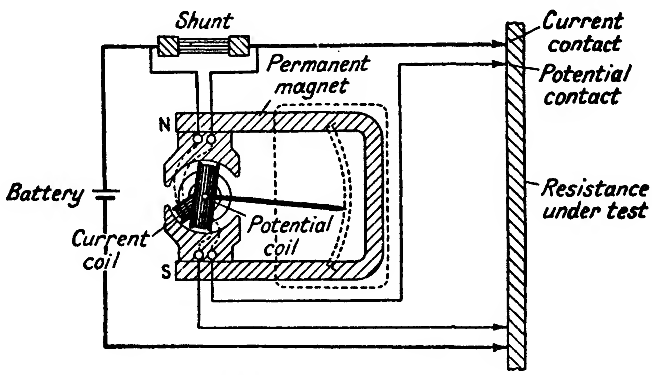

FIG. 25A.—Diagram illustrating the principle of the 'Ducter' low resistance testing set.

charging currents flowing into or from the condenser as the voltage varies. 'Megger' Testing sets are supplied in which a special clutch is used for the mechanical connection of the generator to the turning handle. When the speed of the handle exceeds that corresponding to the rated testing voltage, the clutch slips and the generator pressure remains constant.

The 'Megger' earth tester has a generator which provides A.C. for the earth circuit (to avoid polarisation errors), D.C. being used in both coils of the ohmmeter.

(v) The 'Ducter' Low Resistance Testing Set is similar in principle to the 'Megger'. Its essential parts are shown in Fig. 25A. It is seen that current from a battery is passed through the unknown resistance. The value of this current is proportional to the drop in the shunt. The two circuits of the Ducter are energised, one by this drop, and the other by the pressure drop in the unknown resistance which is communicated to the instrument by means of the two potential contacts. The reading is proportional to the ratio of volt drop in the unknown resistance to the current in it, and the instrument is therefore a true ohmmeter.

We are indebted to Messrs. Evershed and Vignoles for the above information relating to the 'Megger' and the 'Ducter' and for permission to reproduce the illustrations Figs. 25 and 25A.

(vi) The electrostatic ohmmeter is an electrostatic voltmeter measuring the P.D. across a known resistance produced by the leakage current through the resistance to be measured. The polarising voltage of the instrument is the same as that used for the resistance test, hence the indications are independent of the actual voltage.

120. The Wheatstone Bridge.—The principle of this method, which is used in innumerable forms, is illustrated by Fig. 26. Four resistances, including x, of which the value is required, are connected as shown; a and b are known as the ratio arms, and may either be of equal value; or as 1 000 to 100 or as 10 to 1; or as 1 to 10 or 100 to 1 000. The remaining arm, r, is the adjustable resistance, which is altered in value until it bears the same ratio to x as a bears to b. When this is the case the current from the battery will divide up between the two parallel circuits and there will be no deflection of the sensitive galvanometer G. Keys k_1 and k_2 are provided for opening and closing the battery and galvanometer circuits; they are generally placed one below the other, so that on depressing the handle the battery circuit is closed first and opened last. The unknown resistance $x = r \times b / a$ when a balance is found, *i.e.* when there is no deflection of G. As usually made, the arms a and b consist of coils of 1, 10, 100, and 1 000 Ω, and the ratio arms actually used should be chosen of the same order of magnitude as x.

(ii) In the Post Office bridge a number of resistance coils for the arms r, a, b (Fig. 26) are mounted in a box and connected to terminal blocks on the top thereof. By removing a plug between adjacent blocks the resistance connected to those blocks is placed in circuit, and the values of the resistances are so chosen that any resistance between, say, 0·01 Ω and 1 megohm can be measured conveniently. Portable testing sets (§ 106) frequently embody a bridge circuit arranged on this principle, but with dial switches instead of plugs for varying the resistances in circuit. One of the moving-coil instruments in the set may be used as galvanometer, and small dry cells to provide current for the bridge test may be placed in the same case. Such sets may also be arranged for resistance measurements by voltmeter or by voltmeter and ammeter readings (§ 119); great ingenuity is displayed in multiplying the functions of these sets and in reducing the risk of damaging the instruments by using incorrect combinations.

(iii) The Evershed 'Bridge Megger' testing set comprises a 'Megger' (§ 119) fitted with switching arrangements and terminals to enable it to be used for resistance measurements by the Wheatstone Bridge method. The apparatus is used as an ordinary 'Megger' for the measurement of high resistances. Where low

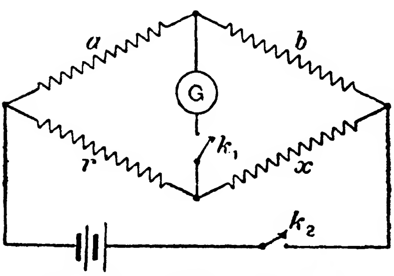

FIG. 26.—Wheatstone's bridge.

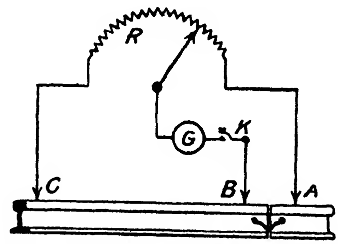

FIG. 27.—Determining resistance of rail bond.

resistances are concerned a bridge circuit is formed with the resistance to be measured, an external adjustable resistance, and two ratio arms (of variable ratio) as the four arms of the bridge, the generator as source of current (a switch providing for lowering its voltage), and the ohmmeter as a galvanometer indicating balance when its pointer is at a marked position on the scale.

(iv) The bridge circuit shown in Fig. 27 may be used to measure the resistance of a rail-bond in terms of the equivalent length of solid rail without opening the rail circuit. Contact points ABC carried by, but insulated from, a rigid bar are applied to the rail as shown, and the dial-type variable resistance R is adjusted until the galvanometer, G, shows no deflection. The only current used is that flowing in the rail which should be heavy at the time of the test, the exact value being immaterial. The resistance of the bond (in terms of the length BC of solid rail) can be calculated by the ordinary Wheatstone bridge formula, but it is more convenient to calibrate the dial of *R* to indicate directly the equivalent length of rail.

(v) Any bridge-circuit with non-inductive resistances can be used with A.C. to measure the resistance of electrolytes or of earth plate circuits (in which polarisation prevents accurate results being obtained with D.C.). When using A.C. the balance of the bridge may be indicated by the more or less complete cessation of buzzing in a telephone used instead of a galvanometer, or a vibration galvanometer (§ 96) may be employed.

Resistance variations as a measure of temperature are discussed in § 122; and leakage detectors in Chapter 40.

120a. Continuity Tests.—According to circumstances, different methods are used to check the continuity of circuits: (i) in the sense of distinguishing between continuity and discontinuity; or (ii) ascertaining that a joint or contact is of sufficiently low resistance to make the circuit continuous in the sense of substantially uniform conductivity.

Testing a wiring circuit or a winding for electrical continuity in the literal sense may be effected by means of a battery (a few dry cells) and a detector galvanometer or bell, the conductor to be tested forming part of the circuit. Where lead-covered or copper-sheathed cable systems are used, continuity of the sheath is of vital importance, and a test current of several amperes should be passed through, sufficient to break down a weak spot; a heavy current electric bell and a portable battery may serve the purpose, but a more definite test is obtained by using an ammeter, a storage battery, capable of, say, 10A discharge, and a variable resistance to regulate the current. The 10th edition of the I.E.E. Regulations (Wiring Rules) requires that the electrical resistance of the earth continuity conductor, including metal conduits, metal sheathing of cables, together with the resistance of the earthing lead, shall not exceed 1 ohm between the earth electrode and any other point in the completed installation. This clearly involves much more than mere continuity.

Continuity, in the sense of at least a reasonable uniformity of conductivity, may be tested by an ohmmeter designed specially for low-resistance measurements (§ 119 v) or by a specially arranged bridge circuit (§ 120 iv).

121. Measurement of Magnetic Flux.—As in the case of electric current, magnetic flux can be measured by any of the effects which it produces (*e.g.* change of electrical resistance, induction of E.M.F., or development of torque in conjunction with an electric current). The flux traversing a known cross-section having been measured the flux density (§ 40) can at once be calculated.

The electrical resistance of bismuth (§ 65) changes when the metal is placed in a magnetic field, and the resistance of a search coil wound with this metal can be used to measure fields of 2 000 gauss or higher density. The temperature of the coil must be taken into consideration because this affects the electrical resistance and the effect of the field thereon.

If a search coil wound with copper wire be withdrawn from the field to be measured, the quantity of electricity induced in the coil varies with the strength of the magnetic field (§ 35) and may be measured by a ballistic galvanometer (§ 96) or by a Grassot fluxmeter. The latter is a moving-coil galvanometer with practically no mechanical control; the deflection varies with the linkages cut (§ 36) and is practically independent of the rate of withdrawal of the search coil.

In a moving-coil instrument (§ 101) the field is normally constant and the current in the coil is the quantity measured. For the routine testing of permanent magnets a moving-coil system may be built to suit them, each magnet in turn being applied to the movement. The latter is connected, in series with an ammeter and regulating resistance, to a convenient supply. The current required to produce a definite deflection of the testing movement is then a measure of the strength of the magnet applied to its pole-pieces, and the ammeter in the circuit may be calibrated to indicate directly the flux produced by the magnet tested.

122. Measurement of Temperatures: Pyrometry.—Electrical methods are now used most extensively for the measurement of temperature, the property applied being either the variation in the electrical resistance of a conductor (§ 61) or the change in E.M.F. of a thermo-couple (§ 129). Any number of resistance thermometers or thermo-couples can be made to give indications or records at a control station or other central place with which they are connected by small insulated wires. A change-over switch permits a single indicating instrument to be connected to any one of any number of thermometers.

Mercury thermometers are often used to measure the temperature of oil, etc., and of windings when there is no danger of shock. Where not otherwise obtainable, good thermal contact may be secured by a wrapping of tinfoil round the thermometer bulb; a wad of cotton wool reduces loss of heat by radiation. If there are stray magnetic fields of considerable intensity and frequency (as when drying out transformers), mercury thermometers give a high reading due to the heating effect of eddy currents induced in the mercury; a spirit thermometer should be used in such cases. (*See also* § 1024, Vol. 3.)

(*a*) *Resistance Thermometers.*—A resistance of platinum, nichrome, or other resistance material (§ 67) wound on a mica former and placed at the point where the temperature measurement is to be made assumes a resistance $R_t = R_0(1 + at)$ (*see* § 61) whence $t = (R_t - R_0) / R_0a$. Actually this simple relation between resistance and temperature does not apply to very wide temperature ranges, the coefficient a then changing, but for any particular thermometer it is possible to prepare a calibration curve so that the temperature corresponding to a measured value of resistance can be read at once. With a platinum resistance, temperatures from − 200° C. to 900° C. can be read regularly, and at the risk of rapid deterioration temperatures up to 1 200° C. can be measured. It is said * that the resistance of tin varies directly with its temperature up to 1 680° C. but the metal melts about 232° C.

In industrial resistance thermometers the thermometer coil forms one arm of a Wheatstone bridge circuit which is in balance at a temperature (0° C. or other conveniently fixed temperature) corresponding to the position of the mechanical zero of the indicator. The remaining arms of the bridge are of an alloy with negligible resistance temperature coefficient. When, due to the alteration of the resistance of the thermometer coil, the bridge is thrown out of balance, a current appears in the galvanometer which depends upon the temperature of this coil. The galvanometer can thus be scaled to read temperature direct. The connections of a temperature-measuring circuit are usually arranged as shown in Fig. 27A. An alteration of the temperature of the leads connecting the temperature coil to the network affects two adjacent arms of the bridge simultaneously and equally, if the leads are of equal resistance and of the same material, and consequently does not affect the reading of the galvanometer, which is responsive solely to the temperature of the thermometer coil.

* *Jour. Inst. of Metals*, Vol. 22, p. 396.

The mean temperature of a machine winding, etc., can easily be determined from its resistance when hot and when at atmospheric temperature. It will be found that equation (2), § 61 (*see also* § 1024, Vol. 3), can be put in the form—

$$t_h = \{R_h(234{\cdot}5 + t_c) - 234{\cdot}5\ R_c\}\ /\ R_c,$$

where t_h, t_c = the mean hot and cold temperatures of the winding, in °C.; and R_h, R_c = the corresponding resistances of the winding as measured by Wheatstone bridge (§ 120). Assuming the 'cold' temperature t_c to be 20° C. the above formula reduces to—

$$\text{Mean temperature } \textit{rise} \text{ (°C.)} = (R_h - R_c)\ /\ 0{\cdot}003\,93\ R_c.$$

Instead of measuring the resistance of the winding when hot and cold and calculating the mean temperature rise as above, an indicating ohmmeter (§ 119) may be connected permanently in circuit and calibrated in degrees of temperature. This arrangement is applicable only to a D.C. winding (field coil, etc.), one coil of the instrument being connected in series with and the other across the terminals of the winding; the calibration then applies only to the winding concerned.

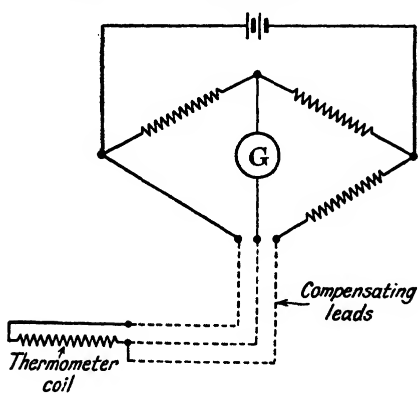

FIG. 27A.—Indicating resistance thermometer circuit.

Alternatively, small test coils may be placed permanently at various points in the winding, the resistances of these being measured by a bridge circuit or by an indicating instrument (calibrated in °C.). The provision of a number of resistance thermometers (or thermo-couples) at selected points in a machine- or transformer-winding makes it possible to locate and observe the hottest point and the 'hot spot temperature' with considerable precision. This is important because it is the maximum temperature attained which determines the life of the insulation (§ 80). The mean temperature rise, t_m, of a winding (as determined by resistance measurements) is, almost invariably, considerably less than the maximum temperature rise t_h. According to Vidmar the value of t_h is given by: $t_h = 2t_m - t_o$; where

t_0 = minimum temperature rise on the surface of the coil (measured by mercury thermometer).

(*b*) *Thermo-couples.*—The E.M.F. of a pair of similar thermo-couples (§ 129) connected in opposition is measured by a high-resistance instrument so that the small current flowing may not cause appreciable pressure drop (§ 24); this E.M.F. forms a measure of the hot-junction temperature if the temperature of the cold junction be constant. The voltmeter may therefore be calibrated to indicate the temperature of the hot junction. Sometimes the cold junction of the couple can be located where it is always at atmospheric temperature, the indicator scale being then set (automatically or otherwise) to suit the actual temperature of the cold junction. In other cases, the cold junction is immersed in oil in a vacuum flask.

Almost any pair of dissimilar metals will develop a thermo-electric E.M.F. (this being a possible source of error in shunts, potentiometers, etc.), but in choosing metals for a thermo-couple regard must be had to the magnitude of the E.M.F. developed, the uniformity of its variation with temperature, the constancy of the characteristics of the couple, and the temperature up to which the couple can be used. A couple consisting of a platinum wire and a wire of platinum-rhodium alloy can be used up to 1 400° C. (1 550° C. temporarily), but the materials are costly and the E.M.F. is low. Base metal couples give much higher E.M.F. but cannot be used above, say, 800° C.; this, however, covers many industrial requirements.

The approximate characteristics of various couples are given in Table 9; the values of E.M.F. are rough averages—actually, the E.M.F. does not vary linearly with the temperature, and every couple must be used with a calibration curve or with the direct-reading instrument for which it is intended.

Where practicable, couples for use at high temperatures should be sheathed for mechanical protection and to retard corrosion. Nickel-nichrome couples can be used bare for most industrial measurements up to 900° or 1 000° C.; the iron-constantan gives a higher E.M.F. and can be used up to nearly the same temperature but is subject to rapid corrosion. Copper-constantan is an excellent couple for measurements at comparatively low temperatures.

TABLE 9.—*E.M.F. and Temperature Limits for Thermo-Couples.*

Couple.	Average E.M.F. Per 100° C. Difference Between Hot and Cold Junctions.	Maximum Temperature of Use for Ordinary Service.
	mV	° C.
Platinum—platinum-rhodium (10 %)	0·9-1·1	1 400
Platinum—platinum-iridium (10 %)	1·2-1·4	1 000
Nickel—nickel-chromium (10 %)	2·0-2·4	1 000
Chromel *—Alumel †	4·0	1 100
Iron—Constantan ‡	5·5	900
Silver—Constantan	5·5	800
Copper—Constantan	5·5	400

Thermo-couples make possible the measurement of temperature at practically any point in any apparatus, and they can be made to follow accurately rapid variations in temperature. One indicator or a multiple recorder (§ 93) can be used with a great number of couples. Notes on the manufacture and use of thermo-couples are given in a paper reprinted in *El. Rev.*, Vol. 77, p. 748.

(*c*) *Radiation Pyrometers* are specially useful for temperature measurements above 1 000° C. A tube pointed towards the furnace or other hot body receives radiant energy (in amount varying with the fourth power of the absolute temperature) and this energy is focussed upon a thermo-couple the temperature of which (generally about 100° C.) forms a measure of the high temperature observed. The instrument in the thermo-couple circuit is calibrated to indicate the furnace temperature directly

(*d*) *Optical Pyrometers.*—In one useful type, a small lamp filament, viewed against the furnace as background, is made hotter (by increasing the current through it) until it 'matches' the furnace and disappears. An ammeter in the filament circuit is calibrated in degrees of temperature. In conjunction with an absorption screen, this pyrometer can be used to measure temperatures up to 3 000° C.

(*e*) *Magnetic Pyrometers.*—The fact that carbon-steel becomes non-magnetic (§ 84) at that temperature from which it should be quenched, to obtain the finest grain and best hardening in the

* 90 % nickel, 10 % chromium. † 98 % nickel, 2 % aluminium.
‡ 60 % copper, 40 % nickel.

metal, has been utilised as follows: The steel is heated in an electric furnace, the heating winding of which also magnetises the metal. When the metal reaches the correct hardening temperature it becomes non-magnetic, and the collapse of its magnetic field induces a current in an auxiliary winding connected to a galvanometer or alarm-relay. With a few exceptions this method is not applicable to the hardening of alloy steels.

123. Measurement of Speed of Revolution.—Three methods of measuring speeds of revolution, which depend upon electrical apparatus and are of great service in the operation and testing of electrical machinery, utilise respectively: (*a*) the variation in E.M.F. of a magneto-generator; (*b*) the variation in frequency of a magneto-generator or a contact maker; (*c*) the stroboscopic principle.

(*a*) *Speed Measurement by Voltage.*—The E.M.F. of a constant field magneto-generator varies nearly in direct proportion to the speed at which the armature is driven. The machine is therefore direct-coupled or geared to the shaft, etc., under investigation, and the deflection of a voltmeter connected to the magneto-generator is read on a scale calibrated in revolutions per min. By using a D.C. generator in conjunction with a centre-zero moving-coil instrument (§ 101) the direction as well as the speed of rotation can be signalled at a distant point. An A.C. generator of the rotating-magnet type needs no commutator or slip rings, and the direction of rotation can still be signalled by a phase-rotation indicator (§ 150). A uniform scale can be obtained by using a rectifier voltmeter. Special types of speed indicators and signal repeaters are made for use in ships, aircraft, and colliery winding.

(*b*) *Speed Measurement by Frequency.*—The frequency of the E.M.F. developed by an A.C. magneto-generator varies directly with the speed of the machine. It may be measured by a reed-type frequency meter (§ 112) which is calibrated to show the R.P.M. of the driving shaft or machine. Alternatively, a contact maker driven by the shaft, etc., concerned may be used to make and break a D.C. circuit which includes a reed-type frequency meter suitably calibrated. Speed measurement by frequency is exempt from error due to weakening of generator magnets.

(*c*) *Stroboscopes.*—If a disc bearing any geometrical pattern (except a concentric circle) be mounted on the shaft of a synchronous motor and illuminated by an arc lamp connected to the same supply as the motor, the disc will appear to be stationary because, at the moments of maximum illumination from the arc, the pattern on the disc is always in one of two definite positions relative to the poles of the motor if the latter is a two-pole machine. If the motor has more than two poles the pattern is seen successively in a series of definite positions; the apparent form of the pattern is changed but, as seen, the pattern is stationary. If, however, the motor driving the disc be an induction motor the pattern seen will revolve slowly backwards (*i.e.* in the direction opposite to that of the motor revolution), the apparent speed of the pattern being the difference between the synchronous speed of the motor and the actual r.p.m. of the rotor. This difference is the 'slip' of the machine (Chapter 28). The principle involved in both the cases mentioned is that of determining an unknown speed by matching or comparing it visually with a known speed or frequency; the identity of or difference between two speeds can thus be determined with great accuracy over a wide range of values.

Instead of using the fluctuating light of an A.C. arc as the basis of observation, an electrically-operated tuning fork carrying a shutter may be used to open and cover a narrow slit through which is viewed a disc marked with concentric toothed circles with different numbers of teeth. If there be n glimpses through the slit per sec., and if there be N teeth in the ring which appears stationary, it is clear that the disc makes $(1 / N)$ of a revolution in $(1 / n)$ sec., *i.e.* the speed of rotation is n / N revs. per sec.*

Special stroboscopic discs are supplied which assume different geometrical patterns at known speeds, so that from the appearance of the disc and the apparent direction and speed of its rotation it is possible to determine the actual speed over a wide range, with almost perfect accuracy and without taking any power from the machine under test. The relation between speed and time can be determined very accurately by pressing the key of a recording chronograph when the stroboscope indicates known speeds.

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* If there be a larger ring containing $2N$ teeth this will also appear stationary, hence the above calculation must be based on the smallest ring which appears stationary.

Another application of the stroboscopic principle is to the apparent arresting or slowing down of high-speed motion or cyclic events for examination at leisure. For instance, if an A.C. arc be viewed through a narrow slot in a disc driven by an induction motor connected to the same supply, the slip of the motor will cause the arc to be seen at a later moment in each succeeding cycle. If the motor has p pairs of poles and n °/₀ slip, the disc will make $(100-n)/np$ revs. before the same point in the cycle of the arc is again seen. In other words, if a 2-pole motor with 2 °/₀ slip be used, one cycle of the arc will (apparently) be drawn out to occupy $(100-2)/2 = 49$ revs. of the disc or about 1 sec. assuming 50-cycle supply. By retentivity of vision (as in a kinematograph picture) the 49 glimpses of as many consecutive cycles will appear as one slow accurate cycle, unless there are differences between successive actual cycles or unless irregularities occur between the points 'glimpsed.' Such irregularities may be detected by reducing the slip of the motor, thus increasing the number of glimpses per cycle.

The principle explained in the previous paragraph is employed in the Elverson 'oscilloscope' or 'slowing-down' lamp. A neon lamp, mounted in a reflector which screens the observer from direct rays, is switched in circuit by a contact maker driven from the machine observed. If the flash is produced at the same point in successive cycles of the machine's operation the machine appears to be stationary. If, however, a creeper gear be used to advance the phase of the flash by $\frac{1}{100}$ rev. per revolution of the machine, then glimpses from 100 actual revolutions appear as one slow revolution. There is, in fact, an 'optical gear ratio' making the machine appear to run at $\frac{1}{100}$ of its actual speed. By this device the conditions at a particular point in the cycle of operation or the events of a complete cycle can literally be seen under the actual working conditions of the machine. Aero engines, gear teeth, chains, dynamo brushes, and in fact the parts of any machine, whether in rotation or translation, can be examined and vibration can be located and analysed.

124. Relays.—The function of a relay is to control the opening or closing of one or more circuits if and when predetermined conditions arise, such as current overload, reverse power, etc. In delicacy of construction and accuracy of operation relays are comparable with instruments, and they are generally made by instrument makers. A relay to control or be operated by a certain electrical quantity generally works on the same principle as an instrument designed to measure that quantity; indeed, the relay is often identical with the measuring instrument except that the indicating pointer and scale of the latter are replaced by a contact arm moving between fixed contacts. The functions and applications of the more important types of relays are considered in Chapter 15.

125. Bibliography.—(*See* explanatory note, § 58.)

STANDARDISATION REPORTS, ETC.

(1) *I.E.C. Publications.*

No. 38. I.E.C. Standard Voltages.

No. 43. I.E.C. Recommendations for Alternating Current Watt-Hour Meters.

No. 44. I.E.C. Recommendations for Instrument Transformers.

(2) *British Standard Specifications.*

No. 37. Electricity Meters.

No. 81. Instrument Transformers.

No. 89. Indicating Ammeters, Voltmeters, Wattmeters, Frequency and Power Factor Meters.

No. 90. Graphic (Recording or Chart-Recording) Ammeters, Voltmeters, and Wattmeters.

No. 107. Rolled Sections for Magnet Steel.

No. 156. Enamelled Plain Copper Wire for Electrical Instruments and Apparatus; Tentative Dimensions and Resistance of.

No. 354. Photometric Integrators.

No. 358. Measurement of Voltage with Sphere-Gaps, Rules for the.

BOOKS.

Electrical Measurements in Principle and Practice. H. C. Turner and E. H. W. Banner (Chapman & Hall).

Industrial Electrical Measuring Instruments. Edgcumbe and Ockenden (Pitman).

Electrical Measuring Instruments and Supply Meters. D. J. Bolton (Chapman & Hall).

Meter Engineering. J. L. Ferns (Pitman).

Commercial A. C. Measurements. G. W. Stubbings (Chapman & Hall).

Oscillographs. J. T. Irwin (Pitman).

Pyrometers and Pyrometry. Ezer Griffiths (Pitman).

I.E.E. PAPERS.

The Measurement of Flux Density in the Air Path of a Magnetic Circuit. W. P. Conly. Vol. 61, p. 161.

A Direct-Reading Thermionic Voltmeter and its Applications. E. B. Moullin, Vol. 61, p. 295.

Permanent Magnets in Theory and Practice. (Second Paper.) S. Evershed. Vol. 63, p. 725.

Permanent Magnets in Electrical Apparatus. E. A. Watson. Vol. 63, p. 822.

The Use of the Cathode-Ray Tube as a Wattmeter and Phase-Difference Measurer. Sir A. Fleming. Vol. 63, p. 1045.

The Cathode-Ray Oscillograph. A. B. Wood. Vol. 63, p. 1046.

Measurements by means of Cathode-Rays. J. T. M. Morris and R. Mines. Vol. 63, p. 1056.

Recent Advances in Alternating Current Measuring Instruments. K. Edgcumbe and F. E. Ockenden. Vol. 65, p. 553.

Integrating Electricity Meters. E. Fawsett. Vol. 66, p. 443.

Electrical Instruments other than Integrating Meters. C. V. Drysdale. Vol. 66, p. 596.

Precautions in the Use of Standard Instruments. W. H. Lawes. Vol. 67, p. 541.

The Rotor Bearings of Electric Meters. W. Lawson. Vol. 67, p. 1147.

Precision Permeability Measurements. (N.P.L.) C. E. Webb and L. H. Ford. Vol. 67, p. 1302.

Alternate Current Potentiometers. C. V. Drysdale. Vol. 68, p. 339.

Instrument Transformers. T. G. Wellings & C. G. Mayo. Vol. 68, p. 704.

Earthing Resistances. P. J. Higgs. Vol. 68, p. 736.

The Piezo-Electric Crystal as a Frequency Standard. H. J. Lucas. Vol. 68, p. 855.

Apparatus for Precise Measurement of Alternating Current. (N.P.L.) R. S. J. Spilsbury and A. H. M. Arnold. Vol. 68, p. 889.

Frequency Variations in Induction Watt-Hour Meters. A. E. Moore and W. T. Slater. Vol. 68, p. 1023.

Development of the Thermionic Voltmeter. E. B. Moullin. Vol. 68, p. 1039.

A Voltage Transformer for use in the Measurement of Small Voltages. A. H. M. Arnold. Vol. 69, p. 156.

Electrical Measuring Instruments. C. V. Drysdale. Vol. 69, p. 170.

Integrating Meters. E. Fawsett. Vol. 69, p. 545.

Accurate Maintenance of Large A.C. Energy Meters. E. Fawsett and G. E. Moore. Vol. 69, p. 647.

Pivots and Jewels in Instruments and Meters. V. Scott. Vol. 69, p. 751.

High Voltage Precision Measurements. Prof. W. M. Thornton. Vol. 69, p. 1273.

The Metering of Three-Phase Supplies. O. Howarth. Vol. 69, p. 381.

Future Progress in Electrical Measuring Instruments. C. V. Drysdale. Vol. 72, p. 365.

The Equipment and Operation of a Modern Meter and Test Department. J. B. Lees. Vol. 75, p. 41.

A Study of the Induction Watt-Hour Meter, with special reference to the Cause of Errors on Very Low Loads. T. Havekin. Vol. 77, p. 355.

Some New High-Tension Measuring Instruments. W. M. Thornton. Vol. 79, p. 483.

Organization of a Meter Test Department of a Large Supply Undertaking, with special reference to the Electricity Supply (Meters) Act, 1936. C. W. Hughes. Vol. 82, p. 410.

PART II.—GENERATION: PRIME MOVERS: SALE OF ELECTRICAL ENERGY.

CHAPTER 4.

GENERATORS AND THEIR ACCESSORIES.

126. Sources of Electrical Energy.—Electricity being a form of energy it cannot be 'generated' in the strict sense of the word, but can only be obtained by conversion from some other form of energy. It is desirable that this fact should be realised, but having emphasised it, we may follow universal practice by speaking of electric 'generators' and the 'generation' of electrical energy without qualification. Probably every form of energy can, by appropriate means, be converted into electricity, the losses incidental to the conversion varying with the initial form of energy and with the method of conversion employed. The principal sources and methods known at present are discussed in the succeeding paragraphs; they are:—

(i) Electro-chemical generators or primary cells.
(ii) Thermo-couples.
(iii) The piezo-effect.
(iv) Electrostatic generators.
(v) Dynamo-electric or electromagnetic generators.

Of these well-defined types only the electro-chemical and dynamo-electric generators are of any importance as sources of electricity for lighting, power, and similar commercial purposes; and for all but weak currents, or under special circumstances, dynamo-electric generators are alone employed. Without dynamo-electric machines electrical engineering, as we know it, would be non-existent, but the other sources of electricity are of definite importance.

127. Electro-Chemical Generators: Primary Batteries.—Although the terms are used somewhat indiscriminately, a 'battery' more properly consists of a number of single 'cells' connected together—each cell consisting of two plates or elements of dissimilar substances (one electro-positive to the other, *vide* Table 10) in a bath of 'electrolyte' which has a chemical affinity for one or both of them. Between the two plates there will then be a fixed difference of potential, and if they are connected together externally, a current will flow in the circuit in accordance with Ohm's Law (§ 17 as modified in § 21). The electrical energy generated is due to chemical change in the elements and is proportional to it in amount.

Conversely, a current from an external source will cause chemical changes to take place in a similar arrangement of plates and electrolyte, as in an electroplating bath and the like. On this latter principle elements are obtained from their compounds by 'electrolysis'; and accidental electrolysis, from leakage currents, or currents using 'earth' as a path, may also have a destructive effect on water pipes or the lead sheathing of wires and cables.

The distinction between primary cells and secondary cells (Chapter 18) is as follows: The component parts of a primary cell are assembled in the form in which they are used, and then yield electrical energy as the equivalent of chemical action which proceeds until the active elements are consumed; the cell is then exhausted and must be more or less completely rebuilt with fresh materials. In a secondary cell, on the other hand, the plates are 'formed' and brought to a suitable state of dissimilarity by passing electricity through the cell, which is then said to be 'charged' and is capable of yielding a current by reversal of the chemical changes effected during the charging operation. When discharged, a secondary cell can be recharged as before, and the cycle can be repeated until the plates disintegrate or become deteriorated by permanent chemical action.

The practical applications of primary cells are restricted to weak current services—such as bell ringing, portable flash lamps alarm and signal circuits, etc.—unless the convenience of electricity and the absence of any other source thereof justify the abnormally high cost of producing it by chemical means. The electro-positive element or 'anode' (generally zinc) is dissolved away in the electrolyte in proportion to the ampere-hours generated (§ 28), and the electro-negative element or 'kathode' (commonly copper or carbon) generally remains unaltered. The two elements constitute a galvanic 'couple.' The conventional direction of the current is from the anode, through the electrolyte, to the kathode and thence back to the anode through the external circuit; the zinc or electro-positive element will therefore be the negative pole of the cell and the electro-negative carbon or copper will be the positive pole in a ZnC or ZnCu cell. In an electrolytic cell (*e.g.* a plating vat) the anode is similarly the plate through which the current enters the electrolyte and the kathode is that by which the current leaves the same.

Table 10 represents approximately the electro-chemical series of certain elements. Those occurring at the head of the list are said to be electro-positive relatively to those lower down; but the sequence depends to some extent on temperature and electrolyte.

TABLE 10.—*Electro-chemical Series of Elements.*

1. Cæsium.	8. Manganese.	15. Tin.	22. Gold.
2. Potassium.	9. Zinc.	16. Bismuth.	23. Antimony.
3. Sodium.	10. Iron.	17. Copper.	24. Carbon.
4. Calcium.	11. Cadmium.	18. Hydrogen.	25. Nitrogen.
5. Magnesium.	12. Nickel.	19. Mercury.	26. Chlorine.
6. Aluminium.	13. Cobalt.	20. Silver.	27. Oxygen.
7. Chromium.	14. Lead.	21. Platinum.	28. Fluorine.

The farther apart in the list the elements chosen, the higher the E.M.F. produced. The E.M.F. developed in a primary cell composed of any two of these elements in a suitable electrolyte is proportional to the heat of formation of the resulting compound.

Various types of primary cell are made according to whether a considerable steady current is required or merely an occasional momentary current, as for electric bells, and so forth. In a cell of the original type devised by Volta, the electrodes are zinc and copper, and the electrolyte is dilute sulphuric acid; when such a cell is in use it 'polarises' rapidly owing to hydrogen collecting on the copper, thus increasing the internal resistance of the cell besides establishing a back E.M.F. which reduces the E.M.F. available at the terminals. In the Daniell cell the zinc anode is in sulphuric acid contained by a porous pot, the latter being immersed in an outer vessel containing the copper kathode and a solution of copper sulphate; copper instead of hydrogen is liberated at the kathode of this cell, polarisation is eliminated, and the E.M.F. remains so nearly constant (at 1·1 V) that the cell can be used as a standard cell (§ 128) for rough standardisation tests. The bichromate or Fuller cell uses zinc and carbon electrodes with sulphuric acid as active electrolyte and potassium bichromate as depolariser; this cell has high E.M.F. (2·2 V) and low internal resistance, and is therefore suitable where relatively heavy current is required. The Leclanché cell uses zinc and carbon electrodes in an electrolyte of sal-ammoniac, with manganese dioxide as depolariser round the carbon; when suitably constructed this cell is capable of maintaining relatively heavy current for long periods, but the ordinary porous-pot type polarises quickly; the E.M.F. is about 1·45 V per cell. So-called 'dry' cells are of the

Leclanché type with only sufficient water added to render the paste between the electrodes a reasonably good conductor; the internal resistance is much higher than that of the wet-type cell, and whereas the latter deteriorates very slowly on open circuit, a 'dry' cell may become exhausted by 'local action' within a few months of its being moistened, even though no current be taken for an external circuit.

Secondary batteries (accumulators) are dealt with in Chapter 18, Vol. 2.

128. Standard Cells.—For the accurate determination of electric pressures 'standard cells' are used, these being primary batteries whose potential difference at any temperature is very accurately known; practically no current is drawn from them, the E.M.F. being merely balanced against a known proportion of the E.M.F. to be determined (§ 95). The Clark standard cell consists of zinc and mercury, in an electrolyte of mercurous and zinc sulphate. Its E.M.F. is 1·432 8 V at 15° C., decreasing by 0·083 °/₀ per 1° C. rise of temperature. The Weston normal standard cell, which is now generally used, employs cadmium amalgam instead of zinc and cadmium sulphate instead of zinc sulphate. The E.M.F. is 1·018 3 V at 20° C. and the temperature coefficient is almost negligible, *viz.* 0·004 °/₀ per 1° C.

It is important to note that a standard cell should be regarded as a generator of known E.M.F. and not as a source of current. It should be used only to calibrate potentiometers (§ 95), no current flowing through the cell when balance is established. During the process of balancing, the cell should be in circuit for as short a time as possible because it is subject to appreciable polarisation, and its E.M.F. (on open or balanced circuit) then differs from standard until depolarisation has been effected; this may take hours if much current has passed through the cell.

129. Thermo-couples.—If two wires of different metals be joined at their ends and one junction be hotter than the other there is produced a thermo-electric E.M.F. which sends a current round the circuit so long as the temperature difference between

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* The zinc gradually becomes encased by crystals which should be scraped off, the clean metal then being re-amalgamated with mercury. The porous pots increase in resistance from a similar cause and the depolariser becomes exhausted; the pots may be 'revived' to a considerable extent by soaking them for 24 hrs. in weak hydrochloric acid (1 part commercial acid to 5 parts water).

the two junctions is maintained. Many attempts have been made to utilise this property for the direct conversion of heat to electrical energy, but the practical difficulties are great and apparently insuperable. The E.M.F. is low, say 5 mV per 100° C. difference in temperature between the junction as an average (§ 122), hence an enormous number of couples are required in series to produce even 100 V; similarly, an immense number of such groups must be coupled in parallel to give any commercially useful current. The cost of assembling and maintaining the couples is high and, finally, the overall efficiency is low because, although the losses of the steam engine or turbine are avoided (§ 166), the absorption of heat by the hot junctions is of indifferent efficiency and the heat conducted along the couples must be lost by radiation or removed by artificial cooling of the cold junctions. Though there seem to be no prospects for thermo-couples as generators of electricity for commercial purposes, they are most valuable in pyrometry (§ 122). Thermo-electric E.M.F. is also important as a possible source of error in measuring instruments and circuits (§ 107). (*See also* § 165.)

130. Piezo-Electric Effect.—The application of mechanical pressure to crystals of certain substances—among them tourmaline, quartz, and fluorspar—on diametrically opposite faces parallel to the major axis of the crystal, sets up a P.D. between the faces perpendicular to those on which the mechanical pressure is applied. This phenomenon offers a means of obtaining small known charges of electricity for purposes of research on radioactivity, atomic structure, etc. It has been suggested * that the converse phenomenon, *viz.* mechanical distortion of the crystal by the application of a P.D. to its faces, is partially responsible for the gradual deterioration of high-tension porcelain insulators in service. The piezo-electric effect is of no present importance as a means of obtaining a continuous flow of electricity. It has been utilised in the measurement of high pressures † (in guns, etc.) up to 50 000 lbs. / sq. in. Applications of the piezo-electric effect to microphones and gramophone reproducers are described in 'Commercial Piezo-Electricity,' E. W. C. Russell and A. F. R. Cotton, *El. Rev.*, vol. 92, p. 284.

* W. D. A. Peaslee, *Jour. Amer. I.E.E.*, Vol. 39, p. 447.
† Bureau of Standards, Scientific Paper No. 445.

131. Electrostatic Generators.—It is well known that when two dissimilar substances are rubbed together they become electrified; for instance, the vulcanite cap of a fountain pen, after being rubbed on dry cloth, will pick up fragments of paper by electrostatic attraction. This phenomenon is applied to the production of very weak current at high voltage in the *frictional machine* which consists of a disc or cylinder of glass rotated between rubbing pads of soft leather; the charge produced on the glass is drawn off by metal combs. Greater quantities of electricity can be produced with greater ease and certainty by *influence machines*, of which the Wimshurst pattern is the best known, though not the most efficient. The principle employed in influence machines is that of rotating two carrier plates about a spindle placed between two fixed plates. The fixed plates are given small initial charges of opposite polarity (by friction). With the carrier plates temporarily connected electrically to each other and placed adjacent to the fixed plates, the positive fixed plate induces a negative charge on the carrier near it, and the negative fixed plate induces a positive charge on its carrier. The positive charge repelled from the first carrier is neutralised by the negative charge repelled from the second carrier. The connection between the carriers is now broken, leaving isolated positive and negative charges upon them, and the spindle is turned through half a revolution thus bringing the carriers to the similarly charged fixed plates to which they add their charge. By multiplying the number of fixed and moving plates and perfecting the mechanical details influence machines have been constructed which need 1 h.p. or more to drive them and which yield an output of several milliamperes at a pressure in the neighbourhood of 500 000 V (sufficient to break down a 12-14 in. air gap). Modern influence machines find applications in electro-therapeutics, X-ray production, electro-culture (Chapter 33), testing materials, electrostatic separation and precipitation (§ 996, Vol. 3), etc. In his book on the subject (§ 152), V. E. Johnson estimates that the efficiency of the best influence machines is about 45 °/ₒ, and states that there is no theoretical reason why the efficiency should not be as high as that of dynamo-electric generators. The same author describes a $\frac{1}{8}$ h.p. electrostatic motor of his own design and construction. Though it is improbable that electrostatic generators and motors can ever compete with high-power electromagnetic machines, their development should not be overlooked.

132. Dynamo-Electric or Electromagnetic Generators.—The dynamo-electric generator—usually termed a 'dynamo' or 'generator'—is a machine for converting mechanical power into electrical power, through the medium of electromagnetic induction (§ 35); to be effective, it must be driven by mechanical power, *viz.* steam, gas, oil, water, or other; this is converted by electromagnetic induction into electrical energy. The broad principle on which the working of generators is based will be seen from Figs. 28 and 29.

These figures are identical except as regards the arrangements for collecting the current. In both a coil of conducting wire, which may have any number of convolutions, is so placed that it can be rotated between the north and south poles (*N*, *S*) of a permanent steel magnet; in so doing the coil cuts across the lines of

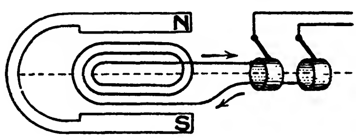

FIG. 28.—Diagrammatic representation of electric generator, with current collection from slip rings.

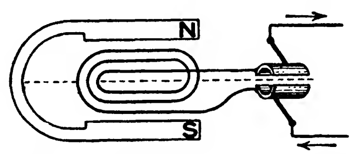

FIG. 29.—Diagrammatic representation of electric generator, with current collection from commutator.

magnetic force, which run from pole to pole, and an E.M.F. is consequently induced in the coil. The latter (the armature or rotor) in the figure is supposed to be spun around the longitudinal dotted axis, the upper portion coming *towards* the observer. The arrows then show the direction of the induced current in the wire, assuming that there is a closed electrical circuit, between the ends of the external wires, in which the current can flow. If there is no such circuit an E.M.F. is nevertheless induced, tending to cause a current to flow in the same direction; but as the resistance is infinite the current is nil. When the coil is at right angles to the position depicted, it is neutrally placed with respect to the poles of the magnet, and for the moment no E.M.F. is induced and no current flows; thereafter the part of the coil that was under the influence of the north pole comes under that of the south pole, and *vice versa,* so the direction of the E.M.F. (and of the consequent current in the coil, if any) reverses. This reversal happens twice in each revolution, so that an 'alternating' current (§ 11) is invariably generated *in the coils.**

Herein lies the distinction between Figs. 28 and 29. In the former the two ends of the coil of wire are connected to two independent metal contact rings, each with a collector or 'brush' rubbing against it, so that the alternating current is led away as it is generated to the external circuit. These two rings will alternately be + and − at each half revolution of the coil. In Fig. 29, however, there is a single contact ring, or commutator, split horizontally, and revolving with the coil, with fixed brushes rubbing on it above and below; at the moment the wave of current in the coil has died down to zero, as explained above, the brushes cross the gap in the ring and consequently reverse their connections to the ends of the coil. The connections of the armature coil to the external circuit are reversed simultaneously with the reversal of current flow in the armature winding, so that the alternating current in the coil is commuted into a unidirectional or rectified current (§ 13) in the external circuit. The top brush will then be always positive and the lower brush negative. It must be remembered that *relative* motion of the magnet system or 'field' and the coil system or 'armature' is essential; consequently, if the coil is stationary and the magnet is revolved around it in the opposite direction, precisely the same results will follow; both methods are in fact used.† In actual generators used for power purposes the permanent magnet is replaced by an electromagnet or a number of electromagnets (§ 32), while a series of armature coils replace the single coil; and the two-part commutator (in a dynamo) is replaced by one with many segments, corresponding with the number of coils. Each coil then in turn generates its own wave, which is rectified by the corresponding segments of the commutator, and the result is that all the separate waves of current overlap, and the succession of waves of rectified alternating current becomes a continuous current, as explained in §§ 13, 14.

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* This statement does not apply to homopolar generators (§ 137).

† Though the direction of a magnetic field and the direction of flow of a current in a conductor are matters of convention (§§ 32, 127) there is a definite relation between the conventional directions of field and current and that of the relative motion between the field and the current-carrying conductor. Professor Sir Ambrose Fleming's rule or mnemonic for the determination of the third of these factors when any two are known is stated in § 35.

The term 'dynamo' is generally reserved for direct or continuous current generators (Fig. 29), machines which deliver alternating current to the external circuit (Fig. 28) being termed 'alternators.'

Reversibility of Generators; Motors.—In theory, and for the most part in practice also, an electric generator is reversible, and can be used also as a motor.* In the two diagrams of a simple dynamo and alternator above, if continuous or alternating current (as the case may be) is supplied to the brushes from an external source the coils will revolve. The current creates a magnetic field around the coil (§ 32), which is under the influence of the steel magnet, and the tendency of the coil is then to set itself at right angles to the poles of the steel magnet. But the reversal of the direction of the current by the commutator in the one case and by the natural alternation in the other case, occurs just at the right moment to cause the coil to make another half turn; and so on indefinitely. By increasing the number of coils this primitive machine is converted into a practical motor. While the coil is thus revolving in a magnetic field, an E.M.F. is generated in it by induction, *opposing* the applied or impressed E.M.F. of the circuit as mentioned in § 35; this is called the back- or counter-E.M.F. (§ 669, Vol. 3).

133. **Component Parts of Generators.**—From the preceding paragraph it will be seen that, according to the method of current collection, the same machine can theoretically be used as either a continuous-current generator or an alternating-current generator, and this is actually done in the case of the rotary converter (§ 408 *et seq.*, Vol. 2). As a rule, however, the general arrangement of D.C. and A.C. generators is different for reasons stated below. In a dynamo the magnets are fixed and the drum of rotating coils (wound on a laminated iron core), in which current is induced, is called the 'armature.' The wave of current is rectified by the 'commutator,' which is a cylindrical body, mounted on the shaft of the armature and revolving with it, consisting of a large number of radial conducting bars insulated from one another, but electrically connected to the coils of the armature winding. The 'brushes' make contact with the commutator, as shown in Fig. 29 (§ 132), collecting and conveying the current to (or, in the case of motors, from) the external circuit.†

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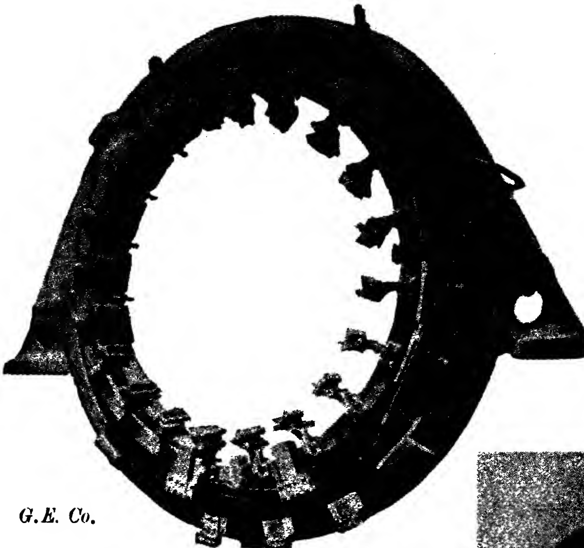
* Sometimes, as in balancing motor-generator sets, the two functions are intentionally combined in a single machine, which is working at one moment as a motor and the next as a generator (§§ 388, 461, Vol. 2).

† Carbon brushes are now employed almost universally because they facilitate sparkless commutation. In practice there are many coils on the armature and a corresponding number of bars in the commutator. The width of the brush is limited (for reasons of commutation) to that of two or three commutator bars and, as the current-carrying capacity of carbon is low (§ 66), it is generally necessary



G.E. Co.

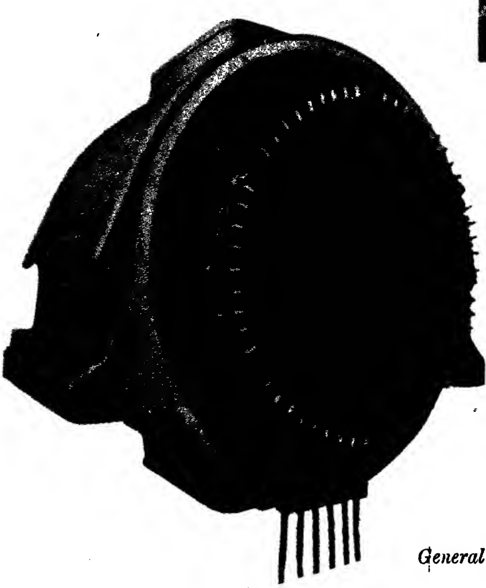
FIELD FRAME AND BRUSH GEAR FOR LOW-SPEED D.C. GENERATOR.

This generator is rated at 1 150 kW, 220 V, 115 r.p.m., and is driven by a gas engine working on blast furnace gas.

ROTATING FIELD FOR LOW-SPEED ALTERNATOR.

This rotor is driven at 115 r.p.m. by a gas engine working on blast furnace gas. The stator output is 1 200 kVA at 440 V, 3-phase, 25 cycles / sec.

General Electric Co., Ltd.

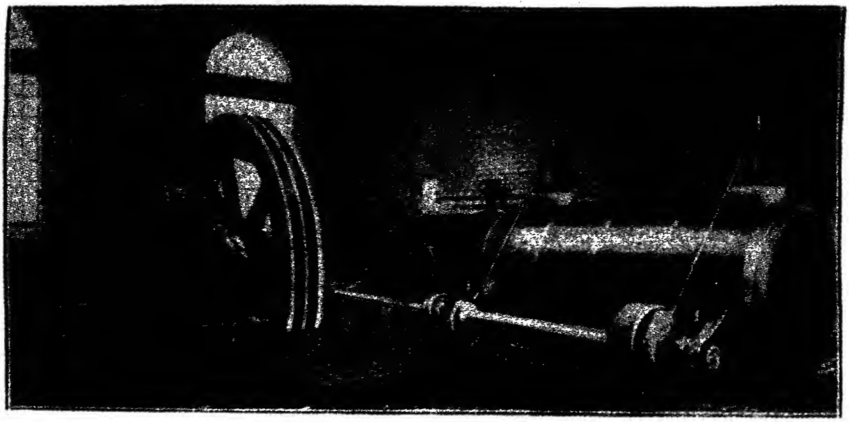


STATOR FOR HIGH SPEED TURBO-ALTERNATOR.

The rating of this machine is 6 000 kVA at 6 600 V, 3-phase, 50 cycles, and the rotor is driven at 3 000 r.p.m. The illustration shows clearly the method of supporting the end windings.

General Electric Co., Ltd. (*London*).

[*To face p.* 220.



Robey & Co., Ltd.

1 100 I.H.P. 'Uniflow' Engine Direct-coupled to a D.C. Generator.

In the 'uniflow' engine the whole range of expansion of the steam from boiler pressure to condenser pressure is effected in a single cylinder. The steam flows from the inlet valves at each end of the cylinder to the exhaust ports at the centre and never in the reverse direction, hence the live steam does not come in contact with surfaces cooled by the exhaust. This greatly reduces condensation losses and it is claimed that the 'uniflow' engine is as economical as a triple-expansion engine.

Mather & Platt, Ltd.

D.C. Generator Driven through Gearing from a Steam Turbine.

Geared turbines are now used extensively to drive A.C. or D.C. generators of from 500 to 2 500 kW capacity. The main advantage in A.C. installations is that the turbine can be run at much higher speed, and can therefore be designed more efficiently, than if direct coupling were employed. For D.C. work there is the additional advantage that the generator can be designed on ordinary lines, avoiding the mechanical and commutation difficulties associated with high speeds. The illustration shows a generator rated at 500 kW, 125 V, 4 000 A, and particular attention is called to the large commutator and separate yoke for the brush gear needed to deal with this heavy current.

[*To face p.* 221.

The system of electromagnets in a generator, with its energising coils, creates the magnetic 'field,' and the coils are called the field 'winding' or 'field magnets.' The exciting or field current may be obtained from the armature of the generator itself in the case of a D.C. machine (§ 138) or a separate 'exciter' dynamo may be used (§ 140); in the former case the machine is 'self-excited,' in the latter 'separately excited.' Alternators are necessarily separately excited. The use of interpoles is discussed in § 139.

In an alternating current machine the fixed part is called the 'stator,' and the moving part the 'rotor'; either may consist of the field system or of the coils in which the current is induced, but it is generally more convenient to place the alternating current windings on the stator, continuous current being then led to the field coils on the rotor through slip rings.

A 'slip ring' or 'collector ring' is a plain conducting ring, revolving with the shaft, for effecting (by means of a brush) a sliding connection between a fixed conductor and a revolving conductor (Fig. 28). Slip rings are used for conveying continuous current to a revolving magnet or for conveying alternating current to or from a revolving armature. In a D.C. or A.C. motor the component parts correspond to those in a generator; motors are further considered in Chapter 28.

Unlike motors, generators are usually placed in dry, clean surroundings and have all the advantages of skilled supervision; it is therefore generally unnecessary to enclose them in the sense that motors are enclosed as protection against dust, moisture, etc. (§ 670, Vol. 3). Where very large generators are concerned, however, the amount of heat to be dissipated from the windings is so great that the natural ventilation from an open type of construction is inadequate, and it becomes necessary to enclose the machine so that a forced current of air or hydrogen may be driven through it (§ 146).

134. Types of Generators and Supply Characteristics.— Classified according to the form in which electrical energy is

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to use two or more brushes on each spindle, *i.e.* on each line of current collection from the commutator. To prevent the brushes from wearing grooves in the commutator they are staggered so that their tracks overlap. If there are more than two brush spindles alternate *pairs* of spindles and *not* alternate spindles should be staggered. Each positive brush then runs on the same track as a negative brush and uneven wear due to polarity effects is eliminated.

delivered to the external circuit there are two main classes of generators, *viz.* continuous-current generators and alternating-current generators, but each of these classes may be subdivided, according to the electrical characteristics of the types of generators available in each group. The homopolar or acyclic D.C. generator (§ 137) is characterised by the fact that it has no commutator; and series-wound, shunt-wound, and compound-wound D.C. generators (§ 138) have quite different voltage-load curves owing to the different methods by which they are excited. Alternators may be single-, 2-, or 3-phase machines; the distinction between the three types is explained in §§ 11, 15, 16.

The relative merits of continuous current, single-phase current, and 3-phase current in relation to the transmission and distribution of electricity are considered in Chapters 14 and 20. (*See also* Chapters 28 to 32.) For heating and cooking D.C. and A.C. are equally suitable (§ 29), except that A.C. supply offers the possibility of easy transformation to low pressures where required. For lighting by filament lamps A.C. of 50 cycles per sec. or higher frequency is for all practical purposes quite as suitable as D.C. supply. For power applications D.C. motors have the advantage of excellent starting and speed-control characteristics (Chapters 28, 29), and where these characteristics are particularly required it is essential to use continuous current. The total load on modern stations is, however, so great that it is economically essential to use high pressure in all but local feeders and consumers' circuits; the supply up to the consumers' premises is at not less than 3 000 V where large industrial loads are concerned. This consideration, and the fact that the pressure of A.C. supply can be changed by static transformers, whereas D.C. requires the use of rotating machinery for pressure changing (Chapter 17), has made A.C. generation and transmission standard in all new installations. Of the three main types of A.C. supply—single, 2-, and 3-phase—2-phase current offers no advantages and is not likely to be employed in any new generating plant. Three-phase current is immeasurably superior to single-phase current for general power applications, and where a simple 2-wire supply is required (as for domestic lighting, small motors, etc.), it can be taken from 3-phase mains provided that the total single-phase load is distributed reasonably uniformly between the three-phases of the main supply. In small stations the simplicity of single-phase circuits, switchboards, and instruments is a consideration, but in this country the majority of such stations will ultimately become distributing centres taking supply in bulk from 3-phase generating and transmitting systems (§ 186).

The standard station voltages (§ 23) for new installations in this country are 250 V and 500 V for D.C. systems, and 440 V, 3 300 V, 11 000 V, and 33 000 V for 3-phase systems. In the latter 11 000 V is the highest pressure (between phases) for which generators are usually wound, and 6 600 V generators are usually the most economical; higher 'station pressure' is obtained by connecting transformers between generator and line.

The standard frequency of A.C. supply in this country is 50 cycles per sec.,* with 25 cycles per sec. as a secondary standard (§ 12); in America 60-cycle supply is used very extensively. The effects and importance of frequency are discussed in the next paragraph.

135. Effects of Frequency in A.C. Circuits.—No frequency of supply can be said to be preferable to all other frequencies; higher frequency is more favourable to some parts of a complete system and less favourable to others, hence the frequency adopted must be in the nature of a compromise. In any A.C. circuit the frequency of supply has as much effect as the voltage on the characteristics of the circuit, but whereas the voltage can be changed easily and efficiently by use of static transformers, it has rarely been practicable to change the frequency until quite recently.

Dr. E. F. W. Alexanderson of the G.E.C. (Schenectady) has, however, developed a method of frequency-changing by means of vacuum-tube control,† which has enabled a synchronous motor to be operated at various speeds. The demonstration equipment consisted of a 400 H.P. motor and 18 Thyratron tubes, into which power was directly fed at 4 000 V. The tubes convert this power to different frequencies, resulting in adjustable speed of the motor. The tubes, in fact, as stated by the inventor, 'perform the function of a commutator. The grid control makes it possible to start with full torque from standstill, and to operate the motor at any desired speed without wasting power in resistances.' This control may help to solve the problem of electric marine propulsion (§ 960) in which a high-speed turbine has to drive a variable low-speed propeller; for it will now be possible to operate the turbine at constant speed and to vary the propeller speed by valve-controlled frequency changing.

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* An internationally recognised name for the unit of frequency (1 cycle per second) is *hertz*, for which the abbreviation *hz* is generally employed. Thus, 50 hz = 50 cycles per second.

† *Gen. El. Rev.*, Vol. 36, p. 292.

The principal effects of changes in frequency are its effect on: (1) the impedance of an A.C. circuit (§§ 44, 46); (2) the E.M.F. induced by an alternating flux; (3) the synchronous speed of generators, motors, etc.

1. *Frequency and Impedance.*—The inductive reactance of a circuit is $X_L = 2\pi fL$ ohms (§ 44), and thus increases directly with the frequency. The pressure drop due to the inductance of a given transmission line, choking coil, or other inductive apparatus, therefore, increases in proportion to the frequency. The capacity reactance, on the other hand, is $X_C = 1 / 2\pi fC$ (§ 46) and, therefore, decreases with increasing frequency. The capacity of a circuit is equivalent to a negative resistance as regards pressure regulation, *i.e.* the voltage along the circuit is increased, and to an extent which increases with the frequency. When the capacity reactance equals the inductive reactance, the condition of resonance (§ 47) is established; the frequency is of equal importance with the inductance and capacity in determining the resonance. The charging current of a transmission line (or any other condenser) increases as the frequency rises. For short distances and low voltages the higher reactance drop in transmission lines at higher supply frequencies is of appreciable importance, but in long distance, high-voltage lines the capacity effect is important, and the net voltage regulation is quite satisfactory at 60 cycles / sec. (the highest frequency used in long-distance lines).

The pressure drop due to skin effect (§ 38) increases with the sectional area and magnetic permeability of conductors, and with the frequency of supply (§ 309). It is an important factor in steel conductor rails (§ 905, Vol. 3); in these, the pressure drop due to reactance and skin effect is roughly twice as great at 50 cycles as at 15 cycles / sec., and is 5 or 10 times as great at 50 cycles / sec. as with direct current, according to the current density employed. The eddy current loss in stator conductors increases with frequency, and has to be taken into consideration in the design of large generators.

(2) *Frequency and Induced E.M.F.*—The general formula for the E.M.F. induced in a coil of T turns by an alternating magnetic flux of maximum value ϕ, and of frequency f, is: $E = kf\phi T$, where k is a numerical factor. Two cases arise: (i) that of a particular winding (*i.e.* T constant) used on or subjected to different frequencies; (ii) that of a winding in which the number

of turns is varied so that the maximum flux ϕ is the same at two different frequencies f_1, f_2. It is assumed that, in both cases, the applied or induced E.M.F. E is the same. These assumptions involve the product $f\phi$ being constant in case (i), and the product fT being constant in case (ii).

Case (*i*) is that of a winding designed for one frequency and operated on another. The consequences are:—

(*a*) Reduced frequency f demands greater flux, ϕ, for the same E.M.F., E. This involves increased magnetising current and lower power factor.

(*b*) The hysteresis loss (§ 34) increases with $\phi^{1 \cdot 6}$, but this increase is partly compensated by the lower frequency with which the cycle is completed. The eddy current loss (§ 39) varies with $f^2 \phi^2$, and is, therefore, constant in the case considered.

(*c*) The higher magnetising current required to produce the greater flux involves higher copper loss and, therefore, reduced efficiency.

Case (*ii*) is that of a constant-flux winding, the number of turns in the latter being varied to suit the changed frequency. In this case, T is increased as f decreases, ϕ remaining constant, but at the lower frequency a higher flux density is permissible for the same hysteresis and eddy current losses, hence the iron circuit may be lighter (§ 41). At 40 or 50 cycles / sec., or higher frequencies, the iron losses often determine the permissible flux density, whereas at 25 cycles and lower frequencies the limit to flux density is that of magnetic saturation (§ 43).

(3) *Frequency and Synchronous Speed.*—The relation between the 'synchronous speed' n r.p.m.; the number p of *pairs* of magnetic poles in a generator, motor, etc.; and the supply frequency f cycles / sec., is $n = 60f / p$. This formula gives the actual speed of any synchronous machine (*e.g.* alternator, synchronous motor, rotary converter), but the actual speed of an induction motor is less than the synchronous speed by the amount of the slip which varies with the design of the machine and increases with the load.

The synchronous speeds of machines with from 2 to 12 poles, when operating on supply frequencies of 15, 25, 50, and 60 cycles / sec. are shown in Table 11. These figures show clearly: (i) The fewer number of poles required at lower frequency for given speed (r.p.m.), and hence the advantage of low-frequency supply where motors of very low speed are required. Except in very heavy driving (*e.g.* steel mills) it is cheaper to use high-speed motors with gear reduction; 50-cycle supply is then as

TABLE 11.—*Synchronous Speed at Various Frequencies.*

Number of Field Poles.	Synchronous Speed, Revs. per Min., with Supply Frequency.			
	15 Cycles.	25 Cycles.	50 Cycles.	60 Cycles.
2	900	1 500	3 000	3 600
4	450	750	1 500	1 800
6	300	500	1 000	1 200
8	225	375	750	900
10	180	300	600	720
12	150	250	500	600

convenient as 25-cycle supply. (ii) The greater number of available synchronous speeds where higher frequency is employed, *e.g.* only one intermediate speed between 500 and 1 500 r.p.m. with 25-cycle supply, compared with three intermediate speeds when 50-cycle supply is used. This is an important consideration.

(4) *Influence of Frequency in Specific Applications.*—The general effects of high and low frequencies, within the range of values used in commercial supply, may be summarised as follows:—

GENERATORS.—The maximum speed for a 15-cycle generator is 900 r.p.m. (Table 11) which is low for driving by steam turbine. At 25-cycles a 2-pole machine must be used for 1 500 r.p.m., whereas a lighter 4-pole machine could be used for 50-cycles and the same speed. The iron losses are lower at lower frequency. The electrical phase angle corresponding to a given mechanical displacement of the rotor is smaller in low-frequency than in high-frequency generators for the same speed; this means that engine-driven generators can be operated in parallel more easily and stably at low than at high frequencies; the distinction does not arise where turbines are used because these have no cyclic irregularity of speed. Large turbo-alternators (say 15 000 kw.) are about 10 °/₀ dearer for 25 cycles than for 50 cycles.

TRANSFORMERS.—The efficiency of a particular transformer is higher at higher frequency for the same E.M.F. (*see* (2) *Case* (*i*) above). On the other hand, in the case of transformers designed for the frequency on which they are operated, the losses are lower at lower frequency; if the maximum flux density is limited by the permissible iron losses the low-frequency transformer is at an advantage, but if special low-loss steel be used the permissible flux density is determined by saturation, and the less weight of steel required in a 50-cycle transformer compared with a 25-cycle transformer more than compensates for the higher losses in the former. Modern 50-cycle transformers are generally 25 to 30 °/₀ lighter and about 25 °/₀ cheaper than 25-cycle transformers for the same output.

TRANSMISSION LINES.—As explained in section (1) above, lower frequency results in lower voltage drop unless the electrostatic capacity of the line is considerable, in which case the inductive drop may be reduced, balanced or even overbalanced (§ 318).

MOTORS.—At given speed a synchronous motor is pulled out of step or caused to 'hunt' more easily if the frequency be higher because the number of poles is then greater (Table 11) and the electrical displacement corresponding to given mechanical displacement is greater.

A given induction motor will generally operate satisfactorily with $\pm$ 10 % variation from the frequency for which it was designed. For given synchronous speed, the number of poles required decreases as the frequency is lowered (Table 11), and the fewer the poles, the higher the power factor (§ 681, Vol. 3) and the higher the overload capacity. On the other hand, the low-frequency motor is generally larger and more expensive. For equal power factor a low-speed 25-cycle machine is smaller and cheaper than a 50-cycle motor, but as the condenser capacity required to compensate for the wattless component is relatively less at higher frequencies (§ 160*a*), the 50-cycle machine can compete if it is designed for low P.F. and used in conjunction with a phase advancer; this is practicable only in the case of large motors.

The series-wound single-phase commutator motor is the principal machine benefiting by a supply frequency lower than 25 cycles. The inductance drop in the field and armature windings decreases as the frequency is lowered, and the power factor and efficiency are therefore improved. At the same time, the E.M.F. induced in the coils short-circuited by the brushes is reduced, and commutation is better at lower frequency. Where these motors are used for traction a frequency of 15-cycles / sec. is sometimes employed, but below 25-cycles there is a risk of slipping at the driving wheels due to variations in the torque which is necessarily zero every half-cycle in a single-phase motor. For the same service 15-cycle motors of this type are lighter than 25-cycle motors and, since greater output can be obtained from a 15-cycle motor of given size, it is often possible to use fewer motors on the train. This more than compensates for the lighter 25-cycle transformers.

LIGHTING.—Arc lamps operate more steadily and efficiently on 50-cycle than on 25-cycle supply, but filament lamps operate equally well on all frequencies above 25-cycles / sec. At lower frequencies flicker becomes evident particularly if the diameter of the filament be small.

ROTARY CONVERTERS.—For many years the performance of rotary converters was much better at 25 than at 50-cycles / sec., but by improvements in design and construction—notably the use of higher peripheral speeds and the use of commutating poles—rotary converters for 50 or 60 cycles / sec. have been made practically equal in cost and efficiency to those for 25-cycle supply. Where high voltage D.C. is to be used for traction service, low-frequency A.C. primary supply offers some advantage in that single-commutator rotary converters can be built for 3 500 V. D.C. when the A.C. supply is at 15 cycles, 2 000 V when the supply is at 25-cycles, and only 1 000 V when the supply is at 50-cycles.

FREQUENCY CHANGERS.—These machines may be used to raise or lower the supply frequency to suit the special requirements of a particular load, but generally they are used as a *link between interconnected distribution systems of different* supply frequencies. The ratio of the number of poles on the two sides of the machine must equal the ratio of the two frequencies; the 2 : 1 ratio between 50- and 25-cycle systems makes possible a much cheaper frequency changer than the 24 : 10 pole combination required between 60- and 25-cycle systems.

(5) *Standardisation of Frequency.*—For twenty-five years or longer the balance of favour has oscillated between 25-cycles on the

one hand and 50 or 60-cycles on the other. In the present state of electrical practice there is no radical difference between the costs and efficiencies of apparatus designed for 60- and 25-cycle supply so far as general power and lighting services are concerned. The technical distinctions between 60- and 50-cycle supplies are practically negligible. There is no likelihood of a frequency higher than 60-cycles / sec. being employed in any new supply system. Typical values of overall efficiency for 500 V rotary converters and their transformers are:—

	Cycles.	Overall Efficiency (per cent.) at Load.			
		1.	$\frac{3}{4}$.	$\frac{1}{2}$.	$\frac{1}{4}$.
1 500 kW	25	$94\frac{1}{2}$	$94\frac{1}{2}$	$93\frac{3}{4}$	$90\frac{1}{2}$
	50	$94\frac{1}{2}$	94	$92\frac{1}{2}$	$87\frac{1}{2}$
250 kW	25	$93\frac{1}{2}$	$93\frac{1}{4}$	92	87
	50	$93\frac{1}{4}$	$92\frac{3}{4}$	$90\frac{3}{4}$	$84\frac{1}{2}$

In America both 60- and 25-cycle supplies are used very extensively, but the higher frequency is likely to predominate. In this country the Electricity Commissioners have decided upon a policy of eliminating all odd frequencies (of which there are at present many), ultimately reducing the main frequencies in use to 50- (standard), 40- and 25-cycles / sec. A very large amount of money has been spent on reducing all stations serving the 'grid' to the standard 50 cycles; and incidentally in maintaining the frequency with a high degree of constancy, so that electric clocks depending upon the frequency for their rating will keep most regular time. Apart from the advantages of unification in reducing the capital expenditure on turbo-alternators, transformers, motors, etc., and the simplification and economy in manufacture due to the employment of fewer types of plant and apparatus, the adoption of a common frequency would remove engineering difficulties in the interchange of energy between different undertakers and the ultimate linking-up of districts. According to the Report of the Electricity Commissioners for 1932, the gross cost of standardising frequency for the whole country will be of the order of £19 000 000 or, after allowing for certain recoverable items of the nature of advances to undertakers, £16 000 000 net; the capital charges on which fall on the supply industry generally in the form of a *pro rata* levy. Considerable progress in the work has been made in Central Scotland and Central England areas.

136. Standard Rating for Electrical Machinery.—(1) *British Standard Rating.*—British S. Specification No. 72 (now superseded by many others, as noted below), attempted to eliminate the somewhat contradictory term 'overload capacity' from the rating of generators, motors and transformers, though we expressed the opinion that the term would not soon disappear. Since then it has been found commercially expedient to restore it as part of the standard rating of electrical machinery. This is done for industrial motors and generators with class A insulation* in B.S. Specification No. 168, with some exceptions stated therein; and for other machines in specifications replacing No. 72 in other applications. Thus, whilst there is a good *prima facie* case for basing the rating of a machine (motor, generator, transformer, etc.) upon the output which *includes* the 'sustained overload capacity,' it may be assumed that the established industrial practice of distinguishing between the 'rated' output and the 'overload capacity' of machines will continue to receive official recognition.

The B.S. Specifications should be studied in the original (the cost of the publications being nominal) for full particulars as to the British Standard Ratings, but the following *(unofficial)* summary of the rating clauses in Specification No. 168 will serve for general information :—

This specification applies to industrial motors and generators of 1 B.H.P., kW or kVA and upwards per 1 000 r.p.m. wound for pressures not exceeding 7 000 V; and does not apply to turbo-type machines, rotary converters, and traction motors, or to single-phase machines.

The *continuous rating* defines the load at which the machine may be operated for an unlimited period without exceeding the limits of temperature rise given in Table 12, the temperature of the cooling air not exceeding 40° C., and the altitude not exceeding 3 300 ft. above sea level.†

Two *standard short-time ratings* are recognised defining respectively the output at which a machine can work, starting at the ambient temperature, for 1 hr. (*one-hour rating*) or for ½ hr. (*one half-hour rating*), as the case may be, the temperature of the cooling air not exceeding 40° C., and the altitude not exceeding 3 300 ft. above sea-level.†

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* Cotton, silk, paper, and similar materials when impregnated or immersed in oil, also enamelled wire.

† In the case of machines to be used at altitudes of 3 300 ft. or more (up to 10 000 ft.) above sea level, the permissible temperature rise is reduced 1½ % for each 1 000 ft. above sea level. Machines for service above 10 000 ft. are not considered standard.

A generator rated for two limits of voltage must have its rated current and output determined at the higher voltage. A change speed motor shall have a definite rating for each speed, and a variable-speed motor for each of its limiting speeds.

Continuously rated machines to this specification (other than totally enclosed machines) have a *sustained overload capacity* as distinct from machines having a continuous maximum rating.

A *sustained overload* is an overload sustained for a period long enough to affect appreciably the temperature of the machine.

A *momentary overload* is one of such short duration that it does not appreciably affect the temperature of the machine.

After having attained the temperature rise corresponding to their rated loads, motors and generators to this specification shall be capable of conveying *momentary overloads* and, when the cooling-air temperature does not exceed 35° C., *sustained overloads* as specified in Table 12A,* at rated voltage and frequency.

When the cooling-air temperature is above 35° C. and it is desired to retain the overload, a machine must be used having a correspondingly lower temperature-rise at rated load.

Machines with short-time rating and all totally enclosed machines are not capable of carrying sustained overloads.

TABLE 12.—*Temperature Limits for Industrial Motors and Generators (Class A Insulation).*

Part.	Temperature Rise † (by Thermometer).	
	Machines (other than Totally Enclosed) with Continuous Rating.	Machines with Short Time Rating, and Totally Enclosed Machines.
	° C.	° C.
Windings and cores with which they are in contact	40	50
Commutators	45	55
Slip rings—open type	45	55
,, ,, —enclosed type	55	55
Single-layer field-windings	50	50
Uninsulated parts, and cores not in contact with insulated windings	Such that there is no risk of injuring insulation on adjacent parts.	

The methods for stating output are: (i) *D.C. Generators*—Output in kW available at the terminals. (ii) *Alternators*—Apparent output in kVA available at the terminals. Unless otherwise specified, the P.F. of the generator is taken to be 0·8. (iii) *D.C. and A.C. Motors*—Mechanical output in H.P. and kW

* The summary here given is arranged for easy comparison of the general requirements; the specification should be consulted where actual tests are concerned.

† See footnote † on p. 229.

TABLE 12A.—*Overload Rating of Motors and Generators.*

	Limits of Output *Per* 1 000 *R.P.M.*	Sustained Overload. Machine not Totally Enclosed.	Sustained Overload. Machine Totally Enclosed.	Momentary Overload. Including Totally Enclosed Machines.
MOTORS (overload refers to *torque*).				
(*a*) *Continuous rating*	Less than 4 and down to 1 H.P.	25 %; ¼ hr.	nil	
	Less than 10 and down to 4 H.P.	25 %; ½ hr.	nil	
	10 H.P. and over	25 %; 2 hrs.	nil	50 %; 1 min.
	All motors *	—	—	100 %; 15 sec.†
(*b*) *Short time rating*	All motors *	nil	nil	100 %; 30 sec.
GENERATORS (overload refers to *current*).				
Continuous rating .	Less than 3 and down to 1 kW or kVA	25 %; ¼ hr.	nil	50 %; 1 min.
	Less than 7½ and down to 3 kW or kVA.	25 %; ½ hr.	nil	50 %; 1 min.
	7½ or higher kW or kVA.	25 %; 2 hrs.	nil	50 %; 1 min.

available at the shaft. (iv) *Transformers*—Apparent output in kVA available at the secondary terminals.

As the average output of an alternator is generally about 80 % of the rated output, the efficiencies of the machine and of the prime mover which drives it should be highest at this output. The prime mover should, however, be capable of driving the generator at 40 or 50 % above the most economical output (12-20 % above rated output), so as to allow for emergent short-period overloads. This is often overlooked in the case of internal combustion engines and water turbines.

(2) *International Standard Rating.*—The I.E.C. 'Specification for Electrical Machinery' (Publication No. 34, 4th edition, 1935)

* Except synchronous induction motors which must stand 35 % overload torque for 1 min. without falling out of synchronism.

† D.C. and induction motors (wound rotor and ordinary squirrel cage types).

establishes an international rating which 'will enable an exact comparison to be made between machines' rated according to it, wherever constructed. The document* should be consulted in the original. After setting forth in Part I. the definitions, classification of insulating materials, methods of measurement of temperature and tolerances allowed, it proceeds in Part II. to the rating of generators, motors (except for traction) and synchronous converters. Part III. deals similarly with transformers; for traction motors see Publication 48. There is in each case a continuous rating and a short-time rating, the former always being understood in the absence of a statement to the contrary.

137. **Homopolar or Acyclic Dynamos.**—These machines, which are sometimes (erroneously) called unipolar dynamos, are based on the fact that if a copper disc be rotated between the poles of a horseshoe magnet (about an axis joining the poles, the flux being perpendicular to the disc) a constant E.M.F. is induced between the rim and the spindle of the disc. It was in this form that Faraday discovered the dynamo. Similarly, if a hollow metal cylinder be rotated in the annular air gap between an internal N (or S) pole and an external S (or N) pole, a constant E.M.F. is induced between the ends of the rotating cylinder. Replacing the solid disc or cylinder by armature bars connected in series we have the two types of homopolar dynamo, *viz.* the disc or radial type, and the cylindrical or axial type. The armature conductors always cut the magnetic flux in the same direction, and this is the only type of D.C. generator in which direct current is actually induced in the armature conductor (§ 132). It is therefore unnecessary to use a commutator, and for this reason many attempts have been made to develop the homopolar machine as a competitor of the commutator-type D.C. generator. A number of armature conductors are connected in series and current is collected by brushes bearing on slip rings.

Unfortunately it is not economical (if possible) to build homopolar machines of useful capacity for the voltages employed in general D.C. distribution. Also, the electrical difficulties of design are increased at turbine speeds, for which the elimination of the commutator is, in itself, most desirable. A homopolar dynamo

*Obtainable from the General Secretary of the I.E.C., 28 Victoria Street, London, S.W. 1, price 4s.

rated at 2 000 kW, 260 V, 7 700 A, 1 200 r.p.m. was built some years ago,* but serious difficulties were experienced in construction and operation, and the experiment does not appear to have been repeated. The homopolar dynamo is essentially a low voltage, heavy-current machine, but even in electro-chemical work where currents of many thousand amperes are sometimes required at a pressure of a few volts, it is generally more satisfactory to employ a motor generator driven from the ordinary supply mains.

138. Shunt, Series, and Compound-Wound D.C. Dynamos.—The general design of the armature and field magnets remaining the same, the electrical characteristics of D.C. dynamos are very different according as the field coils are shunted across the armature (Fig. 30), connected in series with the armature (Fig. 31), or connected partly in shunt and partly in series with the armature

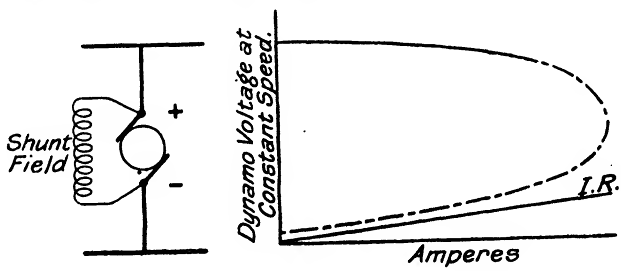

FIG. 30.—Connections and characteristic curve of shunt dynamo.

(Fig. 32), In these three cases the machine is said to be shunt, series, or compound wound respectively.

There may be any even number of magnetic poles from two upwards; but, whereas the applied pressure of the supply ensures the energising of the magnet coils on a motor, a generator has to excite its own magnets. It occasionally happens that the iron of the magnet is free from any vestige of residual magnetism; but under ordinary circumstances it retains a sufficient amount of magnetism to start the cycle of operations known as 'building up the field.' The armature is being driven by its prime mover in the weak field of the iron alone, and this residual magnetism is sufficient to cause a small E.M.F. in the armature coils; this in turn sends a small current through the magnetising coils and so strengthens the field, and thus by imperceptible increments the field is built up rapidly to full strength.

* *See Engineering*, July 19, 1912, p. 92.

(1) *Shunt Dynamos.*—Where batteries are used shunt-wound generators are essential, as the other types would reverse their direction of rotation if accidentally driven as motors; this would happen if the generator voltage dropped below the battery voltage.* The voltage when cells are being charged must be much higher than the pressure of supply to the lamps (Chapter 18) and the necessary regulation is obtained by varying the strength of the

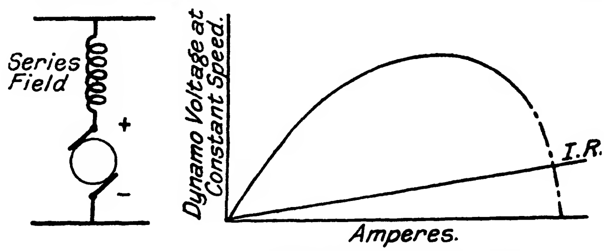

FIG. 31.—Connections and characteristic curve of series dynamo.

shunt current. Shunt-wound generators can also be used in any case where constant pressure is required in the external circuit; by varying the current in the field circuit, by means of a 'shunt resistance' or 'rheostat' placed in series with the magnet winding, the voltage in the external circuit can either be maintained or varied at will, so as to compensate for the loss of pressure in the

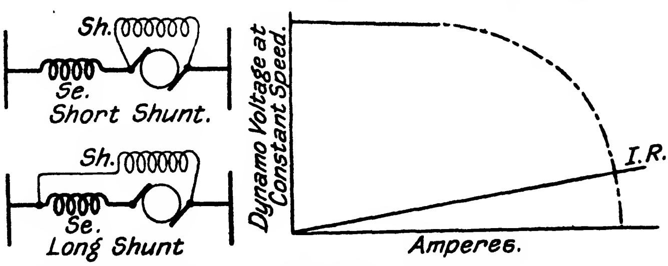

FIG. 32.—Connections and characteristic curve of compound dynamo.

mains and give constant pressure at a distant point. If the brushes of a shunt machine are put down, thus closing the circuit of the magnetising coils, and the machine is then run up to speed with the external circuit open, the field will be built up to full strength; the pressure across the brushes will be at its full value, and the shunt current will be volts ÷ shunt

* Where compounding of the generator is required to compensate for pressure drop in feeders, booster-regulation of the battery must be used, as explained in § 142.

resistance, both of which are practically constant while the speed remains so. Allowance can be made for such variations as occur (§ 1019 *et seq.*, Vol. 3). If the external circuit is now closed the load can be increased from no load to full load. As the amperes increase there is a drop of pressure in the armature, due to its resistance, and the brush volts fall below the armature volts. Consequently the field is weakened. This is shown in the 'characteristic curve' of a shunt machine (Fig. 30), which can be constructed from the readings of volts, amperes, and speed taken on test at various loads, after correction as explained in Chapter 40, Vol. 3, § 1019 *et seq.* The curve shown is called the 'external characteristic'; if the armature resistance is measured, and the value of the lost volts in it (IR in the diagram) is calculated from the amperes at different points, then the 'internal characteristic' of the machine can be plotted by adding these lost volts to the previous curve at each reading. The full curve represents the working range of the machine, and the dotted part shows what would occur with sufficient overload.

(2) *Series-wound Dynamos.*—Series-wound generators are only used where a constant current of so many amperes is required in the external circuit, as in the case of series arc or incandescent street lighting (§ 661; also 446; Vol. 2); the pressure is then varied according to the number of lamps in use. The external characteristic curve of a series dynamo is shown in Fig. 31. In these machines the field circuit is only closed when the external circuit is closed, so that the load comes on; and the current in the field coils is not constant, but varies directly with the load in amperes. It will be noticed that beyond the bend of the curve the current is almost constant, regardless of the pressure, and an arc lighting machine utilises this part of the curve. To obtain the internal characteristic in this case the drop in pressure IR due to the resistance of the armature and the field coils in series must be calculated and added at each reading.

(3) *Compound-wound Dynamos.*—For installations not using batteries the compound-wound generator is usually employed, owing to its automatic regulation; and also for D.C. tramway systems, except those supplied from converters. The shunt coils give a constant excitation, but the additional ampere-turns of the series coils vary according to the current in the external circuit, which is flowing round them; consequently, as the current rises and the

loss of pressure in the circuit increases, the additional strength of the field magnets automatically raises the pressure of generation to a corresponding degree, so that the resulting pressure at the far end of the line remains constant. An examination of the two preceding figures makes this clear, the drop of pressure in the former being compensated by the rise in pressure of the latter. The resulting external characteristic of a compound dynamo is shown in Fig. 32, and in a well-designed machine is almost a straight line over the working range. The line may be either level (level compounding) or rising (over-compounding), so that the drop of pressure in feeders as well as in the machine itself may be compensated for; in this case the ampere-turns on the series coils are designed to raise the pressure in a higher ratio than the current increases; this is especially the case in electric tramway stations.

139. Interpoles.—Owing to the reaction of the armature flux on that of the field magnets there is always some distortion of the magnetic field in which the armature rotates, and hence in the position of the 'neutral zone' (of zero field) in which commutation can be effected sparklessly. This distortion is particularly noticeable at heavy loads or when the main field is weakened very considerably in the course of obtaining wide voltage regulation; or speed regulation over a wide range (Chapter 29), in the case of a motor. In order to prevent sparking, the angle of lead of the brushes may be altered by moving the latter forward, in the direction of rotation in the case of a generator, and backwards in the case of a motor, as the load increases. To obviate this adjustment, small commutating poles or 'interpoles' are placed alternately with the main poles and excited by a few turns of wire in *series* with the load. A suitable commutating field is thus maintained automatically beneath the interpoles at all loads. The polarity of each interpole must be the same as of that main pole towards which the brush would otherwise have to be moved. Clearly, the polarity of interpoles with regard to the main poles is opposite in motors to what it is in generators, but by connecting the interpole windings in series with the armature the correct polarity is produced automatically for either motor or generator action. In practice a shunt having inductance is connected across the terminals of the interpole winding and adjusted for sparkless commutation.

140. Generator Excitation.—Permanent magnets are used to provide the magnetic flux in small magneto generators, such as those used for ignition purposes in automobiles, etc., for some electro-medical work, and for the measurement of speed of revolution (§ 123). All generators for lighting and power supply are, however, 'excited' by direct current passed through solenoids wound round cores which constitute the magnetic poles of the field system (§§ 40 *et seq.*, 133). Direct-current generators are generally 'self-excited' by part of the current produced in the armature, the several methods of connecting the field circuit and the resultant characteristics of the machine being as described in § 138.

Alternators deliver only alternating current, and the direct current for their field circuits must be provided from an independent source. Generally, a small shunt-wound D.C. generator is mounted on an extension of the alternator shaft; this generator —commonly called the 'exciter'—delivers current at from 100-250 V to the alternator field circuit. The exciter is either self-excited or separately excited. By varying the resistance in the field circuit of the exciter, the voltage applied to the alternator field circuit, and hence the A.C. voltage generated by the alternator, can be controlled (§ 147). To allow for the possibility of break-down in the exciter or its circuits, arrangements can be made for the excitation of the alternator from some alternative source of supply, such as a battery or a steam driven D.C. generator. In all large modern turbo-alternators the exciter is separately excited by means of a second auxiliary D.C. generator mounted on the shaft of the machine. This second machine is usually known as a pilot exciter. In water-power plants it is not unusual to mount the exciter between a turbine and an induction motor, so that it can be driven either independently or from the bus bars of the supply. In some stations all the alternators are excited from a common set of bus bars, instead of by individual exciters on each main machine; it is then necessary to provide two independent sources of supply for the D.C. bus bars, one source being held in reserve. In any case provision must be made for separate adjustment of the field strength of each alternator for voltage control.

The power required to excite an alternator rises rapidly as the power factor of the A.C. system decreases (§ 155). Under average conditions the kW capacity of the exciter is from

0·5 to 1·0 % of the kW capacity of high-speed generators (from 10 000 to 1 000 kW respectively) and about twice as great in the case of low-speed generators.

141. Balancers and Three-wire Generators.—In order to combine the advantages of higher voltage for transmission and for the supply of power loads with lower voltage for the supply of incandescent lighting and other domestic circuits, direct-current systems are generally operated on the 'three-wire system.' The energy consumed is fed to the 'outer' conductors at, say, 440 V or 500 V. All but the smallest motors are connected 'across the outers,' but lighting and small power devices are designed for 220 or 250 V (*i.e.* half the voltage between the outers) and arranged in two groups of as nearly as possible equal current consumption, these two groups being connected in series between the outers. As the two groups are distributed in many premises it is necessary to use a neutral conductor to act as a bus bar for the series connection of the two groups and, as it is impossible to maintain exactly equal current consumption in each group, it is necessary to provide some means of dealing with the out-of-balance current, otherwise the voltage division between the two groups would be unequal (*cf.* § 95, volt box).

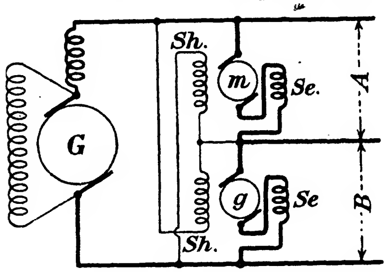

FIG. 33.—Motor-generator balancer for 3-wire system.

The simplest method of supplying a 3-wire system is to use two generators connected in series between the outers, the common terminal of the two generators being connected to the neutral conductor. This arrangement is used in many of the older stations. The two generators may be driven by one engine, and if the load is not balanced accurately between the two sides of the system one generator is loaded more heavily than the other. This system demands constant attention in changing feeders from one side of the system to the other so as to equalise the load, and in regulating the generator fields to maintain equal voltage, notwithstanding some lack of balance in the division of the load. A less costly equipment, and one which needs less attention in service, consists of a single main generator designed for the voltage between the outers, and a motor-generator set the machines of which are coupled mechanically and connected electrically in series across the outers, with their common terminal connected to the neutral (Fig. 33). The operation of such an installation is explained fully in §§ 461-463, Vol. 2. So long as the load is balanced between the two sides of the 3-wire system the two machines of the 'balancer' set run as motors in series across the outers. If, however, the load be unbalanced the machine which is connected across the more heavily loaded side runs as a generator (driven by the other machine) and supplies the out-of-balance current. The action of the balancer machines as motor or generator is determined by the division of voltage between the two sides of the system, and there are many possible arrangements for the field circuits of the balancers. The balancers shown in Fig. 33 are compound-wound (§ 138), the shunt field for each machine being connected across the other half of the system and the series coils assisting the shunt coils. If the load be heavier

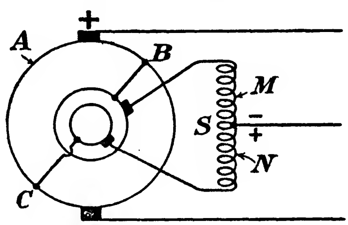

FIG. 34.—Single-phase static balancer for 3-wire system.

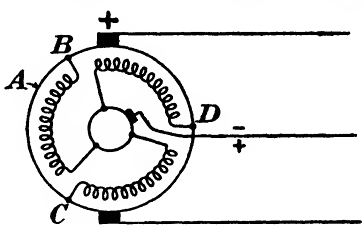

FIG. 35.—Auxiliary armature-winding used for balancing 3-wire system.

on the side *B* of the system, the speed of the machine *m* rises (due to the increased voltage across *A* and the reduced field strength) and this machine drives *g* as a generator, the field of the latter being simultaneously strengthened. Both current and voltage balance are thus maintained within close limits.

An alternative method of balancing is to use two batteries of storage cells (either alone or in conjunction with a booster, § 142) instead of the machines *m*, *g* (Fig. 33).

(ii) Another method is illustrated by Fig. 34 in which *A* represents the armature winding of a D.C. generator (supposed two-pole for simplicity) connected to the outers of a 3-wire system. Diametrically opposite points *B*, *C* on the armature winding are connected to slip rings, the brushes on which are connected to a static balancer *S*. The latter is a choking coil (§ 45) of such impedance that only a small alternating current flows through it from the armature. The neutral wire of the system is connected to the centre point of S and out-of-balance current flows equally in both directions from this point to the armature, encountering only the ohmic resistance of S, which is low. Better results are obtained by connecting the neutral to the common terminal of three choking coils connected in 'star' (§ 143) to three equidistant points on the armature winding. Similarly, if a rotary converter is used to supply a 3-wire system, the neutral line is connected (either directly or through a regulating booster) to the neutral point of the low voltage side of the transformer feeding the converter.

Instead of connecting the neutral directly to the centre point of S (Fig. 34), tappings may be taken from points MN, at equal distance from the centre, to a revolving commutator which rectifies the tapped current and applies it to the more heavily loaded side of the system.*

(iii) Fig. 35 represents the use of a main armature winding A to feed the outers of a 3-wire system, and an auxiliary winding connected between three equidistant points B, C, D on the main winding and a slip ring connected to the neutral. The auxiliary winding is in the same slots as the main winding, but has only half as many turns. Exact voltage balance is maintained; the auxiliary winding deals with out-of-balance current and adds to the output of the machine even when the load is balanced.

142. **Boosters.**—A direct-current booster consists simply of a motor-generator designed and connected in one of many alternative ways according to the purpose which it is to serve. For example, to compensate for pressure-drop in a feeder, the motor of a boosting motor-generator set may be connected across the mains whilst the generator armature, in series with the positive conductor, carries the full current flowing in the latter, and adds a few per cent. to the E.M.F. operating in the feeder circuit, without affecting the pressure in other circuits supplied from the same bus bars. The amount of 'boost' may be regulated by hand control of the generator field, or by such connection of the fields that the motor speed or the generator field (or both) increase with increasing load on the feeder.

An alternative method of regulating the voltage delivered by a feeder consists in 'floating' a storage battery across the *far end* of the feeder. The cells are charged through the cable during

* 'Regulating the Voltages of a 3-wire D.C. System Equalised by Static Balancers,' R. D. Archibald. *Jour. I.E.E.*, Vol. 60, p. 303.

light-load periods; but on heavy loads the supply volts at the end of the cable tend to fall below the battery volts, hence the cells discharge and limit the current taken through the cable. So long as the charge or discharge of the cells is determined solely by the voltage at the far end of the feeder, the voltage variation is bound to be considerable; actually it is about 2·2-1·9 = 0·3 V total variation, or 0·15 V up and down from normal, per cell in the battery (*e.g.* ± 37·5 V variation in the case of a 250-cell, 500 V battery). If, however, the charge or discharge of the cells be determined by a booster, the voltage variations at the far end of the feeder are much reduced. The booster armature is in series with the battery and adds its E.M.F. to the feeder voltage, so that the battery is charged when the load on the feeder is light; when the load increases, the booster E.M.F. is reversed, *i.e.* added to the battery E.M.F., so that the cells discharge and relieve the feeder of some of the total load. The requisite variations in the E.M.F. of boosters used for battery regulation are generally provided by differential excitation of the field system. Thus a shunt winding separately excited by the feeder voltage may tend to cause the booster to charge the battery, whilst a series winding, carrying all or part of the load current, may tend to make the booster discharge the battery. In other systems an exciter (§ 140), on the same shaft as the booster motor-generator, is regulated automatically to produce that direction and strength of excitation in the booster which gives the desired boost.

Whereas a floating battery without booster can only be used with shunt-wound generators, the drooping characteristic of which (Fig. 30, § 138) permits the battery to discharge as the feeder load increases, a battery with booster regulation can be used in conjunction with a main generator which is compounded or over-compounded to compensate for pressure drop in the feeder. The field cores of booster dynamos are laminated in order that the flux may be varied rapidly and without serious eddy current loss.

The use of boosters to augment the generator voltage when charging batteries, and to supplement the battery voltage when the cells approach discharge is explained in § 432, Vol. 2. 'Negative' boosters may be used to reduce the pressure drop in the return feeders of a tramway and thus prevent large return currents straying from the rails (§ 906, Vol. 3).

In A.C. circuits 'boosting' may be effected in exactly similar manner, using static transformers instead of rotary machines. The transformer primary is connected across, and the secondary in series with, the circuit to be boosted; and variable-ratio tappings provide for voltage regulation. If the auxiliary transformer be used to oppose the main pressure it is called a 'bucking' transformer. Where continuous gradation of boost or buck is needed, an 'induction regulator' may be used. This consists of a static transformer, the primary of which is wound on a stator and the secondary on a rotor; there is a very small air gap between the stator and rotor (no more than mechanical clearance), and the windings are arranged so that the E.M.F. induced in the secondary can be varied by changing the setting of the rotor, by hand or servo-motor. The regulator is static in action, the rotor being moved through a fraction of a revolution to change the boost or buck. The presence of the air gap makes the magnetic leakage and exciting current of an induction regulator high compared with those of an ordinary transformer.

The use of synchronous A.C. boosters in the pressure regulation of rotary converters is explained in § 411, Vol. 2.

Whether boosting statically or by rotating machinery, the booster must be capable of carrying the full load current so that if the pressure is to be boosted (or bucked) by n °/$_o$, the kVA capacity of a booster dynamo or the secondary of a boosting transformer must be n °/$_o$ that of the load supplied. On the other hand, the capacity of the motor driving a booster dynamo, or of the primary of a booster transformer, need only equal the maximum kVA of boost (plus an allowance for losses in the booster set). This distinction is important in the case of a booster used for battery regulation; the motor capacity may be considerably less than that of the booster dynamo because the latter must be capable of supplying the maximum voltage of boost and of carrying the maximum current; these maxima do not occur simultaneously, and it is the maximum actual output which determines the size of the driving motor.

143. Synchronous Alternators: Mesh and Star Connection.—The synchronous alternator is the type almost invariably used for the production of alternating current (see, however, § 144), and throughout this book the term 'alternator' is—in accordance with usual practice—taken to mean a synchronous machine unless otherwise specified. This machine (which is reversible and can also be run as a synchronous motor) consists of a field-magnet system, energised by a separate D.C. exciter dynamo, and a system of coils in which A.C. is generated. As explained in § 132, there is no essential difference between a D.C. dynamo and an alternator. Single-phase A.C. is produced in the armature winding of a D.C. dynamo, and if we use slip rings instead of a commutator we make this single-phase current available in the external circuit. By mounting three single coils of wire on the armature, the angles between the coils being 120°, we obtain three distinct single-phase currents differing 120° in phase (*see* Fig. 5, § 15). We might collect these three currents separately by a pair of slip rings for each phase, but it is usual to connect the three phases: (i) in series to form a 'mesh' or 'delta' winding, from the apices of which supply is taken (Fig. 36A); *or* (ii) in 'star' or 'Y' connection, in which case one end of each phase is connected to a common neutral

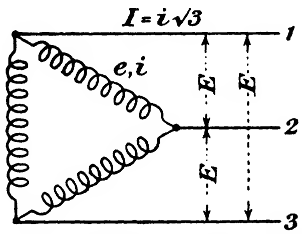

FIG. 36A.—Mesh or delta connection.

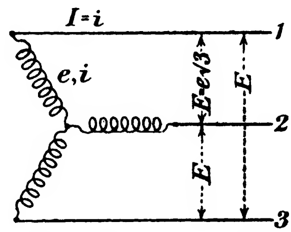

FIG. 36B.—Star or Y connection.

point, and supply is taken from the three remaining terminals (Fig. 36B). (*See also* § 465 *et seq.*, Vol. 2.) In either case only three slip rings are required. There is no essential difference between a single-phase and a 3-phase alternator except for the provision of the additional coils for the second and third phases.

With mesh connection (Fig. 36A) the voltage E between lines equals the phase voltage e of the generator, but each line is connected to two separate phases and the line current $I = \sqrt{3}$ times the phase current i. The power per phase $= ei \cos\theta$ (§ 55) $= (EI \cos\theta) / \sqrt{3}$; and the total power $= 3 \times$ power per phase $= \sqrt{3}\, EI \cos\theta$. With star connection (Fig. 36B), the line current I equals the phase current i, but the voltage between lines equals $\sqrt{3}$ times the phase voltage; the total power $= 3ei \cos\theta = 3(E / \sqrt{3})I \cos\theta = \sqrt{3}EI \cos\theta$, as before. For given phase voltage and current, the mesh connection requires line conductors of larger cross-section, and the star connection requires more insulation between lines. (*See also* § 314.)

The standard pressure and frequency of generation are discussed in § 134; and voltage regulation in § 147.

144. Asynchronous or Induction Alternators.—The asynchronous or induction generator consists essentially of an A.C. induction motor with a phase-wound rotor (§ 681 *et seq.*, Vol. 3), the latter being driven mechanically at higher than the synchronous speed (§ 135 (3)). There is no special field winding and no D.C. excitation in a generator of this type. The machine can only be used in conjunction with synchronous generators (§ 143), the latter magnetising the asynchronous generator and also 'setting' the frequency at which the induction machine operates. As long as the rotor of the induction machine is running below synchronous speed the machine is simply an induction motor (whether or not it is coupled to a prime mover); but directly the prime mover drives the rotor above the synchronous speed corresponding to the frequency of the *synchronous* generators and the number of poles in the induction machine, the rotor absorbs power from the prime mover, and current induced in the stator windings by the rotating polyphase field of the rotor is delivered to the network, thus supplementing the output of the synchronous generators. Under all conditions, however, the synchronous generators supply the magnetising current of the induction generator, hence the use of the latter reduces the power factor of the system. Notwithstanding this serious disadvantage, induction generators offer a convenient means of adding, to an existing A.C. system, power derived from a windmill (§ 165) or small water turbine. An induction generator does not require to be synchronised (§ 149) and can therefore be started and switched into circuit by simple automatic gear whenever there is wind or water power available (§ 187). The main advantage, however, of the induction generator in the utilisation of variable natural power, lies in the fact that the rotor speed bears no definite relation to the frequency of the current produced. The speed of an induction motor can be varied over a considerable range by varying the resistance of the rotor circuit (Chapters 28, 29); similarly, the rotor speed of an induction generator can be adapted to the requirements of a windmill or variable-head water turbine over a considerable range of wind or water conditions by varying the resistance of the rotor circuit. The frequency remains constant at the value set by the synchronous generators on the system. For satisfactory operation of the whole, the kVA capacity of the induction generators should not exceed one-eighth that of the synchronous generators.

145. Mechanical Features of Turbine-Driven Alternators.—Small and medium-sized alternators may be driven by any convenient prime mover (Chapter 6), but the standard machine in all large stations is now the 3-phase alternator driven by steam or water turbine. The mechanical design of steam-driven turbo-generators is influenced primarily and to a very marked degree by the high speed at which the steam turbine must be run to secure highest efficiency. It is possible to use geared turbines, and this arrangement is sometimes applied to the driving of D.C. generators, which can hardly be built to operate well at efficient turbine speeds. A better solution, however, is to use 3-phase alternators for all supply purposes in turbo-driven stations, then producing such D.C. as may be required by use of rotary converters (§ 408 *et seq.*) or mercury vapour rectifiers (§ 418 *et seq.*). The non-salient pole type of alternator, with a cylindrical rotor carrying windings in slots, is practically standard construction for turbine driving. It is compact, economical, and can be built in any required size.

Steam-driven turbo-alternators have been built for outputs up to 160 000 kW. Remarkably high overall efficiency can be obtained in an interconnected or 'grid' system by using sets of say 100 000 kW to carry the base load and sets of say 50 000 kW at other points in the system as required. The aim is to operate the base-load sets continuously at their most economical output; to do this, the sets in question must carry the base load of a more or less extensive area, and, depending on individual circumstances, there is a point beyond which any further gain in generating efficiency by increasing the size of base-load units is more than counter-balanced by transmission losses in delivering the energy where it is required.

The normal speed of water-wheel alternators is relatively low, but the rotor diameter is correspondingly large, and it is necessary that the rotor should safely withstand the 'runaway' speed of the turbine (possibly twice the normal speed). The vertical shaft generators in the Queenston hydro-electric station (Ontario) are rated at 45 000 kVA (each), 3 phase, 12 000 V, 25 cycles, 187 r.p.m., and are coupled directly to 55 000 h.p. water turbines. The height of the generator to the top of the exciter is 35 ft.; the diameter of the generator casing is 24½ ft.; and the main 69 in. thrust bearing is designed for a load of 450 tons including the weight of the rotor and the water thrust on the turbine. (For further details *see El. World*, Vol. 77, p. 697, and *El. Rev.*, Vol. 91, p. 105.)

146. Efficiency and Ventilation of Generators.—The efficiency* of very small generators, up to 1·0 kW capacity, is usually between 85 and 90 %; that of large generators from 1 000 to 10 000 kVA or higher is usually between 94 and 96 %. The value of the efficiency and the load at which it is a maximum can be varied by the designer. Increasing the weight of copper in the machine (relative to the weight of iron) increases the load at which maximum efficiency is reached; whereas increasing the relative weight of iron causes maximum efficiency to be reached at lower load. The best value for the efficiency of a large generator within the range 94 to 96 % is determined by the cost of the higher efficiency compared with the value of the increased output (§ 193).

Engine-driven generators are generally of open construction and, being relatively low-speed machines, they are of relatively large dimensions. There is consequently no difficulty in dissipating the losses without excessive temperature rise. In large turbine-driven generators, however, ventilation constitutes a very serious problem, owing to the increased power and decreased size (per kW) of individual machines. The total losses in a 10 000 kW alternator may be, say, 5 % on full load. Expressed as a percentage, the loss is very small, but in point of fact it represents about 500 kW expended as heat (say 17 therms per hour) in a close-built mass of metal and insulation, the overall volume of which is about equal to that of a large living-room. Natural ventilation by ducts in the cores and openings in the frames is

* B.S.S. No. 205, 1936, the B.S. Glossary of Terms used in Electrical Engineering, defines the 'efficiency' of plant for converting energy from one form to another, as the ratio (expressed as a percentage) of the energy output, available in the specific form and for the specific purpose required, to the energy input. In the case of heat or chemical energy, the datum from which this is evaluated must be specified. The term 'declared efficiency' is defined as the efficiency assigned by the maker under certain specified conditions. For notes on the efficiency of prime movers, see § 166.

no longer sufficient. A network of air-passages must be provided, and through these huge quantities of air* must be driven either by a blower forming an integral part of the machine or by a central blower delivering air through ducts to a number of machines. The latter arrangement is obviously the more efficient, and it permits air to be drawn conveniently from some point outside the power-house and thoroughly cleansed before admission to the generator. Fouling of air-ways and deterioration of insulation are thus prevented. Linen filters take up a good deal of room and need periodical cleaning; should they be set on fire, the generator may be damaged before a safety door and fusible link combination in the air-duct has time to act. Water-spray filters are more compact; they are very effective, offer minimum resistance to air-flow, need a minimum of attention, and are more economical where large plants are concerned. Air is cooled as well as filtered by the waste spray apparatus, and the moisture imparted to the air is no disadvantage so long as actual drops of liquid are not carried forward in suspension. Another type of filter which gives good results consists of a chamber filled with short lengths of metal tubing (about 1 in. long × 1 in. dia.); these tubes are jumbled so that air flowing through the chamber has to follow a tortuous path, in the course of which all dust is retained by the film of non-drying oil with which the tubes are coated. The tubes are cleaned and re-coated at intervals of some weeks or months as required.

In the 40 000 kW alternators of the Gennevilliers station,† the ventilating air is in a closed circuit. This eliminates the problem of filtering huge volumes of air. Condensate from the turbine condenser is passed through an air-cooler which cools the ventilating air and returns the heat of the latter to the boiler, thus improving the overall efficiency.

The temperature rise of air passing through the generator may be calculated from the formula—

Temperature rise (°F.) = 2 916 × kW loss / cu. ft. of air per min. Allowing 100 cu. ft. of air / min. / kW loss, the temperature rise is approximately 30° F

* From 90-100 cu. ft. of free air per min. per kW of loss, or 5 cu. ft. per min. per kW of generator capacity; say, 75 000 cu. ft. per min. in the case of a 15 000 kW alternator.

† *El. Rev.*, Vol. 92, p. 604.

The warm air could be led to the boiler furnaces and would result in about 1 °/₀ increase in overall thermal efficiency; this does not offer a very promising return on the capital and maintenance costs of the ducts required.

The problem of dissipating the losses in large turbo-generators is simplified by the use of water instead of air as a cooling medium because the specific heat of water is 1·0 compared with 0·24 for air, *i.e.* 1 lb. of water removes more than four times as much heat as 1 lb. of air for the same temperature rise. In the Parsons water-cooled alternator rotor, water is fed to a central passage bored along the axis of the solid rotor forging. Thence, the water passes through radial holes at one end of the rotor to weldless steel tubes embedded at the bottom of the winding slots; hot water is collected from these tubes by radial holes at the other end of the rotor and cooled for recirculation. The more extensive use of water cooling in turbo-generators is discussed by J. Shepherd, *Jour. I.E.E.*, Vol. 58, p. 125.

The use of hydrogen for cooling purposes is discussed in § 80*a*.

147. Voltage Regulation.—Whereas in a D.C. generator the alteration of pressure between no-load and full-load is independent of the character of the load, this is not so in an alternator. The British standard definition * of the regulation of an alternator is as follows:—

> 8. The inherent regulation of an alternator is the rise in voltage when the load changes from rated output (at rated power factor and rated voltage) to no-load, the speed and excitation being maintained constant. It is expressed as a percentage increase upon the rated voltage. (*Note*—The above clause refers to the characteristics of the machine itself. In practice the total voltage variation will usually be greater than this, owing to the additional effect of speed variation of the driving power). [B.S.I. Report No. 168.]

The actual value of the inherent regulation varies with the power factor of the load (§ 155), and increases with the reactance of the alternator windings. Formerly it was usual to specify close inherent voltage regulation (say, 5 °/₀) but this involved low

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* The regulation thus defined is often called the "regulation up" in distinction from the "regulation down," which is an alternative (non-standard) definition of regulation as the drop in voltage from no-load to full-load expressed as a percentage of the no-load voltage, the speed being constant and the excitation being constant at the value required to produce rated voltage at no-load. A given percentage regulation is obtained more easily and cheaply when the standard (regulation up) definition is employed.

reactance in the alternator and resulted in the current rising to 20 or more times the normal value in the event of short circuit. Apart from the excessive heating caused by such a current, should it endure, there are produced enormous mechanical forces (§ 338) which may wreck the machine. For these reasons, and because the parallel operation of synchronous machinery is more stable when there is considerable reactance in the circuit, it is now usual to employ alternators of high internal reactance; choking coils are also placed in series with the generator phases for protective purposes (§ 340). Methods of determining the regulation of generators are noted in §§ 1020, 1022, Vol. 3.

With constant excitation the voltage of a modern alternator would drop by from 6 to 10 % from no-load to full-load if the latter were a non-inductive lighting load, and by from 20 to 25 % or more * if the load were of power factor 0·8. In practice the voltage is kept constant, or raised with the load, by altering the excitation of the field. If the load variations be gradual, the field regulation may be effected by hand or by a servo-motor controlled by a contact-making voltmeter. Generally, however, an automatic voltage regulator is employed. There are many types of these regulators in use, differing considerably in construction,† but they all operate by varying the field current of the exciter (§ 140) and so the excitation of the alternator. A relay energised by the alternator voltage is in equilibrium when this voltage is normal. If the voltage rises or falls, the movement of the relay closes the operating circuits of contactors which open circuit or short circuit sections of the resistance in the exciter field circuit, so as to restore the alternator voltage to its correct value. The active coil of the primary relay can incorporate an auxiliary winding, carrying a current proportional to the alternator output current, so that the terminal voltage of the alternator can be made

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* In the 40 000 kW alternators at Gennevilliers (§ 196) the voltage drop between no-load and full-load at 0·8 power factor is 33·3 %. The stator slots are designed so that the magnetic leakage is particularly high; the inductive drop due to leakage is, with normal current, 24 % of the normal pressure (10·2 % due to the slot leakage and 9·5 % to the end connections). The short-circuit current of these machines is only about 4·2 times normal full-load current. (*El. Rev.*, Vol. 92, p. 604.)

† For descriptions *see* C. C. Garrard, *The Electrician*, Vol. 74, p. 107, and Whittaker's *Electrical Engineer's Pocket Book*, 6th ed., p. 502; *also* H. N. George, *British Westinghouse Gazette*, Vol. 4, p. 206.

to rise as the load on it increases. When two or more alternators, each fitted with an automatic regulator, are working in parallel, the operation of the regulators will not be satisfactory unless each relay has an auxiliary control representing the reactive component of the machine output. Without this control the allocation of the total reactive output of the machines will not be stable, and they will be liable to operate at widely differing power factors (§ 149). Auxiliary reactive control ensures, not only constancy of busbar pressure, but also the automatic maintenance of approximate equality of the power factor of the outputs of all the machines working in parallel. Complications in electrical and mechanical construction are required to secure rapid action and to prevent the alternator voltage from 'hunting' above and below normal, but these do not affect the principle of operation.

148. Parallel Running of D.C. Generators.—(i) *Shunt-wound.*—So long as they are of approximately the same construction and designed for the same pressure, any two or more shunt-wound dynamos may be connected in parallel, *i.e.* to supply energy to the same circuit, without any particular difficulty or risk. If two such generators be exactly similar, and if both yield the same E.M.F. at any particular load, each machine will take half the total load. If one should take momentarily more than its fair share of the load for any reason, its E.M.F. would fall below that of the other dynamo (for the voltage of a shunt dynamo decreases with increasing load, *see* Fig. 30, § 138), and hence the state of balance would be restored automatically. The terminal potential difference of a shunt dynamo is $V = (E - IR)$ volts, where E is the E.M.F., I the armature current, and R the armature resistance. If two shunt generators having equal E.M.F. operate in parallel, the terminal P.D. is the same for each, hence $(E_1 - I_1R_1) = (E_2 - I_2R_2)$. In other words, $I_1 / I_2 = R_2 / R_1$, *i.e.* the generators share the load in inverse proportion to their armature resistances, so long as the E.M.F. $E_1 = E_2$; to distribute the load in other than this proportion, E_1 or E_2 is varied by shunt field regulation. If I_2 increases, E_2 is reduced (Fig. 30), so that the normal state of affairs is quickly restored. If the speed of machine No. 1 falls, E_1 decreases, hence I_1 decreases as well, to keep the difference $(E_1 - I_1R_1)$ constant. By weakening the field and decreasing the speed of one dynamo its E.M.F. may be made lower than the terminal P.D. of the other machine. In that event the first machine runs as a shunt motor, but does not take an excessive current (*cf.* series generators below).

The machines need not necessarily be of the same power rating. Thus in Fig. 37 * it is assumed that generator No. 1 is rated at 500 A, 250 V, and that machine No. 2 normally operates at 1 000 A, 250 V. The voltage characteristics of these machines are assumed to be as shown in the figure. The total load is 1 500 A when each machine is operating at 250 V and delivering its normal output.

Assume the prime mover of No. 2 machine momentarily increases in speed. With the total load remaining fixed at 1 500 A for an instant No. 2 machine will tend to carry, say, 1 100 A. This load, however, corresponds to about 243 V, as at point *C*, instead of 250. If unit No. 2 supplies 1 100 A, the output from generator No. 1 is reduced from 500 to 400 A. This load tends to operate at 260 V point *D*, instead of 250. Since generator No. 1 has a momentary high voltage, it will tend to assume more load, and unit No. 2 operating with low voltage will drop part of its load. Thus the units tend to re-divide the total output again in the ratio of

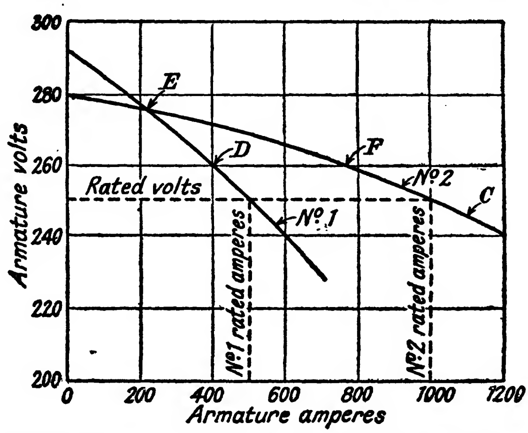

FIG. 37.—Illustrating parallel running of D.C. shunt-wound generators.

1 000 A and 500 A, respectively. With shunt generators the reactions of the system are such as to hold the generators in equilibrium.

By properly adjusting the shunt-field rheostats of the two machines the voltage curves are shifted up or down until the two machines each carry rated load. This is the condition represented by the 250-V ordinate in the figure, each machine being 100 °/₀ loaded.

Assume the total load is decreased to 1 100 A. The voltage rises to about 260 and generator No. 1 will supply about 400 A, while unit No. 2 will furnish about 700 A. The °/₀ loading of the two machines is changed. Machine No. 1 is now working at 80 °/₀ capacity (400 × 100) / 500, and generator No. 2 is operating at 70 °/₀ capacity (700 × 100) / 1 000. This condition continues to become worse as the load is further reduced.

The fields of the generators may be adjusted to give any desired division of amperes at one single load, but for all other loads the ratio of °/₀ loading will not be maintained. Machines in attended stations usually operate in this manner

* H. N. Blackmon, *Power*, Vol. 72, pp. 107, 332, 558.

without trouble. At any demand below full-load, the °/₀ loading will be unequal, but neither generator will be over-loaded.

It is clear from Fig. 37 that without load, if the shunt-field rheostats were not altered, generator No. 1 would tend to generate about 290 V and generator No. 2 only 280 V, therefore No. 1 would cause unit No. 2 to run as a motor. If the motoring effect is not too great, this action is of small consequence, since the motor torque produced in unit No. 2 is such as to rotate the armature in the same direction as turned by the prime mover. However, stations usually have attendants; and when the load demand is sufficiently reduced, one unit is removed from the busbars. For this reason, both machines are rarely on the system when the load decreases past the intersection point E on the two curves. The foregoing statements refer primarily to stations supplying load that is not of a fluctuating nature.

(ii) *Series-wound.*—In the case of two series generators working in parallel, we must still satisfy the condition $V = (E_1 - I_1R_1) = (E_2 - I_2R_2)$. So long as this is done, the generators work satisfactorily in parallel, but if the current through one dynamo, say I_2, increases beyond the value satisfying the above equation, the E.M.F., E_2, of that machine *increases* (Fig. 31). Simultaneously, however, I_1 and therefore E_1 will have decreased, so that a yet bigger share of the load now falls on the second machine, *i.e.* I_2 and E_2 increase yet further, and so on until this machine carries the whole load. The most serious trouble occurs after that, for the unloaded dynamo then begins to run as a series motor, and we have a series dynamo practically short-circuited on a series motor, with the result that both machines burn out. The only way to prevent this action is to interconnect the armature-field connections of the two machines (*i.e.* the brushes to which the series field windings are connected) by an 'equalising' conductor. In order that the latter may be effective, it is essential that its ohmic resistance be low as compared with that of the field coils, which are themselves of low resistance.

(iii) *Compound-wound.*—From these remarks it will be seen that D.C. generators having a drooping voltage-current characteristic can be operated stably in parallel without any trouble, whereas generators with a rising voltage-current characteristic are inherently unsuitable for parallel operation. Compound-wound dynamos, with rising or flat characteristic curve, require an equalising circuit for stable operation in parallel; this is run between the positive brushes of the various machines when working. Each equaliser bar has a switch which must be closed before the machines are paralleled, and kept closed so long as the machine to which it corresponds is working in parallel with one or more others. The following notes (Blackmon, *loc. cit.*) are instructive :—

Compound-wound machines combine the characteristics of shunt and series machines. When self-excited, the shunt field remains fairly constant, varying directly as the voltage across the armature terminals. The series excitation depends on the load amperes, but the flux produced is not directly proportional to the current, owing to the effects of armature reaction and magnetic saturation. In flat-compounded machines, the series field must compensate at full-load for decrease of air-gap flux due to distortion, besides compensating for the volts drop in the windings. This additional field, to compensate for armature reaction, is superfluous until a saturated condition of the iron is reached. For this reason the voltage rises rapidly as the first part of the load comes on, and then gradually declines to the proper voltage at rated load. With a short equaliser lead of sufficient capacity, stability is caused by the internal drooping voltage characteristic of the armature winding proper, and by the fact that the series-field coils are paralleled at both terminals, forcing them to take proportional current at all times, thus compounding both machines equally. When two over-compounded generators of different capacities are to be operated in parallel, the over-compounding should increase at a rate inversely proportional to their respective current ratings. The degree of compounding for any point is the slope of the line at that point.

(iv) *Interpole and Compensated Machines.*—Most modern D.C. generators have commutating interpoles (§ 139). Within certain limits the interpoles establish a fixed zone of commutation, which makes it unnecessary to shift the brushes with a change in load, as was required with the older types of machine. Commutating poles may have a material influence on the volt-ampere curve of a generator and successful parallel operation will be likewise affected.

Direct current machines generate alternating current in the armature coils. The commutator mechanically reverses the coil leads to the outside load at the moment the current in the armature coils reverses. This reversal of load current, on the coil being commutated, creates a reactance voltage within the coil. The interpole neutralises the influence of armature reaction in the commutating zone and also provides a commutating flux to assist the current reversal in the armature coils. Reactance voltage is proportional to the speed of the armature, the number of turns short-circuited during commutation, and the load current. Since the first two factors are constant, the reactance volts vary directly as the load current.

The interpole windings carry load current, but the commutating flux produced by these windings is not directly proportional to the current, as is the reactance voltage. At only certain values of load current is the interpole flux of a correct value. At points below this an excess commutating flux is present, causing local currents to flow in the armature coils and brush faces. At points above, the reactance flux of the armature will be stronger than the interpole flux, and circulating local currents will be produced in a direction opposite to those below the load point to give correct interpole flux. These local currents vary directly as the amount of excess flux and inversely as the resistance of the path.

Over-compensation causes the circulating current to produce a flux which strengthens the main-pole flux. However, the volts drop due to the resistance of the armature winding, and the armature reaction usually is greater than the increase in volts due to this strengthening of the main poles, and the drooping characteristic is retained. The tendency of over-compensation is to cause compounding action. Under-compensation creates a demagnetising flux which bucks the main field. Therefore, this effect is to produce drooping tendencies, and is not detrimental to parallel operation.

It must be remembered that the commutating zone moves with the brushes. If the brushes are given a back lead, the commutating poles assist their neighbouring main poles of the same polarity. This action approaches that of a series field, since the interpole flux varies as the load current. A rising, and therefore objectionable, armature characteristic is produced. A forward brush lead causes a demagnetising effect on the main poles. This is comparable to having a differential series winding and assists the stability of multiple operation. However, commutating poles are primarily for commutation and the brushes should remain on the neutral position (H. N. Blackmon, *loc. cit.*).

Shunt interpole machines will operate in parallel in the same *way as plain shunt-wound machines. Compound-wound interpole* machines will also operate in parallel so long as the brushes remain on the neutral plane. The commutating windings should be considered as part of the armature, when connecting in an equaliser, so that the same amperes flow through interpole winding and armature.

Where compensating windings are provided in the poles faces, for improving the commutation under heavy overloads, parallel running is not always easy; it is customary to add a few series turns on the main poles to provide a differential series field in addition to the cumulative series turns, the net strength being the difference of the two opposing windings; the equaliser is then placed next to the cumulative series winding, so that the differential series turns are arranged to carry only the current output of their own armature.

(v) In most D.C. central stations shunt-wound generators are used, even though batteries be not installed. As explained in § 138, the field of a shunt dynamo is generally built up from residual magnetism in the iron, but this magnetism may be so weak that the generator is incapable of self-excitation, or it may be reversed so that what was the positive brush one day becomes the negative brush next day. It is therefore customary to excite the magnets from the bus bars before putting a machine in circuit; this ensures correct polarity. When starting a plant for the first time, it may be necessary to excite the magnets from a small battery till the building-up process gets under way. So long as the polarity is correct, the incoming machine can be switched in parallel directly its E.M.F. is equal to, or (to allow for the drop occurring directly the machine takes load) a little above, that of the machines already in service. Thereafter load is distributed between the machines automatically or by field regulation, as already explained. If a compound-wound generator refuses to excite normally, it can generally be made to do so by *momentarily* short-circuiting the main terminals—assuming, as in the case of the shunt machine, that the connections are correct and that the brushes are down on the commutator. This short-circuiting is best effected by a small-diameter copper wire put between the terminals before the machine is started; the wire fuses before the short-circuit current reaches a dangerous value. After closing the equalising switch and bringing up the pressure of the incoming machine, the main switch is closed and parallel running established.

149. Parallel Running of Alternators: Synchronising and Synchroscopes.—(i) Alternators of all types and sizes, provided they are wound for *the same number of phases and cycles, and* for the same pressure, can be run in parallel, but it is preferable that their wave forms should be similar; * the 3-phase plant in two hydro-electric stations over 350 miles apart, in California, is feeding the same network in this way. The most satisfactory parallel working is obtained when the alternators are driven by steam turbines, as the turning moment of these during each revolution is absolutely regular; this is not the case with reciprocating engines, although by scientific balancing of the rotating parts, and the use of heavy flywheels, a fair approximation to an even turning moment can be obtained. Even in water turbines there is some periodic variation in turning moment, especially in impulse turbines where the tangential force may vary in the ratio 1 : 2 as the bucket passes through the jet. If through any such irregularity the machines get slightly 'out of step' the magnetic effect of the interchange currents set up between them pulls them back again into synchronism. It is not uncommon, however, for trouble to be experienced in the way of heavy interchange currents between alternators connected in parallel and driven by steam turbines and horizontal reciprocating

* B.S.S. No. 168 requires that the wave form of an alternator on open circuit shall approximate to a sine wave. The maximum deviation of the actual wave from the equivalent sine wave (same R.M.S. value and same wave length), when superimposed on it so as to give the least difference, shall not exceed 5 % of the maximum ordinate of the equivalent sine wave.

engines respectively. Such trouble is due to difference in the 'cyclic irregularity' of speed * of the two prime movers, and may generally be cured by increasing the flywheel effect of the engine-driven alternator. The actual behaviour of machines in parallel depends upon the mechanical constants of all the machines; in some cases two sets may not run well in parallel but each may run satisfactorily in parallel with a third set. Much information on the hunting of alternators in parallel is given by J. Fischer-Hinnen, *Electrician*, Vol. 89, p. 185.

(ii) *Synchronising and Synchroscopes.*—When it is desired to connect another machine into circuit with those already running on load, it is brought up to about the correct speed and the field strength is varied until the voltage, at that speed, is approximately the same as that on the bus bars; it is then necessary to get the successive waves of E.M.F. on the incoming machine into exact synchronism with those already working on the load, so that the periodicities are precisely equal and also the crests of corresponding waves are attained at the same instant. In the early days of alternating current working this was a troublesome matter, and the moment of closing the paralleling switch was an anxious one; at the present day instruments known as synchronisers or synchroscopes render the operation simple. Of these there are a number of types in use, employing either (*a*) a lamp or a voltmeter, or (*b*) a dial and needle to indicate when the exact coincidence of phase occurs. In the former type the lamp or voltmeter is connected to the secondary of a small transformer, having two primary windings connected to the machine and bus bars respectively; the windings are so designed that only when the two primaries are exactly together will the resulting secondary pressure be high enough to light the lamp. As synchronism is approached the lamp lights up and then becomes dark at longer and longer intervals, and when it remains at full brightness the connecting switch is closed. The machines, however, may be as much as 16 (electrical) degrees out of phase before the synchronising voltmeter shows 1 °/ₒ variation from its maximum reading,

* The cyclic irregularity of a prime mover is generally defined as the ratio of the difference between the maximum and minimum angular speeds to the mean angular speed of the driving shaft during one revolution. This ratio should not exceed 1 / 150 and is generally lower.

so that a little error of judgment may result in a considerable shock when switching in, while there is nothing to show which machine is the faster.

Dial instruments consist either of a miniature induction motor or of a dynamometer movement; the needle revolves in one direction or the other according to whether the speed of the incoming machine is too high or too low. When the needle becomes stationary over a mark on the dial the machines are in step. Maintained identity of phase implies equality of frequency, hence it is unnecessary to use a frequency meter (§ 112) for synchronising.

(iii) In the *Weston synchroscope* (Fig. 38) the moving element consists of a very light dynamometer movement pivoted between

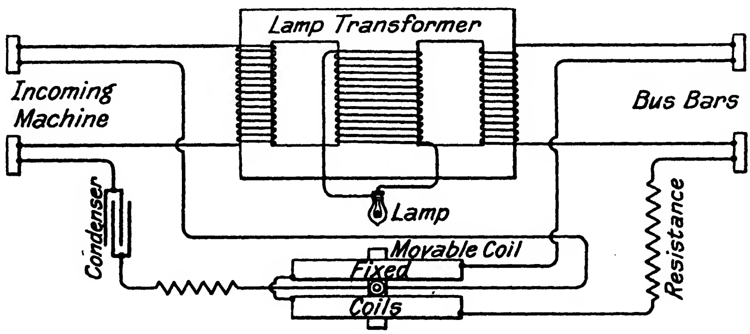

FIG. 38.—Connections of Weston synchroscope.

jewels and connected through a condenser across the terminals of the incoming machine. The fixed coil, which is wound in two sections, is connected across the line through a resistance. The pointer is behind the translucent glass scale, which is illuminated by a lamp connected to the central coil of a transformer, having two primary coils connected across the bus bars and the incoming machine respectively, so as to glow brightly when the machines are in synchronism; thus *only* when the lamp is alight is the shadow of the pointer seen. As the one circuit contains a condenser and the other a slightly inductive resistance, it is possible to adjust their constants so that the currents in the two will be in exact quadrature when the E.M.F.'s are either in phase or in opposition, and under these conditions no torque will be exerted and the pointer will stand in the centre of the scale. Since the lamp is dark when the E.M.F.'s are in opposition and light when they are in coincidence and have the same frequency, the shadow of the pointer will be seen at rest in the middle of the scale when perfect synchronism is attained. But when the E.M.F.'s are not exactly in phase or in opposition, there will be a torque tending to turn the movable coil, and the value of this torque will increase with the phase displacement, its direction depending upon the relative direction of the currents in the coils. If the machines are not running at the same frequency the torque will vary continuously from zero to plus maximum and back through zero to minus maximum, thus causing the pointer to swing back and forth over the scale (Fig. 39). Each swing will coincide with a period of light or darkness, and the pointer will be seen only during every other swing, that is, it will appear to rotate in one direction. The direction of this apparent rotation indicates whether the incoming machine is fast or slow, and the speed of rotation is a measure of the amount by which the frequencies differ. It is clearly better to switch in when the incoming machine is slightly ahead of those already connected, or on a 'rising phase'; the machine will then drop into phase as it takes up load instead of having to be pulled in.

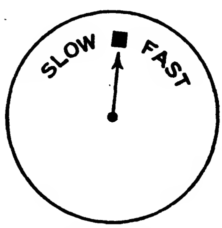

FIG. 39.—Dial of synchroscope.

(iv) The *Everett-Edgcumbe synchroscope* has an indicating dial as shown in Fig. 39, and the pointer is connected to the rotor of a miniature 2-phase motor, in which one set of windings is fed from the bus bars and the other set from the incoming machine. If the bus bar frequency is the same as that of the incoming machine these fields will rotate in step, and the rotor will remain at rest. If, however, the frequency of the current in one set of coils is higher than that in the other set, then the tendency of the two fields to keep in step will cause the rotor to revolve in the same direction as the fields, and thus indicate 'fast' or 'slow.' A red or green lamp, visible from the stop valve, is shown in the opening behind the needle, according to whether the incoming machine is running fast or slow; and, by a relay, similar lamps can also be placed at each prime mover when the synchroniser is out of sight.

(v) Automatic paralleling gear is used in some stations, and its use will probably extend with the increasing adoption of automatic hydro-electric generating plant (§ 187) and automatic substations (§ 428). The utility of this gear probably lies in eliminating continuous attendance in isolated installations rather than in offering greater security where skilled staff is available. The apparatus is rather complicated and delicate but the principle of operation is simple; a series of relays close when there is equality of voltage, phase, and frequency in the two circuits to be paralleled, and the paralleling switch is then closed automatically.

When an incoming alternator is synchronised and connected to the bus bars its speed must remain equal to, or must bear a fixed ratio to the speed of the other machines with which it is in parallel. Unlike the case of D.C. generators in parallel, increase of the excitation of an alternator cannot increase the proportion of the total load it carries, because this cannot reduce the speed to enable the governor to admit more steam to the prime mover. The increase of exciting current increases the internal E.M.F. of the alternator, and this causes an increase of the lagging reactive current generated by the machine, but does not affect its power output. Thus increasing the excitation of an alternator causes the power factor of its output to be reduced in a lagging direction, whilst the power factor of the other alternators in parallel tends to become leading. Variations of the load carried by an alternator in parallel with others can only be made by adjustments of the steam supply to the prime mover, and this is generally accomplished by variation of the governor control. Thus, when it is desired to increase the load on an alternator which has just been synchronised, the governor control is adjusted so that at the speed at which the machine is running more steam is admitted. The speed tends to increase and the alternator takes up load, whilst, due to this tendency, the governors of the other machines reduce the steam supply, and hence the load they carry, correspondingly.

This important matter may be summarised as follows: The total load of a set of alternators in parallel can be considered as the resultant of two components, the active component or kW, and the reactive component, or kVAr (§ 110*a*). The division of the total kW output is fixed by the steam supply to the prime movers of the alternators, and is varied by governor adjustment. The division of the total kVAr output is fixed by the internal E.M.F.'s generated in the machines and is varied by adjustment of the D.C. excitation.

After parallel running is established the load is divided between the various machines by hand regulation of the throttle valve or by the governor; in large generating stations the governors of steam or water turbines can generally be adjusted from the switch-board, through the agency of a small servo motor.

150. Phase Connections and Phase Rotation.—In the case of 3-phase alternators, it is necessary initially to connect the phases correctly to the switchboard, so that armature coils which occur consecutively in the direction of rotation of one machine are in parallel with coils occurring in the same relative position in other machines. Various conventions are used to identify phases, *e.g.* red, yellow or white, and blue, with green for the neutral wire, the colours being used to mark terminals and wires and to show the direction of rotation of the field due to successive waves. (*See also* I.E.E. rule 51, § 280.) The standard method of marking phases with regard to the sequence in which the phase-to-neutral voltages attain maximum positive values is shown in Fig. 40 and in Fig. 16 (§ 110). It is seen that the positive maximum voltage on the blue phase lead occurs one-third of a cycle in time before, or 120° in angle in advance of the positive maximum voltage on the red phase lead. Hence, blue is often said to be the lagging and red the leading phase. If any two of the three leads from a 3-phase supply be interchanged at the source, the phase sequence of these leads will be reversed. A reference to Fig. 4 (§ 15) will show that if the waves do not run in order and as shown, owing to one coil being connected wrongly, the symmetry of the system will be upset and a short-circuit will occur. So long as there are fine fuses in circuit no harm will result from trial and error in making the connections; two terminals are therefore connected together and the resultant voltage across the open ends of these coils is measured under working conditions. If the connection is in delta and correct this should be the same as the voltage between the ends of either coil alone. Obviously this is so, as the third coil (also giving the same pressure) is to be connected across these terminals (Fig. 36A, § 143); this is done through a fine fuse, which will blow if the connection is wrong. In the case of star connection (Fig. 36B) the same procedure on the first two coils will show a resultant pressure 1·73 times that due to a single coil, if the connections are correct. In this case one end of the third coil is then connected to the neutral junction, and the resultant pressure from the open terminal to either of the other open ends will, if correct, give the same result; otherwise the fuse will blow.

The phase rotation of two alternators may be compared by connecting a motor to each in turn, and noting which connections cause the motor to run in the same direction in both cases; these connections are in the same phase rotation. Miniature 3-phase induction motors are made for this purpose with disc armatures.

A method of determining phase rotation, due to Varley, is illustrated by Fig. 40. Two similar filament lamps *F*, *F* and an

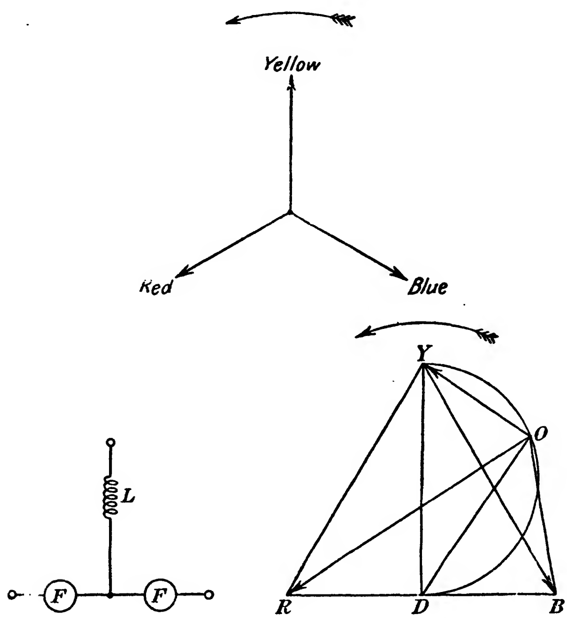

Fig. 40.—Varley phase rotation test.

inductance *L* are connected in star between the phases *ABC* to be identified.

The reversed resultant of the currents in the lamps must be identical with the current in the inductance, and this current must lag 90° on the inductance voltage. In the vector diagram *OR* and *OB* represent lamp voltages and currents since these are of equal impedance and non-inductive. *OD* is one half of the resultant of the lamp currents, and *OY* is the inductance voltage. As the point *O* lies on the semicircle on *YD*, this geometrical condition satisfies the electrical conditions. Hence for all values of the inductance reactance between *O* and infinity, the voltage on the lamp connected to the lagging phase must be greater than that connected to the leading phase. The voltage coil of an induction meter can often be utilised as an inductance for this test. Instead of an inductance, a condenser can be used. In this case the semicircle of the vector diagram must be drawn on the left of the median *YD* of the vector triangle and the rule is reversed; the bright lamp indicates the leading phase.

The connections of synchroscopes can be verified (after checking the phase sequence as above), by disconnecting the phases of the new machine at the neutral point and switching this machine (*whilst stationary*) on to the live bus bars. Both sides of the synchroscope are then excited from the bus bars and, if the connections are correct, synchronism is indicated. Where bus bars are sectionalised it must be made impossible to parallel machines which are in synchronism with different sections of the bus bars.

151. Official Regulations.—The Electricity Regulations of the Factory and Workshop Acts, 1901-1911, contain the following clauses:—

19. All parts of generators, motors, transformers, or other similar apparatus, at high pressure or extra high pressure, and within reach from any position in which any person employed may require to be, shall be, so far as reasonably practicable, so protected as to prevent danger.

21. Where necessary to prevent danger, adequate precautions shall be taken either by earthing or by other suitable means to prevent any metal other than the conductor from becoming electrically charged.

25. Adequate working space and means of access, free from danger, shall be provided for all apparatus that has to be worked or attended to by any person.

The complete text of these Regulations and the official Memorandum thereon should be studied; also, the relevant clauses in the I.E.E. regulations.

152. Bibliography (*see* explanatory note, § 58).

REGULATIONS.

H.O. Electricity Regulations for Factories and Workshops (§ 150).

H.O. Regulations as to Installation and Use of Electricity in Mines (Chapter 32, Vol. 3).

I.E.E. Wiring Rules (§ 150).

STANDARDISATION REPORTS, ETC.

(1) *I.E.C. Publications.*

No. 34. Rules for Electrical Machinery.

(2) *B.S. Specifications.*

No. 77. Voltages for New Systems and Installations.

No. 96. Parallel-sided Carbon Brushes for D.C. Commutator Machines.

No. 168. Electrical Performance of Industrial Electric Motors and Generators with Class A Insulation. Addendum 1931.

No. 169. Electrical Performance of Large Electric Generators and Motors Rating Permitted Overloads. Addenda 1926 and 1929.

No. 171. Electrical Performance of Transformers for Power and Lighting. Addenda 1927 and 1929.

No. 172. Electrical Performance of Rotary Converters (Continuous Rating Permitting Overloads).

No. 225. Electrical Performance of Alternators of the Steam Turbine driven Type.

No. 226. Electrical Performance of Large Electric Generators and Motors Continuous Maximum Rating.

No. 269. Methods of Declaring Efficiency of Electrical Machinery (excluding Traction Motors), Rules for.

No. 270. Electric Motors and Generators for Mines.

No. 280. Field Rheostats for Electric Generators, Motors, Synchronous Converters and Balancers.

No. 397. Leclanché-Type Primary Cells.

No. 445. Copper Commutator Bars for Electrical Purposes.

(3) *B.E.A.M.A. Publications.*

Standardisation Rules for Electrical Machinery.

Books.

Primary Batteries; their Theory, Construction, and Use. W. R. Cooper (Benn).

Electrical Characteristics and Testing of Dry Cells. Circ. No. 79, Bureau of Standards (Washington).

Modern High Speed Influence Machines. V. E. Johnson (Spon).

Dynamo-Electric Machinery. S. P. Thompson, 2 vols. (Spon).

Continuous Current Armature Winding. F. M. Denton (Pitman).

Elementary Principles of A.C. Dynamo Design. A. G. Ellis (Blackie).

Specification and Design of Dynamo-Electric Machinery. Miles Walker (Longmans).

D.C. Dynamo and Motor Faults. R. M. Archer (Pitman).

I.E.E. Papers.

Too numerous to be mentioned fully; papers have been published on all phases of the subjects discussed in this Chapter. The following references may be useful:

Some Problems in High-Speed Alternators. J. Rosen. Vol. 61, p. 439.

Theory of the Magnetomotive Force of Windings. A. E. Clayton Vol. 61, p. 749.

Iron Losses in D.C. Machines. E. Hughes. Vol. 63, p. 35.

The Load Characteristics of a Dynamo giving Constant Current over a large Range of Speed. J. C. Prescott. Vol. 63, p. 206.

Recent Improvements in the Insulation of Electrical Machinery. K. G. Maxwell and A. Monkhouse. Vol. 64, p. 439.

The Magnetic Field of the Dynamo. F. W. Carter. Vol. 64, p. 1115.

Electrical Plant and Machinery. H. M. Sayers. Vol. 65, p. 327.

The Stability Characteristics of Alternators and of Large Inter-connected Systems. W. D. Horsley. Vol. 77, p. 577.

CHAPTER 5.

POWER FACTOR AND ITS IMPROVEMENT.

153. **Lagging and Leading Power Factors.**—The power factor of an A.C. circuit may be defined as the ratio of the true watts to the volt-amperes or apparent power (§§ *56, 110a*). In other words, it is the factor by which the volt-amperes must be multiplied in order to obtain the true watts.* When the current wave is out of phase with the voltage wave the power factor is less than unity; to discriminate between the two cases, a power factor of, say, 0·8 or 80 %, may be termed '0·8 lagging' if the current wave lags behind the voltage wave, and '0·8 leading' if the current wave leads with regard to the voltage wave. With few exceptions, the P.F. of industrial A.C. circuits is lagging, and when a simple numerical value is stated for the power factor it may generally be assumed to be lagging. The ideal condition in an A.C. system is that of unity power factor and, *compared with unity power factor, any lower power factor is equally objectionable whether leading or lagging*. In practice, A.C. loads having a low and leading P.F. are generally welcomed because the resultant P.F. of the system is usually less then unity and lagging, hence the addition of circuits having a leading P.F. improves the P.F. of the system as a whole (§ *159*).

154. ***Watt and Wattless Components.***—*In order to appreciate* the consequences of low-power factor it is necessary to consider the 'composition' of the current under such conditions. Taking the case of a lagging current, as being that generally encountered in practice, the current *OI* (Fig. 41) lags $\phi°$ *with*

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* This simple definition is equally applicable to single-phase circuits and to balanced polyphase circuits, but the interpretation of the definition is complicated in the case of unbalanced polyphase systems in which the currents in the several phases, and the phase angles between these currents and their voltages are not equal. Alternative definitions and methods of calculation and measurement to *be employed in such circuits are discussed in a symposium, Jour. Amer. I.E.E., Vol. 39, pp. 538-46; see also § 111.*

regard to the voltage OE, and may be resolved into a watt (or active) component OA ($= I \cos \phi$) in phase with the voltage (*see* Fig. 8, § 37), and a wattless (or reactive) component OB ($= I \sin \phi$) 90° out of phase with the voltage (Fig. 9, § 37). The power factor $= \cos \phi$. An equal current OI' at a greater angle of lag ϕ' (*i.e.* a lower power factor) has a smaller watt component OA' and a larger wattless component OB'. For the same watt component as before (OA), we must increase the total current to OI'' when the lag is ϕ', the wattless component then increasing to OB''. It should be noted that it is the *vectorial* sum of OA and OB which equals OI, *i.e.* the total current and its components form the three sides of a right-angled triangle, and

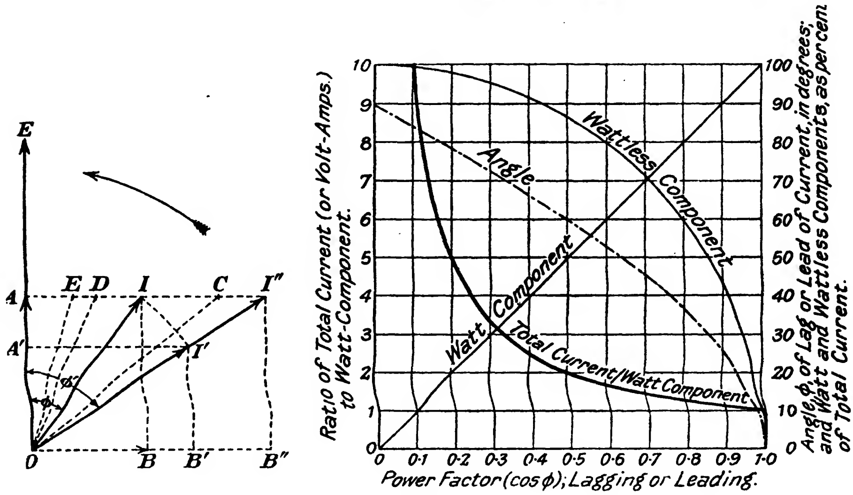


FIG. 41.—Watt and wattless components of current at various power factors.

the *arithmetical* sum of the components is always greater than the total (actual) current.

These points are illustrated by the curves plotted in the right-hand portion of Fig. 41, against a base of power factor. The curve representing the angle of lag or lead corresponding to various power factors is a cosine curve (P.F. $= \cos \phi$). The watt component, as a percentage of the total current, is directly proportional to the power factor and is, therefore, represented by a straight line. The wattless component is proportional to $\sin \phi$, and, when plotted against power factor, gives a curve which is a quadrant of a circle. It will be seen that when the P.F. is 0·95, the watt component is 95 A and the wattless component about

31·3 A for every 100 A total current; and at 0·65 P.F. (not an uncommon value in practice, § 157), the watt component is 65 A and the wattless component 76 A for every 100 A total current.

The value of the ratio: Total current / watt component = sec ϕ = 1 / cos ϕ, and rises from unity at unity P.F., at first gradually and then very rapidly, to infinity at zero P.F. as shown by the heavy curve in Fig. 41.

155. Effects of Low-power Factor.—From the preceding remarks and by inspection of the vector diagram in Fig. 41, it is obvious that the current OI is always greater than its watt component OA. In other words, for the same useful power (true watts) as represented by the voltage OE and the current OA in phase with it, we require a larger current OI if the angle of lag be ϕ, and a yet larger current OI'' if the lag be ϕ'. The larger the angle of lag, the lower the power factor, and the larger the current required for given true power. The current-carrying capacity of the generators, transformers, and transmission lines (§ 301) must therefore be higher, the lower the power factor for a given load (kW); or, the dimensions of the generators, etc., being fixed, the kW which can be supplied is lower, the lower the power factor. We thus arrive at the most obvious—and generally the most important—effect of low-power factor, *viz.* reduced kW capacity of the whole of the electrical equipment and, hence, increased standing (capital) charges on every unit (kWh) of energy delivered. If the kW output of the generators, when working at the maximum safe kVA output, is less than the kW capacity of the prime movers,* part of the investment in the latter is non-productive and there is a further increase in the standing charges per kWh. The working costs are also increased by the fact that the I^2R losses (§ 49) in all parts of the circuit vary with the square of the *total* current (*i.e.* inversely with the square of the power factor); as the total current is 1·43 times the watt component when the P.F. is 0·7 (*see* heavy curve, Fig. 41), the I^2R losses are then $(1{\cdot}43)^2$ = 2·05 times as great as though the same useful load were supplied at unity P.F. The wattless component itself absorbs no energy from the prime movers for its production (§ 37),

* On the assumption that the maximum P.F. likely to be reached in the system as a whole at full-load will be 0·8, it is usual to make the kW capacity of prime movers equal to 80 °/₀ of the kVA capacity of the generators to which they are coupled.

but it takes up current-carrying capacity which might otherwise carry useful power, and the additional I^2R-loss due to wattless current represents a dissipation of energy which has to be supplied by increased output from the prime movers.

At low-power factor (which is particularly prevalent during light-load periods), the generators and other parts of the electrical system are electrically fully loaded at a fraction of the rated kW output of the prime movers, hence the steam, fuel, or water consumption of the latter is higher per kWh than it would be if the same useful load were supplied, at higher power factor, by a smaller number of generators, the prime movers of which could then be fully loaded.

The heavier total current, corresponding to a given watt component, at lower P.F. involves a greater *IR* drop (§ 24) in the ohmic resistance of the circuit. In addition, the inherent voltage regulation of generators and transformers is worse the lower the P.F. The voltage regulation of a transformer may be 1 % at unity P.F. and 3-5 % at 0·7 P.F.; that of a modern alternator with windings of high reactance may be 10 % at unity P.F. and 20-25 % at 0·8 or 0·7 P.F. (§ 147). There is no means in the transformer of compensating for the additional voltage drop with low-power factor. The alternator voltage is held constant by increasing the excitation (§ 147); at the best, operation at low P.F. means that the exciter output must be increased (and the generator efficiency thus reduced), and it may happen that the alternator field coils reach their limiting temperature before the excitation is increased sufficiently to maintain normal voltage—in that event the kVA, as well as the kW capacity of the alternator is reduced at the lower power factor. At 0·8 P.F. the field current must be about 50 % heavier than at unity P.F. to maintain normal voltage and equal kVA output.

The net effect of the increased losses and lower kW capacity at lower P.F. is an appreciable decrease in efficiency in the electrical system. At 0·8 P.F. and rated kVA output the efficiency of alternators is about 2 % lower, that of transformers ¾ % lower, and that of transmission lines 2-3 % lower than at unity P.F. These reductions in efficiency involve higher fuel costs per kWh delivered.

The disadvantages of low power factor may be summarised as follows:—

(1) The prime movers, boilers and auxiliaries, are underloaded (in kW) when the generators are fully loaded (in kVA), hence there is more or less idle investment on the former.
(2) Decreased efficiency of prime movers due to operation at partial load.
(3) Unnecessarily large generators, due to the heavy armature currents; involving higher investment of capital on these also.
(4) The increased field current required to maintain voltage also adds to the size of the machine and necessitates increased exciter capacity.
(5) General increase in cost of station and distribution equipment.
(6) Poor voltage regulation, causing a decrease in quality and quantity of manufactured products.
(7) Increased maintenance and operating expenses.
(8) Higher energy losses.
(9) As regards the transmission and distribution, the effect is three-fold: Low power factor reduces the kW load-capacity of the conductors, or requires increased copper to carry the load; it increases the energy loss per unit kW load; and it causes increased voltage drop or poor regulation.

Thus the kW-capacity of transformers depends directly on the P.F.; at 0·6 P.F. the kW-rating is 60 % of the rating at unity P.F., so that 40 % of the transformer investment is idle.

These considerations may be illustrated by the following examples* relating to generation and transmission:—

Generation.—Take the case of an isolated plant of 500 kW capacity, the generator-driving turbine running condensing. Assume the plant to operate 10 hrs. a day with a load factor of 50 %; that is, with an average output of 250 kW throughout the 10 hrs. With coal costing 27s. a ton and the plant operating condensing, the power costs will be over 5 % higher at 0·70 than at 0·95 power factor.

In actual practice, with an existing plant, a saving in fixed costs is not realised until it is necessary to increase the capacity of distribution, transforming or generating equipment. Then P.F. improvement will show good return by either postponing the need for more equipment or minimising the investment.

Even if equipment is adequate for operation at low P.F., it may be necessary to operate an additional unit, resulting in greater energy loss. With fuel cost per kWh established, estimates of the saving in copper loss by improving P.F. can be readily determined.

Transmission.—Assume a 2 300 V, 3-ph., 60-cycle transmission line to deliver 200 kW over a circuit 1 mile long, with an allowable energy loss of 5 %. At 0·95 P.F., copper of 50 000-circ. mil. section (0·0 393 sq. in.) may be used, weighing approximately 2 600 lbs. With copper at 10d. per lb., this line would cost about £109. At 0·60 P.F., copper of 132 000-circ. mil. (0·1 037 sq. in.) section would be required, weighing about 6 500 lbs. and costing approximately £271. If the 50 000-circ. mil. (0·0 393 sq. in.) line were used with the load at 0·60 P.F., the line loss would be increased to 12·5 %.

Examples might be multiplied indefinitely, but enough has been

* F. W. Hotchkiss, *Power*, Vol. 68, p. 152. The data given are here converted to British units.

said to demonstrate that low P.F. is of serious economic consequence in any A.C. system.

156. Causes of Low Power Factor.—The prevailing power factor of all commercial supply systems being lagging (§ 153), it may be taken that any increase in inductive reactance (§ 44) will lower the power factor, whilst any increase in charging current will raise the power factor. The greater the inductive reactance, *i.e.* the greater the inductance and the higher the frequency, the lower the power factor, other conditions being constant. Similarly, the larger the capacity and the higher the frequency, the higher the power factor, other conditions being constant. (*See also* § 135 (1).)

The effects of the inductance and capacity of a line on the power factor are exemplified in §§ 300, 305. The line itself may cause the current to lead or to lag with reference to the E.M.F. according to whether the capacity or the inductance predominates. Underground cables have considerable capacity (§ 311), while inductance is more important in most overhead lines (§§ 299, 305, 306). In the case of long distance, extra high voltage lines, however, the charging current is an important factor and may compensate more or less accurately the inductive drop in the line at full-load (§§ 158, 318, 331); on light load, in such cases, it may be necessary to compensate for the charging current by switching inductances into circuit. At all pressures up to 50 000 V or so, and for all distances up to about 50 miles, the inductance of overhead lines predominates over the capacity effect and causes a reduction in the P.F. of the system.

The magnetising current and magnetic leakage of transformers cause the total current to lag with regard to the E.M.F., but the effect on the P.F. is small at normal load. When a transformer is on light load (secondary circuit open) its primary current power factor is low; for this reason house-lighting transformers have a very bad effect on the P.F. of the system during the daytime.

Arc lamps have relatively low P.F. due to the characteristics of the arc itself (§ 56), the inductance of the operating coils, and (where used) the inductance of regulating chokers; the P.F. of these lamps is commonly 0·85 for the arc itself and 0·7 or 0·6 including the operating coils and ballast. Filament lamps are practically non-inductive and constitute a load of unity power factor; thus the more of these lamps there are in use, the higher the average P.F. of the system. If the lamps be used in conjunction with condensers (§ 480, Vol. 2), the latter cause leading currents and raise the P.F.

Electric heaters are non-inductive if the circuits be so arranged that the magnetising effect of each wire is neutralised by the equal but opposite effect of an adjacent wire carrying the return current; if this precaution be not taken the apparatus is inductive, to a degree which increases with the proximity and amount of iron near the conductors. Arc furnaces are of relatively low P.F. for the same reason as arc lamps; if the furnace be used to melt iron or steel the circuit is particularly inductive (P.F. 0·6-0·65) until the temperature exceeds that at which iron becomes non-magnetic (§ 84); thereafter, the P.F. may rise to 0·85 or 0·9. The P.F. of induction furnaces (§ 931, Vol. 3) is very low in the larger sizes because of the low resistance of the secondary circuit; in the largest furnaces of this type a supply frequency as low as 5 cycles / sec. has been used in order to improve the P.F. (§ 135).

Synchronous motors and rotary converters may cause either lead or lag according to circumstances; an over-excited synchronous motor may be used simply to counteract the lag due to inductive apparatus or it may at the same time be doing mechanical work (§ 160 (3)).

By far the most important cause of low-power factor in average industrial supply systems is the induction motor. As explained in Chapter 28 (§ 681 *et seq.*, Vol. 3), this motor is essentially a transformer, but, due to the air gap in the magnetic circuit a relatively large reactive current is required to produce the working magnetic flux, and the power factor is consequently low. The actual value of the P.F. ranges from 0·8-0·85 at full-load to 0·6 or 0·7 at ½-load, and 0·4-0·45 at ¼-load in the case of large motors (50-100 h.p.). In small motors, of ½ to 2 h.p., the P.F. may be 0·6-0·7 at full-load, and 0·25-0·3 at ¼-load. From these figures it is evident that induction motors should be operated as nearly as possible at full-load. On light-load the current consumption is almost entirely wattless, the power factor is about 0·1, and the kVA input is about one-third of the full-load kVA. Maximum P.F. is reached at about full-load; on overload the P.F. decreases because of the rapid increase in rotor reactance. The P.F. of high-speed induction motors is higher than that of low-speed machines of equal output (*loc. cit.*), hence the high-speed motor is to be preferred. The P.F. of single-phase induction motors is generally lower than that of 3-phase machines.

157. Measurement and Estimation of Power Factor.—Power factor indicators or phase meters of various types have already been described (§ 111). Such instruments are useful in measuring the P.F. of a particular load and in switchboard service, but from § 156 it will be realised that the P.F. is ever varying, both at different times and in different parts of a circuit at any one time. Average power factor over a period can be determined by means of a recording power factor meter, but a preferable method is to base the average on the registrations of kWh and kVArh meters, as explained in § 116*a*.

For project estimating the values given in Table 13 for the

TABLE 13.—*Power Factor at Receiving End of Line with Various Loads, at Full-Load in Each Case.*

	Angle of Lag. ϕ.	Power Factor. Cos ϕ.	Sin ϕ.*
Continuous current	Nil	Unity	Zero
A.C.—Lighting only	18°	0·95	0·31
Mixed, $\frac{2}{3}$ lights, $\frac{1}{3}$ motors . .	$25\frac{3}{4}$°	0·9	0·436
Mixed, $\frac{1}{3}$ lights, $\frac{2}{3}$ motors . .	$31\frac{3}{4}$°	0·85	0·527
Motor load only . . .	$36\frac{3}{4}$°	0·8	0·6
Ditto, mining work . . .	$41\frac{1}{2}$°	0·75	0·66
Ditto, single-phase . . .	45°	0·7	0·7

P.F. of the load *at the receiving end of the transmission line* will be found sufficiently accurate. The P.F. at the generating end may be nearly equal to these figures if there are no transformers or other inductive apparatus on the way; on the other hand, it will be much lower if there are several transformations. For instance, in a case where there are step-up transformers in the generating station, a transmission line, step-down transformers at the receiving end, distributing transformers beyond these, and in some cases low-pressure house transformers as well, the P.F. on a purely lighting load will be only about 0·65. The P.F. of a circuit containing fairly large 3-phase induction motors, fully loaded, but with two banks of transformers intervening, may be as low as 0·6. A serious error in the predetermination

* The use of sin ϕ (called the 'reactive factor') is explained in §§ 299, 302.

of the P.F. may result in the generators failing to give the required output; they may be giving their full designed pressure and their full-load current, but if these are sufficiently out of phase with one another the actual power in true kilowatts may be below the full output required. It is not that the driving power is insufficient, but simply that the I^2R losses, due to the heavy lagging currents, set a definite heating limit to the output. So far as heating effects are concerned it makes no difference whether the current is a 'wattless' current or is in exact phase with the E.M.F. Thus it will be seen that, having assumed a given P.F. at the receiving end, according to the class of load characterised in the list above, each successive link in the chain up to the generating station must then be taken into account, in order to arrive at a final result, *viz.* the P.F. of the whole circuit or system. This will be seen in the examples in §§ 299, 302, 305, 313.

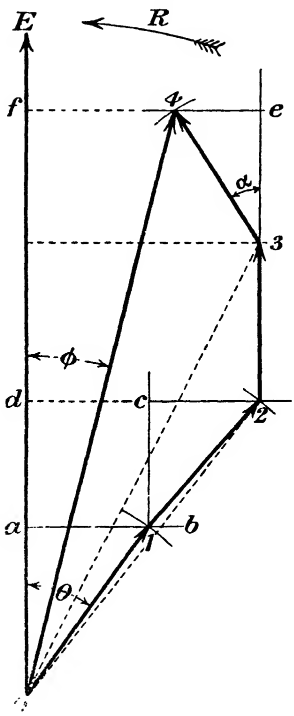


Fig. 42.—Addition of loads of different power factors.

A graphical method * for determining the resultant kVA and P.F. of any group of loads, each of known kVA and P.F., is illustrated in Fig. 42. This figure is arranged consistently with Fig. 41 (§ 154), but the current vector of each successive load is drawn from the end of the preceding current vector.

By way of example assume that the given data are as shown in the left-hand portion of Table 14. The results obtained from the graphical construction are given in the right-hand section of the table, the procedure being as follows: The line *OE* is taken as the axis of E.M.F. and the arrow *R* denotes the direction of vector rotation. In the figure as reproduced the scale of kVA is 100 kVA = 1 in.; greater accuracy would be obtained by drawing to a larger scale.

The vector *O1* representing the current (and therefore the kVA, the voltage being constant) of load No. 1 is obtained by: (i) Setting out *Oa* along *OE* (*i.e.* in phase with the voltage) to represent the *kilowatt* component of the load to scale. In this case kW (= kVA × P.F.) = 100 × 0·8 = 80, which is represented to scale by 80 / 100 = 0·8 in. (ii) Drawing through *a* a line *ab* perpendicular to *OE*.

* Given by J. A. Van Tilburg, *El. Rev*, Vol. 90, p. 436.

(iii) Drawing, with centre O and radius $O1$ = kVA of load to scale adopted (*i.e.* 100 / 100 = 1 in. in this case), a circular arc to intersect ab at 1. The line $O1$ represents the No. 1 load, the angle of lag being θ and the P.F. = $Oa / O1$ = 0·8.

For the No. 2 load we start from the point 1 and repeat the preceding construction, using the appropriate values for the lines $1c$, 1-2. The P.F. of the No. 2 load is $1c / 1\text{-}2$ = 0·75, but the combination of Nos. 1 and 2 loads has P.F. = $Od / O2$ = 1·4 in. / 1·8 in. = 0·78. The kVA of the combined Nos. 1 and 2 loads is represented to scale by $O2$ (= 1·8 in. = 1·8 × 100 or 180 kVA).

The remaining two loads are added in the same way except that No. 3 load (being of unity P.F.) is represented at once by a line 75 / 100 = ¾ in. long parallel to OE, starting from 2; whilst for the No. 4 load (which is of *leading* P.F.) the circular arc is struck on the left-hand side of the line $3e$, thus setting the load line 3, 4 at an angle of lead α with regard to the axis of E.M.F.

The combination of the four loads is represented by $O4$, the length (2·9 ins.) of which corresponds to 2·9 × 100 = 290 kVA on the scale adopted. The P.F. of the combined load is $Of / O4$ = 2·8 ins. / 2·9 ins. = 0·96 and is lagging.

The beneficial effect of non-inductive load (No. 3) and leading load (No. 4) in improving the resultant P.F. is shown very clearly in Fig. 42.

TABLE 14.—*Addition of Loads of Different Power Factors.*

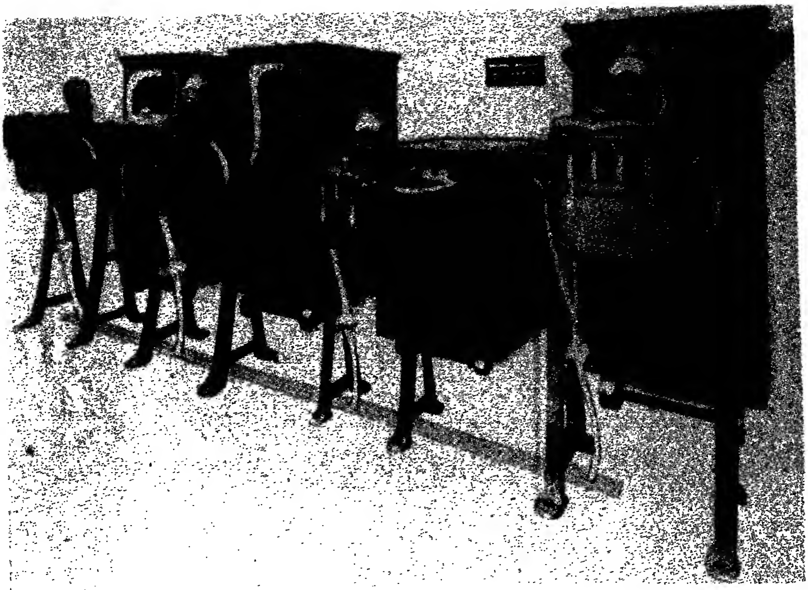
Given Data.			Calculated for Use in Graphical Construction.	Results Obtained from Graphical Construction.		
Load No.	kVA.	P.F.	kW = kVA × P.F.	Load Nos.	Combined kVA.	Combined P.F.
1	100	0·80 lag	80	1	100	0·80 lag
2	80	0·75 lag	60	1 and 2	180	0·78 lag
3	75	Unity	75	1, 2, and 3	245	0·88 lag
4	75	0·85 lead	64	1, 2, 3, and 4	290	0·96 lag

158. Avoidance of Low-power Factor.—Though it may be profitable to employ phase-correcting apparatus it should not be forgotten that it costs money to improve an initially low P.F. A much greater net profit is therefore to be derived from the avoidance than from the correction of low P.F.; this truism deserves to be emphasised, because some of the most serious causes of low P.F. (§ 156) can be avoided by suitable choice of apparatus or operating conditions.

The principal method of avoiding low P.F. in the average industrial supply system lies in the choice and application of motors. Synchronous motors should be used in preference to induction motors wherever possible; as explained in § 679, Vol. 3, there are now available synchronous motors which develop a good starting torque and are self-synchronising. High-speed induction motors should be used in preference to low-speed machines, and no induction motor should be operated at less than its rated output if avoidable (§ 156). In this connection group-driving, § 748, Vol. 3, is preferable to driving by individual motors (see, however, Chapter 29) where induction motors are employed, if the group motor can be operated at nearer its full-load than could individual motors. Often a group of machines can be driven by a synchronous motor (which can also be used for power-factor correction) instead of by individual induction motors. In some cases the use of D.C. motors supplied from a rotary converter or synchronous motor-generator is preferable to the use of A.C. motors throughout a works, because it makes possible higher P.F. at the A.C. supply terminals and also gives the consumer the advantage of variable-speed D.C. motors.

If 3-phase induction motors must be operated for considerable periods at less than $\frac{1}{2}$-load it is worth while to use stator windings which are normally connected in delta, but which can be switched into star connection for operation at low loads. The effect of changing to star connection is to reduce the voltage per phase to $1/\sqrt{3}$ times its initial value (§ 143); the maximum output of the motor varies with the square of the voltage per phase and is therefore reduced to one-third its initial value. With delta-connection the P.F. of the motor might be 0·7 at $\frac{1}{2}$-load and 0·5 at $\frac{1}{4}$-load; with the star connection the values at the corresponding H.P.-output would be about 0·9 and 0·85 respectively. At the same time, there would be an improvement in efficiency at the fractional loads.

159. Principles of P.F. Correction.—The P.F. correction of a particular load or group of loads of constant kW is illustrated by Fig. 43 in which OI_1 represents the initial current, lagging ϕ_1 with regard to the E.M.F. and having a watt component OW and a wattless lagging component OL. If we add a wattless leading component OC, the net lagging component is reduced to OM ($LM = OC$) and the resultant current is OI_2 which is less than OI_1 and lags by a smaller angle ϕ_2. The P.F. is thus raised from $\cos \phi_1$ to $\cos \phi_2$, *i.e.* from 0·7 to 0·89 in the case illustrated, by the provision of a correcting (leading) kVA represented by LM and here equal to 0·5 in. / 1·43 in. or 0·35 of the initial (uncorrected) kVA represented by OI_1; the same result can be read from the chart Fig. 45.

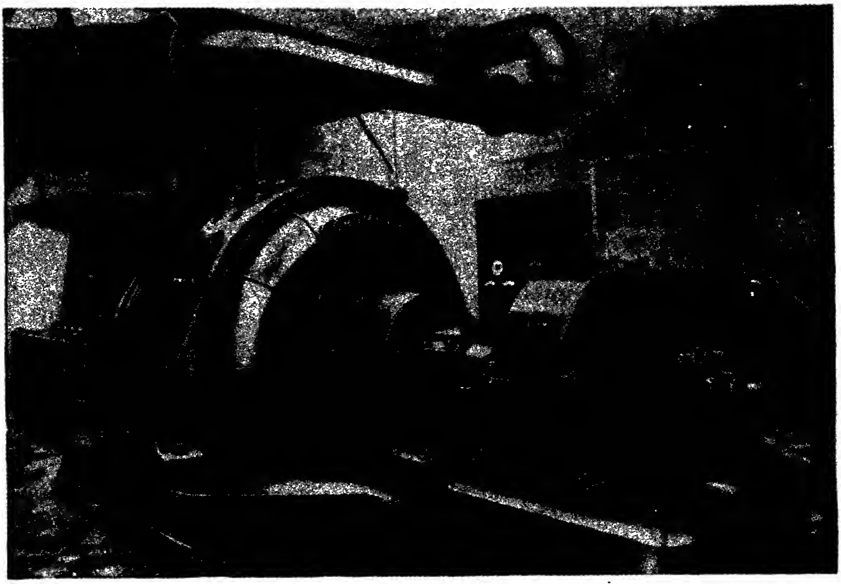


B.I. and Helsby Cables, Ltd.

OIL IMMERSED STATIC CONDENSERS FOR POWER FACTOR IMPROVEMENT.

Static condensers offer the advantage of having no moving parts. They may consist of small box-type condensers used with individual motors or of large tanks. The number in use can be adjusted easily to suit the requirements of the load.

[*To face p.* 274.



Crompton & Co., Ltd.

AUTO-SYNCHRONOUS MOTOR CAPABLE OF BEING USED FOR POWER-FACTOR CORRECTION.

The pure two-phase winding on the rotor (90° phase difference) secures perfect balance and uniform heating during starting and running (*see* Chapter 28). The exciter being connected permanently to the rotor, starting is effected by closing the stator switch and operating the rotor starter. These motors can start against two to three times normal full-load torque, and synchronise automatically, even on overload. If the pull-out torque is exceeded the motor falls out of step but continues to run as an induction motor until the excessive overload is removed, whereupon it synchronises again automatically. The machines can operate at unity P.F., or supply leading reactive power for P.F. correction in the circuit to which they are connected; they are applicable to almost any mechanical drive.

[*To face p.* 275.

In practice, the fact that the total current was reduced from OI_1 to OI_2 (Fig. 43) by the improvement in P.F., would naturally lead to the addition of more useful load to the system until the total current again reached its initial value. This case is represented by Fig. 44, in which $OI_1 = OI_2$ and I_1I_1' represents the additional load (assumed to be at the *uncorrected* P.F., cos ϕ_1) which can be added to the system in order that the current loading of the latter may remain at the initial value OI_1 *after* P.F. correction to cos ϕ_2. In this case the corrective kVA is represented by DE and is 0·65 in. / 1·43 in. or 0·45 of the constant kVA represented by OI_1 or OI_2. The corrective kVA required is naturally greater than in the constant kW case illustrated by Fig. 43, but we have now an increase AB in the kW supplied by the same total current in the mains.

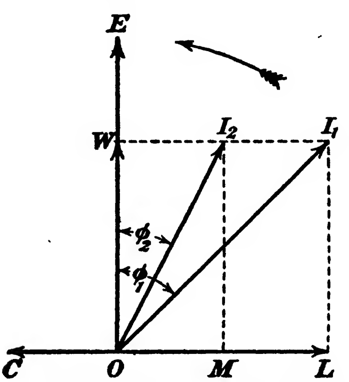


FIG. 43.—P.F. correction with constant kW.

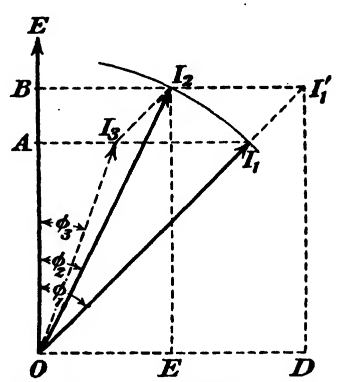


FIG. 44.—P.F. correction with constant kVA.

The construction for Fig. 44 is as follows: Draw OI_1 and OI_2 ($= OI_1$) to represent to scale the constant kVA (or current) at the initial and desired final angles of lag ϕ_1, ϕ_2 respectively. Produce OI_1 to intersect at I_1' the line BI_1' drawn through I_2 perpendicular to OE. Then $I_1' I_2$ ($= DE$) represents to scale the required corrective kVA.

This construction amounts to increasing the uncorrected load to OI_1' and then correcting (at constant kW represented by OB, *cf.* Fig. 43) to the load OI_2 which equals OI_1 but is at higher P.F. The same result is obtained by assuming OI_1 to be corrected to OI_3, at an angle of lag ϕ_3 less than ϕ_2, the extra load I_3I_2 at the initial lag ϕ_1 being then added (as in Fig. 42) with the result that the final load $= OI_2$ at lag ϕ_2. In Fig. 44, cos $\phi_1 = 0·7$; cos $\phi_2 = 0·885$; cos $\phi_3 = 0·935$, if these values be used in the formulæ given below the same results will be obtained as from the graphical construction.

The 'correcting' kVA required to improve the power factor by a given amount increases rapidly as the power factor approaches unity. The reason for this is evident from Fig. 41, § 154. Referring to the curves therein, it will be seen that the power factor increases very slowly as the angle of lag or lead is reduced below, say, 20°; conversely, the wattless component increases very rapidly as the P.F. decreases, and to increase the P.F. from 0·95 to unity it is necessary to neutralise a wattless component which is numerically equal to 31·3 % of the total (uncorrected) current. The same point may be illustrated more clearly by reference to the vector diagram of Fig. 41. The currents *OI″*, *OI*, *OE* have all the same watt component *OA*; if an equal corrective wattless component $I''C = ID = EA$ be applied to each the percentage improvement in P.F. is much greater in the case of the low P.F. current *OI″* than in the currents of higher initial P.F. Thus:—

Current Vector (Fig. 41, § 154).	Angle of Lag, ϕ.		Power Factor (Cos ϕ).		Percentage Increase in P.F. Due to Same Corrective Component in Each Case.
	Initial.	Corrected.	Initial.	Corrected.	
OI″	57°	51°	0·545	0·629	15·4 %
OI	36½°	28½°	0·804	0·879	9·3 %
OE	16°	Zero	0·961	1·000	4·0 %

The corrective kVAr or compensation of wattless component required to improve the power factor from an initial value *A* to a corrected value *B* (decimal values, *not* percentages) is given in terms of the initial kVA by the following formulæ:—

Case (1) Constant-kilowatts (as in Fig. 43).

$$\text{Corrective kVAr} = \left[\sqrt{(1 - A^2)} - \frac{A}{B}\sqrt{(1 - B^2)}\right] \times 100\ \%$$

of initial (*uncorrected*) kVA.

Case (2) Constant-kilovolt-amperes (as in Fig. 44).

$$\text{Corrective kVAr} = \left[\frac{B}{A}\sqrt{(1 - A^2)} - \sqrt{(1 - B^2)}\right] \times 100\ \%$$

of the (constant) kVA of the system.

The curves plotted from these formulæ in Figs. 45, 46 will repay careful study. The much greater corrective kVAr required to change the P.F. from 0·95 lagging to unity or from unity to

0·95 leading, compared with the corrective kVAr required for the other 0·05 increments in power factor is shown very clearly in both sets of curves. The corrective wattless component required for stated change in P.F. is naturally greater when the total kVA is constant, than when the kW is constant; this is particularly noticeable when the initial P.F. is low. Nevertheless Fig. 46 corresponds to the ultimate aim of power-factor correction in the ordinary supply network, *viz.* to increase the kW capacity (in the

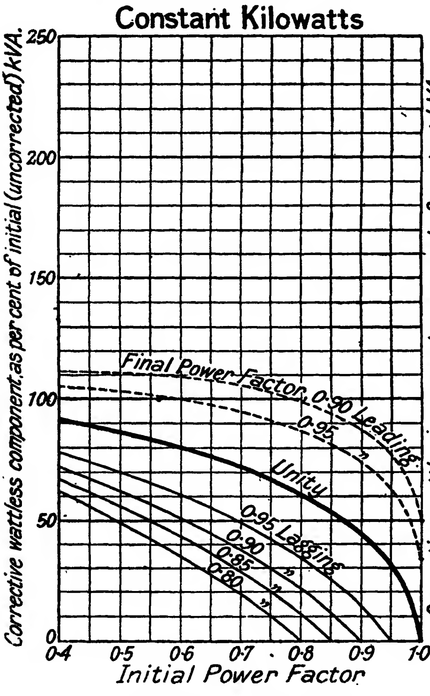


FIG. 45.—Corrective wattless component for stated P.F. correction; *constant kw.*

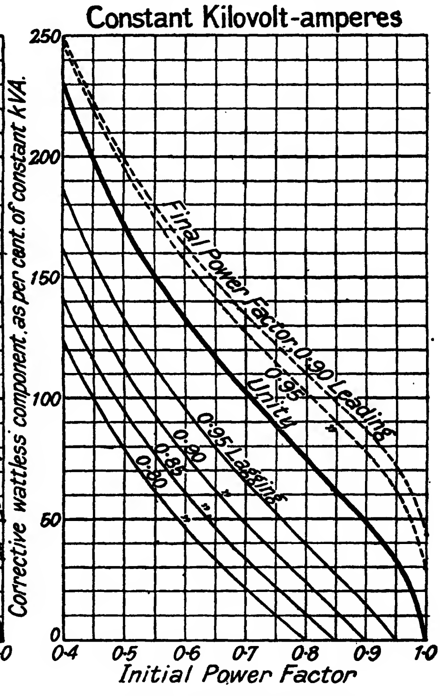


FIG. 46.—Corrective wattless component for stated P.F correction; *constant kVA.*

ratio B / A = final P.F. / initial P.F.) whilst retaining the same current loading in the system. (*See* example, § 160 (3).)

The vector diagrams in Figs. 41-44 are all for single-phase circuits. In the case of polyphase circuits the current (or kVA) *per phase* and the corrective wattless component determined from Figs. 43-46 is that required *per phase* in the polyphase system.

160. Methods of Improving P.F.—There is a number of methods available for the production of correcting wattless kVA, the necessary amount of the correction being determined as explained in § 159. With the exception of the charging current of cables or overhead lines (§ 158) all leading wattless kVA must be produced artificially by either: (1) static condensers; (2) electro-chemical action; (3) synchronous motors; or (4) phase advancers.

(1) *Static Condensers.*—The static condenser consists essentially of two metal plates separated by a suitable dielectric (§ 46). For use in P.F. correction oil-immersed condensers are made in units which can be assembled in parallel to obtain the desired capacity (μF) and in series to suit the supply voltage. The condenser is connected in parallel with the load, the P.F. of which is to be corrected; the current in the condenser circuit leads 90° with regard to the E.M.F. (§ 46) and thus provides the component OC (Fig. 43). The power consumed by the condenser is zero except for the internal losses, which do not exceed 0·5 % of the kVA rating of the condenser. The condenser capacity required, per kVA of leading wattless component to be provided, is $1\,000 / (2\pi f e^2)$ farads or $10^9 / (2\pi f e^2)$ micro-farads, where f = frequency in cycles / sec.; and e = voltage applied to the condenser. If E = voltage between 3-phase lines, $e = E$ for mesh-connected condensers; and $e = E / \sqrt{3}$ for star-connected condensers (§ 143); the mesh connection requires only one-third the condenser capacity required with star connection.* The capacity required increases as the frequency decreases, and it is rarely advisable to use condensers for P.F. improvement in systems of lower frequency than 50 cycles / sec.

Condenser units designed for pressures up to, say, 600 V each may conveniently be assembled in series for pressures up to 3 000 V. Switches may be provided so that the amount of capacity in circuit can be varied to suit the load; to obviate risk of shock the condenser must be short-circuited through an

* The voltage across the condensers is $\sqrt{3}$ times as great in the mesh as in the star connection. If the condensers be exactly proportioned to the voltage the cost of the star and mesh arrangements is practically the same, but if commercial patterns of condensers are used either the star or the mesh connection may be the cheaper. For example, if the only available standard condenser units are for 250 V and 600 V, the 600 V type would have to be used both for mesh and star connection on a 600 V system and the mesh connection would then be cheaper, but the 250 V type could be used in star on a 400 V system and would probably be cheaper than the 600 V type which would have to be used for the mesh connection.

auxiliary resistance when switched out of service. According to circumstances, it may be advisable to leave the condensers always in circuit or it may be better to switch them off with the load to which they are applied in order that no leading current may then be taken from the line. Since the capacity (μF) required for given corrective kVA varies inversely with the square of the voltage applied to the condenser it may pay to use an auto-transformer (§ 396, Vol. 2) to raise the voltage at the condenser above that of the main circuit.

Standard sets of condenser units are available ranging from 172 μF to 2 760 μF at 600 V (19 - 312 kVA output at 50 cycles / sec.); or from $4\frac{3}{8}$ μF to 105 μF at 3 000 V (12-297 kVA output at 50 cycles / sec.); the tanks for these sets measure from 4 × $1\frac{1}{2}$ × $1\frac{1}{4}$ ft. to 6 × $2\frac{1}{2}$ × $4\frac{1}{2}$ ft., and weigh from $5\frac{1}{2}$-46 cwts. complete. For use with individual motors smaller sets of condensers are available, of capacities from 17-139 μF at 250 V, or 9-2 μF at 600 V.*

Static condensers require no special erection and no attendance or maintenance; they offer the only means of phase correction which can economically be subdivided for application to individual small loads (§ 161). If the corrective wattless component to be provided exceeds 300 kVA, it is generally cheaper and more convenient to use synchronous motors.

(2) *Electro-chemical Phase Advancer.*—The same effect as that produced by static condensers, *viz.* storage of energy during one half-cycle and discharge of energy during the succeeding half-cycle, can be obtained by utilising electro-chemical action instead of electrostatic capacity. If two lead grids pasted with red lead be immersed in dilute sulphuric acid and connected in an A.C. circuit they constitute a storage cell or accumulator (Chapter 18) which is 'charged' during one half-cycle and is discharged and re-charged in opposite polarity during the next half-cycle.

The amount of energy thus absorbed from and returned to the A.C. circuit is much greater than could be dealt with by a simple static condenser with equal plate area. On the other hand there are appreciable losses in the electro-chemical cell, hence the P.F. of the latter itself is relatively high. Best results appear to

* For further information the reader is referred to an instructive descriptive list issued by British Insulated and Helsby Cables, Ltd.

be obtained when the electrolyte is at about 80° C.; the resistance of the electrolyte is then low (§ 68), and the chemical activity is enhanced.

According to T. F. Wall (*Jour. I.E.E.*, Vol. 61, p. 119) the P.F. of a particular cell of this type was about 0·7 at 30° C. and 0·35 at 80° C. By connecting two cells in series in each rotor phase of a 4 h.p. induction motor the P.F. was raised from 0·5 (without phase advancer) to 0·64 (with phase advancer) on ¼-load; from 0·72-0·88 on ½-load; from 0·77-0·95 on ¾-load; and from 0·79-0·95 on full-load. Also, the efficiency of the motor between ¼ and full-load was 2 or 3 °/₀ higher with the phase advancer in use than when running with short-circuited slip rings.

(3) *Synchronous Motors.*—The synchronous motor (§§ 679, 680, Vol. 3) is electrically identical with the synchronous alternator (§ 143) but is reversed in action, electrical energy being supplied to the stator, and mechanical energy being delivered at the shaft. In a D.C. motor the effect of varying the excitation of the field is to cause the armature speed to vary in order that the back E.M.F. may remain constant (§ 669, Vol. 3). The speed of a synchronous motor is, however, fixed definitely by the frequency of supply and the number of magnetic poles (§ 135), hence the effect of varying the excitation of the field system is to cause wattless currents to flow in the stator circuit, these wattless currents being such that the resultant strength of the field remains constant notwithstanding the alteration in the exciting current. If the excitation be reduced, lagging wattless current flows in the stator circuit (from the supply system) to maintain normal magnetisation of the field system. With a higher value of D.C. excitation, no magnetising current is taken from the A.C. mains and the P.F. of the motor is unity. At yet higher values of D.C. excitation the surplus field induces (and is magnetically counterbalanced by) a *leading* wattless current in the stator circuit. In other words, an over-excited synchronous motor supplies a leading wattless current to the A.C. mains and may therefore be used, like a static condenser, to compensate for the lagging wattless current taken by other apparatus supplied from the same mains.

Over-excited synchronous motors are sometimes run light (without mechanical load) simply to effect P.F. correction and, when thus used, they are often termed 'rotary condensers.' Synchronous motors are frequently used in this way at the far end of long transmission lines in order that the latter may be relieved of wattless current which would otherwise result in serious voltage drop (§ 155). Formerly synchronous motors were of little use for industrial power service owing to their low starting torque and the necessity of synchronising them (§ 149); now, however, there are self-synchronising motors available which start as induction motors and drop automatically into synchronism (§ 679, Vol. 3); such motors can be used for P.F. correction as well as for driving a mechanical load, but their output for both these purposes is naturally lower than that in either service alone.

On practically all the present-day transmission systems, synchronous condensers of some form or other are floated on the line for the improvement of P.F. A synchronous condenser will deliver 70 % of its rated kVA in energy and approximately 70 % in wattless leading kVA for P.F. improvement. Take a case where it is necessary to raise the P.F. from 0·65-0·90, assuming a load of 450 kW. This amount of energy at 0·65 P.F. is 690 total apparent kVA, and has a component of $690^2—450^2 = 525$ wattless kVA lagging. With this same amount of energy, and the P.F. raised to 0·90 or 500 apparent kVA, the lagging component of wattless kVA is $500^2—450^2 = 220$. Now in order to raise the P.F. from 0·65-0·90 it is obvious that a synchronous condenser with a rating equivalent to the difference between 525 and 220 is required, or 525—220 = 305 wattless kVA leading. On one system the author has in mind, this method of using synchronous condensers went too far at times, and one or more receiving stations where these units were installed had to cut out practically all the exciting current so as to reduce the voltage (W. T. Taylor, *Jour. I.E.E.*, Vol. 47, 194).

A convenient means of estimating the effect of a synchronous motor in P.F. correction and of determining the mechanical load which can be carried in addition to the correction of P.F., is illustrated by the following examples due to Van Tilburg (*loc. cit.*, § 157):—

(1) Suppose that to a load of 100 kVA, P.F. 0·8 lagging, there be added a synchronous motor carrying 35 kW useful load. The maker's data for the synchronous motor are: 50 kVA at unity P.F.; 0·9 P.F. leading at ¾-load; 0·75 P.F. leading at ½-load; 0·4 P.F. leading at ¼-load. What is the resultant load and P.F.?

The solution is obtained from Fig. 47 which is constructed on the same principles as Fig. 42, § 157. In the diagram as reproduced the scale is 50 kVA = 1 in. The initial load of 100 kVA is represented by *OI*, 2 ins. long, drawn at such an angle that $OA / OI = 0·8$ (*i.e.* the initial P.F.). At full-load unity P.F. the synchronous motor (50 kVA) is represented by *IB*, 1 in. long, parallel to *OE*; and the total load is $OB = 2·88$ ins. = 144 kVA (to the scale adopted) at P.F. $= OC / OB = 2·6 / 2·88 = 0·9$ lagging. In this case the improvement is due solely to the addition of load at unity P.F.; the whole output of the synchronous motor is mechanical.

At ¾-load, the mechanical output of the synchronous motor = ¾ × 50 kVA = 37·5 kVA = ¾ in. to scale = *ID* in Fig. 47. As the P.F. of the machine is 0·9 leading, at this load, the total kVA of the machine = 37·5 / 0·9 = 41·6 kVA and is represented by *IE*, 0·83 in. long, cutting *DF* at *E*. (*Note: DE* is drawn to the left because the wattless component is leading.) Thus at ¾-full mechanical load on the synchronous motor, a corrective component *DE* is available; the total load is *OE* = 125 kVA and the P.F. is *OF* / *OE* = 0·94 lagging.

The points *G*, *H* corresponding to ½ and ¼-load are determined in the same way, and the curve *BJ* is sketched in.

The specified useful load of 35 kW is represented by *IK* (= 35 / 50 = 0·7 in.). From *K* drop *KL* perpendicular to *OE*. Then the total load is represented by *OM* (line omitted for clearness) = 2·45 ins. = 122·5 kVA at P.F. = *OL* / *OM* = 0·94.

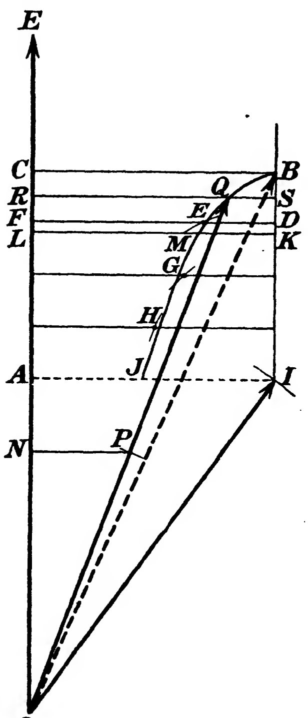


Fig. 47.—Effect of synchronous motor on P.F.

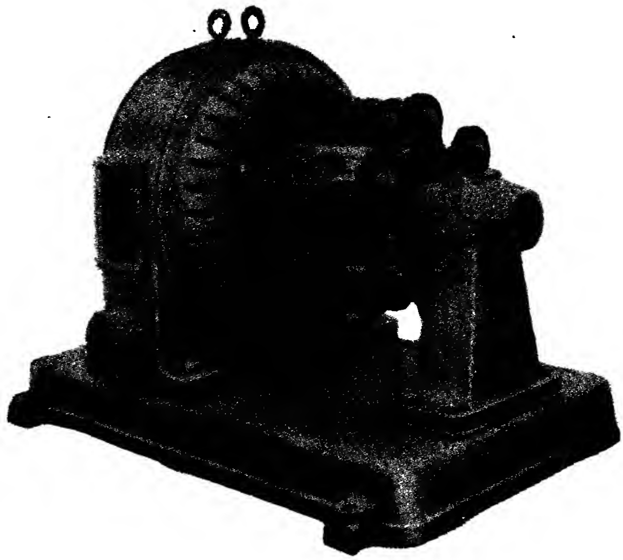
(2) Assuming the same initial load and same synchronous motor as before, what mechanical load can the latter carry whilst improving the P.F. to 0·92?

Take any convenient length *ON*, erect the perpendicular *NP*, and mark off *OP* = *ON* / 0·92; then cos ϕ = 0·92. Produce *OP* to cut the curve *BJ* at *Q*. Draw *RS* through *Q* perpendicular to *OE*. Then *IS* = 0·87 in. = 43·5 kVA to scale, and this is the mechanical load which the motor could carry under the prescribed conditions.

By using an automatic voltage regulator (§ 147), the field of a synchronous motor can be varied automatically as required to maintain predetermined P.F. in a system.

During periods of light load the spare alternators in a station may be operated as over-excited synchronous motors, their prime movers being uncoupled or, in the case of turbines, run idle *in vacuo*. The alternators in service are thus relieved of wattless current, but the improvement does not extend beyond the generator bus bars; the transformers, transmission lines, etc., still operate at low P.F.

(4) *Phase Advancers.*—Though static condensers and synchronous motors are 'phase advancers' when used for P.F. correction, this term is generally reserved for special machines which may be connected in the rotor circuit of an induction motor to improve the P.F. of the latter. The use of such auxiliaries is only practicable in the case of large motors. The principle employed is that of injecting through the slip rings of the motor a current

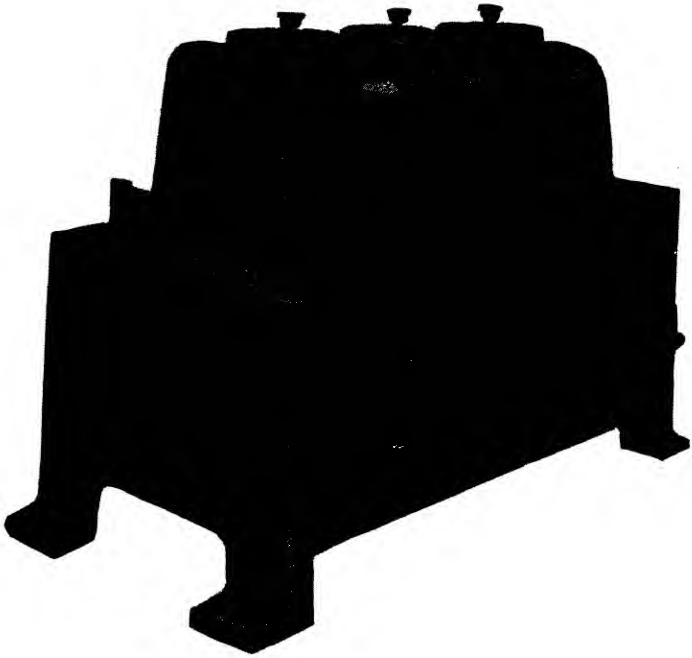


British Thomson-Houston Co., Ltd.

THREE-PHASE EXCITER (PHASE ADVANCER) FOR USE WITH AN INDUCTION MOTOR.

In its simplest form this type of phase advancer comprises an armature wound like that of a D.C. machine and an unwound stator. The armature is driven by an auxiliary motor or it may be belt-driven from or direct-coupled to the main induction motor. After starting the main motor with resistance between its slip rings, the latter are switched on to the brushes of the phase advancer. Three-phase, low-frequency slip current from the main rotor then flows to the armature of the phase advancer and establishes a rotating field. By driving the phase advancer at higher than the synchronous speed corresponding to this rotating field, the advancer can be made to supply all the magnetising current for the main motor which then operates at unity P.F. If the speed of the phase advancer be increased, the main motor supplies leading current to the network in which it is connected. Induction motors of about 40 kW have been built with a phase advancer of this type on an extension of the main motor shaft within one of the end casings of the combined set. The cost of a separate phase advancer is not likely to be justified unless the main motor is 100 kW or more, and normally operating at 0·85 or lower P.F. By varying the speed of the phase advancer unity P.F. can be maintained down to one-third rated load. If phase correction is required at lower loads the magnetisation of the main motor is best effected by D.C. and the machine then becomes a 'synchronous induction' motor. The phase advancer shown above has a capacity of 35 kVA at 770 r.p.m. It is a 4-pole machine, designed for a full-load current of 500 A, and arranged for driving by belt from the main motor. The power required to drive it is only that absorbed by friction and other losses, and is often less than the reduction effected in the losses of the main motor. The maximum torque of the latter is greatly increased by the use of the phase advancer.

[*To face p.* 282.



General Electric Co., Ltd. (London).

THE KAPP PHASE ADVANCER.

This machine is essentially a small D.C. generator. The field circuit is connected to any local source of D.C. supply, while the armature is connected, through suitable control gear, to the rotor of the induction motor. When the induction motor is running and the phase advancer is in circuit with its rotor, the armature of the phase advancer oscillates in synchronism with the low frequency 'slip current' of the rotor, this alternating current causing the phase advancer to act alternately as a motor and as a generator. A back-E.M.F. is thus established which is leading with regard to the normal current of the rotor, and therefore compensates for the lagging component of the induction motor alone.

[*To face p.* 283.

which is leading with regard to the rotor voltage. This current relieves the stator circuit of the duty of magnetising the machine and, as the leading current is supplied to the rotor at the low voltage corresponding to the 'slip' of the rotor, the kVA capacity of the phase advancer need be only 5 °/ₒ (or less) of the kVA correction effected in the main supply circuit. The full corrective kVA would have to be provided if a static or rotary condenser were used in the supply circuit. The 'phase advancer' is thus at a great advantage where high-power motors are concerned.

The Scherbius method of controlling the speed and improving the P.F. of a 3-phase slip-ring motor involves the use of an auxiliary 3-phase commutator motor driving an induction generator. The stators of the main motor and of the induction generator set are connected to the bus bars, and the rotor of the main motor is connected to the commutator motor. On reducing the speed of the main motor, 'slip-energy' is transferred to the auxiliary motor, which then drives the induction generator above synchronous speed and restores energy to the bus bars. Control is by varying the excitation of the commutator motor, and thus applying a variable back E.M.F. to the rotor of the main motor. By use of a special phase transformer, the phase of the current through the auxiliary commutator motor and the rotor of the main motor can be varied, and thus the P.F. of the main machine raised to unity.

The Miles Walker phase advancer is provided with main exciting windings on the stator which permit the phase of the advancer E.M.F. to be adjusted at will. If the advancer E.M.F. acts in conjunction with the rotor E.M.F. of the main motor, the slip of the latter is reduced; the phase advancer is then actually delivering energy to the main rotor. On the other hand, if the advancer E.M.F. opposes the rotor E.M.F. the rotor slip is increased, and the advancer runs as a motor driven by energy withdrawn from the main rotor circuit; this offers a convenient and economical means of slowing down the main motor. Compensating windings on the stator of the advancer ensure good commutation. For further information *see Jour. I.E.E.*, Vol. 42, p. 599, and Vol. 50, p. 329.

The Kapp phase advancer makes use of the fact that a conductor carrying A.C. and oscillating in a D.C. field becomes the seat of a leading E.M.F. which improves the P.F. of the A.C. As applied to a 3-phase induction motor, the phase advancer consists of three bipolar D.C. armatures vertically above each other in a single main carcase. The field magnets of these armatures are connected to an exciter on the induction motor shaft. The three armatures themselves are in delta-connection, and connected to the slip rings of the induction motor. The phase advancer is short-circuited by interlocked switchgear, whilst the induction motor is being started; then the short-circuit is removed and the low-frequency rotor-slip current sets the armatures in oscillation, a leading E.M.F. is induced in them, and the P.F. of the motor is improved and the B.H.P. of the machine increased. For further information *see Electrician*, Vol. 69, pp. 222, 272; and *Jour. I.E.E.*, Vol. 51, p. 243; Vol. 61, p. 89.

The part played by compensating windings in improving the P.F. of A.C. commutator motors is mentioned briefly in § 671, Vol. 3, and the subject is one of too specialised a nature to justify further treatment in these pages.

161. Location and Control of Apparatus for P.F. Correction.—It is clearly desirable that there should be placed immediately adjoining every load of low P.F., phase correcting apparatus which will raise the P.F. of the combination to unity, thus relieving even the feeders of wattless current. P.F. correcting apparatus relieves the generators and the circuit between itself and the generators, but *not* the circuit between itself and the load. The application of synchronous motors or phase advancers to large individual loads is economically practicable. Static condensers can be connected directly in parallel with the load and switched in and out with the latter; condensers are, however, only applicable to relatively small loads and cannot easily be adjusted to suit wide variations in load. P.F. correction for miscellaneous industrial loads is generally best effected by synchronous motors located in sub-stations. By plotting a P.F. map of the system the best situations for the corrective apparatus can be determined and the compensation can be adjusted continuously to suit the load; unless the compensation is thus adjusted there may be leading wattless currents at times, and these are as objectionable as lagging current (§ 153).

Centralised Production of Wattless Current.—Under practical conditions it is impossible to operate an A.C. system at an average power factor of unity, hence the current has inevitably a wattless component which must be produced by the generators which feed the system. It has been suggested that rather than to allow all the generators to operate at or about the mean power factor of the system it would be better to supply all the wattless current from one generator (operating at practically zero power factor), the other generators then operating at unity power factor. This method would concentrate in a single unit all the idle generating capacity and investment which are otherwise divided between all the generators on the network; and, in general, the conditions for controlling the generation of wattless current would be more favourable in a plant devoted specifically to this duty. The zero power factor generator would require little mechanical power to drive it (say 10 % of the kilovolt-ampere output at zero power factor) and this energy—representing the losses due to the wattless current—could generally be supplied more economically by a special prime mover than by a synchronous motor running light and over-excited (§ 160 (2)) for power factor correction. Again, the turbo-generator normally used to supply the wattless current could be used in emergency to supply effective power up to the kilowatt rating of the prime mover. The distribution of the wattless current from a central point would generally involve an increase in the I^2R losses in the mains, but the actual increase in these losses should not outweigh the advantages gained in other directions. It is purely a financial problem to determine the economy or otherwise of centralised wattless generation in any particular system. (*See also* § 320.)

Bearing in mind the effect of low P.F. in reducing the effective kW capacity of plant, on which depend the fixed costs per kWh (§ 272), it seems that wattless current can be produced most economically in stations where the ratio of fixed (capital) to running costs is lowest. In a transmission line the fixed costs are high compared with the cost of energy dissipated in the line, hence the long-distance transmission of wattless current, resulting in reduced kW capacity of the line, is to be avoided.

162. Economics of P.F. Correction.—The desirability of P.F. correction on technical grounds is obvious from § 155, from which it will be seen, however, that the ill effects of low P.F. are at the expense of the supplier of electricity. Unless the charge per kWh increases with low P.F. (§ 274) there is no inducement to the consumer to improve the P.F. of his load. On the other hand, the supplier may be compelled to raise the P.F. of the system in order that the declared voltage may be maintained at the consumer's terminals, or he may find it cheaper to install and operate apparatus for P.F. correction than to leave idle the equipment which is rendered unproductive by low P.F., and to supply the additional losses occasioned by low P.F. This is a purely commercial problem, and must be considered for each case on its merits. In an A.C. supply system operating at 0·6 P.F. the capital charges per effective kW capacity of the generating station and distribution equipment are perhaps 50 °/$_{\circ}$ higher than they would be if the P.F. were unity.

The following excerpts are instructive; the costs mentioned are pre-war values, but the relative values are still about the same.

For an expenditure of 7s. or 8s. per kVA 'corrected,' it is possible to obtain the advantages of P.F. correction throughout the supply system, *i.e.* on cables, transformers, and generating plant. If that is considered for any particular system it will be found that it gives an excellent return on the investment (Larke, *Jour. I.E.E.*, Vol. 53, p. 433).

The cost of phase advancers per wattless leading kVA introduced into the line may be about 10s.; for synchronous condensers about 30s.; and for static condensers about 40s. This is very much less than the cost per kVA of the generators, transformers, and cables for generating and transmitting wattless currents (G. M. Brown, *Jour. I.E.E.*, Vol. 53, p. 662).

The installation of power-factor correcting apparatus is cheaper than increasing the plant capacity of the whole system (for the same final kW load) if the ratio: (Cost per kVA compensated by P.F. correction) / (cost per kVA for whole electrical equipment, generators, switchgear, transformers, cables, etc.) is less than $(\cos\phi_2 - \cos\phi_1) / \sin(\phi_1 - \phi_2)$. This ratio is simply the numerical increase in P.F. divided by the sine of the angle of phase advancement. It is never economical to install P.F. correcting apparatus if the above ratio exceeds $\sin\phi_1$; for any marked economy to result the ratio should be distinctly less than sin ϕ_1 (*Power Factor Correction*, by A. E. Clayton (Pitman)).

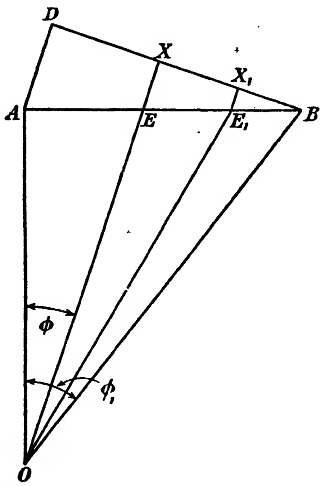


FIG. 47A.—Economic limit of power factor correction.

When the cost of an A.C. supply is made up of a component proportional to the kWh consumption and another component proportional to the maximum demand in kVA, the economic limit of power-factor correction by static condensers can be calculated. Let the demand charge per kVA be £a, and the capital charges per kVAr of condenser plant per annum be £b, and let ϕ_1 be the uncorrected power-factor. In the right-angled triangle of Fig. 47a, OA represents to scale a, the demand charge and AOB is equal to ϕ_1. On AB draw a right-angled triangle such that the ratio $AD / AB = b / a$. Then for any power-factor represented by the angle E_1OA, OE_1 is the demand charge per kW, and E_1X_1 drawn perpendicular to BD is the annual cost of the condenser equipment. The sum of these two annual charges is a minimum when OE_1 and E_1X_1 are in line, that is when the corrected angle of lag is represented by a line OX perpendicular to BD. It follows from this construction that the most economical value of the power-factor cos ϕ is when sin $\phi = b / a$, and it is evident that this value is independent of the value of the uncorrected power factor cos ϕ_1.

163. Bibliography (see explanatory note, § 58). In addition to the papers mentioned in the preceding paragraphs there have been innumerable contributions to technical periodicals and to the proceedings of scientific bodies.

BOOKS.

Power-Factor Correction. A. E. Clayton (Pitman).
Power-Factor Indicator. D. J. Bolton (Chapman & Hall).

I.E.E. PAPERS.

The Improvement of Power-Factor. Dr. Gisbert Kapp. Vol. 61, p. 89.
Power-Factor; its Technical and Commercial Aspects. H. E. Yerbury, Vol. 61, p. 675.
Power-Factor and Tariffs. E. V. Clark. Vol. 64, p. 625.
The Improvement of Power-Factor. E. W. Dorey. Vol. 64, p. 633.

CHAPTER 6.

SOURCES OF ENERGY AND PRIME MOVERS.

164. Methods of Driving Generators; Power Required.— Whether of large or small size, a generator (dynamo or alternator) may either be directly coupled to its prime mover, the two shafts being joined up by half-couplings or flexible couplings, or it may be driven by belt or rope. The cost of a generator depends so much on its speed that where low-speed prime movers are used a belt drive is generally necessary; with low-head water turbines even gearing often has to be employed. On the other hand, with high-speed prime movers direct coupling is generally adopted. In the case of steam turbines the mechanical construction of a sufficiently high-speed dynamo offers difficulties,* and special design is necessary.

The B.H.P. required to drive a given dynamo at its rated full load = (Watts / 746) × (100 / Efficiency %). For example, a generator with an output of 41 A at 220 V gives 9 000 W or 9 kW, and if the efficiency is 88 % the B.H.P. required to drive it will be (9 000 / 746) × (100 / 88) = (say) 14 B.H.P. It must be remembered, however, that all generators are capable of running for a limited time on a 25 % overload (§ 136), and this advantage will be lost if the prime mover cannot do likewise. With oil and gas engines, it is especially necessary to state the *maximum* B.H.P. which is required at the coupling or pulley under the given conditions of fuel, altitude, and so forth (§ 179).

Where a belt drive is necessary it may be noted that the maximum tension which single belting of ordinary thickness (say $\frac{1}{4}$ in.) will stand in practice is about 90 lbs. per inch of width. The H.P. transmitted is $(T - t)v / 33\,000$, where T and t are the tensions on the tight and slack sides respectively, and v is the linear velocity in ft. per min. This gives H.P. = $vb / 750$ or b = H.P. × $750 / v$, where b is the width of single belt in inches; since 746 W = 1 H.P. the product vb represents very nearly the watts transmitted. A double belt will transmit some 60 % more. In the case of ropes the H.P. transmitted is = $Tv / 44\,000$, where T

* *See also* 'Difficulties of Design of High-speed Generators,' by A. B. Field, *Jour. I.E.E.*, 54, pp. 65 *et seq.*; also § 145 herein.

denotes (Safe working load on each rope × Number of ropes). The safe working load is about 200 lbs. per sq. in., and v may vary from 4 000 to 5 000 ft. per min.

165. Sources of Energy.—The mechanical energy required to drive dynamo-electric generators (which are the only type used for commercial supply (§§ 126, 132)) may be that already available in nature (wind or water power), or it may be derived from the heat of solar radiation or the heat of combustion of fuels. The shortage and high cost of fuel in all countries have directed attention to the more extensive development of water power (Chapters 8-10); improved types of water turbines and increased use of automatic plant (§ 187) have made profitable the development of many falls which have hitherto been regarded as useless. In Great Britain, however, coal is still the principal source of electrical energy.*

Though wind power is fickle and cannot economically be utilised in high-power units, it offers a tempting means of providing energy for small estates. In this application the wind wheel is geared to a D.C. generator which is connected in parallel with a storage battery to the supply mains. The storage battery is essential to the maintenance of supply during periods of calm. Though each case must be considered on its merits, it may be doubted whether the capital and maintenance costs of the windmill and relatively large storage battery required do not exceed those of the self-starting petrol engine and small capacity battery (§180) which generally could be employed in its stead. Formulæ for the horse-power of wind turbines are complicated and none too reliable. It is claimed that a wheel 25 ft. in diameter develops about 2¼ kW at the generator terminals when the wind

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* The subjoined data are derived from statistics published by the Electricity Commissioners (*see also* Tables 22, 22*a*, § 191):—

	1920-21	1930-31	1936
No. of stations submitting returns	501	538	442
Total kWh generated in millions (approx.)	5167·3	12,812	20,530†
Percentage of total kWh generated from or by:—			
Coal and coke	95·9	94·81	95·6
Waste heat	3·12	0·99	0·63
Oil engines	0·46	0·67	0·29
Destructors	0·34	0·18	0·22
Water power	0·09	3·25	3·24
Gas engines (town gas)	0·08	0·01	0·02 (town and producer gas combined)
,, ,, (producer gas)	—	0·09	

† Units *sent out* from the stations.

speed is 12½ m.p.h. and 18 kW when the wind speed is 25 m.p.h. The power developed increases roughly with the square of the diameter of the wheel and with the cube of the wind speed. There is obvious advantage in locating the windmill on a hill-top, where there is seldom a calm and where the mean velocity of the wind is higher than in valleys.

Systematic tests * were made some years ago at the Harpenden windmill experimental station of the Institute of Agricultural Engineering, University of Oxford. Seven sets of plant made by five firms were tested, some of the wheels being modified as the work proceeded. The desirability of stream-lined blades, so as to obtain the minimum detraction of pressure in front and the maximum of suction at the back, came out clearly. Eddies due to the supporting structure behind the wheel, even at some distance, were found objectionable; it is advantageous to place the wheel behind the structure, which has the additional advantage of not necessitating direction control, as the position of the wheel behind the pivoting centre ensures this automatically. Owing to the effect of wasteful periods of high wind, when the excess output is useless, the only true basis of wheel efficiency is that of output / cost and not output / input as is usual. Again, if the disc area of the wheel is taken, a multiblade windmill has a natural advantage, whereas on the blade area basis the highest points are taken by four- or five-bladed wheels. The report gives the highest place to an 'Aerodynamo' of 29 ft. 5 in. diam. with four stream-lined blades, giving 10 kW at 220 V with a double-reduction spur-geared generator. This 'stands out clearly above the others, even at low wind speeds, and this margin is so great that it enables the cost per sq. ft. of constructing these blades to be much higher than that of the next best and yet to maintain the highest efficiency on the output / cost basis.' The capital outlay was £900; annual charges, £130 13s. 4d.; total output over a year's run 10 195 kWh; available output, 7 646 kWh; cost per kWh 4·1d. Next to this machine on the blade area basis came an 'Agricco,' followed closely by a 'Garty-Apex,' which is especially good at low wind velocities. The costs per kWh (including capital charges) given in the report rise to 10-12d. in some instances, the available annual output being about 370-320 kWh but 'it is obviously wrong to compare the results from 250 and 400 W sets with those from larger plant of other types, and it is questionable whether any other form of electric generating plant of the same rating will bear comparison with small windmill sets on the score of cost per kWh produced.'

If the hill-top site is far from the prospective electrical load, the scheme cannot be developed with direct current. The use of an alternator would solve this difficulty by making high-voltage transmission practicable, but no storage of energy is economically feasible in an A.C. system. By the use of induction generators (§ 144) at the wind turbine, the latter can be situated at the most favourable site, alternating current

* *El. Rev.*, Vol. 98, p. 385.

being transmitted at high voltage from the asynchronous generator to supplement the output from synchronous generators in an existing A.C. supply system. Interesting suggestions for the use of windmills to pump sea water to the top of cliffs, the water being then delivered as required to Pelton-wheel generators at the bottom, are given by R. A. Fessenden, *Electrician*, Sept. 16, 1910.

Direct utilisation of sun heat to raise steam in large area low-pressure boilers, or in high-pressure boilers at the focus of suitable reflectors, is quite practicable in countries which are practically free from clouds. The solar radiation reaching the earth's surface has been estimated to be equivalent to 5 000 H.P. per acre at noon in summer. The Meadi (Egypt) sun absorber, erected in 1913, had a 4½ : 1 ratio of mirror to boiler surface and, at 40 °/₀ boiler efficiency, developed 63 B.H.P. per acre covered by the plant.* The Shuman engine which was used consumed 22 lbs. of steam at atmospheric pressure per B.H.P.-hr. It was estimated that this installation could compete with coal at £3 10s. a ton. The principal utility of such installations is probably in irrigation and other pumping service.

Trials by G. Claude † confirm the technical possibility of generating power by utilising the temperature difference between the surface and bottom water in tropical seas. Commercial difficulties are the size of plant required to circulate the large volumes of water involved, and the problems of plant location and maintenance, and of transmitting energy to where it is required.

In the geothermic power station near Pisa (Italy) natural steam at a pressure of 3 atmospheres and a temperature of 180° C., drawn from wells drilled some 400 ft. into the volcanic strata, is used indirectly to generate 7 500 kW. As the steam contains about 5 °/₀ of non-condensing and corrosive gases, an aluminium water evaporator is used to produce the pure steam actually used in the turbines, at 0·25 atmosphere pressure. The consumption is 31 lbs. / kWh. Disadvantages are the necessity for evaporators and the large turbines and pipe lines due to this low pressure.

The ideal of reversing the process by which electrical energy can be converted wholly to heat has hitherto only been realised

* For details of this and other sun-absorbers *see* papers by A. S. E. Ackermann before the Soc. of Engineers, April, 1914, and the Royal Soc. of Arts, April, 1915.

† *Génie Civil*, 1932, p. 571; *Power Engineer*, 27, p. 279.

in the very inefficient thermo-couple (§ 129), and on a minute scale. The modern commercial production of heat-resisting alloys coupled with the absence of corrosion has led a research worker* to state that 'the thermo-electric generator has been brought within the realm of commercial feasibility.' The view appears somewhat optimistic. The efficiency of conversion is extremely low; with a coke-fired generator it is some 3 to 4 °/₀ while with gas heating it is far lower, though on short-circuit tests it exceeds these figures 3- or 4-fold. The use of these cells for research work, in the form of single elements in a high vacuum, has also been advanced.†

166. Efficiency of Production of Mechanical Energy by Combustion of Fuel.—Heat derived from the combustion of fuel may be used to raise steam from which mechanical energy is then derived by allowing the steam to expand in a reciprocating engine or turbine, or the fuel may be burned in the engine itself (*internal combustion*), the gases thus formed at high pressure in a confined space being then allowed to expand, and so to develop mechanical energy. 'Waste heat,' such as that in the flue gases from an industrial furnace or in the exhaust gases from an internal combustion engine, can be used to raise steam for use in an auxiliary power plant.

External Combustion Cycle.—The 'mechanical equivalent' of 1 B.Th.U. (§ 48) is about 778 ft.-lbs. but it must *not* be assumed that the whole of the heat developed by the combustion of fuel can be converted to mechanical energy in this proportion. Mechanical energy can be derived from heat only when the temperature changes. If Q B.Th.U. be delivered to any heat engine at an *absolute*‡ temperature T_1° F. and exhausted at absolute temperature T_2° F, the amount of heat which could theoretically be converted into mechanical energy $= Q(T_1 - T_2)/T_1$ and the thermal efficiency would then be $(T_1 - T_2)/T_1$. This

* T. F. Wall, 'The Generation of Electricity Direct from Heat,' *El. Rev.*, Vol. 101, p. 847.

† R. V. Jones, in the Journal of Scientific Instruments; see *World Power*, Sept. 1934, p. 108.

‡ The *absolute* temperature in Fahrenheit degrees = (temperature on the Fahrenheit scale + 459); the absolute zero of temperature being − 459° F., *i.e.* 459 + 32 = 491° F. below the freezing-point of water, at which conductors cease to have any resistance, so that a current will continue to circulate when once started.

shows at once that the thermal efficiency is higher, the greater the range of temperature ($T_1 - T_2$) in the working cycle.

From steam tables it will be found that the absolute temperature of saturated steam at 165 lbs. / sq. in. (absolute) is 825° F., and at 1 lb. / sq. in. (about 28 ins. vacuum) is 561° F., hence the theoretical thermal efficiency of an engine working between these limits is (825 − 561) / 825 = 32 °/ₒ. Allowing for the losses inevitable in an actual engine the thermal efficiency might be 20 °/ₒ, and the engine would then have a *relative efficiency*, compared with the ideal engine, of 20 / 32 = 0·62 or 62 °/ₒ.

The *mechanical efficiency* of the engine, which bears no relation to either the actual or the relative thermal efficiency, is the ratio of the mechanical energy available at the shaft to that developed at the point where the heat is converted to mechanical energy. In a reciprocating engine the mechanical efficiency = Brake-H.P. / Indicated-H.P., and the difference (I.H.P. − B.H.P.) = the frictional loss in the engine plus the power required to drive the air pump (in condensing engines). The mechanical efficiency may be 90-95 °/ₒ in single-cylinder non-condensing engines, and 75-85 °/ₒ in condensing engines.

The total heat of saturated steam at, say, 165 lbs. / sq. in. absolute is 1 195 B.Th.U. / lb. (reckoned above 32° F., *see* steam tables), and that of standard steam at ¼ lb. / sq. in. (about 29½ ins. vacuum) is 1 086 B.Th.U. / lb. Under actual conditions about 1 000 B.Th.U. / lb. of steam consumed is rejected in the condensing water or, in a non-condensing plant, lost to the atmosphere. This loss represents about 60 °/ₒ of the heat value of the coal burned below the boilers. The amount of heat thus rejected could only be reduced by lowering the final temperature of the steam; 100 °/ₒ thermal efficiency in any heat engine is not even theoretically possible unless the working fluid can be utilised down to the absolute zero of temperature (− 273° C. or − 459° F.). In practice the lower limit of temperature is 212° F. for a steam engine exhausting to atmosphere, and from 80°-120° F. for a condensing engine, according to the vaccuum maintained.

The lower limit of temperature for the steam cycle being thus fixed, the only means of increasing the efficiency of the cycle itself (as distinct from reducing the heat losses in the boiler and pipe line, and the friction losses, etc., in the engine) is by raising the upper limit of temperature. This may be done by using higher steam pressures and by superheating the steam to the highest temperature permitted by mechanical considerations (§§ 172, 174).

The use of mercury vapour in a thermo-dynamic cycle offers a means of raising the upper working temperature (and thus increasing the possible efficiency ($T_1 - T_2 / T_1$) without employing high pressures.* The first commercial installation operating on this principle is at the Dutch Point station of the Hartford (Conn.) Electric Light Co.† and has an oil-fired mercury boiler containing 30 000 lbs. of mercury. On top of this is a 2 000 kVA mercury turbo-generator, the exhaust mercury vapour from which is condensed by the water tubes of a boiler which supplies steam to steam turbines as usual. In such a plant mercury vapour can be sent straight from the mercury boiler to the condenser boiler if desired. The mercury boiler and turbine can be added to existing steam plants without affecting the steam cycle; the mercury transfers heat from the fuel to the steam and the additional power, derived from the mercury cycle, is expected to halve the overall fuel con-consumption per kWh.

In a larger mercury-steam plant built for the Schenectady Works of the General Electric Co.‡ the weight of mercury used is 275 000 lb. and the mercury turbine has a rating of 20 000 kW. 325 000 lb. of steam per hour are obtained from the mercury unit, part from water tubes in the lower part of the furnace walls of the mercury boiler, and part from the mercury condensers. Later designs provide for a mercury-steam plant of 44 000 kW, requiring only 6 lb. mercury per kW of capacity. A small power application § consists of a mercury boiler and turbine rated at 1 000 kW, mercury-condenser steam-generator producing 12 500 lb. steam per hr. at 185 lb. pressure, and a steam turbo-generator of 900 kW.

The advantages of mercury as a thermo-dynamic fluid are: (1) Its boiling-points at desired pressures are convenient (about 732° F. at 25 lbs. absolute, 677° F. at atmospheric pressure, and 457° F. at 28 ins. vacuum), thus making possible operation in a range of temperature above that of the usual steam cycle without much exceeding atmospheric pressure. (2) Its high specific gravity (13·6) makes possible gravity feed, gravity sealing of valve stems, etc., and centrifugal sealing of turbine packings. (3) At the temperatures used, mercury is neutral to air, water, iron, and such organic substances as it may come into contact with. (4) The interior of a mercury boiler is always perfectly clean. (5) The vapour density of mercury is so high that the spouting velocity is low and a very simple type of turbine can be used, generally a single wheel. (6) It is expected that there will be no erosion of the turbine blades, these not being wetted. (7) The volume of the vapour at convenient condensing temperatures is such that the turbine buckets

* The pressure of steam rises rapidly with temperature, and the turbine is not well adapted for utilising very high pressures.

† See *El. World*, Vol. 79, p. 1 186.

‡ *Engineering*, April 5, 1935, p. 351.

§ *Engineer*, May 7, 1937.

need not be abnormally high (this is one of the chief difficulties in steam turbine design). (8) The mercury condensing boiler is very small and simple compared with a fuel-heated boiler; it resembles a surface condenser and is immune from scaling and burning.

The cost of mercury is high but only a relatively small quantity is required; the vapour is very poisonous, but the system can be sealed effectively (W. L. R. Emmet, *Gen. El. Rev.*, Vol. 17, pp. 47, 99).

Mercury vapour, in its mechanical capacity for bi-fluid steam cycle work, comes into competition with diphenyl oxide (§ 191 (ii)), the specific gravity of which is 1·083. It is a white solid at room temperature (melting at 80·6° F.) and at atmospheric pressure it boils at 496° F., which is the temperature of saturated steam at 860 lbs. / sq. in. At 200 lbs. / sq. in. its boiling point is 800° F. Its specific heat is about 0·4 or 0·5 and its critical pressure (§ 170 iv) is 465 lbs. at 987° F. Other rival organic substances and their properties are dealt with in *Mechanical Engineering*, June, 1933, p. 369. An aluminium bromide cycle * has also been proposed.

Internal Combustion Cycle.—The inherent advantages of the internal combustion cycle are that: (1) Heat is developed in the actual space where the development of mechanical energy occurs, thus eliminating boiler and pipe losses. (2) The temperature range of the working cycle (and therefore the thermal efficiency attainable) in the engine is greater than that of the steam cycle.

167. Thermal Efficiencies of Prime Movers; Fuel and Steam Consumptions.—A knowledge of the approximate thermal efficiency of various prime movers is useful in practice, because it enables one speedily to form a good idea of the amount of any particular fuel consumed by a particular type of engine. The heat-equivalent of mechanical work is about 42·4 B.Th.U. per H.P.-min., or 2 545 B.Th.U. per H.P.-hr., so that if the thermal efficiency of an engine be E °/ₒ, that engine will require $(2\,545 \times 100 / E)$ B.Th.U. per B.H.P.-hr., and if the calorific value of the fuel used be H B.Th.U. per lb., the fuel consumption of the engine will be $(254\,500 / E \times H)$ lbs. per B.H.P.-hr. If the heat of the fuel is developed in a boiler or gas producer before passing to the engine, the fuel consumption of the engine will be given by $(25\,450\,000 / E \times H \times e)$, where e is the thermal efficiency of the boiler or producer, etc. This method of evaluating fuel consumption is applied in Table 15, the results in which are in good general

* See *Génie Civil*, Jan. 7, 1933, and *Engineering and Boiler House Review*, April, 1933, p. 697.

TABLE 15.—*Thermal Efficiency of Prime Movers, with derived Fuel Consumption Data.* (*See also Table* 20, § 179.)

Prime Mover.	Fraction of Full Load.	Thermal Efficiency. Engine (from Admission to Crank-Shaft).	Boiler or Producer, etc.	Overall (Fuel to Crank-Shaft).	B.Th.U. per B.H.P.-hr.	Fuel Used and Calorific Value: (*a*) per Lb. (*b*) per C. Ft.	Fuel Consumption per B.H.P. hr.* (on Load Stated in Col. 2).
Steam engines—		%	%	%	B.Th.U.		
Simple	1	10 to	70	7	36 400		3·45 lbs.
		15	80	12	21 200		2·1
Compound (condensing,	1	16 to	75	12	21 200	Average	2·1
saturated steam)		18	80	14·4	17 700	Coal	1·7
Triple or quad. exp. (sat-	1	20 to	75	15	17 000	10 500 (*a*)	1·6
urated or superheated)		24	80	19·2	13 250		1·3
Steam turbines—							
Up to 500 kW . .	1	10 to	70	7	36 400		3·45 lbs.
		15	80	12	21 200		2·1
5 000 to 10 000 kW .	1	20 to	75	15	17 000	Average	1·6
		23	80	18·4	13 850	Coal	1·3
Exceptional . . .	1	26 to	75	19·5	13 000	10 500 (*a*)	1·2
		28	83	23·3	10 900		1·05
Highest actual, 1931 .				24·02			
Heavy oil engines (including Diesel)	1	25 to	—	25	10 200		0·55 lb.
		30 or	—	30	8 500	Crude oil	0·46
		36	—	36	7 275	18 500 (*a*)	0·39 and
		(§ 180)		(§ 180)			as low as 0·36
Paraffin engines—							
Small	1	15 to	—	15	17 000	Paraffin	0·87 lb. (or pint
		20	—	20	12 700	19 500 (*a*)	0·65 approx.)
Large	1	20 to	—	20	12 700		0·65
		25	—	25	10 200		0·52
							Lb. Pint.
Petrol engines . . .	1	16 to	—	16	15 900	Petrol	0·8 0·92
		24	—	24	10 600	20 000 (*a*)	0·53 0·61
							Lbs. Coal. C. Ft. Gas.
Gas engines—							
Using producer gas . .	1	20 to	75	15	17 000	Anthracite or	1·22 94†
		25	85	21·3	11 950	bituminous coal	0·85 76†
	¾	20 to	75	15	17 000	14 000 (*a*),	1·22 94†
		2	85	19·6	13 000	yielding suction	0·93 82†
	½	15 to	70	10·5	24 200	or producer gas	1·73 126†
		20	80	16	15 900	135 (*b*)	1·14 94†

* It must be understood that the figures in this column are *calculated* (as explained in text). The basis on which they are calculated is rational, so that the figures are a reliable indication of the results which may be expected in practice. At the same time, it is impossible to lay down hard and fast rules. For instance, in steam plant, the design of engine, pattern of boiler, quality of coal, draught, skill of stoker, or good working of the mechanical stoker, all affect fuel economy to a marked degree.

Assuming 94 % efficiency in large generators at full-load, add 43 % (i.e. multiply by 1·43) to those figures in this column which refer to operation at full-load in order to obtain the fuel consumption per kWh delivered by the generator on full-load.

† These figures are naturally referred to the thermal efficiency of the engine *alone*.

TABLE 15 (*continued*).

Prime Mover.	Fraction of Full Load.	Thermal Efficiency. Engine (from Admission to Crank-Shaft).	Thermal Efficiency. Boiler or Producer, etc.	Thermal Efficiency. Overall (Fuel to Crank-Shaft).	B.Th.U. per B.H.P.-hr.	Fuel Used and Calorific Value: (*a*) per Lb. (*b*) per C. Ft.	Fuel Consumption per B.H.P. hr.* (on Load Stated in Col. 2).
Gas engines—		%	Thermal efficiency of gas-making plant does not concern the engine-user in these cases.	%	B.Th.U.		
Using town gas . .	1	20 to		20	12 700	Town (or lighting gas) 500 (*b*)	25·4 c. ft.
		25		25	10 200		20·5
	¾	20 to		20	12 700		25·4
		23		23	11 100		22·2
	½	15 to		15	17 000		34·0
		20		20	12 700		25·4
Using coke-oven gas .	1	20 to		20	12 700	Coke-oven gas 430 (*b*)	29·5 c. ft.
		25		25	10 200		23·7
	¾	20 to		20	12 700		29·5
		23		23	11 100		25·8
	½	15 to		15	17 000		39 5
		20		20	12 700		29·5
Using blast-furnace gas .	1	20 to		20	12 700	Blast-furnace gas 90 (*b*)	141 c. ft.
		25		25	10 200		114
	¾	20 to		20	12 700		141
		23		23	11 100		124
	½	15 to		15	17 000		190
		20		20	12 700		141
Exceptional . . .	1	25 to		25	10 200	Natural gas 800-850 (*b*)	12·5 c. ft.
		30		30	8 500		10·4

agreement with the practical data given later. Since, however, a fractional difference in fuel consumption represents a large sum of money per annum where the production of large quantities of energy is concerned (§ 193), it is necessary to attach great importance to such differences, in practice, and this involves taking into account small differences in calorific value, degree of superheat, vacuum, barometric height, and so forth. Since all these factors cannot be taken into consideration in such a summary as Table 15 the data there given are correspondingly approximate. Values of fuel and steam consumption taken from practice are given in the later paragraphs dealing with individual types of prime movers.

The economy of steam engines and turbines is generally expressed in terms of steam consumption either per I.H.P.-hr., per B.H.P.-hr. (or particularly in generator sets) per kWh. If a be the percentage mechanical efficiency of the engine and b the percentage efficiency of the electric generator :—

	Lbs. per I.H.P.-hr.	Lbs. per B.H.P.-hr.	Lbs. per E.H.P.-hr.	Lbs. per kWh.
W lbs. per I.H.P.-hr. =	W	100 W / *a*	10 000 W / *a.b*	13 400 W / *a.b*
W lbs. per B.H.P.-hr. =	*a*.W / 100	W	100 W / *b*	134 W / *b*
W lbs. per E.H.P.-hr. =	*a.b*.W / 10 000	*b*.W / 100	W	1·34 W
W lbs. per kWh =	*a.b*.W / 13 400	*b*.W / 134	0·746 W	W

The value of *a* for good steam engines is from 75 to 85 °/₀ for condensing engines (§ 166); 80 °/₀ would be a reasonable average. The corresponding figure for Diesel engines is lower; it may be 84 or 85 °/₀ so far as concerns the motor itself, but, allowing for power required to drive the air compressor, the net B.H.P. averages from 70-77 °/₀ of the I.H.P. in high- and low-speed four-cycle engines respectively, and from 67½-71 °/₀ in high- and low-speed two-cycle engines. The term indicated horse-power has no meaning in connection with a steam turbine, and the nearest approach we can make to a factor corresponding to *a* above is to say that the mechanical output of a turbine is from 70-75 °/₀ of the mechanical equivalent of the heat drop (as reckoned according to the equation for adiabatic expansion). Suitable averages for the generator efficiency *b* are 94 °/₀ in large machines, 90 °/₀ in 100 kW machines, and 85 °/₀ in 10 kW generators.

Fuel consumption data relating to steam engines and turbines, and based on considerations of thermal efficiency, are included in Table 15, but these figures must *not* be converted to steam consumption data simply by multiplying the (lbs. of fuel per B.H.P.) by the (evaporation per lb. of coal); *see* Table 17, § 170. To do this would give an incorrect result, since the evaporation data in Table 17 are referred to 212° F. The heat required to evaporate 1 lb. of water from and at 382° F. (the temperature corresponding to 200 lbs. absolute steam pressure) is 12½ °/₀ less than is required to evaporate the same weight at 212° F.; where steam is superheated, the heat required for the latter purpose compensates to some extent for the decrease in latent heat of evaporation, with rising temperature. Due to the varying heat content of 1 lb. of steam under different conditions, statement of the steam consumption of an engine gives no definite measure of the thermal efficiency of the latter unless the steam conditions be specified fully. It is much better to state the heat consumption per I.H.P.-min. or per B.H.P.-min. Theoretically I.H.P.-min. = 33 000 / 778 = 42·4 B.Th.U. If the actual heat consumption (measured at the stop valve) be h B.Th.U. per B.H.P.-min., the thermal efficiency of the engine is $4\,240 / h$ %. (*See also* § 191.)

As regards the economic possibilities of generating electrical energy from gas, the following figures * relate to a 6-cylinder National engine of 600 B.H.P., consuming 25 cu. ft. of coke oven gas (491 B.Th.U. gross / cu. ft.) per kWh :—

	Pence per kWh.
Direct and maintenance wages	0·020
Maintenance stores—water, oil, waste, sundries	0·025
Repairs	0·0015
Depreciation of engine $7\frac{1}{2}$ %	0·029
Purification of gas	0·0015
Cost of crude gas $3\frac{1}{2}$d. per 1 000 cu. ft.	0·087
Depreciation of gas holder	0·002
	0·166

168. Fuels for Steam Boilers.—By far the greatest part of the electrical energy produced in Great Britain is derived from the combustion of coal, sometimes with the admixture of coke (§ 165, footnote). Generally these fuels are burned below steam boilers but, in relatively small installations, they can be used to advantage in gas producers (§§ 178, 181).

Coal Purchase and Storage.—Coal is frequently purchased under a contract which fixes a basic price for coal of stated calorific value (say, 12 000 B.Th.U. / lb.). A proportionate addition to or deduction from the basic price is made according as the actual calorific value exceeds or falls below the agreed standard. Also the basic price may be modified according to the percentage of ash, moisture, and smalls in the delivered coal. For example, it may be agreed to pay 2d. a ton extra for every 1 % by which the ash content falls below 12 %; to deduct 1 % from the chargeable weight of coal for every 1 % by which the moisture content exceeds 10 %; and to deduct $\frac{1}{2}$ % from the chargeable weight of coal for every 1 % by which the percentage of 'smalls' (passing through a $\frac{3}{8}$ in. mesh) exceeds 20 %. The British Standard Method of 'Sampling and Analysis of Coal for Inland Purposes' is given in B.S.S., No. 420, of 1931.

It is usual to store not less than one month's supply of coal in the immediate neighbourhood of the power station. This frequently involves the storage of some tens of thousands of tons. To reduce breakage and the risk of spontaneous ignition, coal stacks should not be higher than 10 or 12 ft. Dust, slack, and mixtures of coals are particularly liable to ignition. Oily waste and similar material should be excluded, and the stack should not be near hot pipes, etc. Coal may be stored satisfactorily to a depth of 20 or 30 ft. in concrete basins filled with water, but the wet coal should be drained before use. However stored, coal gradually disintegrates and loses somewhat in calorific value but the deterioration is not serious under reasonable conditions.

The use of *pulverised coal*—ground so finely that 85 % will pass through a screen with 200 meshes to the inch and 95 % through a 100-mesh screen—is claimed to make possible the

* *Colliery Engineering*, Vol. 8, p. 284.

efficient use of inferior material, and also to permit the solid fuel to be burned (like gas or oil fuel) with little more than the weight of air theoretically required for the process. Boiler efficiencies of 85 % and higher have been obtained during tests with pulverised coal, and the latter is as flexible to control as gas or oil. The best method of preventing atmospheric pollution by ash and boiler fouling by slag, is probably to catch the ash and slag in a sump below a sudden turn in the path of the products of combustion (on the principle of the steam separator). The cost and risk of drying, storing, and distributing the pulverised fuel are reduced by the use of pulverisers which grind the fuel at each boiler as it is required for use, but there are obvious counter-objections to such subdivision of the pulverising plant.

A mixture of oil fuel with coal ground so finely as to remain in colloidal suspension is claimed to be safer and more economical than either ingredient alone.

Hard coke, when dry, consists of 80-95 % carbon, the remainder being ash and 1 % or so of sulphur. Good coke with only 5 % moisture and 10 % ash is worth about 12 500 B.Th.U. / lb. and is excellent for steam raising. Unfortunately, coke readily absorbs as much as 20 % moisture.

Semi-coke.—This is the solid residue after subjecting coal to low-temperature carbonisation. According to the nature of the coal and the temperature of the ovens, the 'semi-coke' may contain 10-15 % volatile matter and 80-75 % carbon. It is used as a smokeless domestic fuel, and can be used for steam raising where it is available at a low enough price. Semi-coke, especially that from brown coal, is often briquetted on account of its friability.

Lignite or brown coal is used for steam raising in some countries and ranges from 6 000 to 12 000 B.Th.U. / lb., an average value being 7 500 B.Th.U. / lb. Many attempts have been made to utilise *peat* profitably; * the principal difficulty is that of drying the raw fuel economically (peat as dug may contain 80 % of water). The calorific value of dry peat is about 9 000-10 000 B.Th.U. / lb.; and of that with 25 % water, 7 000 B.Th.U. / lb. It is not necessary to dry the fuel so thoroughly

* Reports on the subject are issued from time to time by H.M. Stationery Office for the Fuel Research Board; *see also El. Rev.*, Vol. 90, p. 477.

for use in a gas producer as for burning below boilers, but it is prohibitively costly to transport the bulky, moist, and low-grade fuel for any considerable distance; the power plant must therefore be situated at or near the peat deposits.

Wood, sawdust, cane trash, rice husk and other similar materials may be used profitably where available. Provided that larger grate area is provided the same steaming capacity can be maintained as with coal notwithstanding the low calorific value of the fuel which may be anything from 6 000-2 000 B.Th.U / lb. *Town refuse* varies greatly in composition, but is generally worth from 1 000-2 000 B.Th.U. / lb. and is profitably utilised in many places.

Oil fuel is technically excellent for steam boilers, but its cost is high and unstable. Crude petroleum has a calorific value of 18 000-19 000 B.Th.U. / lb. The oil is atomised by a steam or air blast or by being forced under pressure through suitable nozzles; the rate and conditions of combustion are under immediate control, a very small surplus of air is required for complete combustion, and there is no ash formed. A boiler efficiency of 85 °/ₒ or higher can be maintained, and the steaming capacity of a given boiler is about 15 °/ₒ higher with oil than with coal, if baffles be provided to act as high-temperature radiating surface in place of the incandescent fuel bed. As an approximate guide, it seldom pays to use oil for steam raising if its cost per ton exceeds 1½-1¾ times that of the alternative coal.

Waste gases from blast furnaces, coke ovens, and steel works are used successfully in many large power plants, the gas being fed to burners below standard coal-burning types of boilers, or used in a Bonecourt boiler (§ 170).

In selecting the fuel for use in any power plant, security of supply is a primary consideration. The calorific value of the fuel is of less importance than the cost per 1000 B.Th.U. developed, allowing for the cost of furnace operation and maintenance (including ash removal).

169. Recovery of By-products from Coal.—It is now generally realised that the tar, oils, ammonium sulphate, and other by-products which can be recovered from coal by a suitable process of distillation have a market value comparable with the cost of the coal itself. Though most coal is still burned in the raw state this process involves the irreparable loss of by-products which should constitute a national asset, and which are either of no value as fuel or (as in the case of benzol) would be of greater value as fuel for internal combustion engines than as boiler fuel. The ideal practice would be to subject all coal to fractional distillation, and to use each product in the application for which it was most valuable.

Theoretically, about 112 lbs. of ammonium sulphate is recoverable per ton of coal containing 1·3 °/₀ nitrogen. Actually, 15-25 lbs. is recoverable in high-temperature coke ovens and 90 lbs. or so in low-temperature plant. About 90 lbs. of tar is recoverable, and, say, 12 000 cu. ft. of coal gas and nearly 1 500 lbs. of coke are produced.

TABLE 16.—*Power Generation with and without By-Product Recovery.*

Scheme.	Total Capital Cost per B.H.P.	By Sale of By-Products per B.H.P.-hr.	Running Costs per B.H.P.-hr.	
			Gross.	Net.
	£	*d.*	*d.*	*d.*
Coal-fired boilers and condensing steam engines	7·30	Nil	0·21	0·21
Pressure producers (non-recovery) and gas engines	9·10	Nil	0·18	0·18
Mond recovery plant, gas engines, and exhaust boilers	11·00	0·09	0·23	0·14
Ordinary recovery plant, ordinary gas-fired boilers, and condensing steam engines *.	16·60	0·236	0·47	0·234
Self-steaming high-recovery plant, high-efficiency gas-fired boilers, and condensing steam engines	13·00	0·125	0·292	0·167

Processes for the manufacture of light motor fuels and diesel oils by the hydrogenation of coal, or by synthesis based on hydrogen and coke oven gas, have been developed in most of the leading countries which have no native supplies of petroleum. Technically, the processes are successful and continually being improved, but at the time of writing (1938) the manufactured motor fuels cannot compete in cost with petroleum products without assistance. Justification for their manufacture on a large scale lies mainly in considerations of national security and trade balance.

Table 16 is based on estimates by the late T. R. Wollaston (*Engineer*, Vol. 119, p. 326), and shows clearly the economy of power generation with by-product

* Price includes extra boilers to supply gas producers and to make up for low efficiency of ordinary boilers when gas-fired.

recovery. The data relate to alternative schemes for producing 1 500 B.H.P. (mechanical power), working 7 000 hrs. per annum at an average load of 1 000 H.P., *i.e.* at 53 °/₀ load factor; the costs given are on a pre-war basis, but this does not affect the general purpose of the comparison.

For further information the reader may be referred to a report by the late Sir Dugald Clerk and Professors A. Smithells and J. W. Cobb on the Coal Gas and Electrical Supply Industries of the United Kingdom, addressed to the Institution of Gas Engineers (*see also Jour. I.E.E.*, Vol. 58, p. 765); and to the publications of the Fuel Research Board (H.M. Stationery Office).

170. Steam Boilers.—(i) Large modern boilers have up to 60 sq. ft. of heating surface per sq. ft. of grate area, and up to

TABLE 17.—*Average Boiler Data.*

Type of Boiler.	Heating Surface : Grate Area.	Evaporation per Sq. Ft. Heating Surface per Hour.	Coal per Sq. Ft. Grate per Hour.	Water Evaporated per Lb. of Coal Burned.
		lbs.	lbs.	lbs.
Cornish	20 to 30 : 1	3 to 4	15	7½
Lancashire	20 „ 25 : 1	4 „ 6	15 to 20	7½ to 8
Water-tube, ordinary . .	40 „ 60 : 1	3½ „ 4½	15 „ 25	6½ „ 8½
„ high-power * .	25 „ 30 : 1	5½ „ 8	25	7½ „ 10
Bonecourt (gas-fired) . .	No grate	15 „ 35	—	—

6 or 8 lbs. of water are evaporated per sq. ft. of heating surface per hr. In boilers of older design the ratio of heating to grate surface is from 20 to 30 : 1, and the evaporation only 3-4 lbs. per sq. ft. of heating surface per hr. (*see also* Table 17). Values for the heating surface required in coal-fired boilers per I.H.P. of various types of engines served are as follows: Simple high-pressure, non-condensing engines, 7-8 sq. ft.; compound, non-condensing, 5-6 sq. ft.; compound, condensing, 4-5 sq. ft.; triple-expansion, non-condensing, 4-5 sq. ft.; triple expansion, condensing 2½-3 sq. ft.; turbines, 2-2½ sq. ft. The weight of coal burnt per sq. ft. of grate surface per hr. depends primarily on the draught employed; the figures given in Table 17 refer to natural draught. Using forced draught, 100 lbs. or more of coal can be burned per sq. ft. of grate per hr., but 25-30 lbs. represent about

*** *I.e.* specially compact boilers with high steaming capacity; every provision made to secure brisk circulation and rapid heat transference.**

the maximum for central station practice,* and 15-20 lbs. a more usual value.

The general trend of steam practice may be judged by the present endeavour to secure the adoption of the standard pressures—400 lbs. and 600 lbs.—recommended by the British Standards Institution; but far higher pressures are being used here and there. Thus Bradford Corporation has a turbine working at 1 100 lbs. / sq. in. and the Ford works at Dagenham have adopted 1 200 lbs. / sq. in. Steam superheat temperatures are also rising, the old 700 to 750° F. having risen to 800° F. at Barking; while a British firm has supplied to a Detroit station a 10 000 kW turbine working with steam at 1 000° F. These plants, like those of the Benson boiler mentioned below, use a series of turbines taking the steam in turn, each from the exhaust of the previous one.

(ii) *Water-tube boilers,* which are at present the standard equipment for steam raising in large stations—especially the Babcock & Wilcox and the Stirling types—evaporate up to 100 000 or 150 000 lbs. of water per hr. (150 000-200 000 lbs. / hr. for short periods), the steam pressure being up to 350 lbs. / sq. in., and the total steam temperature (including superheat) up to 700° F. Several such boilers may be required to feed a single turbine. Particulars of very high power, water-tube boiler practice are to be found in the *El. Rev.*, Vol. 75, p. 290. The aggregate rated capacity of all the boiler plant used by authorised undertakings in Great Britain in 1937-38, from and at 212° F., was about 100 million lbs. / hr.; of which nearly 40 °/₀ was in units of 100 000 lbs. / hr. or over. These statistical data may be co-ordinated with those of plant capacity, etc., in Chapter 7 generally—*see* § 191, Table 22, §§ 195, 197, in particular.

Under ordinary conditions and with good coal, about 7½-8½ lbs. of water can be evaporated (from and at 212° F.) per lb. of coal burnt in modern boilers, rising to 9 or 10 lbs. in high-efficiency plant skilfully operated. Coal of calorific value = 13 500 B.Th.U. per lb. would evaporate about 14 lbs. of water from and at 212° F., were it possible to use all the heat from the coal. Actually, the thermal efficiency of a coal-fired boiler is

* The heat developed per hr. per sq. ft. of grate area is then about 350 000 B.Th.U. using coal worth 11 700 B.Th.U. / lb.

considerably below 100 °/₀. The proper basis of comparison between different boiler installations is the overall efficiency of boiler, superheater, and economiser. With a clean boiler and good coal the overall efficiency of boiler, superheater, and economiser may be 85 °/₀, but the distribution of the heat derived from the coal is generally within the following limits: In boiler 58 °/₀, superheater 9 °/₀, and economiser 8 °/₀ (*i.e.* 75 °/₀ of the heat is delivered to the steam, falling to 55 or 60 °/₀ in inefficient installations *); lost in flue gases 15 °/₀ (sometimes 30 °/₀), by radiation 5 °/₀ (often 10 °/₀), and by moisture, unburnt residue, etc., 5 °/₀ (total loss 25 °/₀, rising to 40 °/₀ or more in inefficient installations). Some of the low-temperature heat in the gases leaving the economiser may be used to pre-heat the air for the furnace to, say, 195° F., the temperature of the gases leaving the pre-heater being then about 300° F.

(iii) The *Bonecourt boiler* with feed heater attains an overall efficiency of 90-92½ °/₀. This boiler is of the fire-tube type with refractory brick or twisted iron filling inside the tubes. Liquid or gaseous fuel or waste heat from furnaces, gas engines, etc., is used; with liquid or gaseous fuel combustion proceeds flamelessly, and in all cases the gases in the tubes impinge again and again on the heating surface, the filling material in the tubes meanwhile giving out a high percentage of radiant heat. Only 5 or 10 °/₀ of excess air is required for perfect combustion, and the evaporation is from 15-35 lbs. / sq. ft. of heating surface / hr., from and at 212° F. (Table 17). A Bonecourt boiler 6 ft. dia. × 18½ ft. long is capable of delivering 20 000 lbs. of steam per hr.†

(iv) The *Benson boiler* makes practical use of the peculiar property of steam at the 'critical point,' namely, that the volumes of steam and water are there identical. An experimental boiler rated at 1 000 kw was built by the Benson Engineering Co. and the English Electric Co. at Rugby in 1923, to work at 3 200 lbs. / sq. in. and 706° F., *i.e.* at the critical point of steam. At this temperature and under this pressure water occupies about three times its volume at 60° F. and is suddenly converted into steam without further increase in volume and without the absorption of any latent heat of vaporisation. The construction is relatively simple

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* *See* 'Average Figures for the Performance of Different Types of Steam Boilers,' by D. Brownlie, *Engineering*, Dec. 10 and 17, 1920.

† *See also* 'Recent Development in Gas-Firing Steam Boilers,' by W. Gregson, *Proc. S. Wales Inst. Eng.*, Vol. 36, p. 279.

and inexpensive, as the boiler consists of little more than a coil of tubing, with no drums. No disengaging surface is needed, as in ordinary boilers, because at the critical point there is no difference between the volume of the water and that of the steam; and the automatic reducing valve serves the purpose of the steam drums used in water-tube boilers. The steam is superheated to 785° F., and after being throttled to 1 500 lbs. / sq. in. or possibly a higher pressure, it can be used in a back-pressure turbine exhausting at 200 lbs. / sq. in. The steam is then reheated to 665° F. and the expansion completed in an ordinary turbine. In commercial operation, difficulty was at first experienced with Benson boilers from burning out of tubes, caused by precipitation of salts when the water changed into steam. This was overcome by transferring the transition zone to a region not exposed to the radiant heat of the combustion chamber, but only to flue gases at lower temperature. An important modification of the original system of working always at critical pressure in the boiler is that of allowing the boiler pressure to vary according to the load on the turbine, the temperature of the delivered steam being kept constant. This has the advantage that the feed pump has never to work against a higher boiler pressure than that required by the turbine load. A boiler designed for operation on this system in a peak load central station works at pressures from 500 to 2 000 lbs. per sq. in., for turbine outputs from 5 000 to 20 000 kW respectively.

According to E. Goos * these boilers weigh from 3 to 0·7 ton, and occupy from 100 to 35 cu. ft. per ton of steam per hr. at 1 500 lbs. / sq. in., 900° F. Burning atomised oil fuel with highly preheated air, the heat liberation may be 340 000 B.Th.U. per cu. ft. of combustion space, and the heat transmission 260 000 B.Th.U. per sq. ft. of radiation surface.

(v) *Sulzer Mono-Tube Boiler*.—This boiler consists of a long coil of tube (or a number of such tubes in parallel) into which water is pumped at one end, and from which steam emerges at the other end, at the desired pressure and temperature. Oil or coal firing can be used. According to J. Calderwood † the conditions

* *Steam Engineer*, Vol. 4, p. 272. Other articles on Benson boilers are to be found, *loc. cit.*, Vol. 1, p. 194; Vol. 2, pp. 64, 387; and Vol. 3, pp. 229, 287.

† In a symposium on high pressure boilers presented to the Institute of Marine Engineers, March, 1935; see *The Steam Engineer*, Vol. 4, p. 273. Other articles on Sulzer boilers are to be found, *loc. cit.*, Vol. 3, p. 61; Vol. 5, p. 26.

for satisfactory operation are: Tube length about 30 000 times the internal diameter of the tube, or about ½ mile per inch of tube diameter; a high velocity through this tube, requiring a feed pressure considerably higher than the steam pressure; thermostatic regulation of the rate of feed, controlled by the steam temperature; secondary feed injected in the long tube at about the point where the steam becomes dry saturated.

(vi) *Brown Boveri 'Velox' Boiler.*—Distinctive features of this boiler are combustion under pressure and high-speed flow of products of combustion over the heating surfaces. A turbo-compressor supplies air for combustion, and a pump supplies fuel oil to a relatively small combustion chamber where the pressure is about 25 to 35 lbs. / sq. in. Thence the products of combustion flow at about 660 ft. / sec. through water-jacketed tubes surrounding the combustion chamber and so to a superheater. After leaving the superheater, at 900° F. or lower temperature, the gases flow through a gas turbine which drives the compressor for the combustion-air supply. Finally, the gases leaving the compressor turbine flow through a feedwater heater. Throughout, the tube-sections and heating surfaces required are relatively small owing to the high velocity of the gases and the high rate of heat transference. The mean rate of heat absorption over the total generator surface is of the order of 100 000 B.Th.U. / sq. ft. / hr., or about 10 times that employed in an ordinary boiler. Forced circulation of boiler water is maintained by a pump at a rate equal to about 10 times the steaming capacity of the boiler. The operation of the whole equipment is under fully automatic control. Variations in steam demand are followed with a time lag of about 30 sec., and full steam pressure can be reached from cold in about 6 min. The overall efficiency is of the order of 90 °/₀ at full load allowing for all power absorbed by the auxiliaries, and this efficiency is well maintained down to half-load. At the time of writing (1935) Velox steam generators, in sizes from 26 500 to 70 000 lbs. / hr., are in commercial operation. Further information is to be found in the undermentioned articles.*

(vii) *La Mont Boiler.*—The special feature of this type is the use

* *Brown Boveri Review*, Vol. 20, p. 38, 'Pressure Fixing of Steam Boilers in Combination with Gas Turbines,' W. G. Noack; *Steam Engineer*, Vol. 2, pp. 255 309, 361, 'Velox Boiler for Marine Use,' A. Meyer; *ibid.*, Vol. 3, p. 387, 'Operating Principle of the Velox Steam Generator'; *ibid.*, Vol. 4, p. 246 (with an excellent coloured diagram).

of forced (pumped) circulation through water tubes which may be arranged wherever there is heat to be absorbed. No dependence is placed upon natural circulation, and the maintenance of a proper distribution of water flow through banks of tubes in parallel is ensured by fitting appropriate throttling nozzles to the inlets of the tubes which would otherwise take an undue share of the total circulation. A centrifugal pump, usually with a delivery pressure of 25-40 lbs. / sq. in., draws water from the steam drum, and forces it through the water tubes, which are mounted in parallel between inlet and outlet headers. The mixture of steam and water leaving the outlet header enters the steam drum above the water level.

The amount of water circulated is usually about 8 times the amount of steam produced. The water tubes are of small diameter, favouring rapid heat transmission and facilitating the mechanical design. Also, the high velocity of flow through the tubes helps to prevent deposition of scale and corrosion by adherent air and steam bubbles. The boiler is simple, inexpensive and compact. When circulating water at 8 times the rate of steam generation, the power consumption of the pump is about 0·5 % the power output of the boiler. Duplicate provision must be made for maintaining continuous circulation through the tubes to prevent overheating. The steam drum is generally not exposed to flame or hot gases. Failure of a steam generating tube involves no special danger. Additional heating surface operating on the La Mont system can be fitted to existing boilers, and the flexibility of arrangement of the tubes makes this type of steam generator specially useful in waste heat recovery installations.*

(viii) *Atmos Boiler.*—A distinctive feature of this boiler is the rotation of the water tubes by mechanical means. In a boiler † for a working pressure of 1 425 lbs. / sq. in., the tubes are about 10 ins. dia. × 8¼ ft. long and are driven at 330 r.p.m. The dimensions, arrangement and speed of the tubes may be varied considerably but the principle remains the same. Centrifugal action maintains a layer of water all round the inner surface of the tubes, and the steam generated passes down the centre of the pipe to the steam chamber. The tubes can expand and contract freely. Forced circulation of feed water is maintained by pumping, and a special arrangement of scraper chains prevents the accumulation of scale.

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* Many examples are illustrated in *The Steam Engineer*, Vol. 2, pp. 473, 528.
† *Ibid.*, Vol. 1, p. 247.

Full-load output is available within about 25 min., starting from cold. In later designs, the tubes are mounted in 'squirrel-cage' groups, fuel being burnt inside the rotating cage. Lump coal can be burnt in this way; the steam-generating tubes, with hollow bars between them for air supply, form an efficiently cooled rotating grate. One boiler,* thus arranged, generates 20 000 lbs. steam / hr. at 1 425 lbs., 840° F., burning nut coal at 50 lbs. / hr. / sq. ft. of grate area, the rotor running at 10-12 r.p.m.

(ix) *Loeffler Boiler.*—In this boiler, water, in a drum exposed to no flame or hot gases, is evaporated by injecting superheated steam into it. Steam from the drum is pumped through a radiant super-heater (tubes lining a combustion chamber), and about one-third of the superheated steam is passed to the power main, the remainder being injected into the water in the evaporating drum. The distinctive feature is thus the circulation of steam through the superheater tubes, and an independent supply of steam from another boiler is required to raise the water in the evaporating drum to boiling-point, and provide an initial supply of steam for the superheater tubes. Thereafter, the operation of the boiler is self-contained and continuous. The combustion chamber is usually fired by pulverised coal or oil, but grate firing can be used. Heat in the gases leaving the combustion chamber is utilised in a second-stage superheater and, if required, an inter-stage steam resuperheater; also, to preheat feedwater for the evaporating drum and to warm air for the furnace.

This boiler is essentially a high-pressure type, delivering steam at any desired pressure up to about 2 000 lbs. / sq. in., and always above 750 lbs. / sq. in. The temperature of superheat is generally about 932° F. (500° C.). The low specific volume of the high-pressure steam makes it economically possible to circulate the steam by pumping. With a steam velocity of about 65 ft. / sec. through the small tubes of the superheater, heat transmission at about 40 000 B.Th.U. / sq. ft. / hr. is obtained. As there is only clean steam in the superheater tubes, the inner surface of the latter is always quite free from scale or other deposit. The evaporating drum is of simpler and cheaper construction than would be possible if it were exposed to direct heating, and here again there is no trouble from scale deposits, any solids thrown out of solution being deposited as sludge without affecting the evaporation of water by the superheated steam.

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* *Steam Engineer*, Vol. 4, p. 271.

It is claimed that the Loeffler boiler can be operated satisfactorily with at least 5 times the salt-concentration permissible in an ordinary high-pressure boiler.*

(x) The Gesellschaft für La Mont-Kessel und Kraftwirtschaft m.b.H. has described † an entirely novel experimental type of high-pressure spinning flash boiler, which is incorporated with its own turbo-generator on a single shaft, as a self-contained unit. The boiler consists of a series of tubes which rotate with the shaft; at one end is a water tube, heat insulated and fed from an open tank, connecting with several steam tubes in parallel. The rapid rotation of the system results in high centrifugal forces, and the utilisation of these makes it possible to supply feed water against high-pressure steam without a feed pump. Gas heating was used in the experiments, with distilled water, the condensate being returned to the supply tank; and a heat transmission of 52 B.Th.U. per sq. ft. per hr. per degree Fahr. was obtained at 1 500 to 1 600 r.p.m. It would appear that the problem of balancing the rotating parts under various water and steam contents may be difficult. Low capital cost is claimed, as compared with normal plants, and great saving in space.

With reference to the modern use of very high steam temperatures (§ 191), chromium-steel alloys have advanced matters. Without them, 725° F. was the limit in superheaters, owing to the occurrence of 'creep' in the metal. At present there is no creep at 750° F. with these alloys, while at 900° F. there definitely is creep, the exact critical point being undetermined.‡

Electrically-operated Steam Boilers are dealt with in Vol. 2, § 625, and the domestic type in §§ 621, *et seq.*

171. **Boiler Room Efficiency.**—The minimum equipment and procedure required to determine and maintain efficiency in the boiler room is as follows: Coal-weighing apparatus and periodic determinations of the calorific value of the coal are required to make possible calculation of the heat input. Steam meters record the quantity, and pressure gauges and thermometers show the condition of the steam delivered; thence the thermal

* For further information, including descriptions of illustrations, see *The Steam Engineer*, Vol. 1, p. 154; Vol. 2, pp. 216, 442, 489; Vol. 3, p. 474; Vol. 4, p. 94.

† *Power*, Vol. 76, p. 223.

‡ H. H. Dow, *Mechanical Engineering*, Vol. 48, p. 815.

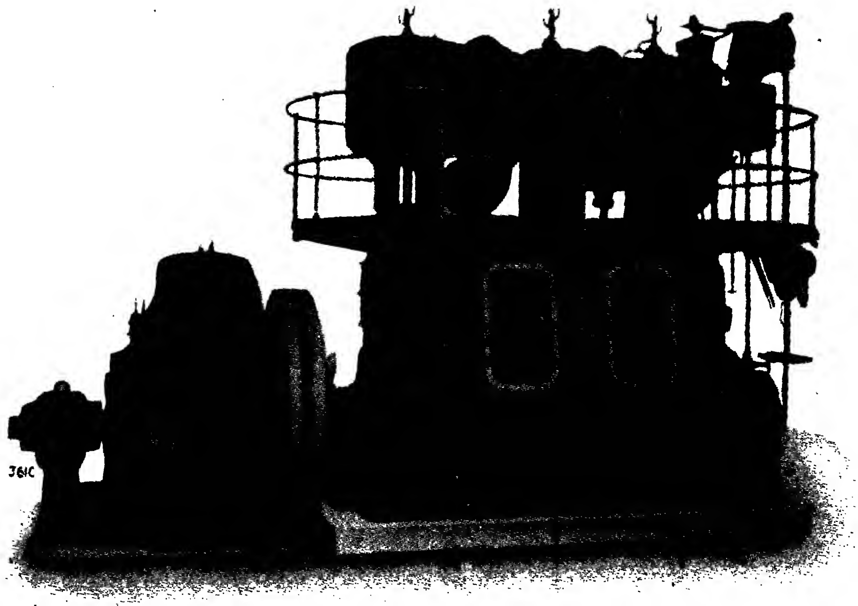
output of the boiler can be determined by reference to steam tables. For the complete control of the conditions of combustion, and to detect air leakage through the boiler setting, irregular fire bed, etc., manometers and thermometers (both distant-indicating) are required at various points in the path of the air and flue gases. Thermometers should be placed also inside the inlet and outlet of the superheater and economiser.

Flue gas analysis is an excellent guide to the conditions of combustion and should preferably be effected by an automatic recording apparatus which determines both the carbon dioxide and the oxygen in the gases. The ideal percentage of carbon dioxide in flue gases from a boiler burning average English coal is 18-19 °/₀; the actual percentage under good conditions and steady high load is 12-14 °/₀, but the average during 24 hrs. is rarely over 10 °/₀, and is often 8 °/₀, 6 °/₀, or less. The theoretical percentage of carbon dioxide should be approached very closely where oil or gas fuel is employed.

It is very important that the steam pipes, etc., be adequately lagged with heat insulating material; the loss by radiation should then be about $\frac{1}{4}$ or $\frac{1}{3}$ B.Th.U. / sq. ft. / hr. / 1° F. temperature difference between the steam and the surrounding atmosphere (compared with 3 or 4 B.Th.U. in the case of bare pipe). Inferior lagging may be worse than useless in that it simply increases the radiating surface.

The efficiency of a boiler plant is improved materially by the use of feed water which does not form scale. In condensing installations a relatively small amount of make-up feed water is required, and if this be subjected to preliminary distillation in a steam-heated evaporator no scale-making material is carried into the boilers. The steam and water circuits can be arranged so that the net expenditure of heat involved by the preliminary evaporation is very small. The feed water should nowhere be exposed to air, because air in solution promotes corrosion of the boilers. The testing of feed water by its electrical conductivity is mentioned in § 119.

172. Reciprocating Steam Engines.—The advantages of reciprocating steam engines compared with other prime movers where the output required is less than, say, 1 000 kW are discussed in § 189. The steam consumption of these engines varies over a wide range. Non-condensing simple engines may consume from

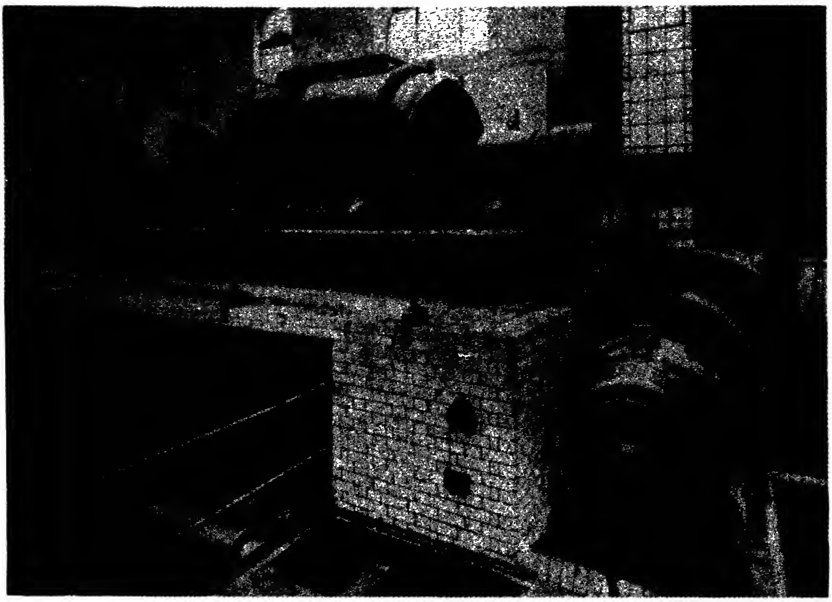


Belliss & Morcom, Ltd.

HIGH-SPEED TRIPLE-EXPANSION STEAM ENGINE DRIVING A D.C. GENERATOR.

The distinctive features are the total enclosure of working parts, and the use of forced lubrication on the arterial principle. Oil is circulated automatically to all the bearings by a pump discharging at 10-20 lbs. / sq. in. Governing is by throttle at light loads, by variable expansion at heavy loads, and by a combination of these methods at intermediate loads. Two-crank compound and non-compound engines are supplied for maximum outputs from 38 B.H.P. at 650 r.p.m. to 720 B.P.H. at 300 r.p.m. The non-compound engines are for steam pressures of 80-90 lbs. / sq. in., and a pressure of 140-150 lbs. is recommended for the compound engines. Triple-expansion engines are supplied for outputs from 260 B.H.P. at 500 / 550 r.p.m. to 2 500 B.P.H. at 187½ / 200 r.p.m., and a steam pressure of 170-200 lbs. / sq. in. is recommended. Where the steam pressure is sufficient and the engine is to operate condensing, the triple-expansion type is best, but the compound type is often preferable for non-condensing or for working against a back pressure. The weight of the compound and triple-expansion engines respectively is roughly ⅝ cwt. and ⅞ cwt. per B.H.P.; or 1 cwt. and 1¼ cwts. per B.H.P., including D.C. generator and bed plate.

[To face p. 310.



General Electric Co., Ltd. (London).

TYPICAL TURBO ALTERNATOR SET WITH EXTERNAL VENTILATING FAN.

The set illustrated is rated at 12 500 kVA, 6 600 V, 50 cycles, 3 000 r.p.m. Steam pressure 190 lbs. / sq. in., temperature 584° F. Vacuum 27½ ins. at 30 ins. barometer. Steam consumption not available at time of going to press. The approximate weight of the turbine is 60 tons and of the alternator 55½ tons. The approximate dimensions of the complete set are: Length, 32 ft. 7 ins.; height, 8 ft. 4 ins.; width, 10 ft. 8 ins. The rotor of the generator is a solid steel forging, and the end-windings of the stator are specially supported to withstand short-circuit stresses.

[*To face p.* 311.

45-60 lbs. steam per B.H.P.-hr. in small sizes and 28-33 lbs. in 100 H.P. or larger units. The same engines worked condensing will consume, roughly, 25 °/₀ less steam or, say, 35-40 lbs. per B.H.P.-hr. in small sizes and 20-25 lbs. in larger engines. Compound, condensing engines may consume as much as 20-25 lbs. steam per B.H.P.-hr., but 15-17 lbs. is a satisfactory range where engines of 200-500 H.P. are concerned. In high-class triple-expansion engines, operating under favourable circumstances, the steam consumption is reduced to 12-14 lbs. per B.H.P.-hr. Sulzer and Allis triple-expansion engines, representing the best practice of the Continent and the United States, have a consumption varying from 11½-12½ lbs. per I.H.P.-hr., and exceptional results as low as 10 lbs. per I.H.P.-hr. (say, 10½ lbs. per B.H.P.-hr.) have been reached. At loads above or below normal full load, these consumption figures are exceeded, usually by not more than 5 °/₀ at 1¼ and ¾-full load, but by 15-20 °/₀ or more at ½-load. In '*uniflow*' *engines* the exhaust port is at the middle of the cylinder, and is opened and closed by the piston moving over it; by eliminating the passage of live steam over surfaces cooled by exhaust steam, this arrangement reduces condensation losses and improves efficiency. A certain 400 H.P. simple, condensing engine of this type consumed about 12 lbs. steam per B.H.P.-hr.*

The advantage of superheating steam for use in reciprocating engines is theoretically very small but is actually very great; there is a small increase in the theoretical efficiency of the cycle where superheated steam is used, but the great advantage lies in the more or less complete elimination of cylinder condensation. In typical cases from 10 to 25 °/₀ reduction in coal consumption is effected by the use of superheated steam in reciprocating engines (*see also* § 174).

The enormous increase in specific volume of steam at low pressures makes it difficult to utilise high vacua as effectively in reciprocating engines as in turbines.

In Germany, W. Schmidt has experimented for many years with the use of pressures up to 900 lbs. / sq. in. in reciprocating engines (*Science Abstracts*, Vol. 25, p. 2). The steam is superheated

* For further information on reciprocating steam engines the reader may be referred to a chapter on the subject, by one of the authors (Mr. Neale), in Whittaker's *Mechanical Engineer's Pocket Book*.

between the high and low-pressure cylinders, and it is claimed that the heat consumption is as low as 146 B.Th.U. / B.H.P.-min. corresponding to 29 °/₀ thermal efficiency. Ordinary compound condensing engines using steam at 120-180 lbs. / sq. in., superheated to 250° C., commonly require 200-250 B.Th.U. / I.H.P.-min. or, say, 250-300 B.Th.U. / B.H.P.-min. It is claimed that the high-pressure engines consume 20 °/₀ less heat than turbines using steam at 225 lbs. / sq. in. Also, the high-pressure engine is particularly suitable for operating with high back-pressure, the exhaust steam being utilised for heating purposes (§ 188).

173. Steam Turbines.—Steam turbines have no marked advantage over reciprocating engines in point of steam economy until comparatively large units are concerned. In units exceeding 1 000 kW the turbine effects great saving in capital cost and space occupied, and its higher steam efficiency (though little superior to that of the best reciprocating engines) represents a large saving per annum. The most efficient steam turbines have 26-28 °/₀ thermal efficiency, which is higher than that of gas engines, and is only exceeded by that of Diesel-type engines. The latter have not the compactness and simplicity of the steam turbine, and cannot yet be built in such powerful units (§ 179).

From the facts stated in § 174 it will be clear that no universally applicable data can be given concerning the *steam consumption of turbines*. Also it will be clear that nothing less than an accurate statement, supplemented by full particulars concerning working conditions, is sufficient in practical working. At the same time, it is useful to know that under average working conditions * the steam consumption of a 500 kW turbine may be taken as 16-19 lbs. per kWh; of a 1 000 kW machine, as 15-16 lbs. per kWh; of a 2 000-5 000 kW machine, as 13½-14 lbs. per kWh; and of 10 000-30 000 kW machines, as 10-11 lbs. per kWh. At ½-load the steam consumption per kWh is from 15-20 °/₀ greater. Exhaust steam turbines, utilising steam at or near atmospheric pressure, usually consume between 30 and 40 lbs. per kWh. Given the steam consumption / kWh of a turbine at two loads, say full-load and ¾-load, the consumption at

* The B.S.I. recommended (in Report No. 72, now cancelled) that the turbine output at which highest steam economy is obtained should be 80 °/₀ of the maximum continuous output of the generator, except in special cases. The more recent B.S.S. No. 225, which superseded the above, omits this.

any other load or at no-load can be predicted accurately enough for practical purposes, by applying the Willans' straight-line law; the known consumptions are plotted against the values of load to which they correspond, and a straight line is drawn through the two points thus obtained. The consumption at any other load can be read at once from the line drawn. This method is not applicable to mixed-pressure turbines, owing to the use of different proportions of 'live' and 'exhaust' steam at different loads. Mixed-pressure turbines, which normally operate on part 'live' and part 'exhaust' steam, have about the same consumption as high pressure or exhaust turbines respectively when operating on live or exhaust steam alone.

Turbo-alternators of 30 000-50 000 kW capacity have become almost commonplace during recent years, and units up to 160 000 kVA capacity have been manufactured (see also § 196).

The guaranteed steam consumption of the 40 000 kW, 1 500 r.p.m. turbines in the Gennevilliers station is 9·6 lbs. / kWh on full-load (9·5, 9·9, and 11 lbs. / kWh on $\frac{3}{4}$, $\frac{1}{2}$, and $\frac{1}{4}$-load respectively), using steam at 380 lbs. / sq. in., 708° F.

A 60 000 kW triple cylinder turbine of the Interborough Rapid Transit Co. (U.S.A.) consists of a high-pressure turbine receiving steam at 205 lbs. / sq. in., 150° F. superheat, and delivering steam at 15 lbs. / sq. in. (gauge) to two low-pressure turbines. Each of the three elements drives a 20 000 kW, 25-cycle alternator at 1 500 r.p.m., and the total output available is 70 000 kW for 2 hrs., or 90 000 kW for $\frac{1}{2}$ hr. The low-pressure turbines work with 29-in. vacuum (30-in. barometer) and the steam consumption on rated load is 11 lbs. / kWh, corresponding to about 25 °/₀ thermal efficiency. For output below 25 000 kW it is more economical to use the high-pressure turbine with only one low-pressure turbine.

The use of generating units exceeding, say, 10 000 kVA rating is limited to large cities or networks where the load permits of practically continuous operation at high steam efficiency. The actual amount of labour required to operate such turbines is small, but it must be highly skilled, for obvious reasons. At present (1937) about 96 % of the units (kWh) generated by authorised undertakers in Great Britain are derived from steam stations, and the average capacity of generating units is increasing year by year.

174. Effect of Steam Conditions on Turbine Efficiency.—The maximum total temperature (including superheat) of steam for use in power plants is limited to 850°-1000° F.; above this temperature the mechanical strength of steel is reduced dangerously, and cast iron cannot safely be used for fittings or casings exposed to this temperature. The use of copper for steam pipes (as at bends) is dangerous at much lower temperatures. A total temperature of, say, 700° F. may be reached by using low pressure and high superheat, or high pressure and low superheat; the advantages of higher pressure are increased available heat drop (§ 166), and the smaller size of pipes required for the denser steam. The steam consumption of a turbine decreases about 0·1 °/₀ per 1 lb. / sq. in. pressure increase above, say, 150 lbs. / sq. in.

The reduction in steam consumption of turbines due to 10° F. additional superheat is about 1 °/₀ up to 100° F. superheat, 0·83 °/₀ between 100° and 200° F., and 0·72 °/₀ between 200 and 300° F. superheat. The limiting steam temperature (800°-1000° F.) dictated by the strength of materials is already used extensively.

TABLE 18.—*Effect of Vacuum on Steam Turbine Efficiency.*

Vacuum Between.	°/₀ Gain at Full Load and Per Inch of Vacuum, in Heat Available During Adiabatic Expansion. Using Steam at 160 Lbs. (Gauge) and 150° F. Superheat.	Using Steam at Atmospheric Pressure.
	°/₀ Per Inch.	°/₀ Per Inch.
23" and 24"	3	9
24" ,, 25"	3	10
25" ,, 26"	4	11
26" ,, 27"	5	12
27" ,, 28"	6	14
28" ,, 28½"	8 *	17 *
28½" ,, 28¾"	9 *	20 *
28¾" ,, 29"	11 *	23 *
29" ,, 29¼"	13 *	27 *

Turbines are extremely sensitive to vacuum, as shown by Table 18 (based on data due to G. Gerald Stoney, *Inst. Mech. Engrs., November 20, 1914). Practically the same savings as* shown in col. 2 are obtainable with dry saturated steam as with superheated steam. With 28-28½-in. vacuum, the percentage saving in consumption would be increased (above the value given in Table 18) by about 1 °/₀ at ½-load and about 2½ °/₀ at ¼-load, using throttle governing; but would remain about the same at all loads, using nozzle governing. It is not possible to realise the

* *Note.*—These are percentage gains *per inch* of vacuum; the actual gain between 28 and 28½-in. vacuum is 4 °/₀ (or 8½ °/₀), and so on.

full savings indicated above, particularly at very high vacua,* owing to terminal losses in the blading; nevertheless, there are few cases in which it does not pay to maintain the highest vacuum of which the equipment used is capable. Exhaust passages should be proportioned and shaped to give minimum loss of vacuum, and there should be minimum difference in vacuum between steam and air-pump connections to the condenser. A vacuum of 28 ins. (barometer 30 ins.) may be taken as a satisfactory standard value for high-pressure turbo-sets, and of 27½ ins. for exhaust turbines operating on steam at or near atmospheric pressure. Increasing the vacuum from 28 to 29 ins. practically doubles the volume per lb. of steam, and introduces evacuation and condensing problems of a mechanical nature which more or less completely offset the advantage derived from the greater available heat drop.†

As an illustration of the care which must be given to drawing up conditions of test, it may be mentioned that at a certain central station in India, the acceptance tests of a new turbine set were held up by a dispute as to whether all the test consumption of steam was to be based on a 28-in. vacuum at all loads, or whether the contractors were entitled to take advantage of the considerably higher vacuum obtainable in practice. As is not unusual, the consultants' specification was silent on the point.

175. Steam Condensers and Auxiliaries.—The exhaust steam from engines or turbines may be condensed in various ways:—

(1) In a *jet condenser* it is mixed with jets of water. From 20-30 lbs. of water is required per lb. of steam condensed. If space be particularly valuable the water jet and exhaust steam may mix in a small chamber at the top of a pipe down which flows the mixture of condensing water and condensed steam; this form is called the *barometric condenser,* because the height of the downtake pipe must exceed the height of the water barometer (about 34 ft.), to which height water from the hot well is driven by atmospheric pressure when a vacuum is maintained in the condensing chamber.

(2) In an *atmospheric* or *evaporative condenser*, the exhaust

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* Nearly the full theoretical gain is obtainable between 26-in. and 27-in. vacuum, but only 50-60 % of the theoretical between 28 ins. and 29 ins.

† A valuable paper is 'Choice of Steam Conditions in Modern Power Stations,' by L. C. Kemp, *Electrician*, June 30, 1922.

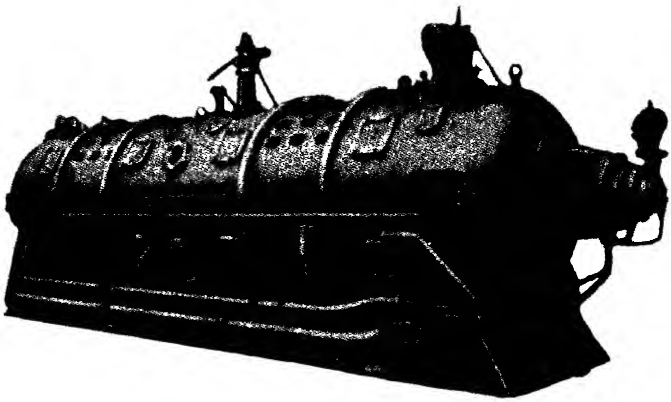
steam passes through nests of tubes over which water trickles. Alternatively, the nest of tubes may be in the form of a hollow cylinder which is rotated about its axis, dipping meanwhile in a trough of water so that the outside of the tubes is covered by a film of water. Whereas the condensing water in jet and surface condensers is heated 50° F. or less, so that each pound of condensing water removes not more than 50 B.Th.U., the cooling water of an atmospheric condenser is *evaporated* and each pound removes about 1 000 B.Th.U. The atmospheric condenser requires only about 1-1½ lb. of water per lb. of steam condensed and is thus particularly valuable where water is scarce; the water used is, however, entirely lost. A natural or artificial current of air is required to carry away the water vapour, and in the saturated air (often 90 to 95 °/ₒ humidity) of some tropical countries the type is almost useless, since very little evaporation is possible.

(3) In a *surface condenser* cold water is circulated through tubes over which passes the exhaust steam. From 50-70 lbs. of condensing water is required per lb. of steam condensed.

Atmospheric and surface condensers are more costly than jet condensers to build and maintain, but the condensate is not contaminated by the circulating water, the condensate is at higher temperature than that from a jet condenser, and all the condensate is used as boiler feed, hence there is minimum loss of heat from the steam circuit.

The large volume of circulating water required by a surface condenser cannot economically be treated to correct any corrosive properties which it may possess. This water is generally drawn from a river or canal through mechanical strainers, preferably of the self-cleansing type. The flow through the adits may be reversed periodically to remove deposits of silt. The condenser tubes should be made of an alloy which is not attacked by the water used. Condensers in which the tubes are not longer than twice the diameter of the tube plates are more costly than condensers of smaller diameter with longer tubes, but the large diameter design results in higher vacuum. Maximum vacuum is required at the turbine end of the exhaust passages, not merely at the centre of the condenser.

If the supply of circulating water is limited, the water leaving a surface condenser may be cooled for use again by allowing it to flow down brushwood, laths, etc., in a cooling tower, up which

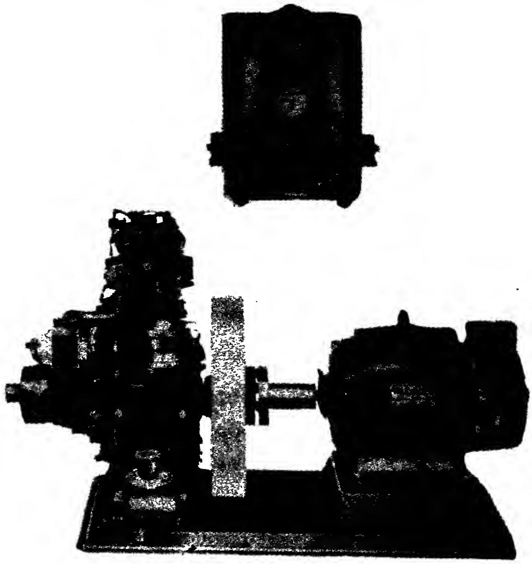


Brush Electrical Engineering Co., Ltd.

BRUSH-LJUNGSTROM TURBO ALTERNATOR; 3 000 kW AT 3 000 R.P.M.

There are no fixed guide blades in the Ljungstrom turbine. Two sets of blading are carried in concentric rings on the faces of two discs which run in opposite directions. Each disc is overhung on the shaft of an alternator, and the discs can be removed without disturbing the generators. The two alternators are in parallel and synchronise automatically whilst running up to speed. Steam enters at the centre and flows radially outwards to an exhaust chamber bolted directly to the condenser. The turbine is of the reaction type and, as the relative speed of the blades is twice the actual speed, very high efficiency is obtained. The number of rows of blades is one-fourth that of an ordinary reaction turbine. A 5 000 kW, 3 000 r.p.m. set using steam at 166 lbs. / sq. in., 662° F., with 28·9 ins. vacuum, consumes 10·36 lbs. steam / kWh at full load.

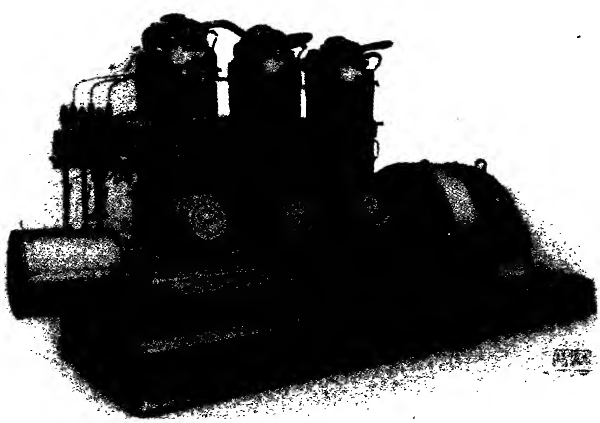
[*To face p.* 316.



Mark Webber, Ltd.

SEMI-AUTOMATIC HOUSE-LIGHTING SET.

This set combines all the control afforded by the usual accumulator charging board with electric starting and automatic stopping. A series field winding is used when the dynamo is run from the cells as a motor to start the engine; and a shunt field winding is used during normal service. Automatic stopping is effected by an ampere-hour meter with a bias on the 'charge' side, corresponding to the ampere-hour efficiency of the battery. The engine will run on petrol, benzol, alcohol, or town gas, and can be used as an independent unit. Standard sizes range from 1 to 2½ kW and from 25 to 140 V.



Robey & Co., Ltd.

CRUDE-OIL ENGINE DIRECT-COUPLED TO A DYNAMO.

The engine illustrated operates on the two-stroke cycle (one working stroke per cylinder per revolution of the crankshaft). Any kind of crude or refined oil can be used, the engine can be started quickly and easily, and no water injection is required. Outputs up to 100 B.H.P. are obtainable from single- and twin-cylinder engines, and up to 300 B.H.P. from multi-cylinder engines of this type.

[*To face p.* 317.

air is blown by fans. Roughly 1 000 B.Th.U. per lb. of steam consumed by the engine or turbine (or, say, half the calorific value of the coal burned below the boilers) has to be carried away by the air in the cooling tower. In climates where humidity is high, the saturation of the air makes it difficult to cool the condensing water to a temperature making possible the maintenance of high vacuum.

Air from the feed water or leaking in to the steam circuit at any point must be removed from the condenser by an air pump. The steam-jet ejector pump is simple and effective for this purpose; the steam consumed equals about 1 % of the consumption of the engine or turbine, but practically the whole of the heat in the steam jet passes to the 'hot well,' *i.e.* the tank in which warm condensate is collected for use as boiler feed, so that the heat is utilised in the warm water.

In order to allow for occasional air leaks in surface condenser systems, provision should be made for the air pumps to deal with at least 1·3 lbs. air per 1 000 lbs. steam in moderate-sized plants, and for 1 lb. per 1 000 lbs. in large plants. It is well to arrange for 1 sq. ft. of condensing surface for every 5 lbs. per hour of steam to be condensed; such a condenser will run a considerable time without cleaning and without much loss of vacuum, so that its cost is well invested. With modern air pumps, condensation of 7-10 lbs. per sq. ft. per hour is possible, even with high vacua. As a standard for testing, a condenser with 1 sq. ft. per 7 lbs. of steam and a water velocity of 6 ft. per sec. in the tubes should transmit (3 days after tube brushing) not less than 450 B.Th.U. per sq. ft. of surface per hr. per 1° F. difference in temperature between steam at inlet and mean water temperature. A difference of 1° F. in the temperature of cooling water means about 0·3 % difference in turbine steam consumption (or, say, £900 capital value; *see* § 174); hence it is a mistake to cut down the height of a cooling tower, on which the amount and efficacy of cooling chiefly depend (*see also* Selvey, *Journal I.E.E.*, Vol. 53, p. 114).

The circulating and condensate pumps, and the air pump (if not of the steam-jet type) may be driven electrically or by steam. The cost of duplicate equipment is generally justifiable on the ground of reliability. If the auxiliaries are supplied solely from the main bus bars they may be incapacitated by an electrical break-down. Frequently a relatively small 'house turbine' is used to drive a generator providing current for station lighting and the driving of auxiliaries. The principal considerations are: (1) There should be minimum risk of the main generators being placed out of action by any failure in the auxiliary services. (2) As much as possible of the heat in the exhaust steam from all sources should be returned to the hot well. The energy consumption of condenser auxiliaries is generally from 3-5 °/₀ of the output of the prime mover.

176. Utilising 'Low-grade' Heat.—It is evident from the examples in § 166 that the exhaust from a steam engine or turbine contains a large part of the heat in the 'live' steam delivered to the prime mover. Roughly 60 °/₀ of the heat value of coal burned in an ordinary steam plant with condensing engines or turbines is delivered to the condensing water. Any reduction in the heat thus rejected constitutes an important saving. 'Low-grade' heat—*i.e.* principally the latent heat of steam which has been expanded in the prime mover—may be utilised by either or both of two methods, *viz.*: (1) By 'bleeding' steam from an intermediate stage in the expansion and using it to raise the temperature of the condensate, thus returning the heat of the bled steam to the feed water. (2) By using exhaust steam (or condensate) for industrial heating or for heating buildings, the back pressure on the engine or turbine being higher the higher the temperature required in the heating service. The basic principle is the same in both cases; some of the heat in the live steam is used to produce mechanical power and the remaining heat (above atmospheric temperature) is used as heat. Greater saving is effected by method (2), when all the exhaust is used for heating, than by method (1) which is limited by the fact that the feed water cannot reasonably be heated above, say, 300° F. It is not commonly realised that even a 'super-station' cannot compete in overall efficiency with the smallest steam plant which can utilise its low-grade heat, unless the former can also dispose profitably of its low-grade heat. In most cases a small power plant can find use for its exhaust steam more easily than a large central station (§ 188).

In collieries and other industrial establishments there are many excellent reciprocating engines which cannot economically be scrapped, but which do not utilise the expansion of steam as fully as could be done in turbines. In such cases exhaust steam from the engine can be utilised in low-pressure turbines which yield additional power (say 50 °/₀ of the engine output) without involving any additional consumption of fuel (*see also* § 817, Vol. 3).

Steam-Pressure 'Transformers'.—So long ago as 1852 Lord

Kelvin proposed the use of a reversed heat engine, *i.e.* a compressor, as a means of heating air; and the problem of utilising low-pressure steam by raising its pressure and temperature has been studied ever since. In industrial evaporative processes, especially, the need for this is felt and a high-pressure steam jet acting on the process steam by an injector has been extensively used; so also has a centrifugal compressor, driven by turbine or motor. In both cases the practical efficiency is far below the theoretical, being of the order of 25 °/o with injectors and 32 °/o with compressors. A process devised by Koenemann uses chemical instead of mechanical methods for compression, and while giving a higher practical efficiency—nearly double that of the compression system—has also the advantage of having no moving parts except a small pump and of obtaining higher steam pressure than is practicable mechanically. For details of the system reference may be made to the paper * from which these data are extracted. The process depends upon the fact that a solution of caustic soda or potash boils at a higher pressure than water at the same temperature. Exhaust steam at 212° F. is blown into a solution with a boiling point of 300° F. and is condensed. The latent heat of the steam is liberated, and also the heat of dilution, and except for the heat used in raising the condensed steam from 212° to 300° F., the liberated heat is available at 300° F. and can be used to generate steam at that temperature and the corresponding pressure (67 lbs. per sq. in. abs.) in a separate vessel. By reconcentrating the diluted solution by live steam coils or other source of heat, and keeping the steam generator supplied with water, the process becomes continuous.

177. Steam Accumulators.—Where exhaust steam is used to drive a low-pressure turbine or for heating or manufacturing processes, etc., some means may have to be provided for storing a temporary surplus of steam to tide over an ensuing temporary deficiency. This provision consists of a steam accumulator, which may be a tank of water (say an old Lancashire boiler suitably lagged) into which the exhaust steam is passed, the water then evaporating when the pressure on it is reduced by the demand for steam exceeding the inflow. Alternatively, the accumulator may consist of a counterbalanced, well-lagged 'gasometer' bell, in which the exhaust steam is stored, and from which it is taken as

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* A Steam-pressure Transformer, L. S. Marks, *Mech. Eng.*, Vol. 49, p. 600.

required. The advantage of the latter arrangement is that it imposes a lower back pressure on (and hence involves less loss of power in) the reciprocating engines supplying the exhaust steam —say ½ lb. per sq. in. as against 2½ or 3½ lbs. per sq. in. in the case of the water-storage system. The back pressure in a water-storage steam accumulator is sufficient to permit admission of live steam to a mixed-pressure turbine to be controlled by the pressure of the exhaust steam available at the moment. In the gasometer-type of accumulator, the variation in exhaust steam pressure is too small for this system of control to be effective, hence admission of live steam is then controlled, through oil-relays or otherwise, by the rise and fall of the storage bell.

Steam accumulators of the water-storage type can be used to store high-pressure steam if desired, and large reservoirs of this type are used in some installations to equalise the demand on the boilers. For example, relatively small boilers may operate continuously at full-load to feed a storage tank from which steam can be drawn intermittently at a rate far exceeding the steaming capacity of the boilers. For given variation in pressure, more steam can be stored per cu. ft. of water at low than at high pressure.* A recent addition to the system of the Berliner Städtische Elektrizitätswerke A.G. consists of a 200 000 kW plant with a 50 000 kW steam accumulator and a large battery reserve.†

178. Fuels for Internal Combustion Engines.—The only fuels at present used commercially for internal combustion engines are gases or liquids which are converted, as far as possible, into gases prior to ignition. With reservations into which it is unnecessary here to enter, paraffin, petrol, alcohol, petroleum, town gas, and producer gas can all be used equally satisfactorily in relatively small engines up to, say, 100 B.H.P., the choice being determined mainly by the relative cost and ease of obtaining the several fuels. For engines of higher power petrol and town gas are generally too expensive, and the choice usually lies between some form of producer gas, coke-oven or blast-furnace gas, and petroleum (crude or refined) or tar oil.

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* About 0·3 lb. of steam is stored per cu. ft. of water when the pressure rises from 265 to 280 lbs. / sq. in. (gauge), compared with 1·3 lb. of steam per cu. ft. of water when the pressure rises from 15 to 30 lbs. / sq. in.

† *Power*, Vol. 76, p. 186.

The calorific value of *petrol, paraffin, and petroleum* is about 19 000-20 000 B.Th.U. / lb. The sp. gr. varies with the composition (each of these fuels being a mixture of 'fractions' distilling at different temperatures); typical values are: petrol, 0·68-0·72; paraffin, 0·75-0·85; crude petroleum, 0·85-0·95.

Tar oil, a by-product of the coking of coal, has a calorific value about 16 000 B.Th.U / lb. When this oil is used in engines it may be necessary to use an auxiliary injection of paraffin or other light oil to ensure ignition; the amount of light oil required is, *at all loads*, about 5 °/₀ of the full-load consumption of tar oil.

The calorific value of *alcohol* is usually between 11 000 and 12 000 B.Th.U. / lb. (according to the percentage of water contained) and the sp. gr. is about 0·82.

Natural gas contains up to 93 °/₀ of methane and has a calorific value of 800-1 100 B.Th.U. / cu. ft. The supply of natural gas is restricted to certain localities (mostly near oil fields) and is variable in quality and dwindling in amount. *Town gas* or *coal gas* is made by the distillation of coal in closed retorts; it may contain 40-45 °/₀ each of hydrogen and methane, and has then a calorific value of 600-700 B.Th.U. / cu. ft.; lately the calorific value has been reduced to 500 B.Th.U. or lower by the admixture of a considerable amount of water gas. Town gas is now sold, in Great Britain, on the basis of calorific value, the unit being the *therm* which equals 100 000 B.Th.U. The term *producer gas* includes a number of mixtures of carbon monoxide, hydrogen, methane, etc., with more or less carbon dioxide and nitrogen as diluents; these mixtures are the products of incomplete combustion of coal, coke, sawdust, peat, etc., in the presence of more or less steam. Simple producer gas or *air gas*, made by blowing or drawing air through a bed of incandescent carbon, consists mainly of carbon monoxide and has a calorific value from 70-100 B.Th.U. / cu. ft. *Water gas*, made by blowing steam and air alternately through incandescent carbon, may contain 50 °/₀ hydrogen and 35 °/₀ carbon monoxide, the calorific value being about 300 B.Th.U. / cu. ft.; if 'carburetted' by the addition of hydrocarbons, water gas may yield about 650 B.Th.U. / cu. ft. Suction gas plant generally produces a mixture intermediate between air gas and water gas (§ 181). *Mond gas* is a producer gas made on a large scale and from bituminous coal with provision for utilising waste heat and recovering by-products (§ 169); its calorific value is about 150 B.Th.U. / cu. ft. *Blast furnace gas* contains 25-30 °/₀ of carbon monoxide and has a calorific value of about 90-100 B.Th.U. / cu. ft. The calorific value of coke oven gas is about 400-450 B.Th.U. / cu. ft.

Internal combustion engines are now available which can easily be adapted to operate on whichever liquid or gaseous fuel is cheapest at the time and place concerned.

179. Horse-power of Internal Combustion Engines.—The general formula for the horse-power of any reciprocating engine is:—

$$\text{Horse-power} = PLAN / 33\,000,$$

where P = mean effective pressure on the piston during the working stroke, in lbs. / sq. in.; L = length of stroke, in ft.; A = effective area of piston, in sq. in.; N = number of working strokes per min. The H.P. of a steam engine can be increased considerably above the rated H.P. by delaying the cut-off, thus admitting more steam to the cylinder and raising the mean effective pressure. In internal combustion engines, however, it is impossible greatly to increase the weight of fuel burned, beyond the value corresponding to the normal output for which the engine is designed. Though the overload capacity of internal combustion engines is small compared with that of steam engines, this does not limit the utility of the former for driving electric generators, provided that the engine be of suitable size; unfortunately some internal combustion engines cannot maintain an output equal to the rating which they are given in makers' catalogues.

TABLE 19.—*Data for Calculating the Output of Internal Combustion Engines.*

	Town Gas.	Producer Gas From		Fuel Oil.	Paraffin.	Petrol.	Two-stroke Liquid Fuel Crank-case Compression.
		Anthracite.	Coke.				
(*a*) Mean effective pressure indicated, lb. / sq. in.	90	75	70	75	70	85	47
(*b*) Ditto, available at crankshaft, lb. / sq. in.	76	61	56	61	56	71	33
(*c*) Mechanical efficiency of engine ($= b / a$), %	84·5	81·3	80·0	81·3	80·0	83·5	70·0
(*d*) Piston displacement (impulse strokes only)—							
Cu. ft. / min. / B.H.P.	3·0	3·75	4·1	3·75	4·1	3·22	7·0
Cu. ft. / min. / kW *	4·5	5·6	6·1	5·6	6·1	4·84	10·5

An empirical but useful method of determining the size of internal combustion engine required to drive electric generators was published by W. A. Tookey in a paper read before the Association of Supervising Electricians, May, 1916. The data extracted therefrom in Table 19 relate to the normal full-load output which can be maintained continuously for 8 hrs.

For continuous (24-hr.) operation at full load the piston displacement per H.P. or per kW should be about 10 % greater than the values given in Table 19; on the other hand, for short periods the power developed may be 5-10 % higher than the value calculated from this table.

Example.—What is the normal full-load output of a town-gas engine with four cylinders, each 8 ins. dia. × 7 ins. stroke, running at 600 r.p.m.? The piston displacement is $(\pi(8)^2 / 4) \times 7 = 352$ cu. in. per stroke. On the four-stroke

* Assuming generator efficiency = 89 %.

Crossley Bros., Ltd.

COLD-STARTING OIL ENGINE FOR REFINED, CRUDE, RESIDUAL AND TAR OILS.

The engine starts from the cold state without preheating, runs with moderate compression, and requires no air blast for the injection of fuel. It operates on the four-stroke cycle, and the oil pump injects a charge of oil into the combustion chamber in the form of fine spray. The fuel consumption at normal rated load ranges from 0·4 to 0·5 lb. / B.H.P.-hr., according to the quality of the fuel and the size of the engine. At half-load the total fuel consumption per hr. is less than 60 °/ₒ of the full-load figure. The engine illustrated is rated at 43 B.H.P. normal (47 B.H.P. maximum), 250 r.p.m., and is direct coupled to a D.C. generator. The weight of the engine, including specially heavy fly-wheel for lighting service, is about 113 cwt. Similar engines are built from 19 to 130 B.H.P. (normal) single-cylinder, and from 38 to 260 B.H.P. double-cylinder.

Mirrlees, Bickerton & Day, Ltd.

DIESEL OIL ENGINES DRIVING D.C. GENERATORS.

The illustration shows two 3-cylinder engines direct coupled to 160 kW dynamos. The cylinder diameter is 16 ins., stroke 19 ins., and normal speed 250 r.p.m. The guarantee figures for this size of engine are 0·44 lb. of fuel oil / B.H.P.-hr. at full load, and 0·46 lb. / B.H.P.-hr. at ¾-load, assuming a calorific value of not less than 18 000 B.Th.U. / lb. of fuel oil. Assuming the dynamo efficiency to be 91 % at full load and 90 % at ¾-load, the fuel consumption / kW.h. is 0·65 lb. at full load and 0·68 lb. at ¾-load. The actual consumption is generally lower under working conditions. The engine can be started (by compressed air) and placed on load in less than 2 mins. Standard sizes of this make of engine range from 50 B.H.P. single-cylinder to 750 B.H.P. six-cylinder.

[To face p. 323.

cycle there are 300 working strokes per min. in each cylinder, hence the total piston displacement (impulse strokes) is 352 × 300 × 4 / 1 728 = 245 cu. ft. / min. From Table 19 the piston displacement required is 4·5 cu. ft. / min. / kW, hence the normal full-load output of the engine is: 245 / 4·5 = 54 kW approx.

It must not be overlooked that at high altitudes a larger engine is required; at 8 000 ft. the loss of power amounts to 20 or 25 °/ₒ in oil and gas engines, or roughly 3 °/ₒ per 1 000 ft. Furthermore, it is often found in hot climates that, even when allowance is made for altitude, oil engines will not continue to give their rated output, owing to the high temperatures experienced and the consequent decrease of mass of the volume of air in the cylinder; the loss amounts to about 1 °/ₒ for every 6° F. above 60° F.

The data in Table 20 indicate the range of outputs for which various types of internal combustion engines are available, and the fuel consumption and thermal efficiency of each under favourable circumstances (*see also* §§ 180-183).

180. Liquid Fuels and Oil Engines.—Under this heading may be grouped all engines which utilise liquid fuel, *viz.:* Petrol engines, alcohol engines, paraffin engines, Diesel engines, and semi-Diesel or hot-bulb engines. All these engines have high thermal efficiencies (Table 20) and are thus at an advantage compared with steam plant for medium and small outputs (particularly below 500 H.P.). The elimination of the steam boiler and its appurtenances is often an important consideration, but the steam engine itself is simpler than any internal combustion engine and is more easily kept in good running order; this is especially important where skilled attendance is not easily available. Petrol-electric sets * are convenient and economical for such purposes as country-house lighting; they require no skilled attention for long periods, but it would be unwise to install them where skilled labour cannot be summoned when required.

The only advantage offered by alcohol compared with petrol engines is a possible saving in fuel costs. Paraffin, petroleum (crude or refined), and tar oil are undoubtedly cheaper fuels than petrol, and engines using these can be employed profitably in units up to, say, 100 H.P. for paraffin engines and 500 H.P. upwards for engines using crude oil. Recent developments in crude oil

* Often of the self-starting type in which a small storage battery drives the dynamo temporarily as a motor and thus starts the engine if more than one or two lamps be switched on.

engines make it probable that these will henceforward be used in the majority of installations requiring anything from a few horse-power up to the largest sizes in which they are available; for high

TABLE 20.—*Horse-Power, Fuel Consumption, and Thermal Efficiency of Internal Combustion Engines (see also Table 15, § 167).*

Type of Engine.	Usual Range of Rated Output B.H.P.	Calorific Value of Fuel Used in B.Th.U. per Lb.	Fuel Consumption per B.H.P.-Hr. at Full Load.*	B.Th.U. per B.H.P.-Hr. at Full Load.*	Thermal Efficiency (B.H.P. Basis) at Full Load * %.
Oil Engines.					
Petrol	Up to 50 (aero 1 200)	20 000	0·55 lb.	11 050	23
Alcohol	Ditto	Various mixtures of alcohol and petrol 10 400-8 500			25-30
Paraffin	Up to 120	19 500	0·62 lb.	12 100	21
Diesel	12½ 10 000	18 500	0·4 lb.	7 500	34
Semi-Diesel	5-2 000 and, when super-charged, 2 500	18 500	0·36 lb.	7 700	33
Still (combined steam and oil)	—	18 000	0·375 lb.	6 750	37·7
Oil turbine	500-3 000 ¶	18 500	0·53 lb.	9 800	26
Gas Engines.					
Town or producer gas . .	Up to 250 **	Vari-able; *see* § 178	According to calorific value.	10 400	25
Blast furnace, coke oven, etc., gas	Up to 6 000 ‡				
Gas turbine	7 500-14 000 †				

* The figures in these columns apply to full-load operation of the largest engines in each class. As a rough guide it may be taken that the fuel consumption per B.H.P.-hr. is 10 % higher at 1¼ or ¾ times rated full-load, 20 % higher at ½-load than at full-load, and 50 % (or more) higher at ¼-load than at full-load. In the smallest engines of each type it may be assumed, for the purpose of rough estimates, that the fuel consumption per B.H.P.-hr. is at least 50 % greater than in the largest engines of the same type.

† 1 500 H.P. from pressure producers.

‡ Claimed to be practicable; *see Times Trade Supp.*, Jan., 1922, p. 9; March, 1922, p. 91. *See* § 183.

¶ These machines are still in the experimental stage, but it is claimed that they can be built for outputs up to 12 000 H.P. *See* § 183.

** Up to 300 H.P. per cylinder is developed in single-acting, four-stroke engines and up to 1 500 or 2 000 H.P. per cylinder in double-acting, four-stroke or opposed-piston, two-stroke engines.

powers, however, the steam turbine is generally the cheapest prime mover for land service. Though all oil engines show to best advantage on steady load near full-load rating, the relative increase in fuel consumption at partial loads is no greater than in steam plants. In small installations where the load, if any, can be supplied from batteries during part of the 24 hours, internal combustion engines eliminate the waste and trouble involved by 'banking' steam boilers.

Diesel-type.—Oil engines of the Diesel type are now used extensively in power stations. In this type of prime mover the liquid fuel, which may be crude oil, is sprayed gradually into the cylinder on the forward stroke and ignited by the high temperature caused by the extremely high compression of the air charge during the previous back stroke; there is therefore no actual explosion as is the case in ordinary oil or petrol engines, and no carburettor, vaporiser, or igniter is required.

The practicable size of Diesel sets has increased greatly in recent years, Berlin having sets of 11 000 B.H.P. and Hamburg sets of 15 000 B.H.P., while the largest so far built is a peak-load set at Copenhagen, delivering 15 000 kW. The engine is an 8-cylinder, double-acting, two-cycle, solid injection unit with cylinders of 33 in. diameter, stroke 59 in. and speed of 115 r.p.m. It has a normal rating of 21 000 B.H.P. and a maximum capacity of 22 500 B.H.P. The makers of this set have prepared designs for a 40 000 B.H.P. 12-cylinder engine to run at 187 r.p.m.* In the set already built the fuel is injected under a pressure of 5 000 to 6 000 lbs. / sq. in. through the atomising valves.

In connection with the discussion on rural water supplies, initiated by Col. Crompton and one of the Authors (Mr. Meares) in 1933,† it was pointed out that 'the development of fully-automatic Diesel electric pumping plants has been very rapid and the running costs surprisingly low.'

Semi-Diesel-type.—A modified type known as the 'semi-Diesel,' 'hot-bulb,' or 'surface ignition' engine is now much used. This engine can work on crude oil, tar oil or any other fuel which can be used in Diesel engines, and its thermal efficiency is nearly as high as that of the latter. The distinctive feature of the semi-Diesel engine is that the compression pressure is lower than in the

* *Power*, Vol. 76, p. 184.

† *The Times*, Sept. 18, 1933, and after; and many local papers.

Diesel engine (say 350 lbs. / sq. in. compared with nearly 500 lbs. / sq. in.), hence the temperature reached by compression alone is not sufficient to ignite the fuel. A blow lamp or electric ignition device is used when starting the engine, and the combustion of the working fuel then keeps a special chamber or surface sufficiently hot to ignite the compressed charge {for fuel consumption data *see* §§ 167, 179 (Table 20)}.

Illustrative of present-day tendencies in this type of plant may be mentioned two well-known makes. The Crossley-Premier horizontal vis-a-vis heavy oil engine, with opposed cylinders, represents a novel design in many respects, including a very ingenious patented big-end bearing. The journals have rectangular crank cheeks, recessed so as to allow the pistons to be withdrawn from the liners with sufficient clearance for easy handling.

The range of sizes for non-pressure charged engines is :—

300 to 550 B.H.P. in 2-crank, 4-cylinder designs,
600 to 1 100 „ in 4-crank, 8-cylinder „

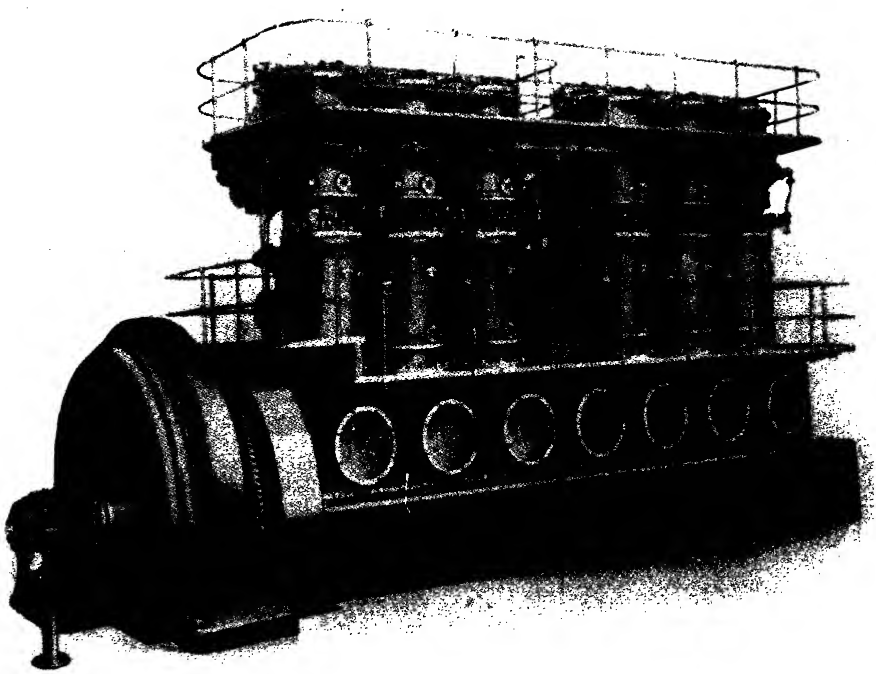
while pressure-charged engines run up to 2 500 B.H.P. The average fuel consumption (Diesel oil) is from 0·36 lb. / B.H.P. at full and three-quarter load to 0·4 lb. at 50 to 40 % load. The exhaust temperature varies between 70° C. running light and 400° C. at 10 % overload. The engine is started on air at a receiver pressure of about 250 lbs. / sq. in., starting valves being provided in alternate cylinders only.

Messrs. Fraser & Chalmers heavy oil engines are built in units of 3, 4, 5, 6 and 8 cylinders, ranging from 825 to 2 240 B.H.P. at a normal speed of 300 r.p.m., with an overload rating of 10 % for two hours, and a rating 10 % below normal for continuous day and night working (B.S.S. No. 120). Some interesting technical data follow :—

Power per cylinder at normal speed, 350 I.H.P.; 275 B.H.P., or 0·76 B.H.P. per sq. in. of bore.
Maximum combustion pressure, 550 lbs. / sq. in., and mean indicated pressure, 120 lbs. / sq. in.
Air injection pressure, 950 lbs. / sq. in.
Cooling water, with outlet temperature 120° to 145° F., 6 galls. per B.H.P.-hr.
Consumption of lubricating oil, 0·004 lb. / rated B.H.P.-hr.
Consumption of fuel oil (18 000 B.Th.U. per lb.), 0·39 lb. / B.H.P.-hr.

The Diesel Engine Users' Association (London) publishes annually a report on the working costs of heavy-oil engines. From the 1936-37 returns, the average fuel consumption of 40 stations was 0·647 lb. / kWh generated, with an average load factor of 67·3 %. The consumption of lubricating oil averages 0·00044 gall. per rated B.H.P.-hr. (2 275 rated B.H.P.-hr. per gall.).

181. Gas Engines.—Coal gas as distributed for lighting purposes is generally too costly for use in large power plants. Producer gas is made by passing air and more or less steam through incandescent fuel; where anthracite is available it is generally

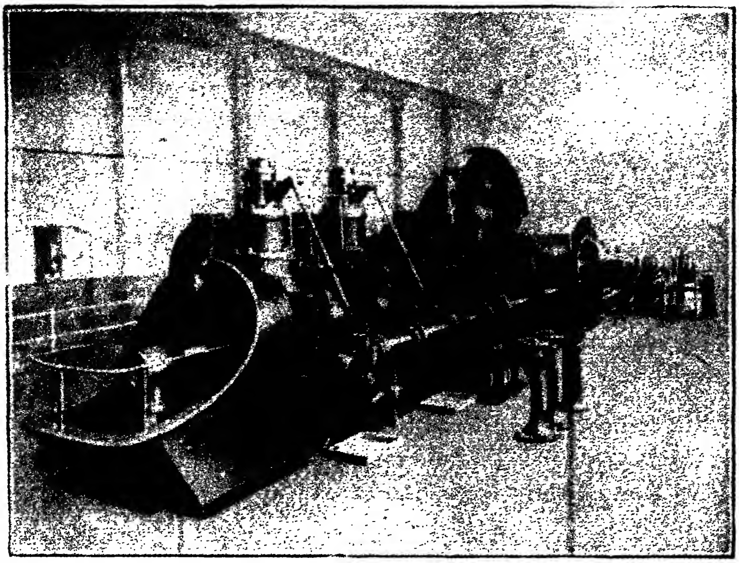


National Gas Engine Co., Ltd.

1 500 B.H.P. VERTICAL TANDEM GAS ENGINE DRIVING AN ALTERNATOR.

There are two cylinders in tandem over each crank and these fire alternately, so that there is a working stroke in one cylinder on every downward stroke. The space between the top piston and the intermediate cover is used as a buffer cylinder, so that the moving parts are cushioned on both the up and the down stroke. Forced lubrication is used, and no moving parts are water cooled. The engine is started by compressed air and can be run on all kinds of gases. The uniform turning moment and close governing obtained are important considerations where the driving of electric generators is concerned.

[*To face p.* 326.



Galloways, Ltd.

TANDEM, DOUBLE-ACTING, HORIZONTAL GAS ENGINE DRIVING AN ALTERNATOR.

The engine operates on the four-stroke cycle and has cylinders of 950 mm. diameter and 1 100 mm. stroke. Its output is 1 170 B.H.P. at 105 revs. per min. Engines of this type are designed to run on blast-furnace gas, coke-oven gas, a mixture of these gases, or on producer gas. Usual sizes range from 600 to 3 000 B.H.P. for single-crank engines (double these powers for two-crank engines). The engines are equally suitable for driving D.C. or A.C. generators, and it is claimed that the heat consumption does not exceed 10 000 B.Th.U. per B.H.P.-hr. at full load.

[*To face p.* **327.**

used, but coke, sawdust, and other refuse are also employed (§ 178). The oxygen of the air combines with the carbon of the fuel to form carbon monoxide, and the steam together with carbon also forms carbon monoxide and free hydrogen. In addition, certain amounts of marsh gas and carbon dioxide are formed. Some of the heat in the hot gases is used to raise steam, but the remainder is lost in the scrubbing tower; the thermal efficiency of the producer is from 70-85 °/。 (Table 15, § 167). The gases as formed contain various impurities, which would foul the cylinder and valves, so they are cooled and purified in a scrubber, consisting of layers of coke with a water spray, and are then dried by passing through sawdust. The gas scrubber requires from $1\frac{3}{4}$-$2\frac{1}{2}$ gals. of water per B.H.P.-hr., and the gas generator about 0·6-1 pint per B.H.P.-hr. In the generator it is necessary that there should be a large mass of incandescent fuel for the saturated air to pass through; if the demand falls below about half normal the fire dies away.

Producer-gas plants have hardly realised the hopes held out for them; they show to best advantage in steady working and in sizes up to 250 or 400 H.P. The larger sizes generally show heavy repair and attendance costs, though much depends on the skill with which they are operated.

The high thermal efficiency of large gas engines makes them tempting where coke-oven or blast furnace gas is available, but it is found that a load factor of 35 °/。 or over is required before they can compete with steam turbine plant in central station practice, after allowing for capital and working costs. (For fuel consumption data *see* §§ 167, 179.)

182. Humphrey Pump and Turbine Plants.—The Humphrey pump may sometimes be used as the ultimate prime mover for generating electricity; for it bids fair to be the most economical water lift, and the overall efficiency of a turbine and generator under a perfectly constant head is also high. It is sufficient here to say that the pump uses the principle of resonance to keep a large amount of water pulsating backwards and forwards in a large pipe, by means of automatically-timed explosions, a certain proportion of the water being discharged at a higher level at each swing of the pendulum. From the high-level reservoir the water would return to the low level through a reaction turbine driving a generator. The loss of water would be confined to that caused by leakage and evaporation. The pump would be working under the ideal conditions of constant suction and delivery, and already fuel consumption as low as 0·93 lb. of anthracite per pump H.P.-hr. has been obtained under ordinary working conditions. A consumption not exceeding 1·6 lb. of coal per pump H.P.-hr. has been guaranteed, and 1·2 lb. is considered probable.

As a practical example, assume the consumption of coal to be 1·6 lb. per pump H.P.-hr.; further assume the cost to be 13s. 4d. per ton or 0·71d. per lb., which is equal to 1·14d. per pump H.P. hr. Assume the head to be 30 ft. then 1 pump H.P. hr. will be equivalent to 18¼ lbs. of water per sec. or 0·29 cusec (§ 201) raised. With an overall efficiency of turbine and generator of 73 %, the electrical output on allowing the same quantity to fall through the same head in 1 hr. will be 0·73 E.H.P.-hr. or 0·54 kWh. The consumption is therefore 2·9 lbs. per unit, costing 0·21d. These are figures which many central stations would envy.

The proposition would depend entirely on the existence of a natural storage site for water, as otherwise the capital cost of a large enough reservoir would be prohibitive. In this respect the problem somewhat resembles that which the advocates of tidal power (§ 230) put forward. A plant capable of giving an output of only 30 kW continuously would require 1 500 000 cu. ft. of storage (say 400 ft. × 400 ft. × 10 ft.) to give an hour's reserve supply on a 30-ft. head. Probably much less than an hour's supply would serve if the power were only to be used for distant irrigation pumping, which seems a promising field of development in the tropics.

183. Gas and Oil Turbines.—There is no reason to suppose that internal combustion turbines will have the same advantage, in point of higher thermal efficiency compared with reciprocating gas and oil engines, that the steam turbine has compared with reciprocating steam engines. Indeed the thermal efficiency of gas and oil turbines will probably remain slightly lower than that of large gas and oil engines, because the combustion is not actually in the working space in the case of the turbines. The advantages offered by the turbine are the elimination of reciprocating parts and the possibility of developing higher power than can reasonably be produced in reciprocating engines (Table 20, § 179). At the time of writing gas and oil turbines are still in the experimental stage. The general principle employed, in the machines which give most promise of success, is the combustion of gas (or oil) and air mixture in a series of chambers which are arranged to deliver the products of combustion through nozzles to a turbine wheel.

The chief practical difficulty lies in the efficient utilisation of the energy developed by the fuel without overheating the combustion chambers and turbine blades; in this connection the mechanical weakness of steel at high temperatures is an even more serious factor than that of corrosion or burning. The hot gases leaving the turbine may be used to raise steam for a turbo-compressor which supplies air to the combustion chambers of the main turbine.

184. Bibliography (*see* explanatory note, § 58).

STANDARDISATION REPORTS.

(1) I.E.C. PUBLICATIONS.

No. 45. I.E.C. Publication on Steam Turbines, Part 1, Specification.
No. 46. I.E.C. Publication on Steam Turbines, Part 2, Rules for Acceptance Tests.
No. 209. Fuels for Heavy Oil Engines (Petroleum and Shale).
No. 210. Pure Mineral Lubricating Oils, Classification of.
No. 211. Heavy Oil Engines for Electrical Purposes, Diesel Type, Air-injection.
No. 212. Heavy Oil Engines for Electrical Purposes, Surface-ignition Type.
No. 213. Heavy Oil Engines for Electrical Purposes, Airless-injection, Cold-starting Type.
No. 352. Phosphor-Bronze Turbine Blading.
No. 403. Sampling of Small Fuel, up to 3 in., embodying some General Principles of Sampling.
No. 420. Sampling and Analysis of Coal for Inland Purposes.

(2) B.S. SPECIFICATIONS.

No. 42. Reciprocating Steam Engines for Electrical Purposes.
No. 43. Charcoal Iron Lap-welded Boiler Tubes.
No. 53. Cold Drawn Weldless Steel Boiler Tubes for Locomotive Boilers.
No. 132. Steam Turbines.
No. 135. Benzol for Motor Fuel.
No. 209. Fuel Oils for Diesel Engines.
No. 210. Pure Mineral Lubricating Oils.
No. 489. Turbine Oils.
No. 649. Internal Combustion Engines for Stationary and Industrial Purposes and for Auxiliary Purposes on Shipboard.
No. 752. Test Code for Acceptance Tests for Steam Turbines.
No. 765. Internal Combustion Engines, Carburetter Type.

BOOKS.

Natural Sources of Energy, by A. H. Gibson (University Press).
Liquid Fuel and its Apparatus, by W. H. Booth (Constable).
Low Grade and Waste Fuels for Power Generation, by J. B. C. Kershaw (Constable).
Fuel and Lubricating Oils for Diesel Engines, by W. Schenker (Constable).
Steam Power Plant Engineering, by G. F. Gebhardt (Wiley).
Steam Boilers and Boiler Accessories, by W. Inchley (Arnold).
Boiler Inspection and Maintenance, by R. Clayton (Pitman).

Heat Engines, by D. A. Low (Longmans).
Steam Turbine Theory and Practice, by W. J. Kearton (Pitman).
Steam Engine Valves and Valve Gears, by E. L. Ahrons (Pitman).
The Gas, Petrol, and Oil Engine, by Dugald Clark and G. A. Burls (Longmans).
High-power Gas Engines, by H. Dubbel (Constable).
The Diesel Engine, by A. Orton (Pitman).
High Speed Diesel Engines, by A. W. Judge (Chapman & Hall).
Maintenance of High Speed Diesel Engines, by A. W. Judge (Chapman & Hall).
Diesel Engines for Land and Marine Work, by A. P. Chalkley (Constable).
Lubricating and Allied Oils, by E. A. Evans (Chapman & Hall).

I.E.E. Papers.

Economical Production of Power from Coke Oven Gas, G. Dearle. Vol. 54, p. 646.
Gas Firing Boilers, T. M. Hunter. Vol. 56, p. 57.
High Pressure and High Temperature Steam in Large Power Stations, J. H. Shaw. Vol. 57, p. 73.
Effect of Air and Water on Materials used in Engineering Work, H. E. Yerbury. Vol. 57, Supp., p. 118.
Calculations Relating to High Pressure and High Temperature Steam with Interheating for Power Generation, W. M. Selvey. Vol. 58, p. 28.
Notes on Operating a By-product Producer Gas Plant, W. H. Patchell. Vol. 58, p. 417.
Developments in Large Steam Turbines, K. Baumann, Vol. 59, p. 565.
The Drive of Power Station Auxiliaries, L. Breach and H. Midgley. Vol. 61, p. 829.
Pulverised Fuel and Efficient Steam Generation, D. Brownlie. Vol. 62, p. 385.
Economics of Electric Power Production, W. T. Townsend. Vol. 66, p. 909.
Combustion of Coal as applied to Steam Generation, F. H. Rosencrants. Vol. 66, p. 1101.
Anticipation of Demand and the Economic Selection, Provision and Lay-out of Plant, Capt. J. M. Donaldson. Vol. 67, p. 619.
The Modern Use of Pulverised Fuel in Power Stations, R. A. Chattock. Vol. 67, p. 1213.
Low-Temperature Carbonisation of Fuel, S. McEwen. Vol. 68, p. 205.
Low-Temperature Carbonisation of Fuel, E. H. Smythe and E. G. Weeks. Vol. 68, p. 219.
Power Stations and their Equipment, I. V. Robinson. Vol. 69, p. 183.
Modern Boiler Plant, J. Bruce. Vol. 71, p. 541.
Post-War Developments in High-Pressure Boilers, C. H. Davy and C. H. Sparks. Vol. 72, p. 461.

Miscellaneous.

Other sources of information include the Reports of the Fuel Research Board (Dept. of Scientific and Industrial Research); the Proceedings of the Institutions of Civil and Mechanical Engineers; and the technical press (*see also* Bibliography, §§ 199, 258).

CHAPTER 7.

POWER PLANT DEVELOPMENT AND DATA.

185. Private Generation versus Purchase of Energy.—The relative advantages of private generation and purchase of energy, or, in other words, power generation in isolated plants and in central stations, are governed by many considerations. A central station effects savings in point of (i) the reduced capital costs per kW of large, compared with small, generating units; (ii) the reduced fuel costs and the lower attendance and maintenance costs per kWh made possible by the larger prime movers and higher load factor (§ 261); (iii) and the lower percentage of reserve plant required in a central power plant compared with small installations aggregating the same total capacity. These savings must, however, be compared with the capital and working expenses introduced by transmission and distribution equipment and the losses therein.* The purchase of electrical energy from a central station leaves an industrial consumer free to utilise all his available space and capital for the purpose of his own business, relieves him of the responsibility of operating generating plant, and generally secures greater reliability of supply. Other factors being equal, wholesale production of electrical energy in high-power stations operated by specialists in power production enables energy to be sold (at a profit) to the consumer more cheaply than he can produce it himself. The problem is, however, one which must be considered fully for each case on its merits. Though the capital cost per kW is higher for small than for large prime movers and generators (§ 195), the total cost per kW for the complete plant with buildings and site may be as low in an isolated plant as in a central station. By the judicious use of part-time labour, and particularly by the use of low-grade heat (§§ 176, 188) for manufacturing purposes, the labour and fuel

* This aspect of the problem is discussed in 'The Economic Limits of Distribution from Coal-Fired Stations,' by W. B. Woodhouse, Inst. C.E. Engineering Conference, 1921.

costs chargeable to power may be made much lower than in any condensing steam-electric central station (§ 188). Again, the amount of power required by an industrial consumer may equal the total demand of a medium-sized community, in which case private generation amounts to installing a private central station in the immediate neighbourhood of the load. It is extremely difficult for purchased energy to compete with private generation in such cases, particularly if the latter has the advantage of cheap fuel (as at collieries, iron and steel works, etc., *see* § 816, Vol. 3), very high load factor, as in railway workshops and the like, or can utilise exhaust steam for heating or process work (§ 188), in which case the economy of the 'by-product' power far exceeds that of any condensing turbine.

The electricity supply industry in Great Britain suffered greatly by the ill-considered legislation of the 'eighties, and by the time that co-ordination was decided upon the position had become almost hopeless. The constitution first of the Electricity Commissioners and then of the Central Electricity Board as a means (in political jargon) of 'ensuring a cheap and abundant supply' has brought some order out of chaos, at immense cost. Eventually the combined activities of these bodies will no doubt result in great economies, but not until distribution is at least controlled as well as generation and transmission. Much discontent has been occasioned by a state of affairs in which it is possible for widely different rates of charge to be made on two sides of a street served by different distributors. Meanwhile, doubts have been cast on the ability of the public authorities to compete with private plants.*

Developments in heavy oil engines have made it possible for any consumer, with a demand of, say, 50 kW or over and a reasonably good load factor, to compete closely with central station supply under average conditions and, whilst the general arguments in favour of centralisation are sound, there are so many factors involved that every industrial consumer should prepare estimates for himself.† The improvement of central station operation by

* Private Generating Plant *versus* the Grid Supply, R. S. Whaley. *The Electrical Supervisor*, Vol. 13, Nos. 8, 9, 10.

† It is not easy to estimate accurately the cost of private generation owing to the difficulty of attaching a definite value to the factors of responsibility, reliability, etc. A good model for the preparation of estimates, taking into account all tangible factors, is to be found in 'Economy in Power Generation,' by R. G. Williams, *El. Ind. and Inv.*, Aug. 23, 1922.

the recovery of by-products from coal (*i.e.* the joint operation of gas works and electricity stations) and the utilisation of low-grade heat would make it impossible for any but exceptional private plants to compete with central stations. As matters stand, however, any private plant which embodies these principles can offset most, if not all, of the advantages of central stations in other respects (§§ 188, 191).

Many of the advantages of centralisation, and some other advantages as well, are derived from the electrical interconnection of existing generating stations (§ 186), and some of the latter may be stations originally erected as private installations for the supply of a particular works, colliery, etc. It may be noted that one manufacturing company * has standardised a complete range of small power stations in six sizes from 330 kW to 3 750 kW, which will be erected with their entire equipment (other than brickwork) ready for service. Three-phase 50 cycle turbo-generators with standard voltages of 400 V in the smaller, and 3 300 V in the larger, units are employed, with either Lancashire or water-tube boilers; the building, all accessories for boiler and turbine, and the switchboard are included (*see also* § 747, Vol. 3).

186. Interconnection of Generating Stations.—Interconnection between two or more generating stations or transmission systems reduces the amount of reserve plant required in the system as a whole and improves the load factor and efficiency of operation.† It is highly improbable that the load curves of the two stations or systems will be identical, and even a few minutes' difference between the times of incidence of peak loads in the interconnected systems means that a considerable percentage of the generating plant in each system is available to help in supplying the peak load of the other. The difference between the thermal efficiencies of generating sets in large interconnected stations and those of the larger sets which could be used in a single central station supplying the same district is not great, and it is offset by the fact that the interconnected stations are at load centres and only a balance of power has to be transmitted through

* Metropolitan-Vickers, *Elec. Rev.*, Vol. 105, p. 334.

† At the time of writing (1938) the percentage of reserve generating capacity in public supply stations in Great Britain has been reduced to about 25 % by the 'Grid' rendering spare generating capacity available wherever it is required. The advances in thermal efficiency since the inauguration of the 'Grid' are noted in § 191.

the 'tie lines' or 'Grid' (§ 320) instead of the whole demand having to be transmitted from a central station. The effective capacity of two or more generating stations is often increased 25 °/₀ by interconnection, owing to the improvement of the diversity factor.

Interconnection between generating stations is now utilised on a most extensive scale, and generally the cost of inter-connection is very small compared with the value of the benefits derived. In America, interconnected transmission lines, fed from many generating stations, extend for hundreds of miles. Voltage differences form no obstacle to the interconnection of A.C. systems because the connection can be made through static transformers (§ 391, *et seq.*, Vol. 2); frequency difference is a more serious factor owing to the fact that it involves the use of frequency changers (§ 390, Vol. 2) which are rotating machines; they suffer from 'swinging' or 'hunting' difficulties because a certain mechanical displacement of the rotor corresponds to a higher electrical displacement on the high frequency than on the low frequency side of the machine. The Thury constant current system has advantages where the interconnection of different stations is concerned (§ 317).

The greater the difference between the load curves of two stations, the greater the benefits to be derived from interconnection; this will be understood from Chapter 11. Interconnection is equally valuable where the time curves of available power differ, as in hydro-electric and wind power installations; indeed, many small water-power schemes, which would be commercially worthless if developed independently, can profitably be tied together and to an existing network (§ 187). Similarly, interconnection between two or more stations at different levels on one stream enables the electrical load to be distributed so that additional water flow through the up-stream station can be used effectively, and without storage, at the down-stream station.

As explained in § 185, many private industrial power plants are able to operate at higher overall efficiency than central stations. By connecting them electrically the average thermal efficiency is improved, the hitherto independent consumer gains the advantage of increased security of supply, and the central station has additional generator capacity during some hours of the day and night. To take only one example, the industrial plant could supply some or all of the power required to carry its employees to and from work, this traction demand naturally preceding and following the internal demand of the works itself.

A very practical and advantageous form of interconnection between private and public generating plants is effected by the industrial consumer contracting to supply his own peak requirements above a specified kW-demand, and purchasing his base-load requirements, below this kW-demand, at a favourable price per kWh.

187. Automatic Generating Stations.—In the automatic petrol-electric generating set (§ 180), the engine starts automatically directly the demand exceeds the capabilities of the small storage battery employed at other times. The same or the converse principle is applied to the utilisation of small water-power developments, particularly on low falls with irregular flow (§ 217). A suitable turbine is coupled to an induction generator (§ 144), and the latter is switched automatically in parallel with an existing transmission system whenever the load on the system demands additional generator capacity or whenever there is sufficient water-power available to justify operation of the set, as the case may be. Wind-power (§ 165) may be utilised in the same way. Attendance costs are practically eliminated by the automatic gear * and, in the case of low falls, the dams erected for automatic generating stations may be useful in flood prevention and irrigation.

188. Utilisation of Waste Heat.—Notwithstanding such advances as the use of regenerative furnaces in the iron and steel industries and of continuous kilns in ceramic manufactures, it is probable that 80 or 90 °/$_0$ of the heat value of all coal burnt is wasted. For the reasons explained in § 166, the heat engine cycle is inherently and inevitably wasteful. The fact that the absolute zero of temperature is far below atmospheric temperature places a low and definite limit upon the maximum efficiency of even a 'perfect engine.' Hitherto, effort has been concentrated mainly upon raising the efficiency of actual engines as near as possible to the theoretical value, and in this work a great measure of success has been attained (§ 167). An increasing amount of attention is now being given, however, to the utilisation of 'low grade' heat in the exhaust steam or gases from

* For discussions as to the possibilities of automatic generating stations and descriptions of successful installations *see Gen. El. Rev.*, Vol. 22, pp. 846, 960, 963.

engines, and in this field there are possibilities of far greater savings than could, by any means, be effected in the prime movers themselves.

For example, suppose that 1 000 000 kWh are generated in a certain time by ten 100 kW steam engine driven sets operating at 8 °/₀ thermal efficiency. The heat consumption of these sets would be $3\,412 \times 10^6 / 0{\cdot}08 = 4{\cdot}26 \times 10^{10}$ B.Th.U. If the same quantity of energy were developed by a 20 000 kW turbo-set operating at 28 °/₀ thermal efficiency the heat consumption would be $3\,412 \times 10^6 / 0{\cdot}28 = 1{\cdot}22 \times 10^{10}$ B.Th.U., the generator losses being neglected in both cases. Thus, by going from about the lowest to about the highest thermal efficiency in the steam prime mover there is effected a saving of $(4{\cdot}26 - 1{\cdot}22)\,10^{10} = 3{\cdot}04 \times 10^{10}$ B.Th.U. If now the 100 kW steam engine sets be arranged so that the heat in the exhaust steam is utilised in hot water supply and for heating rooms, etc., the overall thermal efficiency of these sets may be raised to 60 °/₀ by the utilisation of (60 − 8) °/₀ of $4{\cdot}26 \times 10^{10}$ B.Th.U. ($= 2{\cdot}21 \times 10^{10}$ B.Th.U.) in the form of low-temperature heat. This saving amounts to $2{\cdot}21 / 3{\cdot}04 = 72{\cdot}5$ °/₀ of the saving which could be effected by the use of the 20 000 kW set. A corresponding saving could, of course, be effected in the 20 000 kW set by similar utilisation of low-temperature heat.

As thus considered, the example shows how small engines *with* utilisation of low-temperature heat may approach or surpass the efficiency of modern super-stations *without* low-temperature heat recovery. The super-station still shows a considerable saving in heat consumption for given electrical output, but the small sets are also carrying a large heating load and giving high overall efficiency under conditions to which a large turbo-set might be inapplicable, *e.g.* it by no means follows that ten 100 kW installations could be served from a 20 000 kW set.

The distinction between the two cases is shown clearly by considering the output from equal coal consumption instead of the heat consumption for equal electrical output. From 100 tons of coal the small engines would yield the equivalent of 8 tons as electrical energy and of 52 tons as low-temperature heat, whereas the turbo set would yield the equivalent of 28 tons as electrical energy (neglecting generator losses as before). The net waste would be 40 tons of coal in the first case and 72 tons in the second, but the turbo-set would yield $28 / 8 = 3\frac{1}{2}$ times as much electrical energy as the engine sets, and the advantage of the latter, under the conditions considered, would depend upon there being use for the equivalent of 52 tons of coal in the form of low-grade heat. It must again be emphasised that the relative inferiority of the turbine in the case considered is due to its being operated *without* utilisation of low-grade heat.

The general possibilities and difficulties of utilising waste heat will be seen from the preceding example. In every heat engine installation there is more than 50 °/₀ (generally more than 75 °/₀) of the total heat consumption which can be utilised *if there is a sufficient demand for low-temperature heat.* Given this demand it is generally a very profitable proposition to meet it by using rejected engine heat. In America, many central stations distribute hot water or low-pressure steam for 'district heating,' but in this country the milder climate, the more scattered communities, and the national preference for a glowing fire militate against the commercial prospects of such a scheme. Nevertheless, the cost of pipe lines is not prohibitive, the losses in distribution are low (in some American installations the consumers receive 83 % of the steam leaving the station), and the possible saving in fuel is so great that experimental installations in densely populated areas are certain to be made and are likely to be successful. The supply of exhaust steam to adjoining establishments for industrial purposes is already practised in this country.* If high-pressure steam is required for such purposes it can be obtained by raising the back pressure of the engine or turbine (§ 176); in other words, the prime mover is used as an energy-yielding pressure-reducing device,† and the electrical energy is a by-product reduced in amount, compared with the output obtainable by full expansion, but obtained in conjunction with high overall thermal efficiency. Waste heat boilers are now commonly fitted to the exhaust of large gas engines (§ 181). The most difficult class of waste heat to utilise is the low-temperature heat in the circulating water of turbine condensers; so long as the present practice is followed of developing as much power as possible in the turbine, by continuing the expansion to the highest attainable vacuum, the rejected heat is bound to be at very low temperature (about 95° F., 35° C.), and the most promising application ‡ yet suggested for this heat is in warming greenhouses and in heating the soil of market gardens for forced crops.

In an interesting article on the subject of the cost of by-product power § it is pointed out that a rule-of-thumb allowance of half a pound of coal or 5 lbs. of steam per kWh will in almost every case give results that are accurate enough for most practical purposes.

Whenever there is a demand for steam for heating purposes or manufacturing processes it is probable that private generation of power by back pressure or extraction turbines will be more

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* Information concerning British and American installations for the utilisation of exhaust heat is to be found in papers and a joint discussion, *Jour. I.E.E.*, Vol. 60, pp. 265-86.

† Small turbo-generators up to 100 kW output are thus used instead of throttle valves in sugar refineries.

‡ The possibilities of this scheme are discussed by H. M. Sayers, *El. Rev.*, Vol. 90, p. 115.

§ *Power*, Vol. 76, p. 244.

economical than purchased electricity supply. Many examples of such 'power-and-process' installations have been described in the technical press during recent years.

§ 189. Choice of Type and Power of Prime Movers.—This problem is one of many parts, all of which are correlated to such an extent that a final solution in any particular case can only be obtained by comparing several alternative equipments. Having determined the probable maximum demand (M.D.) in kilowatts (Chapter 11), the question of probable extensions must be considered. If the installation is a large one extensions may be met by installing additional generator sets, but in the case of a small plant the full capacity should be laid down at the start, the probable kilowatts M.D. of the extensions being added to that already determined. If a secondary battery, capable of keeping the installation at work for a whole day, is included in the scheme, a single generating set may be sufficient in small installations; but it is very seldom advisable to attempt running without spare plant. In out-of-the-way places, a serious break-down may mean a delay of weeks in effecting repairs or obtaining spare parts. Two identical generating sets, each capable of running the whole of a small installation, are generally advisable. If the plant is of moderate size, three identical sets are recommended: one to work at times of light load beyond the capacity of the battery, two to work together at times of heavy load, and the third as spare; in yet larger plants, at least two reserve sets are required so that there may always be one set ready for immediate service whilst the other is undergoing overhaul or repair. If a battery is not installed, and the plant is large enough to warrant it, a small petrol or oil-driven generator is useful for the light-load hours, as it will work at higher efficiency than a larger set only lightly loaded. Generally speaking, for very small installations, an oil engine set and battery is the best equipment, or alternatively a suction-gas plant with gas engine and battery. For larger installations the relative prices of oil and coal must determine whether a Diesel oil engine or a steam engine is the best prime mover. With the exception of large industrial establishments, isolated installations are seldom large enough to warrant the use of steam turbines, and the use of water power is necessarily restricted by natural conditions, apart from the high cost of its development.

Allowance must be made for the relative cost of the fuel employed when comparing prime movers of different thermal efficiencies (Table 15, § 167); for example, an engine using 25 % of the heat value of oil at £4 per ton will cost as much, for fuel, as a steam engine utilising $12\frac{1}{2}$ % of the heat from coal at £2 per ton. In addition, the capital and maintenance charges per kWh must be considered; saving in capital cost is important where the load factor is low, and in running costs where the load factor is high (§§ 263, 264). Where large scale operation is under consideration, the gains in economy due to higher steam pressures (§ 191), regenerative feed heating, resuperheating and extracting the heat from the flue gases by economisers or air preheaters, all come into the problem and interact on one another; and it is easy to overlook the fact that most of these accessories give improved results in one component at the expense of those in another. The problem of co-ordinating to get the best overall results is a very complicated one. To take one important point, a new plant may be designed as a high load factor base-load station, with every possible aid to economy; but 'the base-load units of to-day become the stand-by (or peak-load) units of to-morrow, with low load factors, and it is possible that the carrying charges on the equipment during this period may overbalance the gain during the earlier life'.* In the article referred to, valuable curves are given relating to heat rates with a great variety of refinements in the plant, the fruit of work at the Research Bureau of the Brooklyn Edison Co. As a general guide it may be taken that suction gas or oil engines are cheapest for outputs up to 100 kW; for higher outputs up to 400 kW or so, the 'locomobile' steam boiler and engine can hardly be beaten for convenience and economy, though it has keen competitors in the Diesel and semi-Diesel engines. Similarly, for outputs from 500 to 1 500 kW the uniflow and Lentz engines are rivalled closely by Diesel and semi-Diesel engines; with cheap oil the Diesel and semi-Diesel engines would be at a considerable advantage.

Comparing steam engines and steam turbines, up to about 1 000 kW there is no advantage in using steam turbines, either in prime cost or efficiency. Table 21 gives the approximate steam consumption (lbs. per kWh) and cost F.O.B. in British port of

* *Power*, Vol. 71, p. 173.

modern combined sets (prime mover and generator) of both types in three sizes, including condensers and exciters, assuming superheated steam at 175 lbs. pressure and working with a vacuum of 27 ins. (*see also* Table 27, § 195).

TABLE 21.—*Cost of Combined Sets (Steam).* (*See also* Table 27, § 195).

Size.	400 kW.		500 kW.		1 000 kW.	
	Turbine.	Engine.	Turbine.	Engine.	Turbine.	Engine.
Total cost (pre-war) *	£3 120	£2 640	£3 300	£3 200	£4 800	£6 000
Cost per kW (pre-war)*	£7·80	£6·60	£6·60	£6·40	£4·80	£6·00
Steam consumption (lbs. per kWh)—						
Full load . .	19·1	17·2	16·3	16·6	15·3	16·0
¾-load . . .	20·7	17·6	17·5	17·0	16·1	16·3
½-load . . .	22·9	19·0	19·1	18·5	17·9	17·7

For outputs exceeding 1 000 to 1 500 kW the steam turbine is generally the most economical prime mover, but large gas engines can be used to advantage where coke-oven or other cheap gas is available, especially if the annual load factor (§ 261) be high, say, 50 °/₀ or over.

The economic advantage of coking coal amenable to this process, and recovering the by-products of the distillation, has already been pointed out (§ 169). Surplus gas from coke ovens may be utilised in gas engines, or it may be burnt under steam boilers (preferably of the Bonecourt type, § 170). The former course may appear more direct and efficient, but steam turbines can be built in much larger units than gas engines (§ 179); also, they occupy much less space and can be used with alternators of higher speed and therefore more economical construction. It is often overlooked that large modern steam boiler and turbine plant yields an overall thermal efficiency comparing favourably with that of gas engines on full load (Table 15, § 167), whilst on low-load factors advantage certainly rests with the steam plant. In the Powell Duffryn collieries (Sparks, *Jour. I.E.E.*, Vol. 53 pp. 389 *et seq.*), certain 1 500 kW coke-oven gas engine and alternator sets averaged 12·8 B.Th.U. per Wh on full load (corresponding to 26½ °/₀ thermal efficiency), as compared with 20·3 B.Th.U. per Wh (16·8 °/₀ thermal efficiency) in the case of a modern 5 000 kW turbo-alternator; in this particular case it was possible to so distribute the total load that the gas plant operated under 72 °/₀ annual load factor.

The fine reciprocating engines of 3 000-5 000 kW capacity set to work in the early years of this century were speedily rendered obsolete by the lower steam consumption of the steam turbine, and the latter is at present unchallenged as the prime mover in the

* Pre-war and post-war costs are compared in Table 27.

largest fuel-burning stations, where units exceeding 5 000 kW are required. The present (1944) tendency in Great Britain is to install generators of 30 000 kW capacity for general service on the 'Grid'. Many of the larger stations include units of 50 000 kW capacity, and units of 60 000-100 000 kW capacity are used in a few stations.* Taking all factors into consideration, it is probably more convenient and about as economical to restrict the capacity per unit to 50 000 kW.

Formerly, it was necessary to keep at least two large sets in reserve in a power station, to allow for one being dismantled. Here again, the 'Grid' has rendered valuable service by reducing the proportion of spare generating capacity necessary for security in individual stations. The total capacity of generating plant in public supply stations in Great Britain in 1938 was about 50 % higher than the total net maximum load; and the total load connected was about 2·6 times the total generating capacity. Without inter-connection the load connected could hardly exceed 1·5-2·0 times the generating capacity.

190. Selection of Units for Service.—In any existing power house there is opportunity for effecting a saving by judicious selection of the plant put in service to supply any particular load. The total capacity of the working sets must exceed the actual load by a reasonable margin (depending on the probable load within the next ½ hr. or 1 hr., which can be predicted with sufficient accuracy from the known form of the daily load curve). There are generally available several combinations of sets which would provide the desired total capacity and, where possible, that combination should be used which consumes least steam. The 'Willans' line' should be plotted for each generating set showing the steam consumption per hr. (including the consumption in auxiliaries) as a function of the output in kW. Thence a table or a chart can be prepared to show at once the most economical combination of sets for any particular load. On a falling part of the load curve the sets in service may be overloaded temporarily, but if a peak load is approaching allowance must be made for this when deciding upon the sets to be placed in commission.

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* A useful analysis of the size, steam conditions, etc., of new plant units in central stations in Great Britain is given in *The Electrical Times*, February 3rd, 1938, p. 153.

In large modern stations, and particularly in those interconnected with other systems (§ 186), a 'load despatcher' is given full information concerning the service characteristics of all machines and stations, and being in telephonic communication with all parts of the system, he is made responsible for the putting of plant in and out of service and for all main switching operations.

191. Power House Losses; Overall Efficiency.—The overall efficiency of electricity stations is commonly expressed in terms of the fuel consumed per kWh generated.* Statistics prepared on this basis by the Electricity Commissioners are summarised in Table 22 for the year 1931 and in Table 22*a* for the year 1936. The reason for giving both these sets of figures is explained in § 194 under the heading *Comparative Analyses of Costs.* The average coal consumption per kWh generated in steam stations was 3·11 lbs. in 1921-22 (396 stations), 1·82 lbs. in 1931 (300 stations) and 1·57 lbs. in 1936 (258 stations).

As, however, the calorific value of the coal burnt varies widely (say from 10 000 to 13 000 B.Th.U. / lb.), such data are of limited value, and it is much better to state the efficiency in terms of the heat consumption per kWh generated. The heat equivalent of 1 kWh is 3 412 B.Th.U., hence a consumption of 1·57 lbs. of coal (of calorific value 10 500 B.Th.U. / lb.) per kWh corresponds to a heat consumption of 1·57 × 10 500 = 16 485 B.Th.U. / kWh, and an overall thermal efficiency of 3 412 × 100 / 1·57 × 10 500 = 20·7 °/₀ approx. as against 17·9 °/₀ in 1931 and 10½ °/₀ in 1922, when our fourth edition was in preparation. About 15 500 B.Th.U./kWh is consumed in average large modern stations with steam turbo-alternators operating at, say, 50 °/₀ load factor, and 12 500-13 000 B.Th.U. / kWh (*i.e.* 27·3-26·2 °/₀ thermal efficiency) is about the best result which can be obtained in such stations. Assuming that 20 °/₀ of the heat value of the coal is delivered to the bus bars as electrical energy, the distribution of the 80 °/₀ lost is roughly as follows (in percentage of heat input at the grate †): Boiler losses, 20 °/₀; rejected in condenser, 52 °/₀;

* An instructive survey of progress in the efficiency of electricity generation is given in *Electrical Industries*, March, 1938, p. 111.

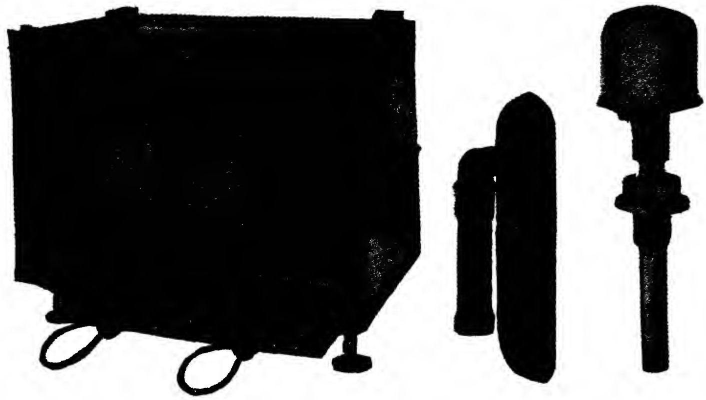
† These percentages must not be confused with the percentages of loss in terms of the input to the individual parts of the system; for instance, the mechanical loss in the turbine = 5 °/₀ of the coal value, but 5 × 100 / (100 − 20 − 52) = 17·9 °/₀ of the input to the turbine after deducting the boiler and condenser losses (*see also* § 193).

Belliss & Morcom, Ltd.

RECIPROCATING STEAM ENGINES IN CONJUNCTION WITH MIXED PRESSURE TURBINES.

The installation shown comprises two 400 kW Belliss compound engines, each exhausting to a 350 kW mixed pressure turbine and condensing plant made by the same firm. The overall efficiency of reciprocating engines exhausting, at atmospheric pressure, to condensing turbines is high, and the combination is flexible in operation. Normally the engine and mixed pressure turbine are run in conjunction, but the engine can be run independently—exhausting to atmosphere or straight to the condenser. The turbine can also be used independently, and it can utilise any low-pressure steam which may be available, *e.g.* the exhaust from steam hammers. By adding mixed pressure turbines to an existing installation of reciprocating engines, the output and efficiency of the plant can be increased.

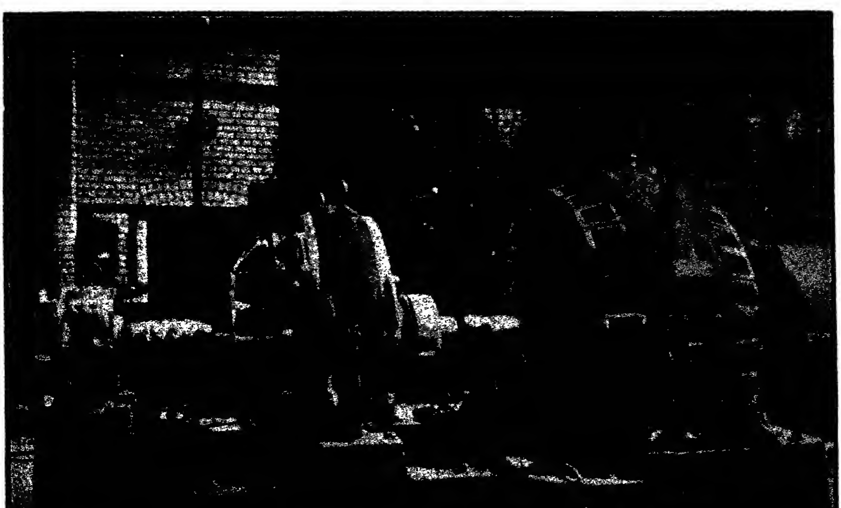
[*To face p.* 342.



Cambridge & Paul Instr. Co., Ltd.

ELECTRICAL RECORDER AND RESISTANCE THERMOMETERS.

This recorder makes four records simultaneously, *e.g.* CO_2 percentage, and feed water, flue gas, and steam temperatures. The pointers of two galvanometers register their positions at, say, 1 min. intervals by being depressed automatically on to inked threads of distinctive colours. The percentage of CO_2 is measured by a bridge circuit depending on the different rates of cooling of similar hot wires in air and in the flue gas respectively. The resistance thermometers are protected in various ways to suit service conditions; that in the centre is for measuring air temperatures indoors, and the other is for positions under pressure, such as steam or bearing temperatures.



Mather & Platt, Ltd.

DOUBLE CURRENT (A.C. AND D.C.) GENERATING SET.

It is necessary in many districts to supply A.C. to some consumers and D.C. to others. In such cases, the steam consumption can often be reduced by using a single turbine to drive both types of generator. The illustration shows a steam turbine driving a 750 kW, 833 kVA, 2 200 V, 100-cycle, single-phase alternator, and a 500 kW, 550 V, D.C. generator. The small machine at the end of the shaft is an 'overhung' exciter.

[*To face p.* 343.

TABLE 22.—*Fuel Consumption of Generating Stations in Great Britain in* 1931.

Number of kWh Generated at Station per annum.	STEAM STATIONS.				GAS PRODUCER STATIONS.				OIL ENGINE STATIONS.			
	No. of Stations.	Fuel Consumption / kWh Generated.		Highest Thermal Efficiency. (Approx.)	No. of Stations.	Fuel Consumption / kWh Generated.		Highest Thermal Efficiency (Approx.).	No. of Stations.	Fuel Consumption / kWh Generated.		Highest Thermal Efficiency (Approx.).
		Average.	Lowest.			Average.	Lowest.			Average.	Lowest.	
Million kWh		lbs.	lbs.	%		lbs.	lbs.	%		lbs.	lbs.	%
Over 200 . .	13	1·57	1·24	24·02	—	—	—	—	—	—	—	—
Between 100 and 200	19	1·60	1·20	23·85	—	—	—	—	—	—	—	—
,, 50 ,, 100	38	1·92	1·44	21·95	—	—	—	—	—	—	—	—
,, 25 ,, 50	54	1·95	1·45	20·73	—	—	—	—	—	—	—	—
,, 10 ,, 25	50	2·41	1·67	17·75	—	—	—	—	—	—	—	—
,, 5 ,, 10	28	2·84	1·92	15·62	—	—	—	—	1	0·63	—	28·03
,, 2·5 ,, 5	26	3·14	1·93	15·35	1	2·06	—	11·84	8	0·81	0·66	28·65
,, 1·0 ,, 2·5	29	4·33	2·88	14·36	2	0·87	—	15·92	19	0·85	0·58	31·80
,, 0·5 ,, 1·0	10	6·30	3·07	9·00	4	2·21	1·69	13·90	21	0·90	0·63	28·24
,, 0·25 ,, 0·5	11	6·75	3·67	8·86	4	2·69	2·02	12·97	23	1·13	0·66	26·17
,, 0·10 ,, 0·25	10	8·65	3·14	10·09	5	2·37	1·73	13·52	35	0·96	0·62	28·36
,, 0·05 ,, 0·10	3	9·77	—	—	8	2·90	1·45	18·10	27	1·08	0·72	26·18
Under 0·05 . .	9	10·52	6·07	5·10	7	3·13	2·47	9·34	28	1·17	0·65	27·94
TOTALS . . .	300	1·82	—	—	31	1·94	—	—	162	0·87	—	—

NOTE.—Where the calorific value of the fuel is not specified on returns, the following average values (B.Th.U. / lb. throughout) may be used for calculating the thermal efficiency: Coal (for steam stations), 10 500; anthracite (for gas producer stations), 13 000; coke (for steam and gas producer stations), 6 000; oil (for steam and oil engine stations), 18 000. Composite stations, containing more than one type of prime mover, are classified according to the type responsible for the major part of the output. In such cases, and wherever more than one class of fuel was used, the actual fuel consumption in each case has been converted into an equivalent tonnage of the class of fuel mainly responsible for the output.

TABLE 22*a*.—*Fuel Consumption of Generating Stations in Great Britain in* 1936.

(*See* general note below Table 22).

Number of kWh Generated at Station per annum.	Steam Stations. No. of Stations.	Steam Stations. Million kWh Sent Out (Approx.).	Steam Stations. Fuel Consumption / kWh Sent Out. Average.	Steam Stations. Fuel Consumption / kWh Sent Out. Lowest.	Steam Stations. Highest Thermal Efficiency (Approx.).	Oil Engine Stations.* No. of Stations.	Oil Engine Stations.* Million kWh Sent Out (Approx.).	Oil Engine Stations.* Average Fuel Consumption / kWh Sent Out.	Gas Engine Stations. No. of Stations.	Gas Engine Stations. Million kWh Sent Out (Approx.).	Gas Engine Stations. Average Fuel Consumption / kWh Sent Out.
Million kWh			lb.	lb.	%			lb. (oil)			lb. (coal)
Over 200 . .	34	12 927	1·41	0·97	27·6	—	—	—	—	—	—
Between 100 and 200	21	2 868	1·66	1·48	21·0	—	—	—	—	—	—
„ 50 „ 100	32	2 189	1·80	1·33	19·7	—	—	—	—	—	—
„ 25 „ 50	21	719	1·93	1·49	18·2	—	—	—	—	—	—
„ 10 „ 25	42	650	2·46	1·84	16·5	—	—	—	—	—	—
„ 5 „ 10	20	143	2·68	2·12	14·0	1	4·9	0·71	—	—	—
„ 2·5 „ 5	23	80	3·05	1·88	14·5	1	3·0	0·62	1	2·6	2·19
„ 1·0 „ 2·5	24	38	4·39	2·81	11·3	20	31·1	0·70	—	—	—
„ 0·5 „ 1·0	17	10	6·45	4·12	7·5	16	10·2	0·85	—	—	—
„ 0·25 „ 0·5	7	2	5·29	—	—	20	7·7	0·80	1	0·3	2·16
„ 0·10 „ 0·25	11	1·2	—	—	—	15	2·1	1·20	2	0·4	3·31
„ 0·05 „ 0·10	2	0·07	—	—	—	5	0·4	0·95	1	0·07	—
Under 0·05 . .	4	0·07	—	—	—	37	0·6	1·04	—	—	—
TOTALS . . .	258	19 627·0	1·57	—	—	115	60·0	0·76	5	3·3	2·32

* NOTE.—Average fuel consumption and thermal efficiency data are not available for all oil-engine stations, these particulars not being returned where the hours of generation are below 2 400 hr. / annum (the equivalent of single-shift operation). In oil-engine stations for which the thermal efficiency is published it is often higher than 25 % and in one station, with maximum load 701 kW, sending out 898 171 kWh during the year (1936), the thermal efficiency is given as 31·3 %.

mechanical losses in turbine, 5 %; alternator and transformer osses, 1 %; losses in auxiliary services, 2 % (*see also* Table 24, § 193).

Writing in 1922, Mr. W. M. Selvey (*El. Rev.*, Vol. 91, p. 727) suggested that the maximum efficiencies which could be expected in new plants were as in Table 23. These figures were higher than the efficiencies then realised, but, whereas the performance indicated for the smaller stations may still be regarded as about the best attainable, the heat consumption per kWh sent out is already below 12 500 B.Th.U. in the most economical steam stations. Additional generating capacity obtained by installing

TABLE 23.—*Approximate Limits of Efficiency in Steam-Driven Generating Stations.*

	New Stations with Generating Sets of (Each)		Largest Stations with High Pressure Steam and Inter-heating.
	3 000 kW.	6 000 kW.	
(*a*) Boiler efficiency	0·78	0·81	0·85
(*b*) Thermo-dynamic efficiency of turbine cycle	0·34	0·36	0·40
(*c*) Mechanical efficiency of turbo-generator	0·70	0·73	0·85
(*d*) Ratio of kWh at bus bars to kWh generated *	0·75	0·80	0·85
Overall efficiency ($= a \times b \times c \times d$)	0·139	0·170	0·245
B.Th.U. / kWh at bus bars	24 550	20 050	13 930

extra-high pressure 'superimposed' or 'topping' plants (*e.g.* 1/200 lb. boiler and turbine exhausting at 200-250 lbs. per sq. in. to existing condensing sets) enables the *additional* output to be obtained at a heat expenditure of about 4 000-4 500 B.Th.U. / kWh. The average heat rate of a central station which has hitherto operated at 200-250 lbs. per sq. in., condensing, may be reduced from 22 000-24 000 B.Th.U. / kWh to 12 000 B.Th.U. / kWh by the addition of a 1/200 lb., 900° F. superimposed unit.

From Chapters 6 and 11 it will be clear that load factor is of the utmost importance in determining the overall efficiency of power plants (*see also* § 217). In general, gas and oil engine plants are affected more adversely than steam plants by low load

* Allowing for consumption in station auxiliaries and for operation and machine load factor losses.

factor because the efficiency of internal combustion engines falls off more rapidly at fractional loads, but this can be compensated for to some extent by the installation of a suitable range of sizes; advantage is then derived from the fact that internal combustion engines have no stand-by losses.

When comparing the consumption of (say) 13 500 B.Th.U. / kWh in a large modern station with the 22 500 B.Th.U. / kWh attainable in a small isolated plant it must be remembered that the distribution of energy from the large station involves at least two pressure transformations (possibly four) and also the losses in the transmission line. Allowing for three transformations (each at 98 °/₀ efficiency) and for 10 °/₀ loss in transmission, the overall efficiency from station to consumer is $0{\cdot}98 \times 0{\cdot}98 \times 0{\cdot}98 \times 0{\cdot}9 = 0{\cdot}846$, and the 13 500 B.Th.U. / kWh generated becomes 13 500 / 0·846 = 15 900 B.Th.U. / kWh delivered. Clearly, this leaves a substantial margin in favour of centralisation, but, as explained in § 188, yet higher overall economy can be secured in private plants where power and heating or process steam-requirements permit of joint operation. Peak load requirements in a public supply system may be supplied more economically by special plant at or near local load centres than by transmission from distant stations. From the standpoint of national security in time of war, there is much to be said for a plentiful supply of relatively small generating plants.

(ii) *Recent Advances in Power Plant Design.*—The trend of practice in America—and necessarily in most other countries—was reviewed by the American Committee of the International Electrical Congress held in Paris in 1932; * and the subject (covering various countries) is also dealt with in the several articles referred to in the

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* A. G. Christie, *Power*, Vol. 76, p. 636. The following references may also be found useful:—

- 'Present Tendencies of Steam Station Design,' V. E. Alden. *Power*, Vol. 65, p. 552.
- 'The General Trend of Modern Development in Steam Turbine Practice,' H. L. Lewis. *Power*, Aug. 7, 1928.
- 'Tendencies in Steam Turbine Design,' H. L. Guy. *Engineering*, Feb. 1 and 8, 1929, pp. 148, 183.
- 'The General Trend of Steam Turbine Development by the General Electric Co,' E. L. Robinson. *G. E. Review*, Vol. 32, p. 638.
- 'Central Station Plant and Performance,' A. G. Christie. *Mechanical Engineering*, Vol. 55, p. 635.

footnote, some of which have been drawn upon. It is in the direction of larger units with higher pressures and temperatures up to 1 200 lb. / sq. in. and 1 000° F. These higher pressures and temperatures, coupled with high-temperature feed, have in recent years reduced the heat consumption by about 2 300 B.Th.U. per kWh; improvements in boiler efficiency have made a further economy of some 2 650 B.Th.U. per kWh; while improvements in turbines have been equivalent to a further 4 760 B.Th.U. per kWh. Thus the total heat consumption in a short period has been reduced from some 26 000 B.Th.U. per kWh in the largest power stations of yesterday down to 16 000 B.Th.U., or lower, with the most modern plant using steam at 450 lbs. per sq. in. and 750° F. with feed at 300° F. The possibility of further advance appears to depend upon the use of even higher steam pressure and of mercury vapour plant * (§ 166). In America, between 1919 and 1931, the average coal consumption per kWh dropped from 3·2 to 1·56 lbs.

A boiler at the East River station in New York city has 60 700 sq. ft. of water heating surface and can generate 1¼ million lbs. of steam per hour. Combinations of convection and radiant superheaters and radiant surfaces are found to give almost constant steam temperatures at all boiler loads. Modern underfeed stokers have enabled as much as 73 lbs. of fuel to be burnt per sq. ft. per hr.; and as many as 80 000 B.Th.U. per hr. have been liberated per cu. ft. of furnace volume; with chain-grate stokers the figure is said to be about half this. Diphenyl oxide (referred to in another connection in § 166) is being circulated through economisers in one of the latest stations, and serves to preheat the air entering the furnace; it is further proposed to use it both to superheat the high-pressure steam and to reheat it between cylinders. Reheating steam by transfer of heat from high temperature steam is being investigated, but it seems doubtful if the gain will compensate for the complications so long as turbines can be built to cope directly with the high pressure. A thermal gain of about 3 °/₀ and a reduction in the wetness of the exhaust are claimed.†

(iii) Welded boiler drums are a development of which more may be heard in the new conditions created by extreme pressures; on the other hand, single-flow and similar boilers, without drums,

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* H. Schult, *Zeits. Ver. deutsch. Ing.*, Vol. 77, p. 781.
† Guy, *loc. cit.*

offer another solution to the problem. Boiler water conditioning has received much attention, for the avoidance of foaming and priming, which cause impurities to be carried over to the turbine; these scale deposits, when soluble, can be removed by washing with wet steam, and this is a matter of growing importance. Boilers using coal with low-fusing ash are now provided with furnaces having vertical coal firing, and with water-cooled refractory-lined bottoms from which the ash is tapped off as liquid slag. Many forms of dust catchers, precipitators (§ 996) and gas washers to remove both ash and undesirable gases are being tried out for cleaning chimney discharges.

In the United States, the use of the hydrogen-cooled (§ 80*a*) synchronous condenser represents an advance in the matter of voltage control on transmission lines. By housing the apparatus in a steel drum, a simple hydrogen-tight and waterproof construction is attained, so that it can be used in the open. The great reduction is windage losses and the more ready transfer of heat conduce to economy; the lower density of hydrogen reduces windage losses by over 90 °/₀, while its better heat conductivity, 7¼ times that of air, permits 30 °/₀ more heat to be removed by forced convection. This atmosphere also prevents oxidation of insulation, so that it retains its flexibility indefinitely. Damage due to corona discharge is reduced, and concentrations of electrical stress are avoided.* Thus in a 15 000 kVA, 60-cycle, 11 500 V, 900 r.p.m. unit the temperature rise of the stator winding was 29° C. against 51° C. with air; the rotor winding rise 62° C. against 84° C.; and the full-load losses were 225 kW against 284 kW.† The cost of asynchronous condensers, taking into account the capitalised value of the losses, is 60 °/₀ greater than that of the synchronised type.

192. Control of Power House Efficiency.—The complete determination of power house efficiency involves the installation of measuring instruments on every piece of the equipment, the taking of readings at frequent, regular intervals, and the calculation of results therefrom. The trouble and expense of obtaining these results is justifiable in large stations, provided that the information derived is applied to the improvement and maintenance of efficiency. In smaller stations a less elaborate procedure is required, but some definite record and comparison of

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* *G.E.C. Rev.*, Vol. 32, p. 582. † *G.E.C. Rev.*, Vol. 35, p. 430.

fuel consumption, water consumption, and electrical output should always be maintained, in addition to suitably tabulated records of expenditure on oil, general stores, repairs, etc. Probably the simplest and best method of controlling the overall efficiency of a steam-driven station is as follows: * The weights of coal burnt and of water evaporated per shift are plotted (on separate sheets) against the kWh generated. After doing this for a fortnight or so it will be found that straight lines can be drawn showing what is an average consumption of coal and water for any output (kWh) per shift. The lines, known as 'Parsons Lines,' will cut the axis of coal or water above the zero point and will there show the minimum consumption of coal and water respectively required to keep the unloaded plant ready for service. Once these lines are obtained the coal and water consumptions for each shift are compared with the 'standard' value for the kWh concerned. Unusually high coal consumption means that the boilers have been mismanaged, or that inferior coal has been used, or that steam has been wasted by blowing off, etc. In the latter event the point plotted on the water chart will be above the normal line. The primary function of these charts is to call immediate attention to abnormal results so that they may subsequently be striven for if good or avoided if bad. If the general indication afforded by the charts is followed up by an intelligent search for causes of inefficiency, it will soon be possible to establish fresh standard lines corresponding to higher overall efficiency.

Comparison between the weight of water fed to boilers and the amount of steam fed to the main turbines (or the weight of condensate from the latter) leads to detection of excessive consumption in auxiliaries. Steam turbines should be tested over their full range of load every few months in order to detect deterioration of blading, etc.

193. Relative Importance of Efficiency in Various Parts of Plant.—The coal bill seldom represents less than 20 °/₀ and sometimes 40 to 50 °/₀ of the total working costs (*i.e.* cost excluding capital charges) in central stations in Great Britain (Tables 38), hence reduction in the fuel consumption is one of the most valuable economies which can be effected. The importance of small

* For a full explanation with examples *see* brochure on 'The Coal Consumption of Power Plants and Bonuses for Coal Saving,' by R. H. Parsons (*Electrical Review, Ltd.*).

differences in steam consumption of large generating sets, and certain risks attached to assessing the value thereof, are brought out by the following excerpt:—

A 10 000 kW turbo-generator loaded to an average of 7 500 kW for 8 000 hrs. per annum will supply 60 000 000 kWh per annum. A variation of 1 °/₀ in this output, on a coal cost of 0·15d. per kWh, equals £375 per annum, which is equivalent to £3 000 on an 8-year life. One set may consume 12·5 lbs. steam per kWh and cost £25 000. If a second set be offered, consuming only 11·5 lbs. per kWh (*i.e.* 8 °/₀ less), it is worth £24 000 more than the first set, but the actual difference in cost of manufacture will be no more than £2 000 or £3 000 [pre-war]. Naturally, substantial bonuses or penalties are offered or imposed for high or low steam consumption respectively. Large sums of money thus depend on the accuracy of test figures, which may be 3 °/₀ or 4 °/₀ in error, while the actual sums are often given in terms of one-tenth of a lb. of steam per kWh, *i.e.* less than 1 °/₀ of the total consumption (W. M. Selvey, *Jour. I.E.E.*, Vol. 53, p. 109).

It should be noted that the value of 1 °/₀ higher efficiency in any piece of apparatus varies with the actual efficiency of the latter. Doubling the efficiency of any step in the train of conversions between the coal pile and the bus bars would halve the coal bill for given kWh output; for example, the coal consumption / kWh would be halved by increasing the efficiency of any piece of the apparatus from 10 to 20 °/₀, from 20 to 40 °/₀, or from 40 to 80 °/₀, but the increase in the percentage efficiency of the apparatus itself would be 10 °/₀, 20°/₀, and 40 °/₀ in the respective cases. This shows that 1 °/₀ increase in apparatus efficiency is more valuable the lower the initial efficiency (*see* col. 7, Table 24). On the other hand, the percentage gain in overall efficiency (reckoned from the coal pile) per 1 °/₀ increase in apparatus efficiency decreases with the energy input to the apparatus concerned (*see* col. 6, Table 24). For example, the input to the boiler (Table 24) is 100 B.Th.U., and increasing the boiler efficiency from 80 to 81 °/₀ results in 1 °/₀ higher overall efficiency and in 100 [1 − (80 / 81)] = 1·25 °/₀ saving in coal;* at the turbine the input is 79·2 B.Th.U., and the effect of raising the turbine efficiency from 27 °/₀ to 28 °/₀ is to raise the overall efficiency (coal to turbine shaft) by 0·77 °/₀, but the saving in coal for equal output at the turbine shaft is 100 [1 − (27 / 28)] = 3·57 °/₀.

In choosing between alternative plants which may be available,

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* The saving in coal effected by increasing the efficiency of any apparatus from x °/₀ to y °/₀ is $100\left(1 - \frac{x}{y}\right)$°/₀.

the *loss* in each plant should be plotted to the same base as the load curve, the loss being calculated (for each load shown by the load curve) from the appropriate efficiency as shown on the load-efficiency curve of the plant. That plant which has the smaller

TABLE 24.—*Approximate Distribution of Losses in an Electrical System and Relative Value of Efficiency Improvements.*

Apparatus.	Assumed Efficiency of Apparatus %.	Equivalent Heat Units.			Effect of 1 % Higher Apparatus Efficiency.	
		Input.	Lost.	Output (= overall Efficiency from Coal Pile).	Increase in Overall Efficiency from Coal Pile, %.	Saving in Coal Consumption for Equal Output, %.
Boiler	80	100	20	80	1·00	1·25
Steam pipes . .	99	80	0·8	79·2	0·80	1·00
Turbine . . .	27	79·2	57·8	21·4	0·77	3·57
Alternator . . .	95	21·4	1·1	20·3	0·24	1·05
Step-up transformer .	98	20·3	0·4	19·9	0·20	1·01
H.T. mains . . .	90	19·9	2·0	17·9	0·20	1·10
Step-down transformer	98	17·9	0·4	17·5	0·18	1·01
L.T. Cables . . .	98	17·5	0·3	17·2	0·18	1·01
Motor	90	17·2	1·7	15·5	0·18	1·10

total area below its daily loss curve will be the more efficient in the service concerned. It will be found that plant which has high efficiency at low loads will give particularly favourable results when the load factor (§ 261) is low (*see also* § 217).

194. Distribution of Generating Costs.—The cost of generating electricity may conveniently be divided into fixed charges (principally interest on capital, and depreciation) which do not vary greatly in total amount with the kWh output per annum, and works or running costs (principally for fuel) which increase roughly in proportion with the kWh output. The capital charges / kWh obviously decrease as the output increases, but the running costs / kWh vary little within a wide range of output. Table 25 (due to C. W. Charlesworth, Inc. Munic. El. Assoc., 1921, and brought up to date) illustrates the composition of the total costs of electricity supply in average central stations. It may be stated, as a general rule, that where the load factor is high fuel economy is the prime consideration; the most expensive plant, with every refinement that will reduce the fuel bill, will be the best. On the other hand, where the load factor is poor, capital charges are of far greater importance, and a less expensive plant will give the lowest total charges.

An analysis of the distribution of working costs in typical central stations in Great Britain is given in Table 26. This is based upon data extracted from the Tables of Costs and Records published by the *Electrical Times* (1932). If this Table is compared with Table 38 (§ 269) the agreement will be found fairly close, considering that the groups of stations have purposely been selected differently, though each group is fairly comprehensive. Comparing the last two lines of the present Table with the corresponding part of the same Table in our fourth edition (1923), it will be found that the costs per kW connected have dropped substantially; but the same anomaly appears, namely, that the largest 'super-systems' cost more both per kW connected and per kW of maximum demand than those of the next lower group. Their 'works costs,' however, are some 18 °/ₒ lower on average.

TABLE 25.—*Composition of Total Costs of Electricity Supply.*

	Percentage of Total Cost in Year.				
	1913-14.	1916-17.	1919-20.	1931.	1938.
Capital charges	36	30	31	43	28
Fuel	25	40	35	57 (Fuel to Local rates, etc., together)	72 (Fuel to Local rates, etc., together)
Repairs, maintenance, water, stores, etc.	18	11	14		
Shift and running wages	5	6	8		
Local rates, management expenses, and salaries	16	13	12		

Comparative Analyses of Costs.—Special interest attaches to Tables 26 and 38 (§ 269) based upon data extracted from the Tables of Costs and Records published by the *Electrical Times.* These figures relate to the year 1932, which is taken as the year of 'basic demand' in calculating the fixed kilowatt charge for energy supplied under the Central Electricity Board's (Grid) Tariffs (§ 275*a*). The analysis of running costs in stations of different sizes (kW) and load factors, which forms an interesting and important study wherever the operation of independent power plants is concerned, has a different significance where stations are interconnected, purchase all or a substantial proportion of their total output in bulk from the 'Grid,' and rely upon the collective reserve capacity of the 'Grid,' instead of having individually to maintain sufficient reserve plant for local needs.

Tables 26 and 38 as regards costs, and Table 22 (§ 191) as regards fuel consumption, have a permanent interest as indicating about the highest stage of central station performance in Great Britain on a basis of individual operation. Since 1932 the price

TABLE 26.—*Analysis of Working Costs and Capital Expenditure in British Central Stations.*

Total kWh sold per annum, millions	1·6 to 4	34 to 56	120 to 880
Plant capacity, kW from	1 000-2 000	15 000-25 000	52 000-296 000
Working costs per kWh sold, pence:—			
Fuel	0·54	0·21	0·19
Oil, waste, water, stores	0·04	0·01	—
Wages of workmen	0·20	0·05	0·04
Repairs and maintenance	0·29	0·16	0·11
Rent, rates, and taxes	0·19	0·10	0·11
Management, salaries, office and legal expenses, insurance, etc.	0·28	0·12	0·08
Total	1·54	0·65	0·53
Percentage of fuel cost to total	33	33½	36
kWh sold for private supply per head of population	(61 to 162) 106	(95 to 359) 217	(217 to 888) 348
Annual load factor	(19 to 31) 26	(25 to 39) 32	(30 to 39) 34
Capital expenditure on whole system—			
£/kW connected	(17 to 53) 25·7	(10 to 37) 22·7	(18 to 28) 25
£/kW of maximum load	(82 to 168) 99·0	(45 to 104) 73	(53 to 92) 75

NOTE.—The figures given are the *averages* for a number of stations in each group calculated from figures given in the *Electrical Times* tables, December 1, 1932 (*see also* Table 38, § 269, for further analysis).

paid for energy bought in bulk, or the net amount paid to the C.E.B., has replaced the items fuel, salaries and wages, repairs, maintenance and stores in the analysis of 'generating' costs at almost every station giving general supply in its area. Exceptions are small, isolated stations (often with oil engines) and, of course, the main central stations serving the 'grid' and using 'base-load sets of 50 000 kW or larger unit capacity, which run steadily day and night at their most economical output, thus reducing costs below the general level attainable without interconnection.

For these reasons no analyses can now be given directly comparable with those for the year 1932, but the figures in Table 38*a* (§ 269) afford an indication of the composition of works costs in present-day electricity supply and may usefully be compared with Tables 26 and 38 provided that the radical change in conditions be borne in mind. The basis of grouping in Table 38*a* is the maximum load on the undertaking, classification by plant capacity in kW being impracticable with interconnected stations. If the stations were still operated independently they would need installed kW-capacities from 1·5 to 1·33 times the maximum loads stated in Table 38*a*; bringing them approximately into the kW groups of Table 38.

At the time of writing (Feb. 1938) the latest available data indicate that the works costs for a steam power station capable of carrying 500 000 kW maximum load (with the advantage of 'grid' reserve capacity) and supplying about 2 000 million kWh per annum, corresponding to about 45 °/₀ load factor, would be approximately as follows:—

	d./kWh
Coal	0·13-0·14
Salaries and wages	0·01-0·02
Repairs, maintenance, and stores	0·02-0·03
Rent, rates, and taxes	0·02-0·04
Management, insurance, etc.	0·01-0·03
	0·19-0·26

i.e. fuel alone represents from 68 to 54 °/₀ of the total works cost.

195. Capital Cost of Central Station Plant.—Table 27 will serve as a guide, and for further information the reader should refer to the technical press. In 1920-21 the cost of equipment was generally from 3 to 4 times the pre-war price; in 1921-22 the factor was about 2-2½; in 1922-23 about 1·75-2; and in 1937-38, before the rise due to the political situation, it averaged 1·5-1·66, but varied greatly between different classes of plant, lamps and some accessories being cheaper than before the war.

In *Power House Design* (first edition) Sir John Snell gave pre-war costs for a 25 000 kW Mond producer-gas plant, and the same authority, in his presidential address to the I.E.E. in 1914, gave what he considered the minimum costs likely to be attainable in erecting a large turbo-driven central station at any time in the near future. At the time of writing (1938) the costs for the items in this table would be far higher. In Table 28 we have entered what we believe would be the

[*Continued foot of* p. 356.

Table 27.—*Approximate Capital Costs of Power Plant Components.* (*See also* Table 21, § 189).

	Per	Pre-War.	1937 (Approx.)
		£	£
Horizontal return tubular boilers	Per 1 000 lbs. of water evaporated per hour into steam at a working pressure of 200 lbs. per sq. in. with 200° F. of superheat.	60-70	108
Water tube boilers, including integral superheater, and mechanical stokers with driving gear and accessories for the stokers . . .		100-130	187
Lancashire boilers, hand-fired, including superheater		100-150	190
Economisers for water-tube boilers, per 1 000 lbs. evaporated per hour in the boilers under conditions stated in col. 2		20-25	42
Economisers for Lancashire boilers, per 1 000 lbs. evaporated per hour in the boilers under conditions stated in col. 2		30-40	58
Pipework for main steam, auxiliary steam, feed and blow down, including feed pumps but not including piping for exhaust steam and circulating water		30-40	50
Coal conveyors and overhead bunkers . .		40-50	77
Ash handling plant		15-20	27
Corliss engine, with piping and foundations .	B.H.P.	5-8	9
„ „ and generator	kW	13-15	20
Turbo-alternators, 1 000 kW	kW	2	5·0
„ „ 2 500-5 000 kW	kW	1	3·3-3·9
„ „ 15 000-25 000 kW	kW	—	3·0
High-speed engine (Belliss) and 3-ph., 50-cycle alternator, including exciter, regulator, surface condenser, with motor-driven pumps, pipework between engine and condenser and erection (or packing for shipment) but not foundations :—			
500 kW	kW	—	7
1 100 kW	kW	—	7
The same, but without condensing plant :—			
100 kW	kW	—	7
250 kW	kW	—	5
Gas engines, vertical, 150-1 000 B.H.P. . .	B.H.P.	4·5	6
„ „ with generators, 500-2 500 kW .	kW	5·5	7
Suction gas producers, 100-200 B.H.P. . .	B.H.P.	1·5	2
„ „ „ 500-1 000 B.H.P. . .	B.H.P.	1·25	1·5
„ „ engines, 100-250 B.H.P. . . .	B.H.P.	4·5-5	7·5
Gas producer plant with engines and generators complete, about 300 kW	kW	20-25	30-36
Diesel engine and generator, about 500 kW .	kW	14-17	21-24
Semi-Diesel engine and generator, 50-200 kW	kW	16	20
Oil engine and generator, 10-30 kW . . .	kW	25-30	32-42
Barometric condensers, 250-2 500 kW . .	kW	0·5-2	0·8-3·0
Surface condensers, with pumps, 250-1 000 kW .	kW	1-2·5	1·5-3·6
„ „ „ „ 10 000-25 000 kW	kW	0·5	0·7
Cooling towers, with fan	kW	1·5	2·0
„ ponds with spray nozzles, concrete basin	kW	0·75-1·5	1·1-2·0
„ „ „ „ „ puddled clay basin	kW	0·5-0·85	0·85-1·5
Transformers, 200-500 kVA	kVA	0·5-1·0	0·5
„ 1 000-2 000 kVA	kVA	0·4-0·8	0·3
Rotary converters, 500-1 000 kVA	kVA	2-3	3·0-3·5

TABLE 27 (*Continued*).

	Per	Pre-War.	1937 (Approx.).
		£	£
1 000 kW set of mercury rectifiers . . .	kW	—	3-5
Switchgear for 1 500 kW turbo-alternator and rotary converter	kW	0·25-0·5	0·5-1·0
Switchgear for complete station, 5 000 kW upwards	kW	0·5-1·0	1-2
110-220 V generating set with switchboard and steam engine and boiler, *or* gas engine and producer, *or* oil engine . . . 5-10 kW	kW	50-75	73-110
20-25 kW	kW	30-40	43-60
Gas engine plant, 1 000-2 000 kW, without ammonia recovery, including generators, switchgear, and buildings	kW	15-20	23-30
Gas engine plant, 10 000-15 000 kW, with ammonia recovery, generators, switchgear, and buildings	kW	15-20	23-30
Complete steam-driven central station, including buildings, 10 000-100 000 kW	kW	8-15	23-26
Complete hydro-electric stations (*see* Table 35, § 216)	—	—	—
Substation, complete with transformers and converters, 2 000-5 000 kW	kW	4-7	5-10

TABLE 28.—*Approximate Pre-War Capital Costs of Large Gas and Steam Plants.*

Mond Producer-gas Plant.	Per kW.	Modern Steam Turbine Plant.	Per kW.
	£		£
Slack handling, regenerator plant, and gas producer	1·5	Land, river walls, and sidings .	0·4
Acid towers, recovery and sulphate plant	1·0	Buildings, coal silos, foundations, and cranes	3·0
Steam-raising plant and sundries .	1·2	Boilers, economisers, coal and ash plant chimneys and mechanical draught	5·5
Gas engines and electrical plant (25 000 kW)	12·0		
Pipework, cooling towers, buildings and foundations	2·6	Turbo-generators, condensers, air filters, piping, tanks, and switchgear	5·0
	18·3		13·9

corresponding figures at the present day; but a tolerance of at least 10 % should be allowed, since at the moment of writing the European situation has caused a rise (temporary, it may be hoped) in the cost of all raw materials. Sir John Snell is in no way responsible for our figures.

The capital cost of existing central stations in the United Kingdom, as represented by the total capital investment divided by the present kW capacity of plant installed, is very heavy in many cases. This is due to various causes, among which may be noted heavy legal and Parliamentary expenses, costly purchase of vested interests, extravagance in original buildings, costliness of early electrical apparatus, failure to recognise and provide for the rapidity with which plant would become inadequate or obsolete, and failure or inability to meet from revenue all charges which should be thus met. In the past every central station scheme has had to start on a relatively small scale, and this has resulted in disproportionately heavy capital expenditure per kW; with

TABLE 29.—*Generating Plant Installed and Capital Expenditure for Authorised Public Supply (excluding Traction) in Great Britain.*

Undertakings.		Generating Plant Installed.	Capital Expenditure at end of 1935-36 on Generation.	
Class.	Number.	kW.	Million £.	£ / kW.
Local Authorities	371	4 811 097	88·68	19·1
Companies and Persons	247	3 288 773	65·67	
Central Electricity Board	1	—	—	—
Joint Electricity Authorities	3	—	—	—
Joint Boards	5	—	—	—
Totals	627	8 099 807 97·1 % A.C.	154·35	19·1 (average)

interconnected stations and 'superstation' schemes this factor is not operative.

According to the *Electricity Commissioners' Report* for 1921 the average capital expenditure in the United Kingdom on lands, buildings, sidings, wharves, etc., and generating plant (but excluding transmission and distribution items) up to December 31, 1918, was £22·2 per kW installed for public supply other than traction. According to the Return of Engineering and Financial Statistics relating to Authorised Undertakings in Great Britain for 1935-36, issued by the Electricity Commissioners, the capital expenditure on generation alone, amounting to 29·1 % of the total, represented an average of £19·1 per kW of generating plant installed; see Table 29. The remaining capital expenditure on main transmission, distribution, etc., averaged £46·5 per kW of generating plant, making a total for the supply industry as a whole of £65·6 per kW of generating plant. The table covers 398 generating stations with 8·1 million kW of plant, of which local authorities owned about 60 %. Of the total number of generating stations, 93·5 % were generating at the standard frequency of 50 cycles/sec., 3·7 % at 25 cycles, 2·6 % at 40 cycles, and 0·2 % at other frequencies. The capital expenditure on main transmission lines amounted to £34 640 000 on the 'Grid,' £19 080 000 on other main transmission lines, and £253 260 000 on distribution.

Referred to the basis of load connected (23·17 million kW in 1936) the capital investment in existing English stations including transmission and distribution averages about £20 per kW (*see also* Table 26, § 194). The actual value of this figure in particular cases gives the basis on which the fixed charge per kW demand should be estimated in framing tariffs (*see* § 272).

196. Power-House Buildings; Space Occupied by Plant. —The main feature of modern central station buildings is their simple and economical construction; steel-framed structures of a strictly industrial type are employed; no expenditure is made upon purely architectural effects; and provision is made for easy extension. Ample supply of condensing water is indispensable in a steam turbine station, and in several instances shortage of water has made it necessary to go to other sites when additional generating plant was required. Cheap coal transport is also a primary consideration, and the question of ash disposal materially affects the selection of a site for a large station. The difference between, say, 5s. a ton and 6d. a ton to dispose of ashes (of which there may be 100-150 tons per million kWh) may exceed the capital charges on the additional transmission equipment required if the station be placed on the site where ash disposal is cheap. In a particular instance the total costs were distributed as follows:— *

Boiler house	26·7 %
Turbine	20·7 ,,
Piping and insulation	4·5 ,,
Feed water and cooling water handling	3·4 ,,
Electrical auxiliary service	8·0 ,,
Substations and switching equipment	13·0 ,,
Store, workshop and office, buildings, cranes, hoists, railroad and harbour, control, miscellaneous	17·9 ,,

* *Power*, Vol. 76, p. 187.

The extended applications of electric power and the perfection of the steam turbine have led to rapid increase in the capacity of generating sets installed, till, in the latest 'big-unit' stations, there are, say, half a dozen turbo-alternators, each of 20 000 kW, 60 000 kW, or even greater power (§ 173). For the small space occupied by boiler plant, the twin set, million lb. per hr., sectional-header, end-to-end, pulverised fuel boilers at the Hell Gate station at New York are noteworthy. The ratio of building volume to steaming capacity is 680 cu. ft. per 1 000 lbs. per hr. gross; but correcting for space devoted to railway tracks, etc., reduces the figure to 636 cu. ft. per 1 000 lbs. per hour.*

The cubic content of the 15 000 kW station of the Central Arizona Light and Power Co., from the top of the floor slab to the top of the parapet walls, is given as follows:—†

Boiler room	288 000	cu. ft.
Auxiliary bay	181 000	„
Turbine room	357 000	„
Total	826 000	„

or 55 cu. ft. per kW. The electrical bay is 42 000 cu. ft.

The modern horizontal turbo-alternator occupies only $\frac{1}{10}$-$\frac{1}{20}$ sq. ft. of floor area per kW, and it is quite a problem to accommodate the necessary boilers in convenient and efficient manner round a 'big-unit' power-house. Adopting the most compact arrangement of boilers and coal silos, the ground space required is 4 or 5 times that occupied by the corresponding section of power-house (including all auxiliaries and a fairly high percentage of gangway area), and 2 or 3 times that occupied by power plant and switchgear together. The largest horizontal turbo-alternators yet built (35 000-60 000 kW) occupy about 0·045 sq. ft. ground area and 0·72-0·82 cu. ft. overall space per kW. In a large-unit station, the total floor area required by power, switch, and boiler houses is about 0·6-0·75 sq. ft. per kW.

The 110 000 kW steeple-type compound turbo-generator recently installed at the Rouge works of the Ford Motor Co. occupies only 0·013 sq. ft. per kW of rating, owing to its special construction, the high-pressure turbine being mounted above the low-pressure turbine with steam reheaters between. The overall length of this set is 57 ft.; maximum width of turbine and generator 21 and 23 ft.; height from floor to top of control valve 21 ft. The weight of the unit is about 1 000 tons. Both turbine elements rotate at 1 800 r.p.m. and drive identical and inter-connected

* *Power*, Vol. 77, p. 355. † *Combustion*, Vol. 4, p. 14.

55 000 kW (90 °/₀ P.F.), 60-cycle, 13 800 V alternators. Steam at 1 200 lbs. /sq. in. and 725° F. is used in the high-pressure turbine and, exhausting at 70 lbs., is reheated to 550° F. for the low-pressure turbine.* The average consumption of the set at three-quarter load, including reheating, is 9 600 B.Th.U. per kWh.†

In New York, the Hudson Avenue station has a tandem turbine installation, each component being rated at 160 000 kW at 1 800 r.p.m. The single-winding generators are rated at 200 000 kVA (80 °/₀ P.F.). Steam pressure of 400 lbs. / sq. in. and at 730° F. is used, and the performance has exceeded the guarantees.‡

The sets generate 40 kW per sq. ft. of turbine-room floor area (0·25 sq. ft. per kW) in a position originally designed for only 50 000 kW. Similarly the condenser space below the turbines was very restricted, and each of the single-pass condensers serving the 160 000 kW sets has a tube surface of 101 000 sq. ft.§

The following data may be useful as a rough guide to the space occupied by boiler and power-houses in plants of the stated installed capacities :—

Installed kW.	Boiler and Power-Houses.	
	Ground Area, Sq.ft. / kW.	Space Occupied, Cu.ft. / kW.
10 000	1·3-1·5	64-78
50 000	0·75-0·92	56-64
100 000	0·6-0·75	51-58
150 000	0·55-0·7	47-55

Modern practice is to use switchgear of the remote-control type, placed in a building distinct from the power-house, and so constructed as to reduce fire risks to a minimum. Storage space for many thousand tons of coal is required, owing to the huge actual daily consumption of fuel and the importance of maintaining continuity of supply. Mechanical conveyers of various types are used to deliver coal to the boiler bunkers, the fuel being weighed automatically *en route ;* and mechanical or pneumatic ash-handling plant is generally installed. The tendency is to use higher boiler draught (up to, say, 6 ins. water-gauge), produced mechanically, smoke stacks being reduced to the height required to carry fumes (there need be no smoke) clear of buildings.

197. Central Station Output.—The Electricity Commissioners publish annually statistics showing the total kWh per

* *Power*, Vol. 73, p. 994.
† *Combustion*, Vol. 4, p. 7.
‡ *Power*, Vol. 76, p. 815.
§ *Ibid.*, p. 823.

annum generated by stations in Great Britain; also, the number of stations in service, grouped according to the kWh generated, and their area grouping in the Regional (Grid) scheme. During the year 1936, 442 stations of authorised undertakers in Great Britain sent out, on the average, 46·5 million kWh each (as against an average of 23·6 million kWh *generated* by each of 483 stations in 1931-32, and 10·4 million kWh average in 1921.

Of the 442 authorised undertakers submitting returns (against 483 in 1932) the distribution in magnitude of output was as shown in Table 29*a*.

TABLE 29*a*.—*Number and Output of Central Stations in Great Britain.*

Output per Year, Million kWh.	1932. % of No. of Stations.	1932. % of Total Units Generated.	1936. % of No. of Stations.	1936. % of Total Units Sent Out.†
Under 0·1	4·4	0·03	12·7*	Under 0·01
0·1 to 0·5	15·3	0·19	17·0	,, 0·09
0·5 to 2·5	15·7	0·95	20·4	0·5
2·5 to 10	17·3	2·74	12·2	1·3
10 to 50	30·2	22·15	16·7	8·0
50 to 200	14·9	43·10	13·3	27·1
Over 200	2·2	30·84	7·7	63·0

These figures do not include many private generating stations for which no data are available.

The output in one year from the whole of the public generating stations in the United Kingdom was roughly 2 000 million kWh maximum prior to 1914, 12 800 million kWh in 1932, and 20 530 million kWh in 1936.

Sales of electricity in Great Britain increased by an average of 769 million kWh per annum during the 15 years preceding March 31, 1936, and by an average of nearly 1 200 million kWh per annum during the five years 1931-36. In 1936, the average consumption per head of population in Great Britain was approximately 15 049 million units sold / 45·6 million population, or 330 kWh per head per annum, while per consumer it was 1950 kWh per annum on an average connected load of 3·0 kW. Table

* In 1936 there were 42 oil engine stations in the groups generating 100 000 kWh or less per annum.

† The E C. Returns published for 1936 referred to kWh sent out, instead of kWh generated as in previous returns.

29*b* shows the percentage of supply undertakings in Great Britain in 1935-36 averaging stated sales in kWh per head of population per annum; in a number of large cities the sales averaged 350-550 kWh per head per annum, full particulars being given in

TABLE 29*b*.—*Sales of Electricity per Head of Population per Annum in Great Britain.*

kWh per Head per Annum (excluding Bulk in 1935-36).	Per Cent. of Total Number of Undertakings.
Under 50	14·9
50 but under 100	23·3
100 „ 200	26·2
200 „ 300	13·8
300 and over	21·8
Average for the country 330 kWh	100·0

the *Return of Engineering and Financial Statistics relating to Authorised Undertakings in Great Britain* issued by the Electricity Commissioners, from which this summary is prepared.

Sales to consumers in 1935-36 amounted to 15 049 million

TABLE 29*c*.—*Distribution of and Revenue from Electricity Sold for Various Purposes in Great Britain* (1935-36).

	Million kWh Sold (1935-36).	Per cent. of Total kWh.	Per cent. of Total Revenue.	Average Revenue d / kWh.
Lighting, heating and cooking	5 504·7	36·6	62·4	1·921
Power	8 250·0	54·8	32·1	0·659
Public lighting . . .	270·8	1·8	1·9	1·170
Traction	1 023·9	6·8	3·6	0·589
Totals and overall average .	15 049·4	100·0	100·0	1·125

kWh, of which 36·6 °/₀ was for lighting, heating and cooking, and 54·8 °/₀ for power, details being given in Table 29*c* from the same source as before. These figures compare with 27 °/₀ for domestic purposes and 62 °/₀ for power in 1930-31; *see also* Table 26, § 194.

It will be seen that the sales for domestic purposes account for 62·4 % of the total revenue.

198. Electricity Supply Legislation; National Organisation of Supply.—In the past the development of electricity supply in Great Britain has been retarded and restricted by the hopeless inefficiency (from the electrical standpoint) of the legislation which governed the industry for so many years, and partly perhaps by the fact that the average electrical engineer has taken little interest in this question. It should be obvious that every one engaged in the industry ought to have a knowledge of the man-made laws as well as the physical laws which govern his activities. The principal legislative measures concerning electricity supply in Great Britain are summarised in Chapter 41, Vol. 3. The trend of these measures, as affecting the present position and future developments, was outlined clearly in the *First Annual Report of the Electricity Commissioners;* and their subsequent Reports, of which statistical use is made in this volume, should also be consulted.

Under the Electricity (Supply) Act, 1919 (9 and 10 Geo. 5, c. 100), as amended first by the Electricity (Supply) Act, 1922 (12 and 13 Geo. 5, c. 46) and later by the Electricity (Supply) Act, 1926 (16 and 17 Geo. 5, c. 51), the Electricity Commissioners are empowered, *inter alia:*—

(i) To determine electricity districts, to approve or formulate schemes for improving the existing organisation for the supply of electricity in such districts, and to make Orders embodying such approved Schemes which may provide for the formation of Joint Electricity Authorities.

(ii) To consent or to refuse consent to the establishment of a new, or the extension of an existing, generating station or main transmission line, subject to certain provisos.

(iii) To require the alteration of the type of current, frequency or pressure employed in the undertakings of authorised undertakers, subject to certain provisos.

As pointed out by the Commissioners in their 'First Annual Report' the reorganisation of electricity supply in this country 'is not a question of starting, *ab initio*, to develop a comprehensive and standardised system of generation, transmission, and distribution on the basis of present-day knowledge and technical practice, as there already exists an extensive and heterogeneous development representing the unco-ordinated growth of many years. The problem of reorganisation resolves itself into the determination of the best method of adapting, modifying, and expanding the existing development with the view of ensuring as speedily as possible an improvement in the supply of electricity for the numerous and growing needs of the community. It is only after thorough investigation at all stages, with full opportunity afforded to all interested parties to make representations at each stage, that a scheme for the reorganisation of supply in any district can become of statutory effect through the medium of an Order of the Commissioners, confirmed by the Minister of Transport and approved by Parliament.'

The provision made for the submission of schemes for improving the organisation of the supply of electricity in a district, and for safeguarding the interests of all parties concerned, is entirely to be commended provided that it is not abused by obstructionists. Legislation on the subject is somewhat complicated from having been undertaken piecemeal and largely by reference; but it is clearly explained in the books mentioned in the Bibliography (§ 199) as well as in Chapter 41 (Vol. 3) of this work.

A phase of electrical development which follows naturally from the treatment of electricity generation on a national basis, with widespread interconnected networks (popularly known as the 'Grid') is that of exporting electricity. Electricity has been transmitted satisfactorily from Sweden through a partly submarine cable (§ 292) to the Danish island of Zeeland for some years past, and schemes are in hand for a Norway-Sweden-Denmark transmission line which will make possible the utilisation of about 1 000 000 kW of water power at present going to waste. In Switzerland electricity is exported during the spring and summer, and imported from foreign steam-driven stations when the native water-power is insufficient to meet the home requirements. Canada exports 1 000 million kWh per annum to the United States through a dozen transmission lines. Countries possessing surplus water-power will probably, in the near future, export electrical energy derived therefrom for distances up to 1 000 miles. There is much to be said for international electricity supply in preference to the export of coal.

199. Bibliography (*see* explanatory note, § 58).

B.S.I. Specifications. *See* §§ 152, 184.

Books.

Large Electric Power Stations. C. Klingenberg (Crosby Lockwood).
Steam Electric Power Plants. F. Koester (Constable).
Modern Central Stations. C. W. Marshall (Pitman).

Hydro-Electric Power Stations. D. B. Rushmôre and E. A. Lof (Wiley).
Power Plant Engineering and Design. F. T. Morse (Van Nostrand).
Power House Design. Sir John F. C. Snell (Longmans).
Electric Power Systems. W. T. Taylor (Pitman).
Central Electrical Stations. C. H. Wordingham (Griffin).
The Steam-Engine and Other Heat-Engines. Sir J. A. Ewing (Cambridge University Press).
Return of Engineering and Financial Statistics Relating to Authorised Undertakings in Great Britain; annual (Electricity Commissioners).
Will's Electric Lighting. J. C. Dalton (Butterworth).
The Electricity (Supply) Act, 1926. J. C. Dalton (Butterworth).
The Law Relating to Electrical Energy in India and Burma, 5th edition, 1937. J. W. Meares (Thacker).

I.E.E. Papers.
Electricity Supply of Large Cities, G. Klingenberg. Vol. 52, p. 123.
Power Plant Testing, W. M. Selvey. Vol. 53, p. 109.
Coal and its Economical Use, P. S. Thompson. Vol. 53, p. 184.
Electricity Supply of Great Britain, E. T. Williams. Vol. 54, p. 581.
Thermal Efficiency of the Generation and Use of Gas and Electricity, Sir Dugald Clerk. Vol. 58, p. 765.
Utilisation of Exhaust Steam from Electric Generating Stations, C. I. Haden. Vol. 60, p. 265.
Utilisation of Waste Heat from Electrical Generating Stations, F. H. Whysall. Vol. 60, p. 271.
Interconnection of A.C. Power Stations, L. Romero and J. B. Palmer. Vol. 60, p. 287.
Some Factors Affecting the Working Costs of Small Electric Generating Stations, E. G. Kennard. Vol. 62, p. 713.
Justifiable Small Power Plants, A. B. Mallinson. Vol. 63, p. 896.
Power Stations and their Equipment, W. M. Selvey. Vol. 64, p. 485.
Higher Steam Pressures and their Application to the Steam Turbine, A. H. Law and J. P. Chittenden. Vol. 66, p. 89.
Direct Generation of Alternating Current at High Voltages, Sir Charles Parsons and J. Rosen. Vol. 67, p. 1 065.
Recent Developments in Turbo-Generators, J. A. Keyser. Vol. 67, p. 1 081.
Electric Plant and Machinery, A. R. Everest. Vol. 68, p. 139.
Voltage Control of Large Alternators, H. W. Taylor. Vol. 68, p. 317.
Collection of Current from Commutators and Slip-Rings, H. G. Taylor. Vol. 68, p. 1 356.
The Cooling of Electrical Machines, D. B. Hoseason. Vol. 69, p. 121.
The Present Practical Limits of Power Station Efficiency, W. S. Burge. Vol. 73, p. 369.
Power Stations and their Equipment (Progress Review), I. V. Robinson. Vol. 76, p. 289.
Fire Precautions in Major Electrical Stations, F. C. Winfield. Vol. 81, p. 289.

(*See also* Bibliography, § 184.)

CHAPTER 8.

WATER-POWER: GENERAL CONSIDERATIONS

200. Wide Range of Water-power.—Although countries which had insufficient supplies of fuel have been developing their hydro-electric resources for many years, it is only recently that all civilised countries have undertaken systematic surveys of their available water-powers. At the present day experts in this branch of engineering are scarce, and even elementary knowledge of the subject is often lacking. It is only possible in this book to give a general outline of the subject, and specialist treatises must be consulted for details of hydraulic machinery and particulars of the civil engineering works involved in laying-out projects. These may comprise almost any conditions, from developing a 3-ft. fall on a river or canal up to that of a 5 000-ft. fall in a range of mountains; and from utilising the whole flow from the catchment area of a great river, such as the Mississippi, down to that from a few square miles of country with heavy seasonal monsoon rainfall. The power may be obtained from the normal flow of a river or canal alone; or from the same supplemented by storage; or (for the greater part of each year) from stored water alone. In every case water-power is the simplest example of power as represented by the rate of expenditure of ft.-lbs. per min.; in the old-fashioned overshot water wheel this was directly exemplified by each bucket carrying so many gallons of water and depositing it into a tailrace so many feet below the headrace. In hydro-electric practice the actual fall may be either a natural waterfall, or an artificial fall created by a dam or weir, or a fall developed by carrying the water along in a canal until sufficient drop has been accumulated above the original and more rapidly falling source.

Head.—It will be as well to state here that the fall of water is specified in terms of 'head.' The 'gross head' is the vertical difference in level, stated in feet or metres, between the level of the water where it is tapped at the source and that of the tail-race where it is finally discharged. There are, however, many deductions to be made before we arrive at the 'net head' or working head available for operating the wheel, which is the gross head diminished by the losses. In every case there is the frictional loss (depending on the velocity of flow and on the bends and curvature) in the pipe or penstock or spiral casing feeding the wheel; and in the draft tube or suction tube where one is employed, as in reaction and propeller wheels. If a canal or open channel is employed above the forebay, there will be the slope of that to be deducted also, with the loss at screens and weirs in it. Furthermore, in order to ensure that the works may be secure from flood damage, it may often be necessary to locate the plant above the normal level of the tail water, and with impulse wheels any such margin is entirely lost. Similarly, the actual draw-off level at the headworks is seldom such as to utilise the whole of it, apart from the obvious fact that in a river the bed slope continues up to the source. If there is storage, there will be considerable difference between the full and lowest draw-off levels; while even if the draw-off is direct from the source, without storage, the rise and fall of the river and the possibilities of flooding out the headworks involve losses. In the approximations given in these Chapters, for ascertaining the power available, the term 'head' (unless otherwise stated) is the gross head of the *actual* development; losses are taken into account along with efficiency.

201. Power Available from Water.—It is often assumed that an actual visible waterfall is necessary for the generation of power. In canals, and in streams where the slope of the bed is extremely small, this is true, and power can only be generated where there happens to be an artificial fall (such as a lock or weir) or a rapid capable of being converted into a fall. On the other hand, the slope of rivers is generally greater, and an artificial head can often be obtained by carrying the water for some distance along a comparatively level artificial channel. The horse-power available in any case is, theoretically, the product of the weight of water in lbs. per sec. (*i.e.* cu. ft. per sec. × 62·3) multiplied by the vertical head in feet and divided by 550. The result must, however, be reduced in proportion to the inefficiency of the turbine or wheel, and the loss of head in the pipes, in order to find the actual B.H.P. available on the shaft.

The efficiency of modern wheels varies from about 65 up to over 90 %, but for rough calculations and including pipe losses 80 % will not be far wrong. Taking this into account we have:—

Theoretical water H.P. = cu. ft. per sec. × head in ft. / 8·83.
Available B.H.P. = cu. ft. per sec. × head in ft. / 11.

A cu. ft. per sec. or 'cusec'—a useful irrigation term little known outside India—will therefore give 0·09 B.H.P. on the turbine shaft per ft. of fall; 0·9 B.H.P. per 10 ft. of fall; 9 B.H.P. per 100 ft.; and 90 B.H.P. per 1 000 ft. For rough project estimates the overall efficiency of medium-sized electric generators working at full load may be taken as 94 % (Chapter 40); if driven otherwise than directly off the turbine shaft there will be an additional loss of about 5 % in the drive. The electrical power available at the generator terminals, assuming this efficiency and converting from H.P. to kW, will then be approximately:—

For direct drive: Kilowatts = cusecs × head in ft. / 15·5 (say 15).
For indirect drive: Kilowatts = cusecs × head in ft. / 16·5 (say 16).

Thus, for example, we may have a canal fall of 10 ft. net with 1 000 cusecs flowing, or a mountain stream in which a fall of 1 000 ft. can be obtained with 10 cusecs flowing. In both cases: The theoretical H.P. is 10 000 × 62·3 / 550 (or, in the form given above, 10 000 / 8·83) = 1 150; the turbine B.H.P. is 10 000 / 11 = 910; and the electrical power is 10 000 / 15·5 or 16·5 = 645 or 605 kW, according as the drive is direct or indirect.

202. Constants and Approximations.—Table 30 and the approximate relations given below will be found useful in dealing with water power. Explanations, where required, will follow in due course. Unnecessary decimals are omitted.

TABLE 30.—*Constants of Water for Hydro-electric Work.*

1 cu. ft. of water	= 6·235 Imp. gals. = 62·35 lbs.
	= 7·48 U.S. gals. = 0·02 832 m.^{3} or 28·32 litres.
35·9 cu. ft. of water	= 1 English ton of 2 240 lbs.
35·31 " " " "	= 1 cu. metre.
1 acre-foot (*i.e.* 1 acre covered to a depth of 1 ft.)	= 43 560 cu. ft.
	= 1 223 cu. metres (m.^{3}).
22·96 acre-feet	= 1 million cu. ft.
1 sq. mile-foot	= 27·88 million cu. ft.
Static pressure of water	= 0· 433 lb. per sq. in. per ft. of head.

Flow of Water.

1 cusec or second-foot (*i.e.* 1 cu. ft. per sec.)	= 62·3 lbs. per sec. = 0·028 3 m.³ per sec.
	= 3 738 „ „ min. = 1·699 „ „ min.
	= 374 gals. per min.
	= 86 400 cu. ft. per day = 2 446 m.³ per day.
	= 2·4 to 2·6 million cu. ft. per month.
	= 31½ „ „ „ „ year
	= 892 950 m.³ per year.
1 cu. metre (m.³)	= 35·31 cu. ft. = 2 200 lbs. or 220 gals.
1 m.³ per sec.	= 35·31 cusecs.

Water Power and Energy, Theoretical.

Omitting all losses (*see below*, 'Approximations'):—

1 water H.P.	= 550 ft. lbs. per sec.
	= 8·83 cusecs ft.
1 water H.P. hr.	= 1 980 000 ft. lbs. = 31 730 cu. ft. × 1 ft. head.
1 kWh (theoretical)	= 2 656 400 ft. lbs. = 42 570 „ „ „

For all practical purposes, the limits of efficiency of conversion may be taken as:—

Water turbine from 75 °/₀ in small units up to 90 °/₀ in large ones.

Generators (at full load) from 85 °/₀ to 96 °/₀.

Overall efficiency from water to electrical power, whether E.H.P. or kW, from 64 °/₀ (in very small plants) up to 86 °/₀ under the most favourable full-load conditions of a large plant. Under *average load conditions* of a moderate sized plant, 75 °/₀ overall will not be far wrong; and this figure is used below.

APPROXIMATIONS.—*Storage of Water.*

100 000 cu. ft. stored will give	1·16	cusecs for	24 hrs.
	2¼	„ „	12 „
	4½	„ „	6 „
	9¼	„ „	3 „
	27¾	„ „	1 „

Thirty-one and a half million cu. ft. stored is equivalent to 1 cusec for a year; but owing to losses by evaporation, etc., the actual value is nearer ¾ cusec. The following approximations may be used:—

1 000 million cu. ft. stored will give	30	cusecs for a	year.
	40	„ „	9 months.
	60	„ „	6 „
	90	„ „	4 „
	120	„ „	3 „

Catchments.

A catchment area is the whole area (bounded by watersheds) draining into a river or stream at any particular point in its course. If the whole rainfall within a catchment reached the determined point in the stream (which is far from being the case), then:

1 in. of rain = 100 tons or 3 600 cu. ft. per acre,
= 64 000 tons or 2·33 million cu. ft. per sq. mile.

The actual flow-off is dealt with in § 204.

Power Available Under the Best Conditions.

(i) *From Flow—*

Cusecs × head in ft. / 11 = E.H.P. at generator.
" × " " " / 15 = kW " "

(On small projects and for average results divisors of 12 and 16 may be used.)

(ii) *From Storage—*

Thousands cu. ft. stored × head in ft. / 42 = E.H.P.-hours.
" " " × " " / 56 = kWh.
Millions cu. ft. stored × head in ft. / 370 = E.H.P.-years.
" " " × " " / 500 = kW-years.
" " " × " " × 17 = kWh.

203. Classification of Water-power. — Great advances in water turbine design have taken place since our fourth edition was published. For very low heads, especially when variable, the propeller wheel (and, except in the U.S.A., the Kaplan variety of it) has superseded all others; these types are described in § 214. For quite small powers there may still be room for modified forms of the impulse wheel, such as the Girard; and the Francis wheel is installed in countless plants where it would not now be used, while it has won a new field in heads up to 1 000 feet, previously only served by Pelton wheels.

Subject to these remarks, it may be said that present day practice embraces three main types of prime mover for water power, *viz.* the Pelton wheel or jet impulse turbine for high heads, and sometimes for medium heads on the border line; the Francis or reaction turbine for medium, and, until recently, for low heads also; and the propeller wheel for low heads. To these last named we recur later (§ 214). There is no defined or definable limit of high, medium and low heads, but generally speaking it may be said that any fall over 1 000 feet is high and any fall below 100 feet is low, though medium head lay-outs overlap both these arbitrary limits.

The purely diagrammatic figures (sections and plans) in the accompanying Figs. 47(*a*-*i*) represent a few of the more characteristic types of lay-out, and are now described.

Low Heads.—A typical form of very low head is where there is a fall in a canal—generally an irrigation canal, since navigation canals are usually devoid of flow. The sectional diagram Fig. 47(*a*) shows an 'open penstock' Francis runner, *i.e.* one in which the turbine wheel is not encased. The same type of fall may employ a spiral-cased Francis wheel or a propeller wheel—the latter especially on variable heads. Whichever is employed, a draft or suction tube discharges below the tail-race level, and the gross head is as shown on the diagram.

It may often happen that two such canal falls may occur within a short distance, owing to the natural configuration of the ground. In such circumstances, each fall may be developed separately or the two may be combined; and the power-house may be near either fall or between them, with a subsidiary canal connecting the

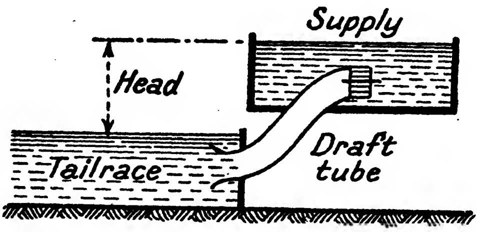

FIG. 47(*a*).—Section of low-head open penstock setting on canal.

head and tail waters, through the power-house, either at head level or tail level or both.

On comparatively level rivers, especially where there are rapids, the lifting dam type of lay-out, Fig. 47(*b*) is common. The dam may be of the gravity type, as shown in the section, or may be a hollow concrete structure, in which case the plant is generally inside the

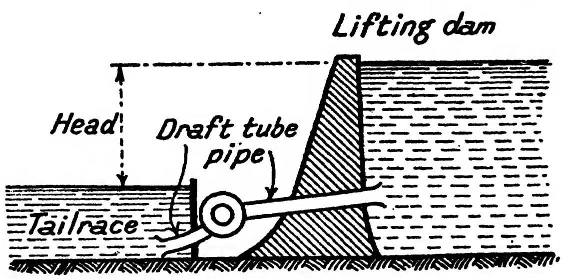

FIG. 47(*b*).—Section of low-head lifting dam lay-out.

dam. Here also, either the Francis or the propeller wheel is suitable, according to circumstances, and a draft or suction tube is employed. Several such lay-outs may be in series.

Medium (or Low) Heads.—The majority of natural waterfalls will come under the medium category, though both high and low ones are not uncommon. Usually the river is tapped off to a forebay on one bank, as shown in Fig. 47(*c*), whence pressure pipes run to the turbine, which discharges below the fall. With either Francis or propeller wheels there is a draft or suction tube, ending below the water level of the tail race, so that the gross head is the difference between forebay and tail race levels. Should any form of impulse wheel be employed on such a fall, the gross head is the difference between the levels of forebay and jet. Occasionally,

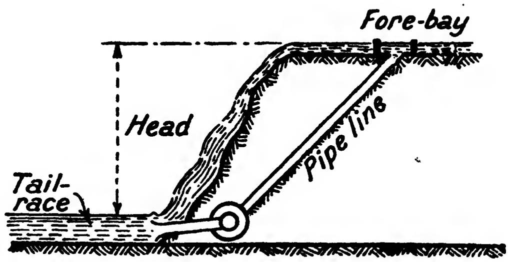

FIG. 47(c).—Section showing lay-out of waterfall.

owing to the nature of the ground, it is difficult to arrange the pipe line externally, as shown in the diagram, and a vertical shaft is constructed in the rock with a power-house at the bottom and a tail race tunnel back to the river.

There may, however, be additional useful fall above or below

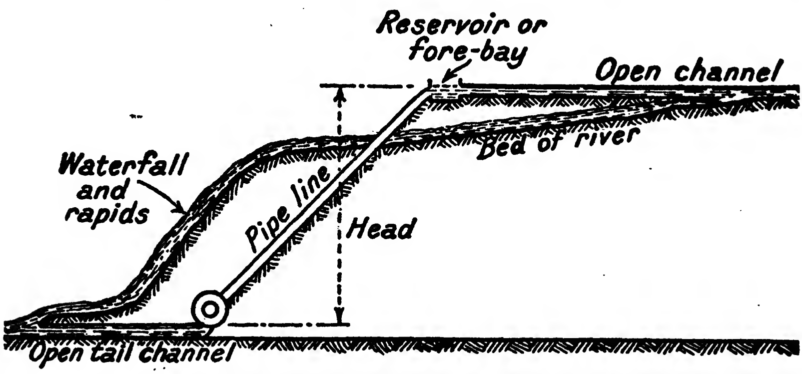

FIG. 47(d).—Section of waterfall with rapids and open channel.

the actual waterfall, extending for some distance either way or both. Here an unduly long and expensive pressure-pipe line would result, so an open channel is used between the headworks and the forebay supplying the pipes, and perhaps another carrying the tail race back to the river. The sectional diagram Fig. 47(d) shows canals both above and below the fall. The head in this case is the vertical height between the forebay and the tail race or jet, as the case may be; the drop in the channels is lost.

Medium or High Falls.—An identical lay-out (Fig. 47(*d*)) is used where there is no actual waterfall, but merely a steeply-sloping river bed, such as may be found in mountainous country, except that the open channel will here be at the top only. Such a channel or canal may run for miles virtually along a contour, until suitable ground is found for as short a pressure pipe line as possible from a forebay or a reservoir. If the forebay and reservoir are not combined, they may be at some distance apart, in which case, in order to use the whole head and to waste no water, the two may be connected by a closed pipe; this, however, will not be subject to water-hammer, and can be of very light steel or concrete construction. It will be obvious that a sudden demand for power in excess of the equivalent of the flow in the channel can *only* be met by storage at

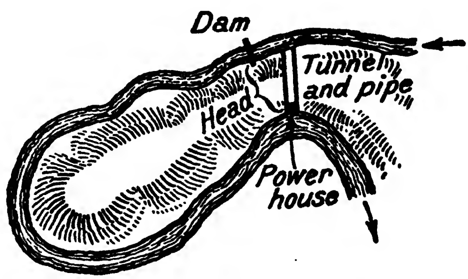

Fig. 47(*e*).—Plan of short-circuited bend on river.

or reasonably near the forebay or by wastefully running the channel full-bore all the time. Conversely, a spillway to carry the whole discharge of the channel must, in the absence of any storage, be provided at the termination, so as to cope with a sudden shut-down; for the long channel will contain much water.

A different configuration and lay-out, applicable to any class of head, and not so far exploited to the full, is shown in Fig. 47(*e*); namely, the short-circuiting of a bend in a river, preferably one with a rapid fall round the bend. Here the natural slope of the river over a long course, perhaps many miles, is reinforced by a lifting dam (Fig. *see* 47(*b*)), which diverts the river through a tunnel to the other end of the bend. Ordinarily the dam would be adjacent to the tunnel, as in the diagram; but the power project might be parallel with or subsidiary to a storage project for gently-sloping closed pipe, required to bring in the full head, can be of the lightest make that is mechanically permissible—wood-stave pipe being often used in America. It takes some time for the flow to steady down in a long pipe—and it may run to a mile or more—when the demand suddenly increases or decreases, and the capacity of the surge tank is such as to deal with the interval.

High Heads with Storage and Watershed Crossing.—Sometimes the upper line of pipes in Fig. 47(*h*) may be replaced by a long tunnel through a hill, from a lake beyond, as in Fig. 47(*i*) where the surge tower, cut up through the rock, relieves the pressure tunnel from dangerous stresses while performing the usual regulating functions. This section shows the lay-out of the Andhra Valley plant in the Western Ghats (India), where a great lake, holding about two years' supply, is formed by a dam on one

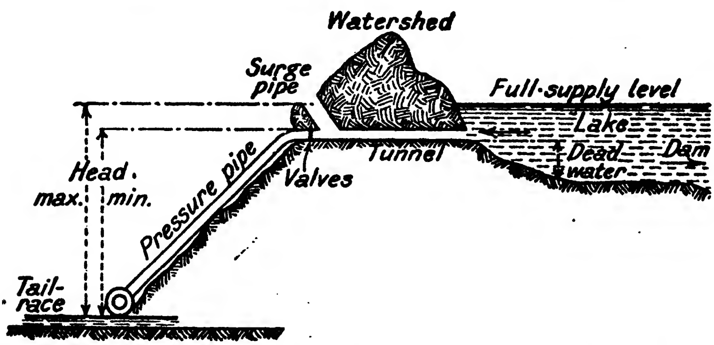

Fig. 47(*i*).—Section showing lake with water-shed, tunnel and surge tower.

side of the main watershed of India, and the water is carried in a tunnel through to the other side, where there is a steep fall of over 2 000 feet. The tunnel is subject to the static pressure of the head above it, in the lake, but not to water-hammer from the sudden cessation of flow in the pipes. The head varies with the level in the lake, which is replenished only in the monsoon period from a small catchment area with very heavy rainfall.

Similar watershed crossings are employed in the other undertakings in the same locality, associated with the Tata firm. Thus the first of the plants serving Bombay has two large lakes, joined by a tunnel through the watershed, the supply being then taken by a long open canal to the large forebay, after the manner of Fig. 47(*d*) above. Fortunately there is a third and much smaller reservoir comparatively near the forebay, so that the problem of sudden demand is simplified. Here, evidently, no surge tower is needed; and the head is the difference between the level of forebay and jet, regardless of the height in the lakes.

Combinations and variations of all these lay-outs will be found; the ground has to be utilised to the best advantage and varies greatly.

204. Catchment Areas and Flow-off.—As the power available is always proportional to the product of flow and head or fall it follows that, whereas high-head plants can operate on a comparatively small flow, low-head plants of the same capacity require a very large volume of water. Except where great storage works are undertaken, nature fits in with these requirements; for while small individual streams in mountainous country, with small catchment areas, offer high-head developments, the great rivers into which they discharge supply the medium and low-head plants. From the point of view of hydro-electric works the absolute minimum flow at the site is the determining factor, except where water storage on a large scale is possible, as upon it depends the size of the plant that can be continuously operated. (But *see* § 209 (3): rating of rivers.) Where large-scale storage is possible, the minimum *annual* flow-off determines the limits of the project, subject to the possibility of being able to carry over a reserve supply from a good year to a deficient one. The maximum flow-off in floods is necessarily always of importance in connection with the safety of headworks and dams and the provision of waste weirs or escapes or under-sluices for discharging the excess water.

Considering *small catchment areas* first, the flow from day to day in the streams fed by them evidently depends primarily on the amount of rainfall; but not *only* on the amount, as the rate or intensity at which the falls occur has a large bearing on the problem. Occasional showers are mostly lost by the way, in evaporation, or absorption by soil and vegetation. If the ground is dry, the first hours of rainfall may have but little effect on the stream; on the other hand, when the ground is already saturated, further rain will mostly run off to the stream. Here the nature of the ground has to be considered; bare steep rocky hillsides allow a very large proportion of rainfall to pass quickly down, while, at the other extreme, flat agricultural or forest land retains a large proportion of the fall and allows more to be lost by evaporation during its slower passage down. Then again, some of the rainfall sinks into the ground and reappears later in the form of springs; while high altitude snow, the most valuable form of 'white coal' to the water-power engineer, may supply a river with water at the time when the ordinary flow is at the lowest and during the driest of seasons. Where large scale storage of water is in question it is the minimum *annual* flow-off of the river (§ 209) that is of the greatest importance, but in the case of small, and probably high-elevation catchments it is the day-to-day flow-off and the maximum and minimum amounts of water arriving at the headworks of the project that matter most. For a full discussion of various empirical formulæ for obtaining the maximum flow-off from a catchment the reader is referred to Buckley's *Irrigation Pocket Book*, where actual results are also given of many known rivers. It will be sufficient here to mention Dickens' formula, *viz.*:—

$$D = CM^{2/3},$$

where D = maximum discharge, in cusecs.
C = coefficient.
M = catchment area, in sq. mls.

The author of this formula took C as 825 where the rainfall was about 36 ins. a year and considered the same figure applicable from 24-50 ins. By actual application it has been found (*loc. cit.*) that the coefficient varies in Indian rivers from 120 up to 1 795. The former figure is for very large catchments with rainfall of the order mentioned; the latter figure is for small catchments with very heavy rainfall confined to a short season. Clearly in the case of small catchments a knowledge of the shape of the catchment—for its length will greatly affect the time taken by the water to reach a given point—of its steepness, of its cultivated area, and of the intensity of the rainfall, will help in arriving at an intelligent estimate. In obtaining the average flow, and to some extent the minimum, of a small catchment comparison with a neighbouring area where the flow has been measured may be of great value, the relative areas, configurations, and rainfalls being approximately known. Naturally a small catchment area is subject to very great variations in flow; for a heavy storm may sweep over the whole of it, just as a dry period affects the whole. To obtain reliable results it is of course far preferable to make actual measurements of the flow (§ 205) over as long a period as possible, for comparison with the rainfall from sufficient gauges in the catchment, and also for comparison with neighbouring catchments. The intervening watersheds may, however, affect the latter comparisons to no inconsiderable extent. In many countries regular gaugings have been taken for years in all promising catchments, either for ascertaining irrigation or power possibilities—the former generally on the larger rivers only.

When *large catchments* are in question it is clear that excesses and defects of rainfall will generally serve to make the limits of flow less extreme, though this is less true in countries subject to monsoon rainfall than elsewhere. In such catchments the annual flow-off in India is found to vary between 29 and 47 °/$_{\circ}$ of the total rainfall, except on the West coast where the rainfall is extraordinarily high. The whole question of the annual flow-off from a catchment is exhaustively discussed by Buckley in the work already cited. Where irrigation systems take off from large rivers the amount available below their headworks will naturally depend on the seasonal requirements, and the lower reaches may almost run dry; where, on the other hand, large scale storage is a part of the irrigation project, the impounding and regulation of flood waters may enable a far larger proportion of the total annual flow to be utilised for power purposes on its way down than would happen with an untrained river.

Until recently the intensity at which rain falls has not been readily ascertained except by an observer with a stop-watch. It is true that approximations can be obtained from the curves of some self-recording clock gauges, but the cost of these precludes their general use and they do not register short periods of extreme intensity with any accuracy. The *fractionating rain gauge* described by one of the authors* will give the daily rainfall, divided up into any required number of intensities, as accurately as the plain gauge gives the total, each fraction or intensity having its own collecting vessel. The principle employed is that of a fine jet with a number of leaping weirs. By an ingenious extension of the principle Mr. J. H. Field, of the Indian Meteorological Department, has also constructed a new type of recorder which, with a single tank collector, can be left for a whole season in a locality difficult of access and will then enable the total

* 'The Experimental Development of an Automatic Integrating "Intensity" Rain-Gauge without Clockwork,' Institution of Civil Engineers, Selected Engineering Papers, No. 2; 1923. (Telford Premium), by J. W. Meares, M.Inst. C.E.

rainfall and the rates and times of fall to be tabulated with fair accuracy. The plain instrument has the advantage of being very cheap to construct, as the inventor has not patented it, and does not intend to do so. The device was in use throughout a whole monsoon in Simla, recording rates up to 7 ins. per hour and amounts up to 5 ins. a day.

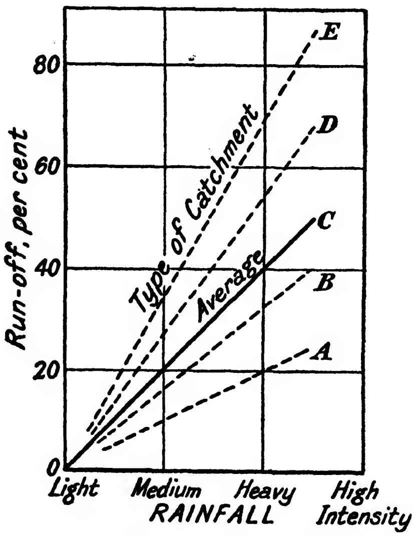

FIG. 47*k*.—Barlow's run-off percentages.

Barlow's Method of Forecasting Run-off.—Brief mention may be made here to the empirical method of arriving at the probable run-off of any catchment, developed by the late Mr. G. T. Barlow, C.I.E., of the Indian Irrigation Department, from observations on reservoirs in the United Provinces (India). It has been fully described elsewhere * and it will suffice here to say that both catchment areas and rainfall are classified and associated by curves of percentage run-off as shown in Fig. 47*k*. The types of catchment are as follows:—

Barlow's Suggested Method of Determining Total Run-off.

Classification of Catchments.

Type A.	Flat, cultivated absorbent soils.
Type B.	Flat, partly cultivated stiff soils.
Type C.	Average catchment.
Type D.	Hills and plains with little cultivation.
Type E.	Very hilly, steep and rocky, with little or no cultivation.

205. Discharge of Notches and Weirs.—A very full discussion of the various formulæ for flow in open channels, which follow, as well as of those relating to the discharge over weirs and through sluices and syphons, will be found in Buckley's *Irrigation Pocket Book;* while Garrett's *Hydraulic Tables and Diagrams for Practical Engineers* gives in addition discharge curves to meet every case likely to arise.

* 'Triennial Report of the Hydro-electric Survey of India,' p. 17, J. W. Meares. *Engineering*, Jan. 11, 1924.

Triangular Notches.—For measuring small and variable discharges with accuracy the triangular notch is unequalled. The notch should be sharp-edged on the upstream side (or a thin plate of metal may be used), and in order to reduce the velocity of approach towards the weir the cross-section of the stream should be large in proportion to that at the notch. The general formula for a triangular notch is

$$Q = (4/15)\, CB\sqrt{2g} \times h^{3/2},$$

where Q represents cusecs, B is the breadth of the water flowing over the notch, and h the depth to the apex, both in *feet*. For a right-angled notch $C = 0{\cdot}59$ and $B = 2h$ so $Q = 2{\cdot}54\ h^{2{\cdot}5}$.

For example, take a depth of 6 ins. or 0·5 ft. and the discharge will be

$$\begin{aligned} Q &= 2{\cdot}54 \times 0{\cdot}5^{2{\cdot}5} \text{ cusecs} \\ &= 2{\cdot}54 \times {\cdot}177 = 0{\cdot}45 \text{ cusecs} \\ &= 27 \text{ cu. ft. per min.} \end{aligned}$$

The above formula is also found in the form—

Gallons per min. $= 1{\cdot}91\ h^{2{\cdot}5}$, where h is in *inches*. In the same example this gives 168 gallons per min. which $= 0{\cdot}45$ cusecs.

The measurement of h is made a short distance upstream, so that the curvature over the fall does not vitiate the results; and while a foot rule placed on a carefully levelled post is often used a hook gauge gives more accurate results. This device consists of a sharp-pointed hook attached by a raising screw to a calibrated scale, such that the top of the submerged hook, when first touching the surface, indicates the depth h. In still water the moment when the upward moving hook breaks the surface can be judged with great accuracy; and where the water surface is likely to be ruffled the device is placed inside a pipe with a very small orifice opening to the stream, which ensures still water. The device is equally applicable in the case of water measurements for steam boilers, and gives a high level of accuracy.

Rectangular Weirs.—Where larger quantities of water have to be measured, sharp-edged rectangular weirs are used. These take two forms; first, where a straight weir is placed across the full width of a channel itself of rectangular section; and, second, where a complete rectangular notch, sharp-edged at both sides and bottom, is placed in a waterway of greater width, so that there are complete 'end contractions.' In the former case there will always be an appreciable velocity of approach, whereas in the latter this can generally be avoided. A further factor is that there should be a free drop below the weir; if the fall is submerged the discharge is decreased and requires different methods of calculation.

The fundamental equation for the discharge over a weir is—

$$Q = 0\cdot 666 \times c \times l \times h\sqrt{2gh} = 5\cdot 35clh^{3/2},$$

where
Q = cusecs.
l = length of weir, in ft.
h = height of water above crest, in ft.
c = a constant.

Taking an average value of 0·618 for c and keeping h in feet, the formula simplifies to the formula given by Molesworth, *viz.*:—

$$Q = 3\cdot 31 \times l \times \sqrt{h^3}$$

while experimental values of c show that it varies from about 0·58 where h is large in proportion to l, and with complete end contractions, up to 0·65 with low values of h and suppressed end contractions. For the practical purposes of this chapter the latter formula is quite accurate enough, both with or without end contractions, so long as there is a *clear fall.*

For example, given a weir length of 5 ft. and a depth h of 6 ins. or 0·5 ft., the discharge will be

$$Q = 3\cdot 31 \times 5 \times \sqrt{0\cdot 125} = 5\cdot 84 \text{ cusecs.}$$

Weirs with Velocity of Approach.—Where, however, there is a considerable velocity of approach to the weir this is equivalent to an addition to the 'head' over and above that of still water. This additional head in feet, H, corresponds to $H = \frac{u^2}{2g}$, where u is the velocity of approach in ft. per sec. This modifies the fundamental formula to

$$Q = 0\cdot 666 \times c \times l\sqrt{2g}\{(h + H)^{3/2} - H^{3/2}\},$$

where the values of c are as already given.

Thus with the same data as in the last example, but with a velocity of approach of 6 ft. per sec. (taking the actual coefficient of 0·611) $H = 36 / 64\cdot 4 = 0\cdot 559$ and the discharge is

$$Q = 0\cdot 666 \times 0\cdot 611 \times 5 \times 8\cdot 01\{(0\cdot 5 + 0\cdot 559)^{3/2} - 0\cdot 559^{3/2}\} = 11 \text{ cusecs.}$$

Drowned Weirs.—When the surface of the tail waters is at a higher level than the crest of the weir, so that the fall is to some extent submerged, the discharge is lowered; in this case

$$Q = cl\sqrt{2gh_1}(h_2 + \tfrac{2}{3}h_1),$$

where h_1 = the afflux, or the difference between the water levels up and down-stream of the weir, in ft.

h_2 = the height of the water surface down-stream above the crest of the weir, in ft.

c = a constant as before, of which 0·63 is the best average value for sharp-crested weirs.

For example, keeping to a length of 5 ft. and a depth h of 0·5 ft., let the afflux, h_1, be 0·3 ft. so that the weir crest is drowned by h_2 = 0·2 ft.; then

$$Q = 0{\cdot}63 \times 5\sqrt{64{\cdot}4 \times 0{\cdot}3}(0{\cdot}2 + \tfrac{2}{3} \times 0{\cdot}3) = 5{\cdot}55 \text{ cusecs.}$$

In the similar example above, with no velocity of approach, the result was 5·84 cusecs with a constant of 0· 618, so that to correspond strictly the above answer would be 5·44 cusecs. For rough work, therefore, a moderate degree of drowning may be ignored without serious error.

206. Discharge of Running Streams.—To ascertain the discharge of streams without using a weir, a fairly straight and level stretch must be found, and the channel made reasonably uniform for a certain distance (say from 25-100 ft.), according to the possibilities of the case. Careful cross-sections of the water are then made at the two extreme points and at several equal intervals between them, by measuring the depth at, say, 5 or 10 points on each cross-section. If the stream is of uniform width a mean cross-section can be plotted, by taking the mean of all the measures of depth in the centre, and similarly of all the measures at each other gauge point in the width; from this section, or directly from the individual areas, the mean cross-sectional area is worked out, and this, multiplied by the *mean* velocity, gives the discharge.

To ascertain the mean velocity floats are used. These should be put in some distance above the upper fixed point, and carefully timed in their passage over the selected length. Where the depth allows it, vertical floats, reaching almost to the bed-level, will give the *mean* velocity of the upper and lower surfaces near enough for practical purposes; but they should be sent down both sides of the channel and the centre in order that the average may give a true mean value. It will be found difficult to ensure this, as the floats will seldom keep a straight course for more than 10 ft. or so. Needless to say, if there are parts of the stream with no appreciable flow these should be omitted completely from both area and velocity calculations. Sometimes practically the whole flow is confined to a deep narrow channel in the centre or at the side. Where only surface floats can be used, the mean observed *central surface* velocity should be reduced by from 25 °/₀ up to 50 °/₀ in very small streams with rough beds; the actual factor by which the observed surface velocity should be multiplied is given in Table 31 (Unwin), according to the nature of the bed and the hydraulic mean depth (*see R* in Bazin's formula, § 210).

In general the seasonal variations in these streams are so great that what is really wanted is the minimum value of the flow, preferably in a dry season following a previous dry season.

TABLE 31.—*Multipliers for Mean Velocity of Water.*

Hydraulic Mean Depth.	Smooth Channels.	Rough Channels. Rubble Masonry.	Very Rough Channels. Channels in Earth.	Channels Obstructed with Detritus.
0·25	0·83 to 0·79	0·69	0·51	0·42
0·5	0·84 „ 0·81	0·74	0·58	0·5
0·75	0·84 „ 0·81	0·76	0·63	0·55
1	0·85	0·77	0·65	0·58
2	—	0·79	0·71	0·64
3	—	0·80	0·73	0·67
5	—	0·81	0·76	0·71
10	—	0·82	0·78	0·74
30	—	—	—	0·74

207. Current Meters.—Instead of obtaining the mean velocity of a stream by means of floats and a coefficient, modern American practice favours the use of current meters, which are similar to anemometers in design. These, when properly calibrated, give the actual velocity of flow at any point where they are used, with a very small error. In regular channels of reasonable depth very accurate results can be obtained by this means; the point of maximum velocity will then be on the centre line of the stream and at about one-quarter of the depth, and the proper coefficient can be applied to this maximum. It is higher than the surface velocity, and Grunsky * gives the coefficients shown in Table 32, where W / d is the width divided by the average depth of the stream.

The mean velocity in such regular channels is found on the

* *Trans. Am. Soc. C.E.*, Vol. 66, p. 123.

centre line and at about two-thirds of the depth. It is preferable however, to take readings at a number of points and obtain the mean in that way. With irregular water courses the latter method is essential. In turbulent water the current meter is apt to give velocities and final results which are too high, sometimes to the extent of even 15 or 20 °/₀ in large rivers; but in the like conditions float measurements will be equally inaccurate. Great care is needed in taking measurements by the current meter, as its axis must be kept correctly at right angles to the flow. In taking readings at, say, 10 points on the cross-section two methods are in vogue. In the one, the meter is slowly lowered at each point on the cross-section, at a uniform rate, allowed to remain for ¼ min. at the lowest point, and then slowly raised

TABLE 32.—*Grunsky's Coefficients.*

W / d.	Coefficient.
5	1·01
10	0·97
15	0·94
20	0·92
30	0·89
40	0·87
50	0·85
100 or more	0·82

again. This gives a summation of the velocities on that vertical line. By the second method, readings are taken at 1 / 5 and 4 / 5 of the depth at each point and the mean result is taken as the mean for that point. For counting the revolutions of the vane accoustic arrangements, either mechanical or electrical, are preferable to visual observation and are generally used. For purposes of calibration, the meter is drawn through still water at a uniform rate.

208. Water Level Recorders and Hydrographs.—Whereever it is desirable to know the discharge of a river under very variable conditions, arrangements are made for observing or recording the height of the water at a point where careful cross-sections have been made. By means of actual gauging by one or other of the methods described the discharge is then calculated for various heights of water and a 'discharge curve' is plotted, with gauge heights as abscissæ and discharges as ordinates. Having established a correlation between the two, intermediate discharges can be read off the curve; and if the cross-section is measured for flood levels rising above the curve, the latter enables a fair estimate to be made of the extraordinary discharges. Where it is not possible to have an observer always on the spot, an automatic 'water stage recorder' can be installed. In this the height is taken by means of a float in a still-water well, connected to the river, and the results are recorded on a roll of record paper on a continuously revolving drum. The drum is actuated by a heavy weight and continuous records can be obtained up to six months without attention, provided that the apparatus cannot be damaged by wild animals or interfered with by inquisitive visitors. Thus not only the maximum and minimum discharge and the discharge at any particular time can be determined, but also the total discharge over the whole or any shorter period. Where storage is involved this is of the utmost importance. The daily discharges in cusecs can also be plotted in the form of a hydrograph, and where the working head is known power can be substituted for flow; similarly, the storage can be plotted in the form of horse-power hours.

209. Mass Curves; Duration Curves; Rating of Rivers.—The problem of determining the value of a river for power purposes has received much attention in recent years. We deal successively with (i) mass curves; (ii) duration curves; and (iii) the rating of rivers.

(i) *Mass Curves.*—If the rate of daily discharge of a river be known and recorded on a hydrograph or in tables a 'mass curve' of the river can be constructed. In this the abscissæ represent time, in days or weeks, and the ordinates represent the *total* cumulative amount of water that has passed the gauge.

Reducing matters to a simplicity which would not occur in practice, let it be assumed, for example, that a mass curve is constructed to begin on a certain date and that the discharge remains steadily at 1 cusec for a week (Fig. 48), or that the mean discharge works out at this. Then at the end of that week practically 600 000 cu. ft. will have passed. If the discharge then rose to 1·5 cusecs and so remained for the next week a further 900,000 cu. ft. will pass and the total at the end of the second week will be 1 500 000; and so on. If the flow at any time practically ceased, as may happen in dry or monsoon countries, the curve would run horizontally for that time.

These curves are used in connection with storage projects, and weekly or even monthly averages are generally sufficient in plotting them; the slope of the curve at any point gives the rate of flow at that time; and the total flow up to any point, divided by the period in which it has flowed, gives the average rate of flow over that period. Clearly if the demand is greater than the supply at any time the balance must be taken from what has been stored. Where the mass curve has the most nearly horizontal slope the inflow is least; and this represents the greatest possible continuous power demand *without* storage. If the draft curve, or line representing the average water drawn off, is plotted on the same paper with the mass curve the intervals between the two show when, and to what extent, the reservoir is being filled or emptied as the case may be.

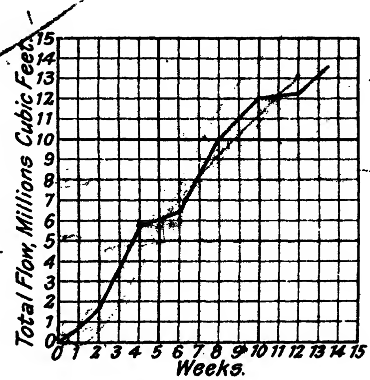

Fig. 48.—Mass curve for hypothetical stream.

The area and useful capacity of the reservoir in any particular case may be known; or it may be designed to meet the conditions disclosed by the mass curve. Similarly the amount of water drawn off from the reservoir for power may be known or the maximum which can safely be drawn off (allowance being made for evaporation) can be calculated from the readings of the curve. Thus the capacity of the stream in conjunction with the storage for power purposes, can be fully nvestigated at the beginning; and the working conditions at any subsequent time can be obtained from the curves of inflow and outflow and the balance of useful water stored.

(ii) *Duration Curves.*—Briefly, a duration curve may be defined as a curve of which the abscissa of any point shows the per cent. of time that the flow was equal to or exceeded an amount shown by the ordinate of the curve at that point. Theoretically, the curve is made by first arranging the daily flows for the period in order of magnitude. Actually, the curve is generally made from tables arranged to show either the number of days that the flow was below any given amount (deficiency), or the number of days that the flow equalled or exceeded a given amount (duration).

Theoretically the area below the curve represents the total run-off of the river at the section to which the records apply; the curve, however, gives other valuable information, as it shows the duration of the flow relative to time. Rates of flow based on the curve are easily defined, and definite rates of flow can be easily checked by computations made independently; and it presents a generalised picture of the flow and the relation of flows of various magnitudes to the duration of time.

A properly prepared duration curve will show the percentage of time that the flow is above or below any rate. It is assumed that the curve will be based on records of mean daily discharge; and curves based on other than daily flows will give rates that are

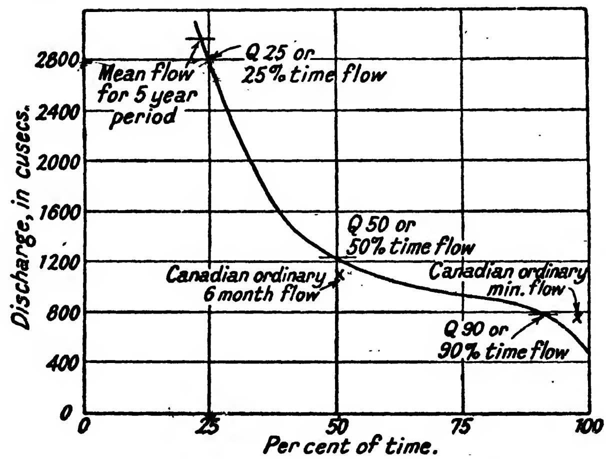

FIG. 48*a*.—Duration Curve. Showing time that flow was equal to or greater than stated amounts.

too high at low water and too low at high water. The usual method of notation, originating in America, is to call that flow which continues during (say) at least 90 °/$_o$ of the time as '*Q* 90' and so on. A curve obtained by averaging the *Q* 90, *Q* 80, . . . *Q* 10 flows, respectively, for a series of years, is not a true duration curve, because it does not show, especially at the low-water end, the relation between duration of time and actual flow.

The arithmetical mean flow of a river is about 15 °/$_o$ less than the *Q* 25 flow of the duration curve, and represents a rate of about *Q* 28; the choice of a method of expressing 'high rating' lay between these figures. It is also useful to note that *Q* 50 averages about twice *Q* 90, ranging from 40 °/$_o$ greater for rivers having a steady flow up to three times in others. The Canadian 'ordinary six-months flow' is not far from Q 50 in many cases, but there is no exact relation.

Fig. 48*a* shows a typical duration curve. For 90 % of the year in question (Q 90), *i.e.* 329 days, the flow was not less than 800 cusecs; for 275 days (Q 75) it was not less than 930 cusecs; for 183 days (Q 50) it was 1 200 cusecs or more; and for 91 days (Q 25) 2 800 cusecs or more; the maximum being over 3 000 cusecs. With a series of such annual curves, it would be possible to lay down fairly definitely what minimum flow would probably be available for any percentage of the year in future. The area between the base and the curve represents the total run-off for the year.

(iii) *Rating of Rivers.*—The necessity for a standardised method of rating rivers for power was first raised by Mr. Meares at the World Conference held at Wembley, but at the request of the I.E.C. was handed over to that body. The British Engineering Standards Association (the name was changed later to British Standards Institution) formed a sub-committee to deal with the matter, and their agreed Report was accepted by the British Committee of the I.E.C. The American Secretariat collated the reports from all countries, and the basis of international agreement was settled at the meeting of the I.E.C. in Stockholm in 1930 where the present writer (Mr. Meares) represented both Great Britain and India. The more detailed proposals of the British committee are summarised here.

Climatic conditions range from humid to arid, and from tropical almost to arctic; while there are also 'monsoon' countries, where there is neither rainfall nor stream for most of the year, but where a vast body of water comes down during a short wet season. In the latter case, storage alone dominates the problem. It is also necessary to remember that there are vast regions where no gaugings have been, or are likely to be, made, so that duration curves must give way to intelligent guesswork. It is generally useless to attempt to estimate the total power in a river basin, because by no possibility could it all be utilised, owing to nearly level stretches, etc., and innumerable tributaries; therefore, 'the term "river" should be confined to those stretches of a river-basin which it is considered possible to develop for power.'

The agreed unit of power, internationally, is the kilowatt.

The rate of flow may be expressed either in cubic metres per second ($m.^3$) or in cusecs (cubic feet per second).

The head may be expressed in metres or feet.

In the computation of power the I.E.C. recommended 'that the full power of the water and the gross head shall be used as the basis in rating rivers.' The British committee amplify this:—

'Computation of power. The rating of any stretch of a river, capable of being developed for power, should be based on the gross head available (as defined below) and on the full accepted value of the rate of flow of that stretch (as laid down below); or, in other words, that the full theoretical power in that stretch shall be expressed in kilowatts at 100 °/ₒ efficiency, without deduction for losses in development.'

In practice, the deduction made for arriving at the actual power to be utilised will vary greatly according to circumstances; 75 °/ₒ overall efficiency is a useful all-round figure.

As regards head, the British report says:—

'In any calculation of rating, the head shall be the gross head in metres or feet which exists on the stretch of river in question; that is to say, the full difference between the elevation of the water at the highest point (or intake) and that at the lowest point of return (or tail-race pool) without any addition for velocity head. If, however, it is evident that an intake dam will be necessary, then the estimated elevation of the water behind the dam shall be taken as the intake level.'

Coming now to the rate of stream-flow, the British committee points out that three categories must be considered, namely:—

(*a*) Where the normal flow is not likely to be affected by storage (other than diurnal).

(*b*) Where the normal flow is likely to be affected by main storage.

(*c*) Where storage must be the predominant factor, and where, in the absence of storage, there would be no appreciable flow for long periods—as in monsoon countries.

The committee left the actual ratings over for international consideration—see below—but recommends sub-division into (i) natural rate of flow and (ii) *additional* rate of flow due to storage, the aggregate rating to be based on the combined values of these two. They further suggest that all values should be specified as 'one-year,' 'two-year,' etc., values, the longest period being desirable. Also that the annual records to be taken should, when practicable, include: (i) a duration curve; (ii) the average daily rate of flow; (iii) the minimum flow (based on two seven-day periods) and its time of occurrence; (iv) the ordinary maximum rate of flow (based on two seven-day periods) and its time of occurrence; (v) the maximum flood discharge and the time of its occurrence. The last figure is required for designing excess-water spillways and power-station levels, unless the flood can be absorbed behind a dam. As to the actual basis of the rating, three separate ratings were put forward by the I.E.C. secretariat, and, though no final decision has been ratified by a plenary meeting, these recommendations are likely to be generally followed.

(*a*) *Low rating* on ordinary minimum flow, defined as the natural or present flow available 95 % of the time = Q 95.
(*b*) *Medium rating* on median flow, defined as natural or present flow available 50 % of the time = Q 50.
(*c*) *High rating* on arithmetical mean flow. This is about 15 % less than the Q 25 flow, as already stated, and it is probable that Q 25 will eventually be accepted.

As regards storage, the I.E.C. secretariat proposed that 'the rating of storage be based on the increase to be obtained in power capacity, expressed in terms of theoretical kilowatt-hours of energy in the water stored,' as proposed by the British Committee also.

[The full text may be found in I.E.C. 14 (Great Britain), 101; and in I.E.C., R.M. 89, of Advisory Committee, No. 14, but these are at present not available to the general public. B.S. Specification No. 610—1935, Rating of Rivers for Power Purposes, was drafted by the present writer (Mr. Meares).]

210. Bazin's Formula.—As a check on results obtained as in § 206, Bazin's formula may be applied to ascertain the mean velocity, namely: $V = c\sqrt{RS}$.

Where R = the hydraulic mean depth, or the area of cross-section of waterway divided by the wetted perimeter, *i.e.* the length of the wetted border in lineal feet; these factors can both be obtained from the cross-section.
S = the sine of the angle of inclination of the water surface, or the fall of that surface in a unit of length.
c = a coefficient, found from the formula $c = 157{\cdot}6 / (1 + m / \sqrt{R})$, the values of m being dependent on the nature of the channel, as in Table 33.

The slope in this case must be determined by precise levelling; and the converse case, where the slope of an artificial channel is

TABLE 33.—*Values of m in Bazin's Formula.*

Nature of Channel.	Value of m in Bazin's Formula.
Very smooth. Smooth cement, planed timber	0·109
Smooth. Planks, ashlar, bricks	0·29
Rough. Rubble masonry	0·83
Rougher. Earth newly dressed or pitched whole or part with stones	1·54
Very rough. Ordinary earth channels	2·36
Excessively rough. Channels encumbered with weeds and boulders	3·17

to be found from the remaining known factors, is the more usual application of the formula.

From a comparison of a number of formulæ quoted by Buckley (*Irrigation Pocket Book; Spon*), it would appear that the results given by Bazin's formula are decidedly low for small values of the hydraulic mean depth. A recent writer has suggested as a value for the coefficient above, $c = 117R^{0\cdot26}$.

211. Size of Open Channel or Flume.—Bazin's formula in the preceding paragraph may be applied to the calculation of the size of an open channel for carrying a given quantity of water from a stream.

For example, suppose 20 cusecs are to be carried along a square or trapezoidal channel. Assume provisionally that a mean velocity of about 3½ ft. per sec. will be used and the area of the cross-section must then be about 5⅔ sq. ft. to give the required discharge. If the flume is rectangular in section and 3 ft. wide the depth of water will then be 1·9 ft.; the actual flume must of course be higher than this, as a margin against overflow is necessary.

The wetted perimeter will be $3 + 1{\cdot}9 + 1{\cdot}9 = 6{\cdot}8$ ft.

The hydraulic mean depth, R, will be $5{\cdot}7 / 6{\cdot}8 = 0{\cdot}84$.

If the flume is lined with cement the coefficient m will be 0·109; and the value of c will be $157{\cdot}6 / [1 + (0{\cdot}109 / \sqrt{0{\cdot}84})] = 141$.

At this stage, if either the slope of the channel or the mean velocity is known, the other can be found.

Thus, keeping the velocity 3·5 ft. per sec., we have—

$$v = c\sqrt{RS}; \therefore \sqrt{S} = v / c\sqrt{R} \text{ and } S = (v / c\sqrt{R})^2,$$

$$i.e.\ S = (3{\cdot}5 / 141 \times 0{\cdot}918)^2 = 0{\cdot}000\,74 \text{ or, say, 1 in 1 400.}$$

If the slope is given as 1 in 1 000, then—

$$v = 141\sqrt{RS} = 141\sqrt{0{\cdot}84 \times 0{\cdot}001} = 4{\cdot}09 \text{ ft. per sec.}$$

212. Manning's Formula.—As a further check on the results obtained by Bazin's formula, whether used for calculating a discharge or for designing a flume or channel, Manning's formula

TABLE 34.—*Values of n in Manning's Formula.*

Nature of Channel.	Value of n in Manning's Formula.
Smooth cement	0·01
Unplaned timber	0·012
Well-laid brickwork	0·013
Rough brickwork	0·015
Ditto, in inferior condition	0·017
Rubble masonry. Coarse brickwork	0·02
Canals in earth, and rivers according to condition	0·022 5 to 0·03
Ditto, obstructed by detritus	0·035
Torrents encumbered with detritus	0·05

may be employed, with the coefficients given in Table 34, *viz.*:—

$$v = (1{\cdot}486 / n) \times \sqrt[3]{R^2}\sqrt{S},$$

$$\text{or, } S = v^2n^2 / 2{\cdot}208\sqrt[3]{R^4}.$$

Taking the same example as in the last paragraph, *viz.* to find the velocity when the slope is 1 in 1 000, the coefficient of roughness n is 0·01 for smooth cemented surfaces and the velocity

$$v = (1{\cdot}486 / 0{\cdot}01) \times \sqrt[3]{0{\cdot}705} \times \sqrt{0{\cdot}001} = 148{\cdot}6 \times 0{\cdot}89 \times 0{\cdot}032 = 4{\cdot}23 \text{ ft. per sec.}$$

213. Discharge of Sluices.—Where water flows through a *small* rectangular orifice with a free fall, and with a very low velocity of approach, the mean velocity through the orifice is about $5\sqrt{H}$ ft. per sec., where H is the head in feet at the centre of the orifice; this expression is deduced from the fundamental formula $V = C\sqrt{(2gH)}$, the mean value of C being taken as 0·625. The discharge in cu. ft. per sec. is then the area of the orifice × the mean velocity. If there is appreciable velocity of approach, a less simple formula is required. If the orifice is submerged, the above relations hold good where H is the *difference* in height between the head and tail waters.

Where the head is small in comparison with the size of the orifice, the coefficient 5 in the mean velocity formula is too small; it may even be as high as 8 in some cases. The general formula in such cases may be taken as

$$V = 3{\cdot}3 \times \frac{h_2^{3/2} - h_1^{3/2}}{h_2 - h_1},$$

where h_1 is the head, in ft., at the top of the orifice
„ h_2 „ „ „ „ bottom „ „ „

214. Water Turbines in General: Pressure; Impeller; Impulse.—(1) *Medium Heads.*—For medium heads (see § 203) and, where the units are comparatively small, for low steady heads also, pressure or reaction turbines are used, in which only a portion of the pressure and potential energy of the water is transformed into velocity and kinetic energy in the guide apparatus, the remainder being transformed in the turbine wheel. In these wheels the water is admitted round the whole periphery of the runner, at a speed lower than the spouting velocity due to the head. The speed can be varied within wide limits according to the design of the runner. The Francis turbine is the modern survivor of many types. The water may pass either radially inwards or outwards; but the mixed flow turbine, which is the usual American form, is designed so that the water enters radially towards the shaft but leaves axially to the draft tube which utilises the suction head. The static pressure is 0·433 lb. per sq. in. per ft. of head. Francis wheels are now used up to as much as 1 000 ft. head, which until recently involved the use of impulse wheels of necessity; their specific speed (§ 215) has also been raised considerably.

(2) *Low, especially Variable, Heads.*—As stated above, the Francis wheel is still commonly used for the lowest practicable heads, and constitutes a very large proportion of all the world's existing plants. In recent years, however, as forecasted in the previous edition, this type has been largely superseded for low, and especially for very variable, heads by the propeller type, of which the Kaplan and Nagler wheels are the protagonists, both having very high specific speeds (§ 215) compared with anything that has gone before. This carries with it comparatively high actual speeds in r.p.m., so that direct coupling to specially designed generators is possible where gearing was formerly necessary. It is worthy of note that, after exhaustive inquiries by experts, the Severn Barrage Committee (§ 230) recommended Kaplan wheels with stainless steel runners for that project. The rival merits of the Kaplan propeller turbine with movable blades and the Nagler propeller turbine with fixed blades have been discussed vigorously in America * and Sweden,† and there appears to be room for both in modern practice.

* *Proceedings Am. Soc. C.E.*, August, 1925.

† 'Kaplan and Propeller Turbines compared.' Elov Englesson, A.B. Karlstads Mekaniska Verkstad, Kristinehamn, Sweden.

English Electric Co., Ltd.

A LOW-HEAD FRANCIS-TYPE RUNNER.

The runner illustrated is 10 ft. in diameter and weighs about 5½ tons. It absorbs 33 000 cu. ft. per min. under a head of 8·8 ft., and has a specific speed of 81 (British units); the power developed is 430 B.H.P. The plates are of thin sheet steel so as to give a large passage for the water and, in order to reduce the frictional losses to a minimum, they are ground and polished before being cast into the top and bottom rings. The edges of the blades are chamfered to reduce the losses due to shock at entrance.

[*To face p.* 394.

English Electric Co., Ltd.

BUCKETS AND FASTENINGS OF A PELTON-TYPE IMPULSE WHEEL.

In the construction illustrated one bolt and one key hold each of the cast-steel buckets to the cast-steel disc. The bolt carries the shear stresses, and the key bears the compression stresses. The bolt is tapered and fits inside a bush which is cylindrical outside and tapered inside. The bush and bolt are both provided with nuts, and the bush is split throughout its length, except at the threaded portion. On tightening the nuts, the bolt causes the bush to expand, and the locking washers are then bent over the lugs of the bucket and the faces of the nuts. The back of every alternate bucket bears against a fixed key dovetailed into and welded on to the disc. The two buckets between consecutive fixed keys are tightened by a pair of oppositely-tapered keys which, when driven home, are bent over on to the face of the disc, thus forming, in effect, a single key.

[*To face p.* 395.

Propeller Turbines (Moody and Nagler Type).—The propeller wheel has been defined as one 'wherein the flow within the runner itself is in a direction mainly parallel to or cylindrical about the axis of rotation,' coupled with a suction tube,* the combination having a high specific speed N_s compared with a Francis wheel. The type is not a modification of the Francis wheel, but a direct descendant of the very ancient 'tub-wheel.' It was anticipated to some extent by the 'Green Mountain' wheel of Truax (1860) which had the same general shape of runner, spoiled, however, by a rim round the blades.† It is usual now to confine the term 'propeller wheel' to that developed and described ‡ by Nagler, who prefers, however, that his name should not be used for the type. The fixed-blade runner of a propeller wheel is extremely simple in design, having four blades of appearance similar to those of a ship's propeller, except that the outer ends, instead of being rounded off, are all on the circumference of a circle struck from the axis as a centre, so as to fit the casing. An end on view shows that only about half the projected area of the full circle is occupied by the blades. In the paper referred to above, Mr. Nagler states that:—

'31. Investigation of thrust and power shows that the force on each blade exceeds the product of blade area and the total apparent head, which can only mean that in such cases there is less than atmospheric pressure on the back side of the blade aside from that due to draft head. This is strictly analogous to the distribution of the total force on the wings of an aeroplane, less than half of which is pressure from below, the remainder being suction on the upper surface. As such suction action is in evidence primarily with these high speeds, the author believes the term "suction" to be peculiarly applicable to this form of turbine runner.'

American practice appears to favour the adoption of the propeller wheel in place of the Francis, on account of its high specific speed (often over 200 British or 900 metric) and general simplicity, coupled apparently with the fact that it is a purely American device. For variable heads it certainly cannot compete with the movable-blade runner of Kaplan. Its efficiency, though high at full load,

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* *Trans. Am. Soc. C.E.*, Vol. 89 (1926), p. 648.

† As to the specific speed of this wheel, *see. Trans. Am. Soc. C.E.*, Vol. 85 (1922), p. 1263 and *loc. cit. supra.*

‡ 'A new type of hydraulic Turbine runner,' Forrest Nagler. A paper presented at the annual meeting of the *Am. Soc. M.E.*, Dec., 1919, and reprinted in Bulletin No. 1640-CAC (Aug. 1925) of Canadian Allis-Chalmers, Ltd.

is not yet equal to that of the best Francis wheels; and as compared with the Kaplan wheel (see below) its efficiency drops off very rapidly at partial loads.

The Kaplan Turbine.—The Kaplan runner is, strictly speaking, also a propeller wheel, but the inventor's name is always associated with it. The excellent results obtained are largely due to experimental work on model sizes carried out at the works mentioned in the preceding footnote (p. 394), by the Swedish associates of Messrs. Boving of London. Three hydraulic laboratories have been designed and built for different classes of investigation,* particularly on the design of runners, guide wheels and draft tubes and on the problem of cavitation. Models have been tested with specific speed (n_s) up to 1 000 metric (228 British) on heads of a few metres, and extraordinary ingenuity has been shown in meeting difficulties. It must suffice here to mention a glass draft tube through which the water flow can be observed † and an Elverson 'oscilloscope,' operated by a neon lamp receiving impulses from an intermittent contact on the wheel shaft, which combines the function of a stroboscope (§ 123) with the possibility of illuminating the runner from *any* angle so that it appears stationary. This novel device is employed for studying (in particular) cavitation, which occurs if the pressure in the runner sinks below the vapour pressure of the water owing to vortices or excessive suction head, and causes the accumulation of vapour on the back of the blades. The 'condensation cracking' of these vapour cavities, when they collapse, causes violent water-hammer,‡ which has been proved to have more to do with the pitting of the blades than chemical action, such as oxidation of the metal. The greatest permissible suction height $h_s = A - CH$, where A is the atmospheric pressure, H the total head, and C (or σ, sigma) the 'cavitation constant.' The constant varies with different wheels and at different speeds for the same wheel; typical values are—

* *Engineering*, Sept. 24, Oct. 1 and 8, 1926.

† Illustrated in a paper on the Kaplan Turbine by G. Molinder; *Swedish Water Power Association's Publication* 140, 1922.

‡ The British Admiralty 'Propeller Sub-Committee,' which investigated pitting on ships' propellers, gave calculations showing that a surface pressure of 24 tons / sq. in. could be attained if a cavity collapsed to one-tenth of its original size and of 765 tons / sq. in. if reduced to 1 / 100. (*The Engineer*, Oct. 17, 1930.)

For Francis wheels:—

n_s	80	100	200	300	400	450
C	0·04	0·05	0·08	0·15	0·3	0·45

For Kaplan wheels:—

n_s	500	600	700	800
C	0·5	0·7	1·2	1·9

The turbine is a propeller turbine with movable blades, capable of adjustment according to the angle required for various heads, and is therefore more complicated and more expensive than all other types; but *per contra* it has a higher efficiency over a longer range and under wider variations of head than any other wheel, and it has also a higher specific speed, which means a saving in the cost of the generator. Owing to the favourable efficiency curve (see below) it is possible to use a few large units instead of many small ones, thus making a considerable saving in the initial cost of a plant. One of the early ones which the present writer has seen at the Swedish Government power-house at Lilla Edet (on the river Gota, below Lake Vanern) has a runner of 19 ft. diam. and gives 11 200 B.H.P. at 62½ r.p.m. on 21·3 ft. head with a consumption of 5 700 cusecs.* The head actually varied from 18 ft. to 25 ft., but further regulation works have diminished this variation. The four blades have no overlap, but considerable space between them, as described above, for normal propeller runners; they can be turned either way, so as to increase or diminish the pitch, by means of an oil-pressure servomotor incorporated in the boss. A second and interconnected servomotor varies the opening of the guide blades. As one result of the laboratory work referred to above, the concrete spiral channel feeding the wheel was at first made unusually high in proportion to its width,† with good results, though subsequent research has shown that this form of spiral is not the most suitable, as it gives a little more friction than one that is not quite so narrow.† Similarly, the draft tube was designed on data obtained by small-scale laboratory tests; and as there is considerable conversion of velocity head into pressure head in the tube, it is a vital factor in obtaining high efficiency. The draft

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* *Engineering*, May 20, 1927.

† Incidentally, this feature of design has also been found to improve the accuracy of measuring weirs, which have hitherto generally been long and shallow.

tube is (in Kaplan's design) of considerable length; running vertically downwards and of circular section at the start; of oval section with the long diameter horizontal at the bend; and thence straight and converging outwards and upwards to the tail race. Efficiency tests were carried out at three different heads; the volume of water was determined by current meter, the head by direct measurement between the upper and lower water levels, and the power by the two-wattmeter method. The most noticeable feature of the tests is the very flat shape of the efficiency curve from about 1/5 F.L. upwards and the superior efficiency to other types at very small loads; pre-construction guarantees were in every case improved upon (by 10 °/₀ at 5 000 B.H.P.) and the results were as follows:—

Efficiencies.

Head in Feet.	5 000 B.H.P.	10 000 B.H.P.	
18·3	91·7	88·0	80·0 at 11 200 B.H.P. max.
21·3	91·3	90·5	82·7 „ 14 130 „ „
23·0	92·5	91·0	81·0 „ 15 000 „ „

The results at fractional loads and the uniformity under varying heads are the outstanding feature of the tests. The efficiencies calculated according to Moody's formula from the test models, which had to be relied on for the guarantees, were fairly close to, but below, the actuals. As this was at the time the largest wheel in the world, it is interesting to note that since then wheels with similar runners of 24 ft. 4 ins. have been constructed for the Svir III power station in Russia, giving 37 500 B.H.P. at 75 r.p.m. under 36 ft. head and 42 000 B.H.P. at the maximum head; these runners are also of stainless steel in order to avoid pitting from any cavitation there may be. Larger still is the runner for the Kaplan turbine for the Vargön power-house in Sweden, namely 26 ft. 3 ins. diameter to operate under a normal head of 14·1 ft. and develop 15 200 B.H.P. at 46·9 r.p.m. This station is to be an automatic one, with no attendance, and without buildings; the generators are of the open-air type (as also proposed for the Severn Barrage), the whole being raised well above water level and fed by a rising syphon inlet, so that the whole of the power is obtained from the draft tube side.

The limit of head for Kaplan wheels appears to be about

115 ft., above which Francis wheels still hold the field until the impulse wheel takes up the running; even at this head the specific speed and suction head must be kept comparatively low to avoid cavitation, the former not above 130 British (600 metric), though on low heads Kaplan wheels are running which have a specific speed of 220 British (1 000 metric).

Taking the point of highest efficiency as the normal rating—and this appears equitable—the overload capacity of a Kaplan turbine is about 50 % as compared with 5 to 10 % for a fixed-blade propeller wheel and 10 to 15 % for a Francis turbine. But the overload capacity of a Kaplan wheel varies with the head; at low heads, *i.e.* up to 8 or 10 metres (26 to 33 ft.), the overload capacity is about 50 %, whereas at the highest heads there is hardly any question of overload, as the efficiency does not fall as the load is increased to full. At the highest heads the turbine could not, because of the risk of cavitation, carry a load more than slightly (10 to 20 %) above that at which it gives its best efficiency. Kaplan wheels are mostly used where the head is very variable; and while at the highest heads there is no real need of overload, this is of paramount importance at low heads. Conditions at low heads being more favourable from a cavitation point of view (this applies to propeller wheels generally), the turbines can be over-opened and thus a considerable overload capacity obtained.

Owing to the comparatively high speed of a Kaplan, the cost of the generator (or, alternatively, of the gearing necessary with a Francis) is much reduced in comparison with a Francis. The cost of generators varies approximately inversely to the square root of the speed, and as this is doubled with a Kaplan, the cost of the generator for the Francis (if direct-coupled) will be some 40 % higher. The extra cost of a Kaplan over the other two types (propeller and Francis), for the same maximum output and for heads up to about 10 metres (33 ft.), varies from about 50 % with small runners of 3 ft. down to 15 % for 20 ft., though for runners of the same diameter (instead of power) these percentages are about 75 and 35 respectively. For higher heads, prices are a little less favourable for Kaplan wheels; but, on the other hand, there is the advantage of being able to reduce the number of units as compared with Francis wheels with their much less level efficiency curve. As the cost of the turbine averages only about

10 °/₀ of the total cost of the plant, the extra cost becomes insignificant compared with the advantages gained in level efficiency over great ranges.

(3) *High Heads.*—For high heads impulse wheels (§ 253) are invariably used; in these the water is thrown on to the wheel from a nozzle at the full velocity due to the head. Here the casing is not filled with water, as in the former case, so a draft tube cannot be used. The form of the buckets is too well known to require description; the Doble form, in which a portion is cut away to allow the jet unimpeded access to where it can act most efficiently, is universally employed.

For a full discussion of the theory of these different types of turbines and their various subdivisions, the reader is referred to the works mentioned in the Bibliography, § 258, and to manufacturer's lists. The theoretical velocity in ft. per sec. of the water issuing from a nozzle $=\sqrt{(2gH)}$, where g is the acceleration (32·2 ft. per sec.^{2}) due to gravity, and H is the net head in feet, *i.e.* the gross vertical head less the friction losses in the pipes (§ 247). Thus on 10 ft. head the theoretical velocity is 25·3 ft. per sec., on 100 ft. head it is 80 ft. per sec., and on 1 000 ft. head it is 253 ft. per sec.; the actual issuing velocity is less by about 3 °/₀. The peripheral speed of an impulse wheel is a little less than half the theoretical velocity of the water, while in low-pressure wheels the speed can be varied within wide limits according to the design, as noted in dealing with variable heads.* Obviously, in either case, with a given head, the angular velocity will depend on the diameter of the wheel. It is often necessary, or advisable, to use two or four smaller wheels on a single shaft, instead of one large one, in order to increase the speed or reduce the cost of construction.

215. Specific Speed of Turbines.—In order to compare the performances of different turbines, and to utilise a standard design under varying conditions, a common basis is found in the 'specific speed' or the speed which would result if the wheel were reduced in exact geometrical proportion until it gave 1 H.P. under a head of 1 ft.—or, on the Continent, of 1 metre, though British units are used here.

* *See also* 'Run-Away Risks of Water Turbines,' P. Attlmayr. *Elek. u. Maschinenbau*, Vol. 40, p. 487; *Sc. Abstr.*, 304 B, 1923.

Rushmore and Lof define the specific speed as 'the number of revolutions per minute at the point of maximum efficiency that a homologous or geometrically similar wheel would give if it were to deliver 1 H.P. under unit head'—*Hydro-Electric Power Stations* (Wiley).

The specific speed should be as high as is practicable in reaction wheels working on low, and especially on variable low heads. Assuming a constant head and a wheel in which all parts and passages are of exactly the same relative proportions the velocity of the water will remain constant; in which case the quantity of water and the H.P. developed will vary as the square of the diameter, D, of the runner and the r.p.m. will vary as $1/D$, whether the unit head h is taken as 1 ft. or as 1 metre:—

$$\text{Specific speed} = \text{r.p.m.} \times \sqrt{\text{H.P.}}/h^{5/4}.$$

If the head is expressed in metres (= ft. / 3·28) and the power in metric H.P. (= 0·986 British H.P.) the formula is of course unchanged, so the results expressed in metric specific speed are larger; thus:—

Metric specific speed = 4·38 × British specific speed.
British „ „ = 0·228 × Metric „ „

With more than one runner or nozzle the H.P. of a single one should be used.

Pelton wheels have comparatively low specific speeds, varying from as low as 1 up to 6½ or 7 (British) = 4 to 31 metric.

Thus in a particular instance, the head is 550 ft. and the 500 H.P. Pelton wheels work at 500 r.p.m. This gives

$$\text{Specific speed} = 500 \times \sqrt{500}/550^{5/4}.$$

But $550^{5/4} = 550\sqrt{\sqrt{550}} = 2\,660.$

So specific speed = 500 × 23·7/2 660 = 4·45 in British units = 4·38 × 4·45 = 19·5 in metric units.

On the other hand, Francis wheels have much higher specific speeds, varying from as low as 20-30 British (88 to 130 metric), on comparatively high heads of 400 ft. or more, up to several hundreds on very low heads. Efficiencies of 90 °/ₒ at full load have been obtained at all values of N_s from 25-90.

Thus a 500 H.P. reaction wheel working at 500 r.p.m. on a 50-ft. head would have a specific speed of $500 \times \sqrt{500}/50^{5/4} = 84{\cdot}1$ or, in metric units, 368.

If any catalogue of small turbines is examined it will generally be found that the whole of the wheels in one series have the same specific speed, which is generally not stated in the case of British manufacturers.

Propeller type wheels have far higher specific speeds than Francis wheels, for which the highest record is 500 metric. Since 1912, when Kaplan published his new turbine theory, great advances have been made, a specific speed of 900 metric being reached within a year. By 1921 a figure of 1 200 had been reached, largely by a reduction in the wetted surfaces of the runner wheel through reducing the length of the blades, which was originally nearly double the pitch, but also by reducing the number of blades. Further advances up to 1 600 metric appear probable, though there are cases where too high an actual speed (and this corresponds more or less to the specific speed) is undesirable for reasons connected with the frequency of the alternators. These new types of wheels are discussed in the preceding paragraph.

216. Cost of Water-power Plants.—It is difficult to give any reliable estimates of the cost of water-power development, as no two undertakings are alike. In a table given by Dawson, the *pre-war* capital outlay per H.P. ranges from £3 10s. to £84. Table 35 gives the capital cost (*pre-war*) of a number of hydro-electric developments in the East; the figures represent the total cost per kW capacity of everything up to the power station end of the transmission line.* Developments in mountainous country with heavy rainfall are generally subject to additional expense on account of landslips, where the ground has been cut away for open channels, etc. A substantial percentage should invariably be added to allow for this costly contingency. The prices of turbines given in makers' catalogues are useful as a general guide, but the turbine is a comparatively small item in the total cost, especially on high falls where a simple impulse wheel is used. In 1918, *Engineering* (Jan. 25, 1918, p. 100) gave as an approximation for wheels alone:—

For low heads, up to 25 ft., £4 per H.P.
,, high ,, ,, ,, 500 ,, £1 ,, ,,

but present-day prices are still well above these limits. The cost of the Serra hydro-electric plant, at São Paulo, Brazil, including a certain amount spent with a view to later extensions, was £30 per

* The pre-war capital cost of hydraulic construction up to and at the power site, and of the power station and equipment, averaged £14·40 in 70 representative Canadian hydro-electric stations, aggregating about 750 000 H.P. (*El. Wld.*, July 31, 1920, p. 230).

kVA for 66 000 kVA of plant. (*Jour. I.E.E.*, Vol. 68, p. 1 300.) The cost of ten comparatively small low-head stations, working on falls on the Ganges canal, was about £25 per kW. The capital cost of a hydro-electric scheme is generally high compared with that of a steam or oil-driven plant; but the working expenses are lower and almost independent of the load (§§ 194 and 217).

When any particular scheme has been designed, quotations

TABLE 35.—*Approximate Capital Cost of some Indian Hydro-Electric Developments.*

Head in Feet.	Plant Capacity. kW.	Approximate Capital Cost per kW.	Short Description.
High heads—		£	
1 000 to 1 800	30 000	25	Small average flow; large storage; no open channels.
	2 000	30	Small average flow; large storage; open channel.
	500	66	Small average flow; small storage; no open channels.
500 to 1 000	800	66	Moderate average flow; small storage; open channel.
	500	62	
	500	30	Small average flow; large storage; no open channels.
	50	73	
Medium heads—			
250 to 500	7 000	37	Large average flow; no storage; open channel.
	4 000	43	
	4 000	53	
	300	39	Small average flow; small storage; open channel.
	150	49	
Low heads—			
6 to 30	500	60	Canal falls.
	450	20	
	250	42	
	200	100	

should be obtained from manufacturers or their agents for the turbines, generators, and regulating gear; the price may be anywhere between about £5 and £10 per kW, being higher for small sets and also for low heads. To this freight, carriage and erection must be added. High-class governors vary from £100-£300 each, according to size and power. When estimating for buildings (§ 195), it must be remembered that plenty of space is essential, and that there must be ample head room for an overhead travelling crane to erect or dismantle the sets. Concrete work is always a heavy item, and must be carefully taken out in quantities; foundations, head and tail races, pentrough, sand traps, reservoirs, channels, etc., vary enormously. The cost of the pipes and their freight and carriage to site can be estimated by the weight and cost per ton of steel work for the time being, and the ruling freights and cost of carriage; for size and thickness, *see* §§ 247, 248. Specials may amount to about 10 °/₀ extra on the totals. The cost of making the pipe line and anchorages and erecting the pipes must be added, and no general figures for this can be given.

217. Economics of Steam and Water-Power.—In all cases of water-power, large capital expenditure is necessary on the hydraulic development; furthermore, as water-power must be developed where it is found, a long transmission line is often necessary. For these reasons the total cost of construction is almost invariably higher than that of a steam-driven plant of the same capacity; and the annual capital charges for interest and depreciation are correspondingly higher. There is, however, a very large field for small automatic hydraulic plants (§ 187) accessory to central stations, and these do not fully come within the scope of the discussion in this paragraph.

Against this may be set the fact that the running costs of such a station are relatively low, as no fuel is involved. The total cost of running does not depend to any appreciable extent on whether the plant is fully or only lightly loaded; it is practically a fixed sum per annum; so that the cost *per unit* (kWh) is practically proportional to the total number of units generated. With fuel-consuming stations every extra unit generated involves the consumption of a definite amount of fuel with a definite cost; and while the *total* cost rises with the number of units generated and the cost *per unit* falls somewhat, the latter cost is by no means proportional to the total units. In any particular case, therefore, the practicability of a hydro-electric scheme depends on the cost of fuel in the locality where the power is wanted.

To take an example, assume a plant of 5 000 kW capacity is required at a certain place where sufficient water-power exists within transmission distance and that the total cost of the hydro-electric scheme and transmission line is £500 000. Taking interest and depreciation together at 10 °/₀, the annual cost on this account will be £50 000. Let the cost of a steam plant of the same capacity, built where the power is actually needed, be assumed to be £150 000 with similar annual capital charges of £15 000. Now, if for simplicity it be assumed that the annual charges for wages, stores, repairs, and supervision are the same in both cases (an assumption near enough to the truth) there will be the difference between £50 000 and £15 000 or £35 000 to set off against the cost of fuel for steam raising. Under the ideal conditions of large electro-chemical works this plant, allowing 1 000 kW to be kept for spare, and, therefore, 4 000 kW for work, would generate about 28 000 000 kWh per annum (with 80 °/₀ load factor, § 261). Under ordinary industrial conditions the output would be less than half this, or, say, 12 000 000 kWh per annum. Clearly, therefore, not only the cost of coal but also the load factor of the plant or the ratio of its actual to its possible output is of immense importance. If it is assumed that the low amount of only 2 lbs. of coal will be required per unit, with modern plant of large size, the consumption would be 25 000 tons for 28 000 000 kWh, and 10 700 tons for 12 000 000 kWh. As the amount available to make the costs just balance out between steam and water-power is £35 000, it follows that with the larger output, coal at £1·40 per ton would absorb this amount, while with the smaller output the figure would be nearly £3·27. From this example it will be inferred that as the load factor rises towards the ideal limit the advantage of hydro-electric power increases. Bearing in mind the vast rise in the cost of fuel at the present day the example is full of significance.

An interesting sidelight on the above discussion is also worthy of mention. The inexperienced financier is notoriously apt to look at present capital expenditure, and neglect to take into consideration future recurring costs; consequently, he often accepts the lowest tender to his ultimate detriment.

For instance, in the above example, it is assumed that a steam plant of 5 000 kW total capacity cost £150 000 and requires 2 lbs. of coal per unit. On the two total outputs assumed, the consumption of coal on this basis is 25 000 and 10 700 tons per annum. Would it pay to accept a tender of £120 000 for cheaper plant of the same output if the fuel consumption were then 2½ instead of 2 lbs. per kWh? The extra fuel used would amount to 6 250 and 2 675 tons in the two cases. Taking 10 °/₀ on the capital cost *saved* by accepting the lower tender, the annual saving is £3 000; the extra fuel used, even at £1 per ton, comes to about £6 000 with the large output of units and to about £2 700 with the lower output.

Thus with very cheap fuel and a 'bad load' it sometimes pays to buy comparatively uneconomical plant; but with expensive fuel and a good load factor *never*. If the cost of fuel assumed were £2 instead of £1 the more expensive plant would prove the cheaper on either the large or the small load in the example given. Much money has been wasted, and much disappointment caused, by the neglect of these principles.

In the matter of load factor an interesting contrast may be drawn between steam and water. No matter how ideal the conditions may be, every unit sold from a steam station costs a definite sum in fuel; and, therefore, even though some of the plant may be idle, there is an absolute limit to the charge per kWh below which sales would result in loss. Paradoxical though it may seem in view of all other commercial transactions, there is often practically no such limit in the case of a hydro-electric station: an exception being where the whole of the available energy can be sold without difficulty, owing to limitations of the available water. The total working costs are not affected by the generation and sale of additional units. Therefore, when all the load has been obtained that is in sight, at normal tariff rates, extra sales at any price will pay so long as they do not involve an increase in the size of the plant. They bring in money without involving any expenditure.

For example, assume, for simplicity, that a hydro-electric plant with a working capacity of 4 000 kW actually had this load during the whole working day from 6 A.M. till 6 P.M., but that for the remaining 12 hrs. its average load was only 1 000 kW, the average generating cost of a unit being ½d. under these conditions. If there were no prospect of obtaining work for the idle plant during these night hours on the ordinary tariffs it would pay to take on consumers at 0·3, or 0·2, or even 0·1d. per unit *provided* they were restricted to the use of power at night only.* Their additional consumption would bring down the average cost of a unit; thus, if night-working factories were started, using the whole available 3 000 kW, the average cost would be reduced from 0·5 to about 0·3d. per kWh; but in order to get the extra revenue it would pay to supply this factory at a far lower figure than the reduced average. It is, in fact, constantly done in actual commercial undertakings.

In considering the value of sites for industrial manufacturing work, one of the first points to consider is undoubtedly that of freight and carriage; for it has a triple application. In the first place, the raw material must be brought to the site, unless already on it; secondly, the finished product must be taken to its market; thirdly, the plant must be delivered at the power-house. Cases are known where the carriage of plant over twenty miles of mountain roads abroad cost more than its freight from the land of manufacture to the railway terminus. Cheap power is useless if the saving is swallowed up in expensive freight. In order to get the plant to the power-house there must be a road, and this road will generally be built so as to afford a suitable track for a railway. In the case of water-power from mountainous country

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* It is assumed, as stated above, that there is sufficient water for continuous working at the higher output.

there may be insuperable difficulties of ground or cost in laying out a railway to the site, though the plant can be transported there. Even if these difficulties do not exist, if the raw material of the industry is within the limits of transmission it will probably prove cheaper to erect a long transmission line rather than a railway, which may use more power than will be lost in transmission. It is simply a question of estimating which method gives the cheapest finished product. Either the material can be brought to the power-house; or the power to the factory; or a combination of both methods may be the best.

Bibliography.—*See* § 258.

CHAPTER 9.

WATER-POWER (*contd.*): DEVELOPMENTS ON LOW AND MEDIUM HEADS.

Low Falls.

218. Canal Falls.—Low-head hydro-electric installations are generally found either on irrigation canal falls or on rapids in rivers. In the case of canals the fall has generally been constructed primarily to alter the alignment of the canal from a higher to a lower level where the natural slope of the ground made this necessary; usually therefore the fall is fixed in height, subject to the variations due to the actual flow and to the rise of the tail waters. In these cases a power station can either be built across the canal itself or can be constructed at the side and connected by short diversions to the head and tail waters. The majority of such canals have falls of from 3-10 ft. or so, and turbines of the 'open-penstock' type, fixed on foundations in the water passage itself, are often used, the draft tubes either passing under the power-house or discharging into a tail race tunnel which passes under the same. An open penstock setting is one where the entry to the runner wheel has no casing, but is simply placed in an opening in the forebay, at any convenient depth below the water surface such that eddies and suction of air through vortices will not take place. Fig. 47(*a*) (§ 203) shows the plan and section of such an arrangement, representing an ordinary canal fall development.

On very low heads the width of the waterway may be insufficient to accommodate the wheels for developing the full power; if so, a short length of subsidiary canal can be constructed parallel to the main one, either on the upper or the lower level, and the power station built along the island between. In this way any length can be obtained to suit the number of generating sets. The subsidiary canal may be designed as a head race taking off above the fall, in which case the tail waters discharge into the main canal; or the head race may be the canal itself, in which case the low level subsidiary canal tails the water back lower down.

Where two canal falls occur within a comparatively short distance it will probably pay to combine them into one. This may be done by a subsidiary head race or tail race canal, as above, or by a combination of the two. More rarely it is possible either to raise the banks on the intervening stretch, so as to bring the whole fall to the lower point, or to lower the same and bring the whole fall to the upper point. The various methods are a matter of comparative capital costs.

Occasionally sites are found on irrigation systems where a canal takes off from one river and discharges into another, from which it is tapped again at some lower point. In such cases there may be a much more considerable fall, and the open-penstock system is replaced by a pipe system (§ 224).

A disadvantage of utilising canal falls is their liability to closure for annual repairs or because irrigation water is not required in the particular section involved. Continuity of supply is generally essential, so steam or oil reserve plant may be necessary, and it then becomes a question of estimates whether the double outlay is justified.

An interesting example of an extensive electrical system fed from multiple canal falls has been constructed by the Irrigation Department of the Government of the United Provinces (India),* some of the sites having been reported upon by one of the Authors (Mr. Meares) over 35 years ago. The falls in the Upper Ganges Canal are used. The discharge available at the canal headworks at Hardwar varies between 5 000 and 8 000 cusecs, and there are 13 falls between 6 ft. and 12 ft. spread along 200 miles of the canal with, of course, diminishing flow towards the tail. Kaplan turbines (§ 215) are used on the very low falls. Some 34 000 kW is available in practice, and will be developed as required, the transmission system being designed to deal with this load. The 37 000 V lines aggregate 900 miles, spread over 10 000 sq. miles of country, the cost of them (mainly steel-cored aluminium) being

* The Ganges Hydro-electric Scheme, including a System of Village Electrification; W. L. Stampe, C.I.E., *Journal of the Royal Society of Arts*, No. 4105, July, 1931.

£660 per mile for double-circuit 2 000 kW lines and £300 per mile for the 11 000 V district branches. The total cost of the original installation of 9 000 kW of hydraulic plant, with a further 1 800 kW of oil engine reserve, 900 miles of transmission, 98 transformer stations, and 220 miles of rural extensions was just over one million sterling.

219. Low-head River Developments.—Probably the commonest form of hydro-electric development is where rapids on a river are concentrated into a single low fall by means of a 'lifting dam.' A good example of this form is found above Notodden in Norway, where there is a series of dams converting what was once a mighty torrent into a series of lakes, each delivering its quota of power from a power station at the artificial fall. In this particular instance there is the additional advantage, seldom obtainable, of a series of extensive natural lakes higher up in which the excess water from the mountains can be stored and regulated exactly as required. The lifting dams in this instance are so arranged that the crest of one is almost on a level with the foot of the one above, giving a comparatively still-water reservoir in between; very often, however, in low-head river developments, the dam is little more than a low diversion dam across the stream into a penstock or forebay and pipe. In the former case, the storage can be drawn upon to a small extent for diurnal regulation but the latter case necessitates a fairly steady flow independent, of storage at the headworks. Fig. 47*b* (§ 203) shows a lifting dam lay-out with a gravity dam, which may be replaced by a hollow dam, the plant in the latter being located within the dam. A third method, proposed for the Severn tidal barrage (§ 230), is to have the whole of the electrical plant suitable for work in the open air, with very large turbine wheels inside the masonry, capable of operation in either direction according as the tide is rising or falling.

Lifting dams vary from a few feet in height up to 100 ft. or more, according to the nature of the ground, and they may be of the gravity or arched type or hollow dams of reinforced concrete. The turbines are often placed in the dam itself, the water entering and discharging through it; with hollow dams the whole power house may be contained inside it. More often, the power station will be below the dam, the turbines being fed by pipes on the bank. Sometimes a short canal may even be necessary, leading to a forebay from which the turbines are supplied; especially, as

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BELOW-FALLS VIEW OF RAANAASFOSS LOW-HEAD POWER HOUSE AND DAM.

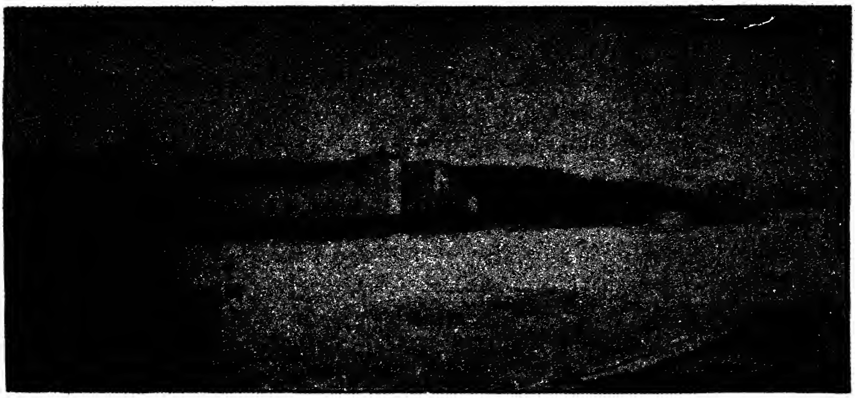
This 72 000 kVA station is arranged to utilise a minimum flow of 11 300 cusecs. For seven or eight months of the year the flow is 17 700 cusecs, and during floods it reaches 128 000 cusecs. The head on the turbines is 42½ ft. Water from the turbines passes under the power house.

Metropolitan-Vickers Electrical Co., Ltd.

GENERAL VIEW OF TYSSEFALDENE HIGH-FALL POWER HOUSE AND PIPE LINE.

This 117 000 kVA station utilises water from the 390 000 000 cu. yd. storage in Lake Ringadalsvand. The net head at the turbines is 1 260 ft. and, when this photograph was taken, there were four pipe lines, two feeding the turbines of seven 4 100 kVA generators, and two feeding the turbines of five 12 000 kVA sets. A fifth pipe, of 67 in., 59 in. and 49 in. inside diameters, feeds two 14 000 kVA sets.

[*To face p.* 410.



Metropolitan-Vickers Electrical Co., Ltd.

ABOVE-FALLS VIEW OF RAANAASFOSS LOW-HEAD STATION.

The dam is divided into sections for regulating the river. There is an outlet for ice nearest the power house. Sluices, with sluice gates at the bottom of the dam, can take the whole flow during the winter if necessary. The sector regulating gates are not used during the winter and are protected against ice by wooden needle gates. There is a tubular gate in the dam at the end opposite from the power house.

Metropolitan-Vickers Electrical Co., Ltd.

INTAKE OF THE PIPE LINES SERVING TYSSEFALDENE HIGH-FALL STATION.

Water is brought to this intake from the storage lake by two parallel tunnels, each 3 700 yds. long and 97 sq. ft. in cross-section, cut through the mountain. Each turbine is arranged so that it can take water from either of two main pipes. There is a main sluice valve at the top of each pipe, and flap valves are also fitted which, in case of emergency, can be operated by push buttons in the power house.

[*To face p.* 411.

mentioned in the preceding paragraph, where there would otherwise not be room for all the wheels. Yet again, there are instances where a tunnel has been made through the rock at the side and used (lined or not lined) in place of a pipe line.

In the case of low lifting dams, the storage above the dam is seldom sufficient to cope with more than the hour-to-hour variations of demand; if the water is drawn off faster than it flows in, the head is lowered and the capacity of the plant diminished. On medium heads (§ 225) this may be permissible. With low dams the surplus water is generally discharged over the crest of the dam itself. Arrangements have to be made for preventing debris, and especially floating timber, from entering the wheels in an open-penstock setting, or the pipes where these are used. In cold climates arrangements also have to be made for preventing anchor-ice (frazil) from blocking up the water way or even forming in the wheels themselves. Both steam pipes and electrically heated grids have been employed for the purpose. Where timber flotation is carried on, or ice is found, it is desirable, if the layout admits it, to take off the water at right angles to the river; it is then easier to deflect the floating matter by means of booms and gratings so that the forebay is kept clear, but even so additional and finer screens are necessary to protect the intake to the wheels. Automatic revolving screens are frequently installed.

Mention should also be made of rolling weirs (§ 244), installed at the top of dams, their function being automatic regulation of the overflow. At one Swedish station there is a vertical shaft sunk in the forebay, leading to a point below the falls, which automatically keeps the water level nearly constant.

220. General Design of Low-fall Plants.—The head of water available in a low-fall plant is the vertical distance between the head and tail waters immediately above and below the wheel when running on full load; both the pressure head and the suction of a draft tube being utilised. On a fall of 8 ft. every inch represents 1 °/₀, so it is necessary to ensure full size for both the head race and the tail race unless power is to be sacrificed; the velocity in these channels should not exceed 2 ft. per sec. If the depth of water over the turbine is insufficient, there is a danger of drawing in air and destroying the suction; about 5 ft. should be allowed when possible. A serious difficulty in low-head plants is the reduction in the working head which occurs from the backing-up of the tail waters in times of flood. In the Moody ejector turbine there is a connection from the water behind the dam to the draft tube, with gate control. When the head is reduced, water under the full head is thus allowed to enter the draft tube, increasing the velocity in it and compensating for the reduction due to change of level.* The depression below the 'standing wave' has also been utilised for the same purpose of compensation.† Both vertical and horizontal reaction wheels are used, and for very low falls they are generally placed directly in an open penstock or flume, and not cased in at all. The use of automatic generating stations to make profitable the utilisation of small streams with variable flow has been mentioned in § 187.

221. Low-fall Turbines and Regulation.—At the present day propeller wheels [§ 214 (2)] which can be made of very large diameter and capacity, are mainly used for very low variable heads. For steady heads the Francis wheels still holds its own; and until the advent of the new types it was almost universal. Frequently two or four Francis runners are used on a single shaft, both with horizontal and vertical wheels, and even eight runners have been used on a horizontal turbine of this type; the number is determined by the power required, as on low heads the size of a single runner soon reaches practicable limits. The regulation of the entry of water is effected by gates actuated by the governor, and as lubrication can only be carried out when the wheel pit is emptied there is always a possibility of the mechanism sticking. The gates may be of three types, *viz.*: a cylinder gate moving parallel with the shaft; a 'register' gate, revolving so that the passages in it may be made to correspond or otherwise with fixed openings; or a pivoted series of wicket gates, actuated by a ring and crank so as to increase or decrease the water way.

222. Power on Low Heads; Water Used; Speed.—Owing to the low speed of turbines (other than those of the propeller type) under very low heads, an indirect drive is always necessary, as the cost of direct-coupled generators would be prohibitive. We have then (§ 201)—

$$\text{kW} = \text{Cusecs} \times \text{Head} / 15{\cdot}5,$$

so that, for a 7 or 8 ft. head, the kW output will be about half

* *Science Abstracts*, *B*, 453 (1922) and 749 (1922).

† Professor Gibson in *El. Rev.*, Vol. 91, Nov. 17, 1922.

the number of cusecs. Dealing with such a great volume of water as this means a large expenditure on excavations and foundations. According to the design of the blades, a considerable variety of speeds is possible without reducing the efficiency; for particulars of speed and output, manufacturers' catalogues must be consulted. In order to obtain a higher speed for a given output, double or quadruple wheels, mounted on a single shaft, are often used; the smaller diameter, with the same peripheral speed, gives a greater number of revolutions per minute. With propeller wheels both the specific and actual speed are far higher (§ 214) and direct driving is possible with very high efficiency. It may be taken that kW = cusecs × head / 13·5.

223. Variable Heads.—In the case of low falls the working head often varies considerably. If the available quantity of water is much in excess of the demand, it may be convenient so to arrange the head and tail channels as to work always on the minimum head, the excess of head (when present) being sacrificed. This is not difficult to arrange in the diversion channels, by means of an adjustable weir in both head race and tail races. If the whole of the available power can be utilised, according to the head for the time being, then (*a*) the output of a given turbine varies directly as the square root of the cube of the head, (*b*) the normal speed with fixed blades varies directly as the square root of the head, and (*c*) the quantity of water used varies as the square root of the head also.

Thus, suppose a Francis turbine giving 100 B.H.P. on a normal working head of 10 ft., running at 130 r.p.m. and using 109 cusecs. Then, if the same wheel is made to work on 5-ft. head,

$$\text{Output} = 100\sqrt{(5/10)^3} = 100\sqrt{0\cdot125} = 35\cdot4 \text{ B.H.P.}$$
$$\text{Speed} = 130\sqrt{(5/10)} = 130 \times 0\cdot71 = 92 \text{ r.p.m.}$$
$$\text{Quantity} = 109\sqrt{(5/10)} = 77 \text{ cusecs.}$$

A reference to any catalogue will show that these relations hold good, and the specific speed (§ 215) will be found to be 74 in both sets of conditions.

The actual speed in r.p.m. can be varied by making the diameter larger or smaller and also by varying the bucket design and the angle at which the water enters; thus for a given head and power the highest practicable speed may be six times the lowest.

With movable-blade (Kaplan) propeller wheels (§ 214) it is possible to keep the speed uniform over an extreme variation of head, which simplifies such problems as that of tidal power greatly.

Under great variations of head with Francis wheels, the voltage is maintained constant by shunt regulation and interpole generators; at Chester the working head varies from 2 to 9 ft. The use of two turbines on the same shaft is also sometimes adopted. There are some advantages in the use of vertical shaft Francis turbines geared to umbrella-type generators. Such turbines can be provided with a correctly formed suction tube for the utilisation of energy which would otherwise be lost, and the spiral inlet chamber makes possible higher inlet velocity than could be used with horizontal turbines. The generator may run at 10 or 12 times the turbine r.p.m. and can therefore be a relatively small and cheap machine. The vertical shaft permits the power-house floor to be well above flood level, and the fact that the turbine and generator are not co-axial permits the turbine runner to be removed without disturbing the generator (*see also Science Abstracts*, Vol. 25, B, p. 581).

Note.—Paragraph 230 (*Storage and Tidal Power*) *should logically come here, under "Low Heads"; but the original arrangement has been adhered to, since paragraph* 230*a is cognate but deals with medium heads.*

Medium Falls.

224. General Lay-out for Medium Falls.—The limits of a medium head of water are incapable of definition; low heads gradually merge into medium, and medium into high. It is often doubtful whether an open-type, low-fall turbine should or should not be used on heads of the order of 10 ft. and upwards, or whether an enclosed reaction turbine with a supply pipe will meet the needs of the case better. When dealing with heads where a supply pipe must necessarily be used, the question arises as to where an impulse wheel becomes preferable to a reaction turbine; probably the limit here will be in the neighbourhood of 800-1 000 ft. Recent advances in the design of Francis wheels, under the stress of competition with propeller wheels, has raised the head up to which they can be used to these limits.

As in the case of low falls, so long as the reaction type of wheel is used the 'head' is the vertical distance between the head and tail waters at full load, a draft tube being employed to utilise the suction head. When the jet impulse or Pelton wheel is employed the fall is classified as 'high head' (Chap. 10). There is an immense variety in the forms of hydraulic lay-out suitable for medium heads, some of which have already been discussed in connection with low heads, the difference being only one of degree; others follow.

225. Lifting Dam Lay-outs.—There is no reason, other than one of cost, why lifting dams should not be used, where the conditions are suitable, to give very considerable heads; but capital cost sets a limit. Where, however, this type of scheme is adopted the dam generally impounds a far greater quantity of water than with low heads, while the draw-off, for given power, is reduced in proportion to the increase of head. It is therefore possible to use the ponded water to a much greater extent than with low heads, as a given drop in the water level means a far smaller percentage drop in the available head. Again, the volume of stored water corresponding to 1 ft. of depth near full supply level is very much greater than when the reservoir is partially empty; the lower depths give a comparatively small volume of 'dead' or unutilised water. If the head depends solely on the dam the maximum draw-off will be of the order of one-third of the depth, as beyond that regulation would become impracticable. In designing a scheme employing a lifting dam it is necessary to investigate the extent of the afflux of the water up-stream, in order to prevent the flooding of the surrounding country. Even when there is a fair bed slope the velocity of the stream is checked and the waters bank up. A natural gorge has the same effect where a river has cut through hills.

For example, a site was investigated at Maheswar on the Narbada River in India where there were rapids giving a fall of some 20 or 30 ft. in the dry weather; it was proposed to build a low-lifting dam and utilise the site. The river, however, had but little slope except at this one point, and it was found that a gorge about 100 miles down-stream had, about a century earlier, backed the water up no less than 63 ft. at the site, where the banks were high. The consequent afflux, even without the addition of a dam, probably flooded the flat country over thousands of square miles. The small head would in any case disappear completely, as in fact it was found to do in the monsoon; and the whole power station site would be under a great depth of water.

226. Natural Waterfalls.—Most natural waterfalls come under the category of medium head falls, but there is a considerable variety of ways of developing them, as shown by Figs. 47(*c* and *d*), § 203. There must be an intake from the river above the fall into a forebay, protected as already explained in the case of low heads from the entry of floating debris. At the forebay there is an intake chamber for the pipes supplying the wheels, also protected by screens, and capable of being isolated in sections by gates in case repairs are necessary. The power station will generally be on the bank below the fall, and in favourable cases the length of pipe line will be short. The draft tubes will discharge into a tail race directly connected to the stream below the fall.

Special conditions, however, have been met by other arrangements. Thus several of the Niagara Falls power stations have deep vertical wheel pits containing the turbines, which discharge their tail waters through a tunnel; the wheels are connected by vertical shafts to the umbrella-type generators in the power-house on the surface, and by vertical pipes to the forebay. In other cases the whole power station has been placed at the bottom of a vertical shaft in the rock, with a similar tail race tunnel, because no suitable site could be found for surface buildings.

227. Combination Falls.—Often the nature of the ground admits or demands additional works, such as head or tail canals and diversion dams. Thus, with a natural waterfall, additional head may often be obtainable by tapping the stream above rapids higher up than the fall itself and carrying an open channel or canal to a forebay at or beyond the fall. Similarly, rapids below the fall can be utilised by locating the power-house farther downstream and using a canal to shorten the costly pipe line. Or, again, a combination of these two variations may be employed. Low diversion dams across the river are often required to level up the bed above a waterfall and ensure the supply at low water reaching the intake. These will not necessarily increase the available head appreciably, for instance where a head canal is used; but they may sometimes be sufficiently high to act as lifting dams and to raise the forebay level. Again, where the head is primarily due to a lifting dam, the use of a tail canal may enable rapids lower down to be utilised. Naturally a canal can only be employed when the ground enables it to be constructed on an approximate contour. Fig. 47(*d*), § 203, illustrates one such combination.

228. Bends in Rivers.—An occasional form of lay-out on medium heads is where a river makes a great bend and turns back on itself. If the bend has been caused by cutting through a range of hills there may be a considerable fall round it, and, by tunnelling through the intervening spur, this can be utilised for power.

A very good example of this type of lay-out (not yet developed) is found on the River Sutlej, where it emerges from the Himalayas, as reference to any ordinary atlas will show. Here an effective fall of some 300 ft. or more is obtainable with a minimum flow of about 3 000 cusecs (say 60 000 kW), which can be greatly increased if necessary by storage; and while the bend extends for many miles the tunnel and pipe line will be quite short. Fig. 47(*e*), § 203, illustrates this.

This type of lay-out might even reach the 'high-head' level.

229. Storage on Medium Heads.—As a general rule artificial storage is impracticable until the 'high head' type of development is reached, and storage is therefore dealt with more fully in Chapter 10. Until a fairly great head is reached the quantity of stored water required to tide over any considerable period renders it impracticable. Reference has already been made to the use of the water ponded by a lifting dam; but this is little more than regulating storage, to enable a varying load to be met by a constant inflow of the source. If the quantity so stored is very large it may enable a period of drought to be surmounted; but this will seldom be practicable unless the ground is extraordinarily favourable. Such conditions may, however, occur where a large level basin can be formed into a lake by a comparatively low dam, and the rainfall and run-off enable it to be refilled periodically.

Thus a project is mentioned in the Second Report of the Hydro-Electric Survey of India, 1919-20, where it was proposed to use a storage of 7 000 million cu. ft. in conjunction with a fall of only 110 ft. in a locality where the rainfall is very precarious and the minimum flow small.

Fig. 47(*f*), § 203 (from the writer's report on the Hydro-electric Survey of India), illustrates the works at the Cordite factory in the Nilgherry Hills (India) which are of the nature described.

230. Storage and Tidal Power.*—No doubt as fuel becomes more expensive tidal power may supplement other forms of hydro-electric and fuel-produced power, and projects are being examined at the present day. For the most part such projects

* This paragraph, as noted at the end of § 223, deals generally with low rather than medium falls.

will be of low-head status, but it will be convenient to consider the matter briefly here, in connection with storage. The head obtainable by damming up a tidal estuary is an intermittent one; as the tide rises, its level will reach that of the water above the dam; furthermore, it is widely variable between spring and neap tides. Only where an enormous volume of water can be stored is there an economic possibility of obtaining power on a large scale, and then it is essential to make that power continuous; the natural conditions for large storage are, however, more often found in estuaries than on dry land. In order to continue generating power during the period when the tidal head disappears it is necessary to install reserve plant. This may be fuel driven; but an alternative exists where there are natural storage sites at a considerably higher level than the tidal basin itself. In such a case, part of the tidal power can be set aside exclusively to pump water to the higher-level basins, from which it can flow down through the turbines of the reserve plant when needed. This arrangement is expensive in capital cost, as it involves double sets of plant and great expenditure on storage works; it is also uneconomical, as a large part of the initial power is subject to double conversion losses; but it may hereafter be rendered necessary owing to the increasing cost of other forms of power. It may be possible in some instances to utilise the high spring tides to fill high level basins, which can be kept in reserve to supplement the reduced power at times of neap tide; but the amount of storage required to carry over a large power station for a week or so on a comparatively small head will always render the problem a difficult one of economics and finance.

The Severn Barrage.—The principles enunciated above, which appeared in the fourth edition (1923) have been adopted entirely in the project for a tidal barrage on the River Severn.* The project has proved to be financially impracticable by itself and a working proposition if, and only if, high-level pumping to storage from the tidal power is utilised to operate an auxiliary hydro-electric station on a very large scale. By these means, the potential power of the exceptionally high spring tides of the river could be brought

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* Report of the Severn Barrage Committee of the Economic Advisory Council, with Appendix, Plans, etc.; H. M. Stationery Office, 1933.

in; whereas it is obvious that it would not pay to spend capital on plant that would otherwise only be in commission for a few days in each month, though the complete barrage would be none the less necessary.

A feature of the investigation was the construction by Professor A. H. Gibson of a model of the estuary, in which the effect of various types of barrage on the tidal levels, silting, and navigation were investigated over the equivalent of many years. As the barrage would have to allow for locks to pass the shipping and for a road and railway over it, these data were essential.

In broad outline, the project involves an embankment dam (vertically above the present Severn tunnel) across and at right angles to the deep channel called the 'Shoots,' about 1 200 ft. wide, and with a maximum depth of 60 ft. below the level of low water at spring tide, the velocity in this channel reaching 8¾ knots. It is proposed to deposit two roughly parallel banks across the channel, from 500 to 1 000 ft. apart, filling the space between them with sand to give 'an approximately watertight core.'

This embankment would run to the right bank (over shallow water) and in mid-stream, beyond the deep channel, would terminate in three shipping locks. The proposed road and railway continue thence on two viaducts, giving alternative routes either up or down stream of the locks to ensure continuity. From a point just beyond the locks the turbine dam would run downstream at right angles to the embankment dam, *i.e.* in the direction of the down-flow, its length being some 4 550 ft., so as to house 72 turbo-generator units 61½ ft. centre to centre. This dam would run near the edge of the 'Shoots' on the shallow part known as the 'English Stones.' From the end of this dam, the sluice dam is to be taken off at right angles some 6 825 ft. to the left bank, on the English Stones, the dam containing 130 sluices giving an effective width of waterway of 5 200 ft.

The working head on the turbines will vary from 35 ft. down to 5 ft., so that vertical propeller-type wheels of the movable-blade pattern (Kaplan wheels; *see* § 214) with high specific speed (§ 215) are indicated. With these a constant speed of 62·5 r.p.m. can be obtained, to suit the 50-cycle direct-coupled alternators, and the guaranteed maximum efficiency is above 90 °/₀ for all heads between 14 and 30 ft. (maximum, 91·6 °/₀), while at 6 ft. it is still 79·2 °/₀. Runners of 20 ft. diameter are suggested, with the usual spiral inlet and with a draft tube with arched roof and invert of an effective discharge area of 1 000 sq. ft. The blades are to be of stainless steel, in view of sea water, to prevent pitting either from this or from cavitation (§ 214). The vertical-shaft 3-phase alternators are designed to work in the open at 11 000 V, which will be stepped up to 132 kV for transmission; eight sets of roughly 100 000 kW each (with a spare set) constitute a 'block' for working and transmission purposes. A special design obviates the provision of gearing between wheel and generator. The auxiliary power needed for the operation of the sluice gates, motor-generator sets, various oil and water pumps, the lock caissons and bridges, etc., and for lighting, is to be obtained from the grid, through step-down transformers in a service station, from which it will be transmitted all along the barrage at 11 000 V to eight substations, where it will be further transformed down to 440 V. The control of this auxiliary supply will be effected along with that of the eight 'blocks' of power, from a main control station by means of a supervisory control system (§ 869).

Each of the 72 turbine sets is to have a maximum spring-tide capacity of 17 000 B.H.P. The output per tide with 67 sets working would vary from 4·68 million units at spring tide down to 1·3 million at neap tide, giving 2 252 000 000 units per annum, with a net output (after allowing for power used on the works) of 2 207 000 000 units available for use. Put into the grid, these units could not be fully utilised, nor would they save any plant additions in selected stations, owing to the hiatus occurring at slack water.

The Report therefore proposes the construction of a high-level reservoir on the tributary river Wye, with an area of some 750 acres, containing 53·3 million cu. yds. of water between the levels of 500 ft. and 450 ft. above datum, with an effective head of 440 ft. at the subsidiary power-house. The above quantity represents over 20 000 000 H.P.-hr. stored, with a further 6½ million which could be used in the next 50 ft. of the storage. The secondary power-house, containing the motor-pump-turbo-generator units is intended to be on the lines of those described in the next paragraph (230*a*).

An efficiency of 60 % is obtainable for the double conversion of power in the secondary station, so that three-fifths of the units used for pumping are recoverable. After allowing for these conversion losses, the net result is that 1 610 000 000 units (instead of the original 2 207 000 000 from the barrage alone) would be available for the grid at *any* time and at *any* load factor, of which 700 000 000 would be from the primary plant and the balance from the secondary system. The total is about one-thirteenth of what is likely to be required for the whole country in the year 1941, when the scheme might have been under constrnction.

The estimated cost of the whole has been allocated between the power project and the road, railway and shipping portions, the former accounting for £20 334 000 out of £29 325 000, to which a further £8·4 million must be added for interest during construction. The secondary works are estimated to cost a further £11·5 million, including interest. With the reduced useful output of the combined scheme, the total cost per unit is estimated to be 0·2 372 pence, against a hoped-for overall cost in a few years of 0·3d. for a coal-fired super-station of the grid, showing a very appreciable saving on the assumed load factor of 34 %; the Committee, after taking into account the new transmission lines involved, find a margin of £1 285 000 capital expenditure in favour of the project. Bearing in mind the fact that the road, railway and shipping components (none of which is a necessity) bear a large extra amount of capital expenditure, the saving is not very great in so hazardous an enterprise. The estimated load factor of 34 % mentioned above applies to about one-half of the output of the Severn scheme; the balance (9/16th) 'would be utilised at load factors varying from 15 to 10 % for supply at periods of peak demand, when at coal-fired stations the cost of generation is more than twice that at other times'; it is about 0·9d. per unit in fact, and often more. This is the greatest advantage the subsidiary scheme possesses, for it enables *the excess power at the fortnightly spring tides to be stored up and delivered daily at peak load.* Fig. 48*b* is reproduced by the kind permission of H.M. Stationery Office from the Report of the Committee, the original covering a whole lunation. The two typical extracts here presented show the allocation of the power at spring tide and at neap tide; the former showing the elevated reservoir being filled during the working tidal hours and drawn upon at slack tide; the latter showing very little pumping, but a large draw-off between tides. In each case *D* represents barrage output direct to mains; *P*, remainder of barrage output utilised for pumping to reservoir; and *S*, output to mains from secondary (reservoir) hydro-electric plant. The combined

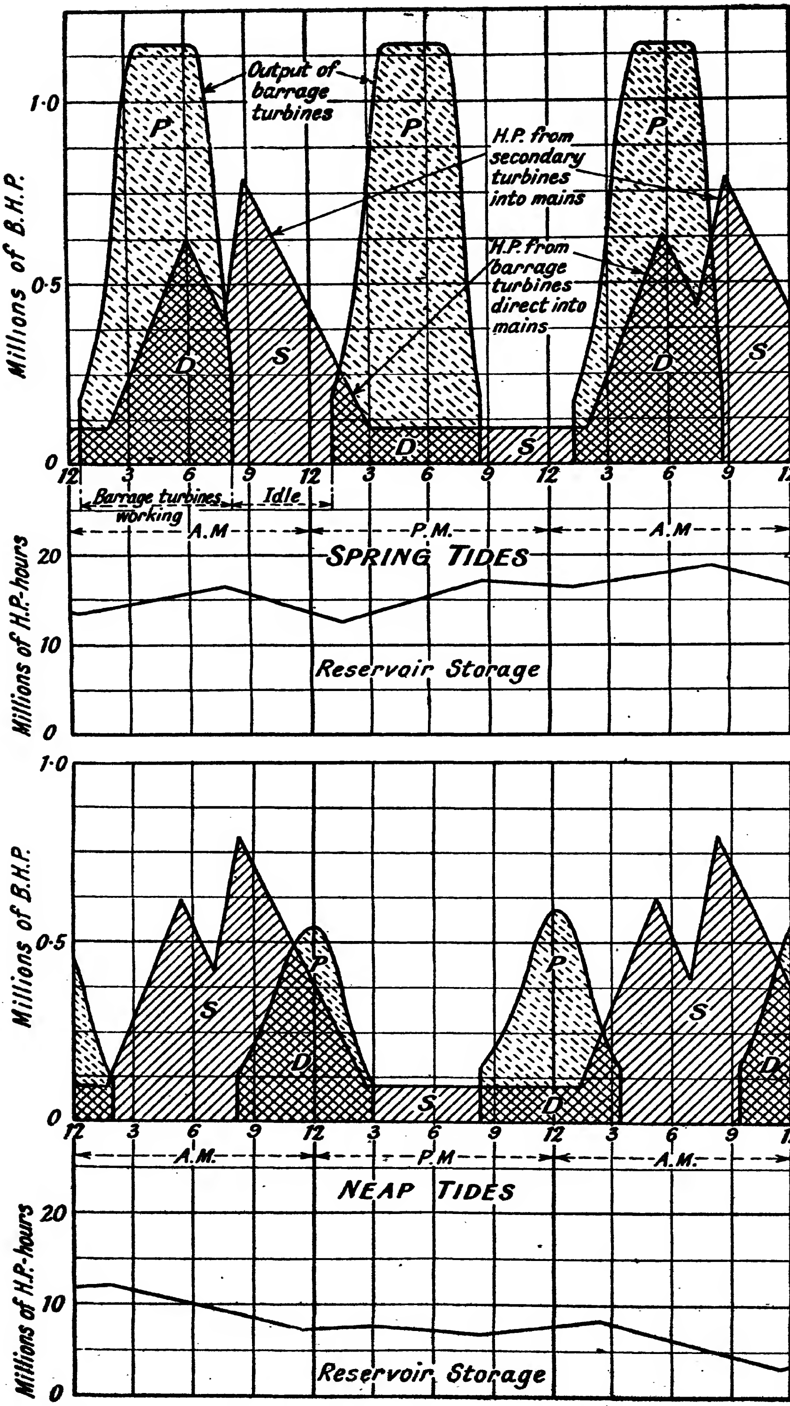

Fig. 48*b*.—Severn barrage power curves at spring and neap tides.

profile of the two lower curves (excluding the pumping power) marks the energy to be put into the grid from the combined scheme. The reservoir is gradually replenished until it is full three or four days after spring tide, and then holds 20 million H.P.-hr.; thereafter it drops and reaches its working minimum three to four days after neap tide.

Five additional double-circuit 132 kV transmission lines would be required to connect up the scheme with suitable points on the grid in the Metropolitan, central England, South Wales and South-west England areas and to transmit 550 000 kW. Four hundred miles of double line would be required, costing some £3 000 000; but much of this would be equally necessary in any case as the load rises, and only half the amount is charged to the scheme.

An obvious corollary to the scheme is that subsidiary pumped storage may be equally applicable to the off-peak idle capacity of steam plant, and this is dealt with in the following paragraph.*

230*a*. Pumping to Storage as Auxiliary to Water-power or Steam-power.—What appear to be roundabout methods may sometimes be economically sound, as for instance in the application of electric heating from a fuel operated plant, with all the losses from coal heap to radiator, in competition with a coal fire. To use hydro-electric power—and, still more, steam-power—for pumping water to the top of a fall whence it is piped to provide power again seems at first sight to be a paradoxical and inefficient attempt at perpetual motion; yet the importance of the subject is increasing and the principle is in use. At the time when the possibility of using the Humphrey pump for indirect hydro-electric development (§ 182) was first put forward in the original edition of this book, the idea of pumping water up at even small cost in order to let it fall back through turbines was considered visionary and impracticable, and that particular method has made no headway;† but, as pointed out in 'storage and tidal power' (§ 230) it may play an

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* See also 'Electricity from Pumped Storage; a corollary to the Severn Barrage investigation,' by J. W. Meares in *Elec. Rev.*, May 5, 1933, p. 629. Also 'The Grid Supply; a Severn Barrage alternative,' by the same writer in *The Times*, Aug. 24, 1933, with leading article in same issue, and subsequent correspondence. The matter was discussed at the I.E.E. (informal meeting) in Jan. 1933.

† The root idea appears to have originated with Professor George Forbes, F.R.S., who put it forward at the meeting of the British Association in Edinburgh in 1892; a fact brought to the notice of the writer by a letter in the *El. Rev.*, Oct. 13, 1933.

important part in any such project in which there are hours during which slack tide allows no generation. When discussing the economics of water-power (§ 217), the practical independence of the total running costs from the load is stressed; and it is pointed out that the by-product power (over and above what can be profitably sold) does in fact cost practically nothing with water-power and only fuel with steam. Hence it follows that if it can be made by any means to produce revenue, it is good for the undertaking.

Pumping offers this opportunity. With favourable conditions for headworks storage, coupled with shortage of natural replenishment, off-peak power can be used to refill reservoirs for use at times

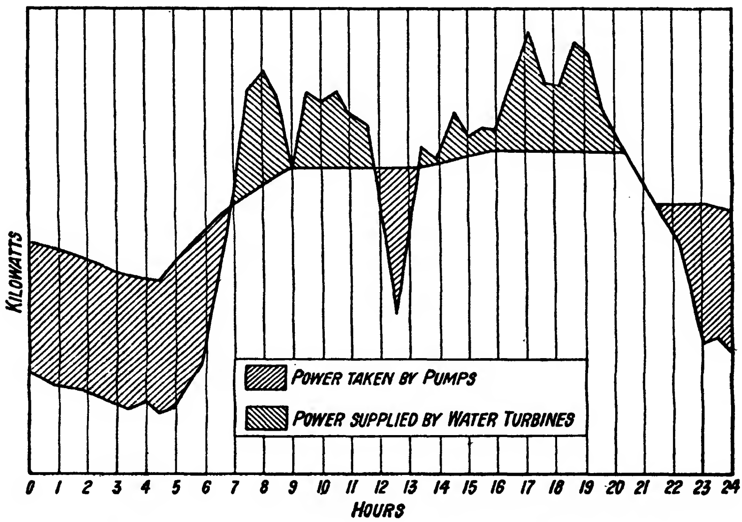

Fig. 48c.—Load curve of Herdecke pumped-storage power plant.

of heavy load; and the amount of power so taken can be varied from hour to hour so as just to keep the main plant fully loaded, without increasing the total costs in a hydro-station, and at the irreducible minimum with steam. Thus the saleable units eventually generated from the stored water (to the amount of about three-fifths of the by-product units producing the storage) cost little more than the annual capital charges of the auxiliary plant, while saving the higher annual charge on extensions of the main plant. And, as shown in Fig. 48c, this extra power cuts off all the peaks in the load curve.

The Herdecke scheme,* working on these principles, is operated

* *Power Engineer*, Vol. 26, p. 50.

in conjunction with the Goldenberg steam plant of the Rheinisch-Westfälisches Elektrizitätswerk A.G. and is coupled to a system of over $1\frac{1}{4}$ million kW capacity. Fig. 48*c* shows a typical load curve of the scheme, the hatched areas being those for which storage is responsible; the total storage is equivalent to 500 000 kWh and the combined pumping and generating plant amounts to 128 000 kW in four units. A steel-lined tunnel and pipe line (Fig. 48*d*) connects the upper and lower reservoirs, between which there is a difference of level of 535 ft. Automatic valves are installed for safety in case the velocity in the pipe rises unduly through a burst, and also air

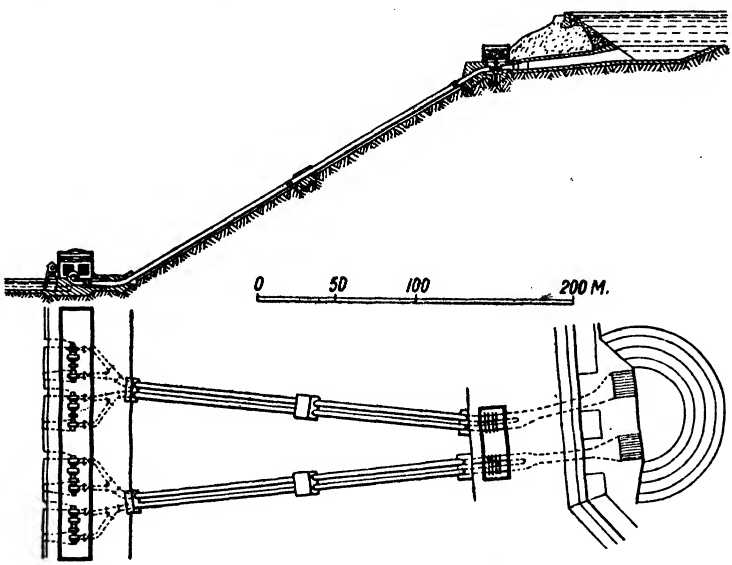

FIG. 48*d*.—Lay-out of Herdecke pumped-storage hydro-electric plant.

valves for safe filling of the pipes. The electrical machines (generator or synchronous motor as required) incorporate a rotor with high inertia (1 540 tons-metres^2) to aid the governing of the turbines, which have standard oil-pressure governors. The sets (Fig. 48*e*) are of 40 000 kVA output at 11 250 V, and are synchronised through reactors. A machine is brought up to within 2 % of synchronous speed and then allowed to hunt; the main oil switch is next closed through the reactor, which leaves only about 15 % of normal voltage on the machine; when the surges have ceased, the reactor is short-circuited and excitation applied. The connection between the pump and the turbo-generator consists of a combination of a mechanical friction clutch with a hydraulic slip coupling (similar to the 'fluid flywheel' of a Daimler car); the latter consisting of two bucket wheels, one on the driving shaft acting as a pump and the other on the driven shaft acting as a turbine, into which liquid is admitted for coupling up. In action, the combination (Föttinger's patent) starts on the hydraulic component, which brings the driven shaft up to a speed where the mechanical coupling can be engaged without shock.

The installation for utilising the surplus energy of the Kembs station on the Rhine * is another instance. Some 32 miles away are Lac Noir and Lac Blanc, half a mile apart and with a maximum head of 420 ft. between them in normal service. The volume of water which can be pumped up to the higher lake and returned through the turbines to the lower lake exceeds 70 million cu. ft.

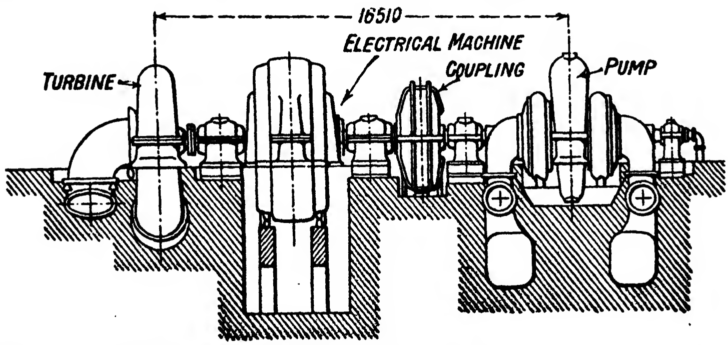

FIG. 48e.—Showing arrangement of hydro-electric set with provision for pumped storage.

An 18 ft. tunnel and 15 ft. pressure pipe connect the lakes, delivering 3 530 cusecs maximum, the velocity in the conduit being much higher than would be economical ordinarily, in order to save cost. The station contains four groups each consisting of a pump, a turbine and an alternator on the same vertical shaft. The pump and turbine of each set are connected to the pressure pipe by a Y-piece, and no provision is made for uncoupling either of them; while the pump is in action, water is expelled from the turbine runner by compressed air and vice versâ. 100 000 kVA are being installed and it is estimated that the peak energy available from the storage will average about 57 °/ₒ of the by-product energy applied to pumping.

A third plant of this nature is that at Niederwartha near

* *Loc. cit.*, Vol. 27, p. 113.

Dresden. The surplus power of the steam-operated State electricity works at Hirschfelde and Bohlen, and of the city of Dresden works is utilised at night for pumping between two artificial reservoirs. The plant groups are much as those already described. The upper reservoir has a useful capacity of 67 m. cu. ft., allowing for a drop of 31½ ft. in its water level; its earthern dam was made from material excavated from the delivery canal, which ends in a service reservoir from which the pressure pipes take off. The lower reservoir is a shallow one, with an earthen dyke, and no more capacity than is required to store the 67 m. cu. ft. until pumping begins again. The mean head between the reservoirs is 470 ft. Eventually 120 000 kW will be installed in this subsidiary power house, built on the dyke of the lower tank. Here the plant is so arranged that when the turbine is idle it is drained of water, except so much as is needed for blade cooling; while the pump is disconnected by a clutch when not in use. Interlocking prevents any wrong sequence of operations, and there are safety devices to meet all such contingencies as pipe bursts or an empty tank.

These three instances serve to show the great possibilities of the departure, provided that the necessary site for the elevated reservoir exists and that below the fall there is either a river, an estuary or another reservoir. The large interconnected power system of Great Britain has a load factor of roughly 30 °/ₒ on the average, and it is not impossible that the huge idle plant-hours capacity shown by that figure may hereafter be employed, wherever suitable ground exists, in off-peak pumping for subsequent peak-load power generation. The efficiency of the double conversion, as has been mentioned, is sufficiently high; and these subsidiary stations could be made almost fully automatic and thus cost little in running charges.

The preceding paragraph contains some information as to the pumping proposals connected with the projected Severn Barrage; and the salient fact stands out that a practicable reservoir site exists on the River Wye capable of storing 20 million H.P.-hr. So great an accumulator would offer almost insuperable difficulties in the transmission of the power to the general system of the country; but a dozen smaller ones, well distributed, would be invaluable and almost certainly cheaper than tidal power if supplied from the by-product power of the Grid. The references in the preceding footnote contain the writer's contribution to the problem.

Hydrautomat.—We may here refer to a non-electrical device, briefly referred to in § 772, Vol. 3, for raising water automatically and noiselessly through the medium of air compression and expansion. On a small scale the hydrautomat may hereafter serve a useful purpose as a subsidiary to power pumping to storage as dealt with above. Falls of water down to a few feet can be utilised advantageously.

This apparatus has been used successfully on various canals in India to provide power for such services as opening sluices, as well as for the irrigation of areas uncommanded (*i.e.* at too high a level) by the gravity supply from the canal. It follows that if in cases of tidal power the high level basin can be filled without the use of power from the plant, it is advantageous. The efficiency of the hydrautomat is generally higher than that of a ram, except on falls of only a foot or two. No attention whatever is required when once it is started, and there is nothing to get out of order. The absence of maintenance and attendance costs quickly balance any excess of capital charges, which, however, when patent rights expire, will be lower than the corresponding costs of power-driven plant.

231. Canals and Forebays for Medium Heads.—Medium falls will generally be obtained from rivers, and according to whether there is an actual waterfall or merely a series of rapids, there may be a short or a long canal or flume leading to the forebay from which the pressure pipes take off. In the former case it may sometimes be practicable to build the forebay directly on the up-stream side of the fall, and to dispense with a canal altogether. Formulæ for calculating the size of flumes and canals are given in §§ 211 *et seq.*; if the quantity of water is considerable, an earthwork canal will be used, puddled or lined if the ground renders it necessary; other types of channel are dealt with in Chapter 10. The water will be led into a forebay, from which the pressure pipes will be taken off. The supply at this point will be controlled by valves or gates, and an overflow and scour must be provided. As a rule nothing in the way of silt traps (§ 238) will be required with fairly large discharges, but strainers are necessary for catching weeds and other floating matter; a coarse 'trash rack' should be placed at the intake to protect the channel, and a finer one in the forebay, close to the gates, to protect the wheels. The usual arrangement is to have a separate intake chamber for each pipe, controlled by gates and screens, but open to the air at the top although protected there from the entry of foreign matter. This ensures that under no circumstances can a pipe collapse from external air pressure, and enables repairs to be effected easily. The capacity of the forebay needs careful consideration where any length of canal intervenes; generally a canal on a plant of this nature is kept always full, and a spill-way is constructed at the forebay so that in case of reduction of load the excess water can pass away over it; if, however, there is a necessity for economising water, as will be the case when storage is depended on, it is necessary to regulate the water at the canal intake. There must then be sufficient water stored in the forebay to enable a sudden rise of load to be coped with until the canal flow can be increased and can reach the forebay. Often it is convenient to have a long spill-way at or near the canal intake, so that when water is plentiful an excess may be always entering and when the afflux reaches the spill-way level no further appreciable rise can occur.

232. Pipes for Medium Falls; Surge Tanks.—Where the conditions are such that an open wheel in a flume cannot be employed, the water is piped down to a cased-in wheel, and a draft tube leads into the tail race. The velocity of the water in the supply pipe, if short and on a moderate head, may be as high as $0{\cdot}1\sqrt{(2gH)}$, giving 3·6 ft. per sec. for 20 ft.; 5·1 ft. per sec. for 40 ft.; and 7·2 ft. per sec. for 80 ft. Whether these maximum velocities can be realised, depends on the conditions in each case. The size of pipes and the loss of head in them under different conditions is dealt with more conveniently in connection with high heads (§ 247). As regards the thickness of metal in steel pipes (§ 248) on comparatively low heads, the result of the ordinary calculations may give too low a result for mechanical reasons. The author once saw a very large pipe (about 12 ft. diameter) on a head of about 50 ft. which had collapsed inwards; the water had been let out through the draft tube when the gate at the top was closed, so that practically the full atmospheric pressure of 14 lbs. to the sq. in. was acting upon the upper part. The pipe was more than strong enough to resist the internal water pressure, but this contingency had been overlooked. The draft tube, which on very low falls is usually a matter of 2 or 3 ft. only, may theoretically have a suction of nearly 30 ft., but in practice it should seldom exceed 20 ft.; even so, unless perfectly air-tight, there will be a loss of efficiency. At high elevations, with the barometer standing at 22 or 23 ins., the suction must be reduced proportionally, as well as in very large pipes.

Surge Tanks.—Where the slope of the pipe line or part of the same, on a medium or high head, is very gradual a stand pipe or surge tank may be necessary at the power-house or at the end of the flatter portion, as in the example in § 251. This will be of the full diameter of the pipe protected and will be enlarged at the top, so as to act as a regulator while the velocity of the water is adjusting itself to new load conditions; this stand pipe will be carried above forebay level and will act as a subsidiary forebay closer to the turbines, storing or surplussing water when the draft is checked and supplying it while the long column of water in the pipe is accelerating. Thus the speed of the wheels is kept more nearly constant as the effective head varies but little; and the larger the surface of the water at the top of the surge tower the less will the variation be. In addition to the simple type of stand pipe there is a differential type, consisting of a plain vertical stand pipe surrounded by a storage tank of larger dimensions, connected to it by inlets of restricted size. Here, if it be assumed that there is a steady load, the water in the inner and outer compartments will be at the same level. If now load is thrown off, the check to the flow causes the water in the plain stand pipe to rise to a higher level than that in the outer tank, into which it will discharge; but, as the passages are restricted, the level in the outer tank will take some time to rise to the new level, according to the difference of head. If, on the other hand, extra load were thrown on, the stand pipe would at once respond to the demand and fall in level, while the outer tank, now standing at a higher level, would refill the stand pipe at a rate corresponding to the difference in head.

Design of Surge Tanks.—The general formula for the height of the surge on instantaneous closure of the turbine supply is

$$S = V_c\sqrt{\frac{L}{g} \times \frac{A_c}{A_s}},$$

where S = height of the surge in feet; V_c = velocity in the conduit in ft./sec.; L = length of conduit in ft.; $g = 32{\cdot}2$; and A_c, A_s are the areas in sq. ft. of the conduit and surge chambers respectively. In this formula, however, no account is taken of the loss due to change of direction of flow or of eddying due to change of section at the entrance to the chamber. To allow for these a constant, C, less than unity, should be inserted before V_c.

But for a *fixed* value of C, S will vary not with CV_e but with CV_e^2, since the constant must in fact vary with the velocity V_e. In the course of an unpublished investigation of the conditions on the Andhra Valley plant in India the late Sir Michael Nethersole tentatively adopted a constant (found graphically) of 0·065 for instantaneous closure; and he further assumed that as the closure must in fact be gradual, it would be safe to assume the regulated surge, $S_r = 0{\cdot}8\ S$, giving a final constant C of 0·052. The above formula then becomes:

$$S_r = 0{\cdot}052 V_e^2 \sqrt{\frac{L}{32{\cdot}2} \times \frac{A_e}{A_s}}$$

from which the value of A_s may be calculated from:—

$$A_s = 0{\cdot}000\,084 \times V_e^4 \times L \times A_e / S_r^2$$

and if the surge is to be confined to the level of the reservoir behind the flume, h_e^2 may be substituted for S_r^2. (*See* Bibliography, § 258).

Thus, on the plant named, for a load of 60 000 e.h.p., the data are $V_e = 5{\cdot}84$; $L = 8\,700$ ft.; $A_e = 82{\cdot}5$ sq. ft.; and $h_e = S_r = 13{\cdot}5$ ft. Then

$$A_s = {\cdot}000\,084 \times 1\,172 \times 8\,700 \times 82{\cdot}5/179 = 386 \text{ sq. ft.}$$

and the reverse process gives

$$S_r = {\cdot}052 \times 34{\cdot}2 \sqrt{[(8\,700 \times 82{\cdot}5)/(32{\cdot}2 \times 386)]} = 13{\cdot}5 \text{ ft.}$$

233. Turbines for Medium Heads.—As in the case of low heads, the Francis type of wheel is most generally used on medium heads; but it is of the cased-in type, supplied by a pipe and discharging through a draft tube. The most usual form is the 'spiral-cased' wheel, in which the water passes into the wheel all round the periphery, by means of a passage graduated to suit the diminishing volume of flow as water is taken off through the guide blades. The pipes may enter either at the end of the wheel, parallel with the shaft, or at the side and at right angles to the shaft. The wheels may be classified, according to the direction of flow of the water in them, as inward-flow, outward-flow, parallel-flow, or mixed-flow, the latter being the most generally used. In this last-named type the guide blades are placed round the outside of the wheel and the water entering at the periphery flows towards the shaft as in an inward-flow wheel; then the direction changes to that parallel with the shaft and so the water discharges into the draft tube. The guide vanes themselves are hinged and used as the wicket gate for regulation.

As mentioned in § 215, propeller wheels of the fixed-blade and movable-blade (Kaplan) type are now being extensively used for low and variable heads; and their limits are being extended in the direction of medium heads.

For small powers, impulse wheels of different type from the Pelton wheel were at one time extensively used, such as the Girard, which has done good service. In this type the water from a rectangular jet emerged at the full velocity due to the head and struck the curved vanes; the water passed radially outwards from the jet, which was placed between the shaft and the periphery.

Recently the Banki turbine, an entirely novel type of impulse wheel, has been placed on the market for fairly small powers. This is a modification of the old Poncelet wheel, differing from it in that the buckets of what is practically an undershot water wheel are open at the back instead of closed. The water, entering with the velocity due to the head, passes through the forward set of curved vanes; in doing so, it delivers up about 78 °/₀ of its theoretical power but still continues to travel with considerable velocity. The water, now travelling across the inside of the wheel, in a direction slightly upwards, then strikes the buckets on the opposite side of the wheel from the inside, in the reverse direction, and delivers up the practicable remainder of its power. The wheels are cylinders with the length up to twice the diameter, and the curved vanes run parallel with the shaft; the jet is rectangular and of the full length of the wheel, the breadth being regulated by a plain gate which reduces the breadth of the jet over its whole extent; a deflector is also employed to surplus the water at partial gate opening. As in other impulse wheels, the peripheral speed is limited to a little less than half the jet velocity, or $\frac{1}{2}\sqrt{(2gH)}$; on low heads it is therefore necessary to drive the generator indirectly. The specific speed (British units) of single runners is intermediate between that of the Pelton wheel (say 1-7) and the Francis wheel (say 25-90), varying from about 11 on moderate heads up to 25 on low heads; it is stated by the makers to be 119 metric (=27·2 British) where the breadth is twice the diameter, and can be increased to double these values with four runners.

British Standard Specification No. 353 deals with 'Testing of Hydraulic Turbines'; as also does I.E.C. publication No. 41.

Bibliography (*see* § 258).

CHAPTER 10.

WATER-POWER (*contd.*): DEVELOPMENT OF HIGH FALLS.

234. Conditions of High-fall Development.—As in the low and medium falls already examined, there is a great variety of type in high-fall developments. Broadly, two divisions may be considered, *viz.:* projects depending primarily on *flow* and those depending primarily on *storage;* but combinations of the two are also common. In this connection a clear distinction must be drawn between *regulating storage*, adopted for taking care of day-to-day or possibly week-to-week fluctuations of load, and *main storage*, designed to carry the entire load for extended periods. A high working head can generally be obtained only from the flow of hill streams or the stored water of mountain catchments. The fall is generally obtained by leading off the water in an open canal or artificial channel, with a small slope, until it has reached a point where the accumulated fall is sufficient; there the forebay is constructed and steel pipes convey the water to the wheels. Occasionally sufficient fall can be obtained on the spot to enable the canal to be dispensed with, the pipes being led directly down to the power-house from a forebay at the source; this is naturally cheaper in cost and preferable when the ground admits of it. Figs. 47 *g, h, i*, § 203, illustrate some of these lay-outs; others are mentioned in § 242.

235. High-fall Projects Depending Mainly on Flow.—Where a hill river or stream has a reasonably high minimum flow and a steep descent, the limit of fall obtainable depends mainly on the distance to which the banks allow a contour canal to be constructed. When the limits of the canal are reached, or at an earlier point if the required fall has been obtained, the forebay is laid down from which the supply to the wheels is taken by pipes. If possible a large forebay or an independent regulating reservoir is a useful addition as it enables a fluctuating load to be dealt with, larger than the stream is capable of supplying continuously.

The canal may be on either bank of the stream or may be carried by means of a tunnel through the hillside to a neighbouring stream, where a greater fall is obtainable; the canal can also be continued in this new catchment, and it may be practicable to lead the waters of it into the canal also. Sometimes several streams can in this way be harnessed together, either by open contour channels alone, or in combination with tunnels, syphons, and even suspension aqueducts.

In hill streams the normal flow is generally clear, and moderate or small in amount; after heavy rain the discharge is increased many hundred fold, and the high velocity may cause it to carry along a large amount of mud, gravel, and boulders. These, despite various methods of trapping them, will inevitably tend to block up the channel and reach the forebay and the wheels, so that it may be advisable during spates to close the head-works gates; but this can only be done where sufficient storage is carried to tide over the worst period, and the problem offers much scope for ingenuity in the designer. Occasionally a high fall can be obtained from a comparatively sluggish stream, or one with a natural lake regulating its flow and clearing its waters, when the problem is simplified. By means of a dam in the stream itself it may be possible to reproduce these natural conditions, but there is always the possible silting up of this artificial lake to be reckoned with. If the water is seldom silt-laden the storage obtained in this way may be most valuable for regulating purposes.

236. Head-works.—No two streams require the same treatment at the head-works, where the water is tapped off. If the stream is a comparatively sluggish one, and the ground is suitable, water may be impounded in the stream bed itself by a dam; this will be cheaper than an excavated reservoir in proportion to the amount of water stored. In such a case it may sometimes be practicable to pipe the supply straight from the reservoir, putting in valves and strainers there. Unless the site is abnormally favourable, however, it is useless to build a dam for storage purposes if the debris brought down the stream is considerable, as the capacity will be rapidly reduced. In the case of torrents, if the bed at the head-works site is rock which can be depended upon, an inexpensive diversion into the flume will serve as well as anything; a gang of labourers can ensure continuity of supply. If the bed is not of solid rock it is liable to be scoured out and to drop perhaps 20 ft.; in such cases the flume proper should begin at a somewhat lower level than the point of tapping, so that, whatever happens, it will always be possible to lead the water into it. The loss of 20 ft. of head can perhaps be ill spared, but it is obviously safer to lose it rather than to find the flume high and dry above the remains of the head-works. So long as no such catastrophe occurs the spare head can be disposed of by discharging down a series of steps.

In some cases, following irrigation practice in canal protective works, protection against scour has been sought by means of boulder-crates, sunk deep down and continued up to the surface level; these are made up of heavy-gauge galvanised iron wire, threaded into a large-mesh cubical box, and filled with large stones. The chief advantages of these crates over masonry are that they can easily be unloaded and moved when necessary, and that they are not readily destroyed by the impact of boulders. The less masonry is employed at the head-works of mountain torrents, the more likely are the works to stand; until the flume is well above flood-level, it cannot be considered safe from destruction in flood times, and at this point there should be a by-pass back to the stream. The gates controlling the entrance to the flume should preferably be rough and inexpensive; valves stand a very good chance of sticking after a few weeks owing to mud and debris choking them.

237. **Open Channels.**—Assuming that some distance intervenes between the head-works and forebay, an open channel is generally preferable to pipe-work for conveying the water to a point above the station. The object of the channel is to convey the required quantity of water to the forebay with as little loss of head as possible. If the quantity is very large and the ground suitable a canal in earth will be used; but in the hills the conditions are adverse to this. There remain rectangular wooden flumes and semicircular iron channels, carried on trestles, both of which are very largely used in America; also concrete flumes, and, for very small discharges, even galvanised iron flumes.

In calculating the size and slope of the flume the formula given in §§ 210, 211 may be used, as in the example there given, preliminary data being assumed. The trapezoidal or semicircular shape will generally be the best, as this gives a larger hydraulic mean depth (§ 210) than a rectangular section of the same area. In constructing a flume, it is well to remember that a very slight error in the slope may either bank the water up and cause it to overflow or may increase the velocity sufficiently to wear away the material rapidly. Furthermore, at all angles in the direction of flow the friction is increased, and either the area or the slope should be increased accordingly and the afflux calculated. When in work there is always a danger of a flume becoming blocked by landslips, and the consequent overflow may wash away the track on which it is placed. To minimise the effects of this, the top levels should be varied in such a way that if the water overflows it will do so where the ground will stand it; with slopes of the order of 1 in 1 000 a slight raising of the height of the flume walls at all dangerous points will ensure this. Furthermore, at convenient points, *e.g.* where crossing small streams, the bed of the flume should be dropped and a gate put in, capable of diverting the whole flow back into the main stream. It is evident that, on steep ground, cutting away the hillside should be reduced to a minimum; a wooden or iron flume can be carried along on supports without appreciably disturbing the ground. Where landslips are inevitable, the expense of tunnelling may have to be faced. Where even small streams have to be crossed in hilly country, it is well to remember that they may become violent torrents for long enough to cut away their banks and destroy any pillar or support placed in their beds. It is therefore advisable to span the flume clear over these streams, either by a suspension bridge, where the distance is great, or by a reinforced concrete culvert or single arch for short spans.

238. Sand Traps.—Where the head on the Pelton wheels is considerable, the sand-blast action of solid matter in the water wears away the nozzles, spears, and buckets; and a reasonably clear supply is essential. If there is a large dam and reservoir at the head-works this will be assured, except as regards debris collected *en route* to the power-house; if the reservoir is at the power-house end of the flume it will indeed collect and deposit most of the solid matter discharged into it, but this will have to be cleared out from time to time at considerable expense. It is on this account expedient to build special sand traps arranged for more or less automatic cleaning. Obviously settling such as is effected for water supply is impracticable; fine mud will take days to settle, and must be left in suspension; but all except the finest silt will be quickly deposited if the velocity of flow is sufficiently reduced. Considerable expenditure on sand traps or silt tanks may be justifiable, as worn nozzles, spears, and buckets seriously affect the efficiency of the wheels and even cause considerable leakage between the closed spear and the nozzle.

To prevent the flume getting choked, it is preferable to clean the water before its entry, *i.e.* close to the head-works; this, however, is not always practicable, and traps must be placed wherever the ground is favourable. Two identical arrangements of sand traps are seldom found; the problem must be solved according to circumstances, and it will be found interesting. Practically speaking, the flume is both widened and deepened, so as to reduce the velocity of flow to 6 ins. per sec. or less. A strainer or trash-rack may be used for catching floating debris and stones. In order that a sand trap may be self-cleaning, several large gates should be provided, and the floor level should slope fairly steeply from all sides down to each gate. Baffle walls, raised to the level of the flume bottom, will direct the flow of water towards these gates, and the accumulated mud will be dislodged by the rush of water when the gates are opened. The gates must be strong but not too close-fitting, otherwise they will get jammed owing to the mud; they should be opened regularly every day to ensure freedom, even at times when the water is clear. If there is more water available than is required, a small amount can be discharged continuously at these gates, and this will tend to prevent the accumulation of mud on the floor.

The 50 000 kW plant of the Uhl River scheme in Mandi State (Punjab) works on a head of 1 800 ft. with water brought through a 3-mile watershed tunnel from a hill torrent, which brings down sticks and stones and sand. To clear the water a novel arrangement of 'decantation chamber' was evolved. This is a wide basin or sand trap which checks the speed of the flow in the usual manner, so that foreign matter sinks to the bottom; here it slips through sloping curved concrete slots or vanes into a chamber below, whence it is periodically scoured out by a strong flush of water. A further novelty about this £6 000 000 scheme is that the main supply pipe from the tunnel passes *underneath* the balancing reservoir and opens into it, so that water can automatically flow into or out of storage as the load changes, *cf.* surge towers, § 232.

It is probable that centrifugal action in a suitably designed basin, caused by the radial entry of the water, could be used for the automatic discharge of a good proportion of sand or silt, just as it collects at the orifice of a circular hand basin. The reverse operation, namely the centrifugal grading of solid bodies suspended in or mixed with water, has been successfully developed by Mr. Leonard Andrews, M.Inst.C.E. Plants are at work on a commercial scale dealing both with heavy materials, such as gravels and sand, and with impalpable particles, such as fullers earth and french chalk.

239. Regulating Storage of Water.—A regulating reservoir in a hydro-electro scheme may fulfil two functions; it may serve to augment the quantity of water available at times of heavy load, by storing the unused supply during the hours of light load, and it may act as a reserve against break-down in the water supply between itself and the head-works. Where the supply is plentiful and perennial the first function need not be considered; where the reservoir is of necessity placed at the head-works the second use disappears to a great extent, as a break-down is more likely to occur in the flume than anywhere else.

Consider, by way of example, a hydro-electric scheme with a head of 1 000 ft. and a minimum flow of 15 cusecs. Then about 1 000 kW can be depended upon continuously day and night (§ 201) or 24 000 kWh per diem. If the average load on the station is 500 kW, the daily output will be 12 000 kWh, or half the maximum, *i.e.* the load factor (§ 261) will be 50 °/₀, though the plant installed to meet peak loads would be much greater. Thus we may suppose half of the total output, or 6 000 kWh, to be generated during the three hours of heaviest load, *viz.* 2 000 kW, as would happen in the case of a load mainly for lighting. Then for these three hours the demand would be 30 cusecs and the supply 15 cusecs, so the balance would have to be obtained by storage; 15 cusecs for 3 hrs. = 162 000 cu. ft. In case of break-down to the water supply, this quantity would keep the plant working for 1½ hr. at maximum load, which would not be sufficient unless the risks of break-down were very small; but the amount of storage actually allowed for must necessarily depend on the cost of the reservoir. Where a natural site for a dam exists, it may cost no more to provide a month's full-load supply than to build an artificial tank for one day's supply.

In the example just given the actual output was assumed to be half the maximum possible with 15 cusecs available. Therefore, in the course of 24 hrs., if the efficiency of the turbines remained constant at all loads, half the available water would run to waste, or 648 000 cu. ft. Allowing for the lower efficiency at reduced load, assume that 600 000 cu. ft. would actually run off unused in the absence of storage. This then is the *maximum* amount which could usefully be stored. With this reserve it would be possible to still further increase both the plant capacity (*i.e.* the maximum load) and the total output, assuming that a demand existed. The reserve alone would be capable of giving 5 000 kW for two hours, apart from the 15 cusecs of normal flow still coming in; and the total units of output per diem could be brought up to the maximum possible, viz. 24 000 kWh, on any load factor.

Another example will serve to illustrate how the amount of storage required may be calculated where the dry-weather flow is small and a suitable site exists for a dam across a valley. The data were as follows: Maximum power required at points of utilisation, 224 kW, or 300 E.H.P.; allowing for transmission, 333 E.H.P. from the generators; 370 B.H.P. from the turbines; 493 theoretical water H.P. at 75 % wheel and pipe efficiency. Probable load factor, 30 %; so units delivered to consumers = 224 × 0·3 × 365 × 24 = 587 000 kWh per annum (equivalent to 786 000 E.H.P.-hrs.), and units generated, 650 000 per annum. Net available head of water, 220 ft. It was found that the natural flow of the stream would be sufficient to run the plant during eight months of the year, but during four months supplementary storage would be required. With a large reservoir the minimum flow ceases to be important; the average flow determines the necessary capacity. The average flow during these four months was estimated to be 1½ cusecs, which gives 16 million cu. ft. in the four dry months.

From these data, it will be seen that 786 000 E.H.P.-hrs. delivered to consumers is equivalent to 786 000 × 493 / 300 or 1 290 000 theoretical water H.P.-hrs. in the year; in four months therefore the requirements will be 430 000 water H.P.-hrs. But 1 cusec on 220 ft. head gives 1 × 62·3 × 220 / 550 = 25 water H.P. In one hour this rate of flow uses 3 600 cu. ft. of water and gives 25 water H.P.-hrs., thus using 144 cu. ft. per theoretical H.P.-hr. Therefore the total water used in four months will be 430 000 × 144 = 62 million cu. ft. Deducting the inflow of 16 million cu. ft., the *minimum* storage required to tide over the dry period is 46 million cu. ft. In most cases storage on this scale for so small a power development would be prohibitive in cost; had the head been 1 000 or 1 500 ft. the proposition would have been more favourable.

240. Points in Design of Balancing Reservoirs.—The construction of dams and reservoirs is beyond the scope of this book, but some practical points may be mentioned. If the turbine pressure pipes take off directly from the reservoir, the effective depth of the latter should be a small fraction of the total head; otherwise the variations of head between full and empty reservoir will affect the working of the plant. Symmetry in design of an artificial tank is of no importance; the object is to get as much storage as possible for a given expenditure, and every foot of ground should be utilised; this applies more particularly to hills, where the levelling off of a bluff is generally necessary to obtain a site. There should invariably be a silt trap immediately preceding an artificial reservoir; otherwise the foreign matter collected by the flume *en route* will be troublesome. A natural reservoir formed by a dam in a stream bed must, of course, take care of itself in this respect, unless it is possible to build a smaller dam farther up-stream for use as a silt trap. An overflow weir, with a safe passage for surplus water, is also essential.

It is sound practice to sectionalise the reservoir where muddy water has to be dealt with, so that one part can be cleaned while another is in use. To facilitate cleaning, there should be a slope of the floor towards the scour outlets. The part of the reservoir from which the pressure pipes are led off should be isolated from the rest, and fed normally with clear water from the top surface through fine screens and gates; but there must also be valves at the bottom of this chamber for use when the stored water has to be drawn upon. A by-pass from the flume, similarly protected should be led directly into this draw-off chamber, so that the reservoir can be closed for repairs without shutting down the plant. Obviously this diversion should pass through the reservoir silt trap, or sand will get into the pipes and valves. Continuous gauze screens, revolved by hand or motor, are more satisfactory than fixed screens, which easily get choked. The water-way through these must be sufficient to pass the full draft under the lowest working reservoir depth. If it so happens that the reservoir must be some distance from the power-house, it may prove economical not to run pressure pipes for the whole distance; the alternative is to run the pressure pipes up the shortest route to the reservoir level, and there to put a small open balancing chamber or pentrough [or a proper surge tank (§ 232)] which can be fed from the reservoir by a closed-in horizontal pipe (metal or concrete) which is not subject to any appreciable pressure. If an open channel is used, the head due to the reservoir depth would be sacrificed, and hand regulation of the water would be necessary; this is only practicable where there is a permanent excess of supply over demand.

241. High-fall Projects Depending Mainly on Storage.— A different class of project altogether has been developed in certain areas where the natural conditions are favourable, and especially in the Western Ghat range in Bombay Presidency. Here the monsoon from the Indian Ocean bursts in full force on the crests of the mountains, giving a rainfall of from 150 to over 250 ins. in the course of a few months; for the rest of the year an occasional thunderstorm is the only precipitation. In these circumstances the run-off is extremely high and the streams dry up very rapidly when the rain ceases, so that there is practically no flow for 9 months of the year. In the locality referred to, and possibly elsewhere, there are valleys at a high elevation which lend themselves to storage on an immense scale by means of high dams; but very few such localities have so far come to light.

By storing the whole monsoon flow even over a comparatively small catchment, such as is necessarily found high up on a mountain range, an immense volume of water can be stored, sufficient to keep a large power station at work throughout the year, just as large irrigation systems have long been similarly fed.

Figure 47(*i*) illustrates in section one of the Tata works in question, both involving the crossing of the main watershed of India, so that water which normally would flow to the Bay of Bengal actually is discharged into the Indian Ocean.

Thus it will be seen from the data in § 202 that 200 ins. of rain on 20 sq. mls. of catchment will give some 9 000 million cu. ft. of water; this, neglecting losses by evaporation, etc., will on 2 000 ft. head provide

$$\frac{9\,000 \times 2\,000}{500} = 36\,000 \text{ kW-years,}$$

which on commercial load factors would enable a plant of from 70 000 to 100 000 kW to be installed. There are three contiguous existing plants comparable with this example, aggregating 267 000 H.P.

242. Types of High-fall Storage Lay-out.—In the utilisation of these high level artificial lakes, several methods have been adopted. If there is a direct fall from the lake, or one of a connected series of lakes, to the power-house site the conditions are ideal. If the most favourable fall is on the opposite side of the watershed, or if two lakes are so placed, a tunnel is constructed. Thus, in the Andhra Valley works in India, a dam of 190 ft. forms a lake with a surface area at full supply level of 25 sq. mls. All the water below about 30 ft. from the surface is 'dead,' a lined pressure tunnel being cut through the watershed for about 2 mls. at this point. At the tunnel exit there is a sloping surge chamber (§ 232), also cut in the solid rock, to counteract the changes of velocity in the tunnel; and from here the pipes are carried down a steep slope to the power station some 1 750 ft. below lake level. The junction of tunnel and pipes carries the stop valves.

In other cases open channels (§ 237) are necessary to carry the water from where it is stored to a forebay from which it is piped down, with or without a surge tank.

If in addition to large storage there is also a steady inflow from the catchment area the power possibilities are to that extent increased, as no water need be lost. Thus 1 cusec flowing for a year will give 535 kWh per ft. of head. Storage projects of the nature here dealt with are generally only practicable on fairly high heads, as the cost of the dams per H.P. developed is in inverse proportion to the head.

243. Storage and Flow Combined on High Heads. — The great hydro-electric plants of Norway have the immense advantage of natural storage coupled with perennial flow from snow mountains; the rivers pass through great lakes at high altitude, which before they were used for the purpose had a large water spread. By placing a comparatively low dam at the outlet extra storage capacity is obtained, and the draft can be regulated without waste throughout the whole year. Furthermore, in the Rjukam-Notodden chain of power-houses there is a lake of this nature between the high-fall plants and the series of low-fall developments already referred to (§ 219) so that an excess or deficiency of flow from the upper side can be compensated for.

Sometimes the combination of two perennial streams, each with artificial storage from a dam, may be possible, as in the Laxapana-Aberdeen project in Ceylon, of which a plan (from the Author's report) is given in Fig. 47(*g*), § 203. The advantage of such a site is that each component can be developed separately to its full capacity, if foresight is exercised, without waste of capital on unproductive works. When the power from flow has all been taken up the storages can be developed in turn. In any such case of duplicate or multiple sources the open channels from the head-works to the forebay can be carried either round or through intervening spurs, according to the ground.

In contradistinction to this development of streams in parallel, there are many instances of power stations in series on a single source. Of these the best known is perhaps the combination of the Vermork and Saakem power-houses at Notodden in Norway. The former station utilised part of the head—some 920 ft.—of the great waterfall for the development of 165 000 H.P. for the manufacture of nitrates; and the waters were tailed down to the river below with a considerable sacrifice of the total head of 600 m. When the war broke out it was decided to use the tail waters in a second station. A tunnel 4 mls. long was therefore excavated along the mountain side, which was too precipitous to carry a surface channel; this tunnel took the tail waters from Vermork to a forebay, also excavated in the solid rock, and thence three tunnels at a very steep angle carry three pipes each down to the second power-house, which alone of all the works is on the surface.

The Uhl River Scheme,* briefly referred to in § 238, at present only uses about half the total available fall; and the tail waters of the upper component will eventually be used over again on the remaining 1 200 ft. of fall.

244. Storage Lakes.—Wherever a large volume of water is stored for power purposes it has a definite value in H.P.-hrs. or years, depending on the head (§ 202). By means of the mass curve (§ 209) and the draft curve, the conditions can at any time be seen. A complete contoured plan is made of all storage lakes, showing the capacity (in water or in H.P.-hrs.) at all levels above the off-take. If the locality is one liable to severe droughts or to partial failure of the monsoon it may be necessary to carry over a large volume of water for such emergencies; to calculate the amount so required involves a knowledge of the hydrography of the catchment over a long period, preferably 20-30 years, as well as of the average annual loss by absorption and evaporation. These last may in hot dry climates amount to from 3-10 ft. per annum. The carry-over storage involves heavy additional capital expenditure and therefore merits most careful investigation.

In many cases dams are so arranged that when necessary the water level can be raised by means of temporary flash-boards or permanent collapsing gates; in this way a large extra volume can be impounded at the end of heavy rainfall, or before the close of the rainy season. With low dams the excess water can safely be surplussed over the crest, which acts as a spillway, and gates can be arranged so as to collapse automatically when topped; a similar arrangement is also often used in river head-works below the entry of a canal. Overhead arrangements can then be made for raising the gates afresh as the flood subsides.

Another useful arrangement is the automatic floating or rolling weir. This consists of a long horizontal hollow cylinder carried on an axle with a toothed wheel at each end; the wheels engage with teeth on a sloping ramp, so that as the cylinder rises or falls with the water level it moves up or down the ramp. When at the

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* Uhl River or Mandi Hydro-electric Scheme. Punjab Public Works Department, Hydro-electric Branch. Lahore, Supt. of Government Printing, 1932.

lowest position a projection along the cylinder, parallel to the axis, closes the water-way entirely; the first rise therefore lets more water underneath than a similar rise later on. By means of valves, water can be let into or out of the cylinder, so as to alter its buoyancy as required for regulation. If sufficient excess water comes down the floods top the cylinder while also flowing under it.

With high dams the surplus water may be discharged by under sluices, but cannot be allowed to top the crest; more ordinarily a separate escape is made on a flank or saddle, either over natural rock cut down to the required level or over a masonry weir.

245. The Forebay.—Even when the pipes lead off directly from a reservoir, a section of the latter is generally isolated to act as a forebay for protection and control of the pipe inlets; where an open channel is used the forebay also acts as a small balancing tank to meet minor fluctuations of load. The capacity should then be sufficient, if possible, to carry the plant over the period required for water to arrive along the channel. Thus a plant mainly supplying factories may rise from a negligible load up to full load in the course of a few minutes, and may lose its whole load equally suddenly, at the customary hours of opening or closing. It requires nice calculation to open the full supply into the open channel at exactly the right time so that, after traversing the channel for half an hour or more, it arrives just when it is wanted. But, while late arrival means closing down the plant, early arrival means surplussing the whole flow of the channel unless the forebay can carry it.* Often the ground is steep at the forebay, and the requisite capacity is unobtainable; but the value of sufficient storage is great. Occasionally the forebay can be carried along the contour in the form of a greatly enlarged channel, but this is more expensive to build than a more nearly circular pond. The spill-way may be either at the forebay itself or at the most convenient natural outlet farther up the channel, so long as the levels allow this. Each pipe should have its own intake chamber and screens, shut off from the forebay by gates. Generally automatic arrangements are made by which the gates can be tripped and closed off from the power station in case a break occurs in the

* For example, a plant with a normal load of 30 000 kW on a head of 1 800 ft. requires 30 000 × 15 / 1 800 or 250 cusecs, equivalent to 450 000 cu. ft. for half an hour.

pipe line. If automatic valves are used at the top of the pipes themselves, an air inlet is used in combination, so that the upper and slighter pipes will not collapse under the vacuum formed as the water drains off.

246. Pipes for High-fall Turbines.—Hitherto it has been assumed that the water has been brought along to a point above the power-house, with or without a storage reservoir at some point on the route. From the forebay at the end of the flume or from the reservoir, as the case may be, pressure pipes lead down to the turbines. Various arrangements will be found in different schemes; sometimes a single pipe is used, capable of carrying the full supply, branches being taken off a receiver to the individual machines at the turbine house; preferably each turbine and generator is a self-contained set with its own pipe; or again, several pipes may be put in and interconnected by **T** or **Y** pieces with valves at the power-house. Again, the pipe may be of the same internal diameter all the way or may be graduated, the lower sections being of smaller and the upper of larger size than the average required; with high heads this latter method enables pipes of less thickness to be employed where the pressure is greatest. The static pressure on the pipes is that corresponding to a column of water of the same vertical height, whether the actual pipe line be long or short. It is 62·4 lbs. per sq. ft., or 0·433 lb. per sq. in., per ft. of head; therefore for 2 000 ft. head, which is by no means the highest in use, the pressure will be 866 lbs. per sq. in. The pressure is, of course, reduced when water is flowing; on the other hand, it may increase greatly if the flow is suddenly stopped (§§ 248, 251). A detailed mathematical investigation of the forces in high pressure pipe lines and their supports is given by A. Hruschka, *Elek. u. Maschinenbau*, Vol. 40, pp. 533, 546; *Sc. Abstr.*, 305 B, 1923.

The six-foot pipes of the Lochaber scheme of the British Aluminium Co. form the largest electrically-welded pipe line in Great Britain. The twin pipes are $\frac{1}{2}$ in. thick at the head and $1\frac{1}{8}$ in. at the bottom, and the line is 3 208 ft. long. The longitudinal seams are butt-welded and the circumferential joints are socketed and fillet-welded inside and out. The working pressure is 350 lbs. / sq. in. and the testing pressure was 500 lbs. / sq. in.

247. Size of Pipes; Velocity; Loss of Head.—When calculating the size of pipes, it is well to remember that they will not remain clean indefinitely; and the loss of head increases greatly as the pipes become encrusted. This loss varies as the square of the velocity, and, as it is important to keep the net head fairly constant, low velocities only are permissible. About 3-4 ft. per sec. may be taken as an average; 7 ft. per sec. should be the maximum velocity in the smallest section of a graduated pipe. The loss of head, H, may be calculated from the following formula: $H = v^2 \times 4m \times L / 2g \times D$,

where v = velocity in ft. per sec.
m = coefficient of friction (*see* Table 36).
L = length of pipe in ft.
g = acceleration of gravity; 32·2 ft. per sec.^{2} at sea-level.
D = diameter of pipe, in ft.

TABLE 36.—*Values of m for Flow in Pipes.*

Diam. of Pipe, Ins.	Clean Pipes. m =	Slightly Tuberculated Pipes. m =	Foul Pipes. m =
6	0·006 7	0·007 7	0·011 0
10	0·005 8	0·007 1	0·008 7
14	0·005 5	0·006 6	0·007 9
18	0·005 2	0·006 2	0·007 3
24	0·004 8	0·005 7	0·006 6
30	0·004 5	0·005 3	0·006 0
36	0·004 2	0·004 9	0·005 5

From Table 36 the value of the coefficient m can be found by interpolation on the slide rule near enough for all practical purposes, for such sizes of pipes as will generally be required.

In a particular case the diameter of a turbine pipe was reduced by nearly 3 ins. in a graduated line of 16-in., 14-in., and 12-in. pipe. An incrustation or 'furring up' almost invariably occurs to a greater or less extent; it is as well to provide for it not only by allowing extra diameter, but also with a view to removing the scale after it has formed. This can be done by means of a turbine-type tube cleaner, which is inserted at the top and then driven down the pipe by admitting a limited amount of water behind it. Such a device, however, is unable to negotiate sharp bends (of which there should in any case be none), and must be adjusted where the pipe section alters. It is therefore advisable to provide a chamber of larger diameter than the pipe at all such points, with an isolating valve immediately beyond it, and a scour pipe and valve above this main valve. Here the water and the scale will be discharged, and the cleaner adjusted for the next section. In the absence of the isolating valve there is a danger of choking the lower sections and the turbine nozzles.

Tables giving the loss of head at various velocities, for different sized pipes, will be found in catalogues of turbines; they are generally calculated on clean pipes, so an extra allowance of 30 or 40 °/ₒ will be on the safe side. For small pipes, *see* § 768, Vol. 3.

248. Thickness and Weight of Pipes.—Turbine pipes for high falls are made of steel. For exceedingly high pressures they are made direct from the ingot, weldless and perfectly homogeneous; ordinarily either welded pipes, for moderately high heads, or (for medium heads) double-riveted or single-riveted pipes are employed. The thickness of metal (subject to a minimum value of about $\frac{1}{8}$ in., to allow for possible corrosion or damage from falling stones) may be calculated from the formula $t = pr / f$ where t is the thickness in inches; p the static pressure in lbs. per sq. in.; r the internal radius of pipe in inches; and f the working stress in lbs. per sq. in. Of these factors, p is known from the head ($p = 0{\cdot}433\ h$), and r is found from the quantity of water flowing at the determined velocity :—

$$r = \sqrt{(\text{cusecs} \times 45{\cdot}8 / v)}, \text{ where } v = \text{velocity in ft. per sec.}$$

As regards f, the ultimate strength of steel may be taken as about 25-30 tons per sq. in. and the working stress, f, about 9 800 lbs. for riveted pipes up to 14 000 lbs. for welded pipes. The figures have been arrived at by taking the inefficiency of riveted joints as 0·7 (it should be as high as 0·9) and the factor of safety as 4; in that case

$$f = 25 \times 2\ 240 \times 0{\cdot}7 / 4 = 9\ 800 \text{ lbs.},$$

or, omitting the rivet factor, $f = 14\ 000$ lbs.

If the design is such that the flow in the pipe cannot be stopped suddenly (as with deflecting nozzles), it is not necessary to allow for shock due to water hammer; but if the flow can be stopped suddenly, this factor must be taken into account, as p in the formula is the *static* pressure. The maximum possible additional pressure in lbs. per sq. in., due to stopping the flow instantaneously, is 63 times the velocity in ft. per sec.; in practice, it is fairly safe to assume that not more than double the static pressure will be experienced. In such a case the factor of safety assumed above is halved, and becomes somewhat fine; a lower working stress should therefore be taken.

The weight of plain steel tubes, in lbs. per ft. run, may be taken as $9{\cdot}45t(d + t)$, where t is the thickness of the metal and d the internal diameter, both in inches. For riveted pipes the weight so found should be multiplied by 1½ in small sizes; by 1·4 for a 20-in. pipe; 1·25 for a 40-in. pipe; and 1·15 over 60 ins. diameter.

249. Example of Pipe Line.

By way of example, the following case may be taken. A pipe line was required to serve a 600 kW turbine-driven generator on 1 025 ft. head. The turbine, at normal full load on the generator, would have to give 840 B.H.P., and with an efficiency of 75 °/₀ this involved 1 120 H.P. from the water, requiring 580 cu. ft. per min., or 9·65 cusecs. With an average velocity of 4 ft. per sec. the average area of the pipe would be 9·65 / 4 = 2·41 sq. ft., corresponding to 21 ins. diam. In this instance, owing to the high head and considerable quantity of water, it was desirable to sectionalise the pipes; and the nature of the ground divided the whole conveniently into four parts, *viz.* :—

Section (i) Reservoir to pipe-head proper, laid on hydraulic gradient only—Length 650 ft. Head negligible. (Stand-pipe as surge tank at the junction, *see* §§ 232 and 251.)

Section (ii)	Length 1 140 ft.	Head 420 ft.	
Section (iii)	Length 980 ft.	Adding head 60 ft.;	total 480 ft.
Section (iv)	Length 1 150 ft.	Adding head 545 ft.;	total 1 025 ft.
	Total length 3 920 ft.	Total head, 1 025 ft.	

The pipe line decided on was as follows :—

	Diameter. Ins.	Area. Sq. Ft.	Velocity. Ft. per Sec.
Section (i)	24	3·14	3·14
„ (ii)	24	3·14	3·14
„ (iii)	21	2·40	4·1
„ (iv)	18	1·76	5·6

Taking section (ii), the loss of head at full load, when the pipes become slightly foul, will be—

$$H = 3{\cdot}14^2 \times 4 \times 0{\cdot}0057 \times 1\,140 / 2 \times 32{\cdot}2 \times 2 \text{ ft.} = 1{\cdot}98 \text{ ft.}$$

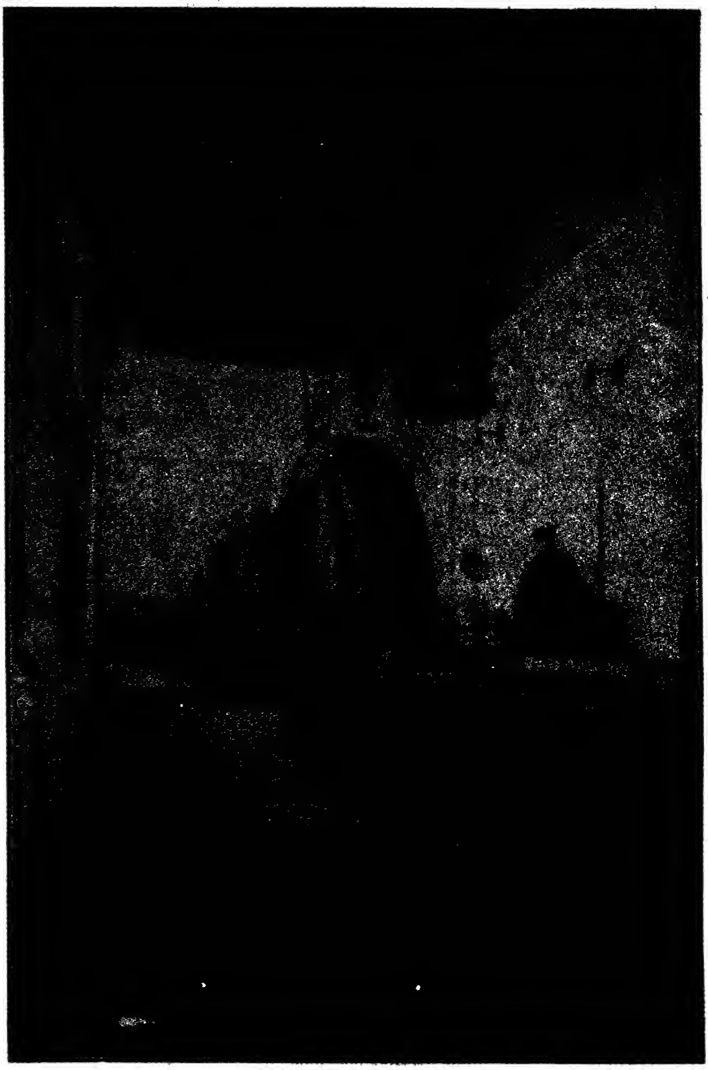
Similarly the losses in the other sections will be (i) 1·14 ft., (iii) 3·5 ft., (iv) 9·4 ft. making a total loss of 16 ft. To this another 4 ft. was added to allow for bends and the obstruction due to rivets, making the total loss 20 ft.

Now these calculations relate to the normal full load of the generators, at which they are able to work continuously, but all generators are designed to be capable of overload to the extent of at least 25 °/₀ for limited periods; therefore the turbines would have to be capable of giving 1 050 B.H.P. at such times. The velocities and losses with the increased quantity of water were therefore similarly worked out to see that they would not be excessive. It will be seen that in these circumstances the maximum velocity in the smallest pipe is 7 ft. per sec.; the total losses also are reasonable, amounting to about 3 °/₀ of the total head. Section (i), being under practically no pressure, was specified for mechanical reasons as $\frac{1}{8}$ in. thick. In section (ii) the head is 420 ft., and the maximum static pressure 180 lbs. Therefore the thickness of metal (§ 248) will be $t = 180 \times 12 / 9\,800 =$ 0·22 in. or $\frac{7}{32}$ in. In section (iii) the total head is 480 ft.; static pressure, 208 lbs.; $t = 0{\cdot}22$ in. again, the diameter being reduced. Section (iv) was divided into two equal lengths of 575 ft. of 18-in. pipe. The pressure in the upper half works out to 326 lbs. per sq. in., giving $t = 0{\cdot}3$ in., while in the lower half it comes to 444 lbs., giving $t = 0{\cdot}41$ in.

250. Special Pipes, etc.—In order to determine what pipes are required, the proposed pipe line must be surveyed very carefully, the exact lie and angle of all bends being determined. A small error may add greatly to the difficulties of erection. Where the diameter alters, special tapered pipes are fitted. At convenient points thrust-blocks are required, the pipes being securely anchored to concrete blocks at these places. Expansion pipes may be necessary, but if the line departs from the straight to any considerable extent expansion can generally take place laterally; covering the pipes in and keeping them full of water reduces the expansion almost to zero. Bell-mouth pieces and valves are required at the reservoir or forebay, and both main and scour valves at the lower end. If a receiver is employed, or if pipes are connected by a Y-piece, isolating valves are employed. Specials may be either of cast steel or, preferably, built up of riveted plates. On very high heads air-cushions are sometimes fitted at intervals on the line, to reduce the shock when the velocity changes; by fitting two vessels side by side, with suitable cocks, the water pressure can be used to force air into the cushion chamber, or this may be done with a pump. In America the upper sections of long pipe lines, where the pressure is comparatively small, are often made of wood-stave construction, built up on the site to save freight; but this method has not found much favour elsewhere, and is useless where white ants are found.

251. Pipes as an Alternative to Open Channels; Surge Towers.—It sometimes happens that for one reason or another an open channel will not prove satisfactory for bringing the water to the pipe head, or will prove more expensive than piping for the whole distance. If the use of piping involves a considerable initial length, almost horizontal, some new considerations come in. The first section of the pipe in the example (§ 249) is a case in point. Although 650 ft. long, it was sloping only on the hydraulic gradient, and the normal pressure on it was negligible. If, however, the pipe had been entirely continuous with the lower sections, there would have been possible danger from water hammer. In order to obviate this, and to compensate for sudden changes in the velocity, a vertical stand pipe, open at the top, was placed at the junction of the first and second sections; it was carried to the level of the top of the reservoir, a matter of some 30 ft., and was made of larger diameter than the pressure pipe. Such an arrangement is illustrated in Fig. 47 (*h*), § 203. As explained in § 232, in the case of a sudden demand, the volume of water stored in the stand pipe would give the main horizontal column of water the chance to come up to speed; in the case of a sudden stoppage, the stored energy of the moving column would force water towards the open top of the stand pipe and thus reduce the shock. Surge towers have been used up to 200 ft. in height, carried on a tower with a small balancing tank on the top. For similar reasons surge pipes are often erected at the foot of descending pipe lines, on the line side of the foot valve. Should the latter be closed quickly in emergency or due to sudden reduction in turbine load, the momentum of the quickly moving water in the descending pipe is expended in forcing water up the surge pipe. Without such a safety device, the valve and pipe would be severely strained or broken. Open surge-towers are obviously impracticable at the foot of very deep descents, but closed ones, with a considerable volume of enclosed air under pressure, are often used (*Proc. Amer. Soc. C.E.*, August, 1917). The design of surge tanks is briefly dealt with in § 232. Automatic relief valves are another alternative.

252. Pipe Joints.—Much ingenuity has been exercised in designing suitable joints for pipes under a high head of water. In the past, plain slip-joints and collar-and-sleeve lead joints have been used for moderate heads; these, however, are not satisfactory except for low heads. A plain flanged joint, with a rubber or copper ring between the faces, makes a satisfactory joint for heads up to 500 ft. or so; such joints have been used on



Metropolitan-Vickers Electrical Co., Ltd.

VIEW ON THE GENERATOR FLOOR OF THE RAANAASFOSS POWER HOUSE.

Six horizontal double Francis type runners are placed in an open pit and coupled to six generators, each of 12 000 kVA, 7 500 V, 3-phase, 50 cycles, 107 r.p m., enclosed type, self-ventilated, with direct coupled exciters. Energy is transmitted to the substations at 50 000 V and 17 000 V.

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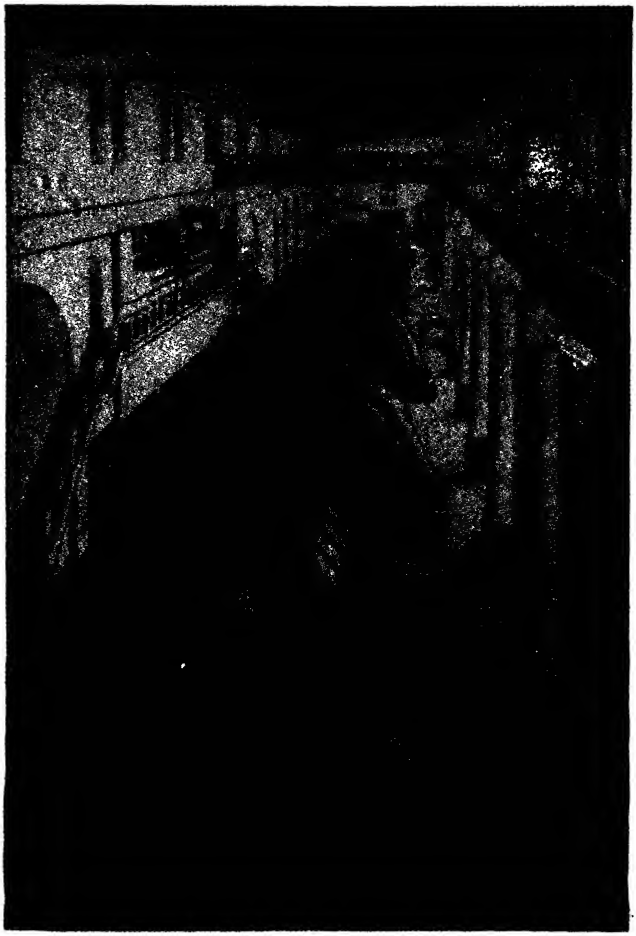

Metropolitan-Vickers Electrical Co., Ltd.

INTERIOR OF THE TYSSEFALDENE HIGH-FALL POWER HOUSE.

Seven 4 100 kVA, five 12 000 kVA, and two 14 000 kVA generators are driven by Pelton wheels. The 12 000 kVA sets in the foreground run at 250 r.p.m. and generate current at 12 500 V, 3-phase, 25 cycles. The outside diameter of the machines is 19½ ft. and the stator bore 12½ ft. Cooling air is led into the machines through shafts in the basement, and is exhausted into a duct leading to the fjord.

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much higher pressures. The flanges, which are riveted on to the pipes, should be pressed out of a steel plate by a die; cast-iron flanges are unreliable where subject to shocks. Various patent flange joints are also on the market, some of them suitable for very high pressures. Riveting the lengths of pipes together on the site is occasionally resorted to, but it involves high-class labour, and is only suitable for straight runs of large diameter. The best modern joints, such as the 'muff' joint, depend on a wedge action for keeping tight, and these have the advantage also of being to some extent self-adjusting, both as to direction and expansion or contraction. Most turbine makers appear to agree that this is the most satisfactory high-pressure joint. Electrically-welded pipes are, however, far better than any form of joint.

253. Pelton Wheels and Nozzles.—In one form or another the Pelton wheel is almost invariably used for the development of power from high heads, and no description of this well-known impulse wheel is necessary. The peripheral speed of such a wheel in ft. per sec. is about $0{\cdot}45\sqrt{(2gH)}$; thus on 1 000 ft. head it will be 114 ft. per sec., and the revolutions per minute can be varied according to the diameter chosen for the wheel. The diameter of the water jet nozzle should not be more than one-fifteenth that of the wheel to get the highest efficiency; if a greater volume of water is required, more than one jet is used. Assuming that in any particular case the working head, H, and the required B.H.P. of the turbine are known, and consequently the quantity of water also, the size of the nozzle may be determined by the formula—

$$d = \sqrt{(1{\cdot}28Q \,/\, v)},$$

where d = diam. of nozzle, in inches,
Q = discharge at the nozzle, in cusecs,
v = velocity of issuing jet (§ 214 = $0{\cdot}97\sqrt{(2gH)}$).

If two or four nozzles have to be used, the discharge, Q, will be halved or quartered in working out their diameter.

Thus if a 340 B.H.P. turbine is required to work on 1 000 ft. net head, the quantity of water required, Q, will be 4 cusecs, assuming 75 °/₀ efficiency (§ 201).

The constant $v = 0{\cdot}97\sqrt{(64 \times 1\,000)} = 245$,

hence $d = \sqrt{(1{\cdot}28 \times 4 \,/\, 245)} = \sqrt{0{\cdot}021} = 0{\cdot}145$ ft. or 1·73 in.

Now the peripheral speed of the wheel is $0{\cdot}45v$, or 110 ft. per sec. If the diameter of the wheel is 15 times that of the jet, or 2·16 ft., the speed will be

$$n = 0{\cdot}45v \times 60 \,/\, \pi \times D = 110 \times 60 \,/\, 3{\cdot}14 \times 2{\cdot}16 = 970 \text{ r.p.m.}$$

In actual practice, the speed will always be chosen such that it enables the correct frequency to be generated (§ 254); the size of the wheel and nozzle being calculated accordingly.

Each wheel must be capable of being isolated from its supply pipe by a valve, apart from the regulating mechanism, and the closing of the ordinary type of balanced gate valve requires considerable power where the head is great; slow closing, however, is necessary, to prevent water hammer. Where more rapid closing is admissible the Johnson balanced cylindrical valve is often used. This consists of a spear attached to a plunger, working in a cylinder concentrically placed in the pipe, which normally allows a full annular water-way; but when forced forward the spear closes the outlet passage. The plunger is actuated differentially, by admitting or discharging water under the normal pipe pressure or atmospheric pressure, as the case may be, by means of an external cock.

254. Speed of Wheels for Driving Alternators.—By increasing the wheel diameter the speed can be reduced; the actual speed (and consequent size of wheel) is generally determined by that of the generator to be driven, unless the drive is indirect, as with belts. In most cases a turbine is required for driving an alternator; assuming that the British standard frequency of 50 cycles per sec. (§ 12) is used, *i.e.* 3 000 cycles per min., the r.p.m. = (3 000 / No. of pairs of poles). This gives speeds of 50, 60, 100, 120, 150, 200, 250, 300, 333, 375, 428, 500, 600, 750, and 1 000 r.p.m., corresponding to various numbers of pairs of poles, and the turbine must be of such size as to run at one or other of these speeds.

255. Regulation of Impulse Wheels.—The power given out by a wheel at its correct speed may be diminished either—

(*a*) by diverting the whole jet from its true point of impact on the buckets;
(*b*) by deflecting part of the jet off the buckets altogether;
(*c*) by reducing the size of the jet; or
(*d*) by breaking up the jet (Seewer system).

Where a diverting nozzle is used the reducing pipe and nozzle are hinged, so that the whole can be moved up or down either by a hand-wheel or an automatic governor. The full discharge goes on, whether the power generated be great or small, so it is only where a large excess of water is available that the method should be used. The same result is obtained by using a deflector, which moves concentrically with the wheel and cuts into the jet from above; this method is equally rapid in action, but is only employed in combination with the needle valve presently described. By reducing the size of the jet the efficiency can be kept sensibly constant at ordinary loads, and the most can be made of a small quantity of water. If a wheel is put in which it is known will not be working at above half its full load for the first year or so, then a nozzle can be temporarily fitted to give this half load; later on it can be changed for a full-sized nozzle. This is often done, but it leaves the question of regulation down to no load (*i.e.* light running) untouched.

In order to keep an impulse turbine wheel running at constant speed under varying loads, it is customary to use a circular nozzle with a tapered spear or needle centred in it; by advancing or retracting the needle, it reduces the area of the jet without breaking it up, and so regulates the power. The adjustment of the needle can be effected by hand; if the governor acts either by deflecting part of the jet or by diverting the nozzle, the attendant can then manipulate the needle valve, and thus save water, and, as the effective area of the nozzle is decreased by the spear, the governor will bring back the jet to its normal action. Of course, if a sudden heavy demand for additional power arises, it cannot be met until the needle has been opened up, and this is not a very rapid process. The best possible arrangement is an automatic combination of needle and deflector or diverter, the whole worked by the governor; rapid alterations in the power demand are met by the deflector or diverter, and the needle then more slowly adjusts its position to give the maximum efficiency under the new conditions. An ingenious method of effecting this is described in *Engineering Record*, August 16, 1913.

The methods already described keep the jet cylindrical but either reduce its size or deflect it from the buckets. In the Seewer system of automatic governing for high-pressure Pelton wheels, which also embraces the two elements of speed regulation and pressure regulation in the pipe system, the jet is made to diverge instantaneously in the form of a cone, more or less according to the reduction in power required; while the usual concentric needle is used, in conjunction with the system, for the more gradual closing down of the jet to a reduced diameter and a return to cylindrical form. The needle is cylindrical up to a short distance from its point and flat diverter plates are mounted between the needle guide and the nozzle. Normally, these plates act as meridional guides and preserve the cylindrical form of the jet; but by inclining them simultaneously through the same angle, a rotating component is introduced into the water flow and the jet diverges. The maximum divergence is about 60° when the plates are turned through 22°. Part of the jet then misses the buckets, while part strikes the back of them; the needle meanwhile closes and the plates return to their normal position. On load increases the needle alone acts. The diverter plates are pivoted on spindles carried into the centre of the hollow needle and are thence connected to the servo-motor actuated by the governor. The power required from the servo-motor is much less than with other types of governing and also varies less with the size of the wheel as, instead of acting at the point of maximum jet velocity, the vanes are working in the comparatively low velocity of the admission pipe round the needle.

256. **Turbine Governors.**—Many types of governors are made for regulating turbines and impulse wheels. They range from simple mechanical governors, with indifferent regulation, up to the most exact hydraulic governors for use in hydro-electric plants. To actuate a hydraulic valve requires far more power than the corresponding process with a steam engine governor; and this is true also with a spear or deflecting nozzle or a combination of the two. Consequently a hydraulic relay is generally employed; the centrifugal governor actuates a light relay, which in turn operates on the valves of a powerful hydraulic cylinder, the movements of which work the regulating gear. Generally oil under pressure is used in the cylinders, involving the use of a subsidiary oil pump; this obviates all danger from dirt and grit. In other cases either the whole or a part of the working head of water is utilised, in which case a subsidiary governor pipe is preferably employed; the quantity of water used is of course very small, but it must be entirely free from foreign matter, and two parallel filters must be used to enable each to be cleaned in turn. Notwithstanding the makers' claims, the governor is generally the most troublesome part of a turbine plant and the most difficult to keep in accurate adjustment; a large plant has on

occasion been completely wrecked through a governor sticking; it is, therefore, economical in the end to buy the best that can be obtained. It is usual to specify the foot-lbs. (from 2 000 to 100 000) which the cylinder can deal with. In the best governors about ½ sec. elapses between the occurrence of a change of load and the commencement of the movement of the turbine gate or spear; the time taken to close the fully open gate, etc., when the whole load is thrown off, varies from 2 secs. upwards. These intervals are sufficient to enable the speed to vary somewhat although the provision of a properly designed flywheel keeps the variation down. If 25 °/₀ of the load is thrown off suddenly, the change of speed will be from 3-5 °/₀; if full load is thrown off, the momentary change of speed may be from 10-15 °/₀, but the normal value is soon restored. In the case of a gate or needle valve closing rapidly, there may be a considerable rise of pressure in the pipe line, due to water hammer; if the line is a long one, special relief valves may be used, but these are less certain in action than surge pipes (§ 251), though cheaper in first cost. The best types of relief valve work in conjunction with the governor, and are thus positive in action.

There is one plant in India which is worked entirely without governors, *viz.* that at Darjeeling. The governors originally supplied were actuated from the pressure pipes without the interposition of filters, and consequently they never worked well. After the whole plant had been overwhelmed by a flood and landslide in 1897, the governors were removed; and from that year up to the present time a coolie has been stationed at each turbine to regulate it by hand according to the tachometer. A subsequent extension was controlled by an oil-pressure governor for some time, but this also failed occasionally and took to 'hunting,' with the result that hand regulation was adopted exclusively. The work is purely mechanical and can be entrusted to a man with no knowledge, but the method is only suitable for small installations and where cheap native labour is available.

Additional excess speed devices are often installed also, for emergency use in case of a runaway.

257. The Tail Race.—Impulse wheels discharge their water directly into the tail race; there is, of course, no draft tube. The tail race must be of ample size to give a free exit to the water, and it should have a deep water cushion to take the actual discharge, owing to the high residual velocity under high heads. Under very high pressures, a water cushion alone is insufficient to protect the masonry or concrete. A cast-iron block or a baulk of timber may be used as an additional buffer, or the water may be made to impinge on a steel plate bent to a suitable transition curve, so as finally to discharge the water horizontally in a long water cushion. The tail race should be so designed that when the jet is deflected off the buckets it has an unobstructed passage to the outside air through the tail race passage.

258. Bibliography (*see* explanatory note, § 58).

STANDARDISATION.

(1) *I.E.C. Publication.*

No. 41. The Testing of Hydraulic Turbines.

R.M. 89. Advisory Committee No. 14 on Rating of Rivers.

(2) *B.S. Specifications.*

No. 44. Cast Iron Pipes for Hydraulic Power.

No. 353. Testing Hydraulic Turbines.

No. 610. Rating of Rivers for Power Purposes.

BOOKS AND REPORTS.

Natural Sources of Energy. A. H. Gibson (Cambridge Univ. Press).

Report of the Water-Power Resources Committee (H.M. Stationery Office).

Water-Power in the British Empire. Sir Dugald Clerk and A. H. Gibson (Constable).

Triennial Report of the Hydro-Electric Survey of India. J. W. Meares (Constable).

Water-Powers of British Columbia. A. V. White and C. J. Vick (Commission of Conservation, Canada).

Applied Hydraulics. H. Addison (Chapman & Hall).

Hydro-Electric Development. J. W. Meares (Pitman).

Tidal Power. A. M. A. Struben (Pitman).

Hydro-Electric Power Stations. D. B. Rushmore and E. A. Lof (Wiley).

Hydraulic Power and Hydraulic Machinery. H. Robinson (Griffin).

Hydraulic Machinery. R. G. Blaine (Spon).

Hydraulic Turbines. R. L. Daugherty (McGraw-Hill).

Water-Power Engineering. F. F. Fergusson (Pitman).

Engineering for Masonry Dams. 2nd Edition, W. P. Creager (Chapman & Hall).

Report of the Severn Barrage Committee, with Appendix (report of technical co-ordinating committee), maps and plans. 1933. H.M. Stationery Office.

Notes on Water-Power Development. A. H. Gibson. Presidential Address British Association, 1921.

Also, many useful publications of the Dominions Water-Power Board and the Hydro-Electric Commission of Ontario. Most countries have now water-power surveys in being or under consideration; particulars of the latest official publications can be obtained from the consular representatives of the countries concerned.

I.E.E. PAPERS.

Development and Storage of Water for Electrical Purposes. J. W. Meares. *Jour. I.E.E.*, Vol. 57, p. 426.

Hydro-Electric Resources of the Scottish Highlands. M. Maclean. *Jour. I.E.E.*, Vol. 60, p. 902.

Hydro-Electric Power Supply. A. Tustin, Vol. 61. p. 174.
Hydro-Electric Resources of the Empire Overseas. W. R. Cox, Vol. 65, p. 944.
Hydro-Electric Developments in Great Britain. E. W. Connon, Vol. 69, p. 203.
Hydro-Electric Development in Great Britain, with special reference to the Works of the Grampian Electricity Supply Co. A. S. Valentine and E. M. Bergstrom. Vol. 76, p. 125.

Other Papers.
The Surge Chamber in Hydro-Electric Installations. R. S. Cole, *Inst. C.E. Selected Papers*, No. 55, 1927.
Progs. Inst. C.E., Vol. 219, p. 161, and Paper No. 4887 of the same also deal with surge tanks.
Hydro-Electric Development; Its Economic Limits in Comparison with Steam. R. B. Fairthorne. *El. Rev.*, Vol. 124, p. 382.

CHAPTER 11.

MAXIMUM DEMAND, LOAD FACTOR, AND DIVERSITY FACTOR.

259. **Maximum Demand.**—Where an electrical installation draws its supply of power from the mains of a public company there is always power available for every lamp or other consuming device therein, although, as explained in connection with tariffs (§ 269), the cost of the supply per unit may vary according to the proportion of the apparatus in the whole installation in use at one and the same time; where, on the other hand, the supply is obtained from private plant, the engines and dynamos must be large enough to meet all demands on them, unless accumulators are also installed. The initial cost of the plant depends on its size and the duty it is called on to perform. It is seldom necessary to install plant capable of supplying power to every lamp etc., at one and the same time, and in order clearly to explain the principles on which the size of plant must be based certain technical terms must be introduced, defined, and explained, *viz.* 'maximum demand,' 'load factor,' and 'diversity factor.' The maximum demand is really self-explanatory, representing in any particular case the actual maximum number of watts or kilowatts required for a specific purpose. Thus one particular person's maximum demand may be equal to the combined power required by all the apparatus he has installed, *e.g.* a small workshop with a single motor and nothing else. Another person's maximum demand may be only three-quarters or one-half of what would be needed by all his apparatus, owing to the use of the different items not being coincident in time. The maximum demand on a feeder or, any line supplying a number of different persons is, therefore, the sum of all the actual *simultaneous* demands (not necessarily or even generally their maxima) from the individuals, at the time when *this sum* reaches its highest point. The maximum demand on a power-house is, in the same way, the sum of the simultaneous

demands on all the outgoing feeders or lines, at the time when this reaches its highest point.

260. Maximum Demand: Analogy from Water-supply and Steam.—Where electric supply is in question a clear comprehension of the meaning of the term 'maximum demand' is essential, and this may best be obtained by considering analogous conditions in other branches of engineering. The simplest illustration may perhaps be taken from water-supply. In the roads are large water mains, and in a house are pipes and taps capable in the aggregate of discharging a certain quantity of water in gallons per minute; if there were a clear passage from the mains to the house an unrestricted supply, and perhaps great waste, would result; and in order to prevent this all the water from the mains has to pass through a small ferrule. Leaving out of consideration the regulating tanks in the house, which modify the conditions in practice, it is evident that if all the taps are left open the ferrule will limit the maximum rate at which the supply can be drawn off to a given number of gallons per minute; in other words, the ferrule is designed to limit the 'maximum demand' to what is deemed necessary for the house. The occupier may draw off water at this maximum rate for the whole 24 hrs. or for 1 hr. only, or he may never require to use the full capacity of his ferrule at all; but he can never draw off from the mains at a rate in excess of what the ferrule allows.

A somewhat more complicated, but perhaps closer, analogy may be taken from steam supply. Suppose a number of small industries to be concentrated at a certain spot, each having a small boiler and engine, some working all the 24 hours, some during the day only, and some during the night only. A member of the community offers to put up a large central battery of boilers and to distribute steam to the colony, thus saving the labour and waste involved in a number of inefficient units. The profit to be obtained from this venture will depend on the total amount of steam sold at a remunerative rate, and in fixing this rate the owner will have two factors to consider, *viz.*:—

(*a*) Capital charges, which are independent of the amount of steam generated and sold, but which depend on the total steaming capacity or horse-power of the boilers installed; and

(*b*) Charges for fuel, etc., varying to a great extent with the total amount of steam generated.

We have here then two distinct factors, *viz.*:—

(i) The *maximum horse-power* which the boilers are capable of supplying; and

(ii) The *total horse-power-hours* which they do in fact supply.

Before laying down his plant the supplier of steam will want to know the requirements of each customer; not only the total amount of steam that customer will want during the day, but also the *maximum rate* at which he will require steam *at any one time*, *i.e.* his maximum demand. This will be proportional to the *maximum horse-power* in use at any time, which will generally be much in excess of the average. This maximum demand is independent of time; it may last for half an hour or five hours. Having thus ascertained the maximum demand of each consumer, and the hours when he will probably be using this maximum, the supplier will be in a position to calculate the sum of all the maximum demands at all the different hours, and thus to ascertain the maximum rate at which he will ever have to generate steam; this will determine the number and size of the boilers and the prime cost of, and capital charges on, the central boiler installation.

It is quite clear from the above that the rational method of charging a consumer for the steam supply would be at a certain rate per pound, covering the fuel and other working costs, *plus* an amount covering the capital charges for which the particular consumer had been responsible by his maximum demand, *i.e.* by his method of demanding supply. The former rate of charge would be the same for all consumers; the latter would not, but would be heavier in proportion for those who demanded steam at the greater rate. This is precisely the basis of the maximum demand tariff for electricity supply, to which reference is again made in §§ 264, 272, 275, *et seq.*

261. Load Factor.—In technical phraseology the load factor is the ratio between the actual output of a power station in units and the output that would result if the average demand was equal to the maximum. Put in the form of an equation it is—

$$\text{Load Factor} = \frac{\text{Number of units sold} \times 100}{\text{Max. simultaneous load on feeders in kW} \times \text{Hours of supply period}} = x\ \%.$$

For example, a plant has been laid down consisting of three sets each of 100 kW, of which one is kept in reserve. The working sets can then give 200 kW, and it may be assumed that the maximum load on them reaches this figure at some time during the year. Now if the average demand were equal to the maximum, the load would be 200 kW throughout the year, and the total output of the plant would be 24 × 200 × 365 = say $1\frac{3}{4}$ million units (kWh). If the actual output is 1 million units per annum the annual load factor is 57 %, and so forth.

As thus calculated, the load factor corresponds to the 'undertaking load factor,' values of which for British electricity supply undertakings are published in the *Electrical Times* tables mentioned in §§ 194, 269 (*cf.* formula given below Table 38*a* for the load factor of an undertaking which purchases energy in bulk as well as generating energy).

Two other terms often encountered are 'plant load factor' and 'station load factor.' These factors are calculated from the following formulæ:—

$$\text{Plant load factor} = \frac{\text{Station output in kWh}}{\Sigma(P_1h_1 + P_2h_2 + \ldots)} \times 100\%$$

where $P_1P_2 \ldots$ = kW-ratings of generating units which ran respectively $h_1h_2 \ldots$ hours per annum,

$$\text{and Station load factor} = \frac{\text{Station output in kWh}}{\text{Installed plant capacity} \times 8\,760} \times 100\ \%.$$

It will be seen that the 'plant load factor' measures the ratio of the actual output to what would have been the output if all the plant had been fully loaded *during the hours it was actually running.* On the other hand, the 'station load factor' measures the ratio of the actual output to what would have been the output if *all the plant installed* had been running *fully loaded all the time* (8 760 hours per annum).

For example, suppose a station contains two 50 000 kW sets, each running 8 000 hrs. a year and one 30 000 kW set running 1 200 hrs. a year; and suppose that the station output is 600 000 000 kWh per annum. The plant and station load factors are calculated as follows:—

$$\text{Plant load factor} = \frac{600\,000\,000 \times 100}{(50\,000 \times 8\,000) + (50\,000 \times 8\,000) + (30\,000 \times 12\,000)}$$

$$= \frac{600 \times 10^6 \times 100}{836 \times 10^6}$$

$$= 71{\cdot}8\ \%;$$

$$\text{Station load factor} = \frac{600\,000\,000 \times 100}{(50\,000 + 50\,000 + 30\,000) \times 8\,760}$$

$$= \frac{600 \times 10^6 \times 100}{130\,000 \times 8\,760}$$

$$= 52{\cdot}6\ \%.$$

The plant load factor is always substantially higher than the station load factor. For example, the Fulham power station, opened on September 26, 1936, generated 557 610 000 kWh during its first year of operation at an overall plant load factor of 61·56 % and a station load factor of 48·44 %.

Sometimes it is more convenient or more logical to deal with the daily, weekly, or monthly load factor. The only difference is in the period over which the actual output is reckoned and during which the maximum demand is observed, but the monthly load factor is generally different from the annual load factor and from that reckoned on a 24-hr. basis.

The load factor of an individual is similarly calculated from—

$$\text{Consumer's load factor } (\%) = \frac{\text{Units consumed} \times 100}{\text{Maximum demand} \times \text{Hours of supply period}}.$$

Except in the case of supply from a plant that is only working for part of each day, the hours of supply are always reckoned as 24 per diem or 8 760 per annum. The importance of good individual load factors, *i.e.* such as approach as near as may be to 100 %, will be appreciated as we proceed. Of all work using electrical energy the various electro-chemical industries have the best individual load factors; such factories may work for 24 hrs. a day throughout the year. This is also sometimes true of pumping plants, especially in mines, but here the power required will be a comparatively small proportion of the total power used for all purposes. Street lighting averaging about 11 hrs. per diem has an annual load factor of $\frac{11 \times 100}{24} = 46\ \%$. Private lighting has the worst load factor of all, often not more than 5-8 %.

262. Diversity Factor.—The term 'diversity factor' is unfortunately defined in several different ways, and although the expert can generally tell what is meant this leads to confusion. It is sometimes stated that diversity factor = ratio of actual maximum load on feeders to the sum of the maximum demands of all consumers, or, in the form of an equation—

$$\text{Diversity factor} = \frac{\text{Max. load on feeders in kW} \times 100}{\text{Sum of consumers' maximum demands in kW}} = d\ \%.$$

Thus, if the maximum load on the feeders is 100 kW and the sum of the individual loads is 200 kW, the diversity factor is 100 × 100 / 200 = 50 %.

On the other hand, the International Electrotechnical Commission in 1908 defined diversity factor as 'the number obtained by dividing the sum of the maximum loads of the individual consumers supplied by any works during a given period of time by the maximum load delivered from the works during the same period.' This gives a number instead of a percentage, *i.e.*

$$\text{Diversity factor} = \frac{\text{Sum of consumers' maximum demands in kW}}{\text{Maximum load on feeders in kW}}.$$

In the example given above this would be 200 / 100 = 2.

This is clearly a rational definition. On the first basis a better diversity factor involves a lower percentage, which is contradictory and confusing; on the I.E.C. basis a better factor is also represented by a large number, as it naturally should be. The same results will of course be obtained if the loads are stated in H.P. or in amperes at the declared pressure of supply. The 'given period of time' may be a day or a month or a year, according to the circumstances, and the diversity factor may be that on one feeder, or other line, or on a whole works. C. W. Charlesworth (*El. Rev.*, Vol. 89, p. 161) gives the following values for the diversity factor of various loads: lighting 1·1-1·5, average 1·25; power 1·5-3·0, average 2·0; heating and cooking 4-10, average 7·0. Examples follow later (§ 264).

263. Diversity Factor and Load Factor; Analogy from Steam.—Pursuing the example of § 260, it will be seen that if the maximum demands of all the consumers happen to be required at the same time the plant must be capable of supplying the sum of them all, and the capital cost will be very high. On the other hand, it will often so happen that the hours at which the different consumers are using their maximum demands differ greatly; in this case the capacity of the boiler need only be such as to meet the *highest sum of maximum demands at any one time*, and the installation is said to have a good 'diversity factor.' Obviously with a good diversity factor the capital charges are reduced and lower inclusive rates can be charged.

If one of the consumers, in the case we are considering, required steam at a steady rate throughout the whole 24 hrs., so that his maximum demand were equal to his average demand, he could evidently be supplied profitably at a lower rate of charge per lb. of steam than another consumer with the same maximum demand and a very low average demand. The former would have a good 'load factor,' *viz.* 100 °/₀, and the latter a bad one, perhaps 10 °/₀. In the case of the central boiler plant, if in the course of working the conditions were such that all the boilers were working near their full power all the time the plant would be said to have a good 'load factor,' and the working costs would be low. Both these two varieties, *viz.* consumer's load factor and plant load factor, are met with in electric supply. The most favourable conditions for cheap supply will obviously be those where the size and cost of the plant is low, owing to a good diversity factor, and the daily output of each unit of plant is large, owing to a good load factor. As shown by the example in Fig. 50, § 266, a high diversity factor is impossible if individual load factors are very high, but this does not matter because the large plant required (owing to the low diversity factor) is highly productive (owing to the high load factor).

264. Maximum Demand, Diversity Factor, and Load Factor in Electric Supply.—If the explanations in the preceding paragraphs have been followed, it will be evident that they can be translated into electrical terms. Horse-power and electrical power in kilowatts are convertible terms, both representing the *rate* at which power is being used: so also are horse-power-hours and kilowatt hours or units, both representing the *amount* of energy used: and yet the confusion of watt and watt-hours is a constant source of difficulty. Substituting motors or other current-consuming apparatus for the independent engines, and an electric power station for the boiler plant in the above illustration, the conditions remain precisely as stated. If the maximum demands of the various motors or other apparatus (expressed in kilowatts) occur at all hours of the day and night, the diversity factor of the power station will be good, and the plant will be comparatively small (and inexpensive) in proportion to what it would be if the contrary were the case. If, in addition, the demand for power throughout the working hours is fairly constant, the plant will have a good load factor, and will be earning a good return on its cost all the time. The consumers' maximum demands and the times at which they occur will always therefore be of importance.

The ideal case of a station supplying a number of loads each of which is constant during the 24 hrs. is unattainable in practice. The actual total load on the station varies from hour to hour and is represented by a more or less irregular curve (*see* Figs. 49-51, §§ 265, 266). Addition of a constant 24-hr. load to the existing load curve will improve the load factor of the station, but a yet greater improvement therein would be effected by adding the same additional output during off-peak hours so as to increase the total output without increasing the maximum load. In other words, whilst the percentage value of the peaks in a load curve can be reduced by adding constant loads to the latter, better results can be obtained by adding loads which will fill up the hollows of the curve.

In 1929 the Wilkinson 'change-circuit' system was brought to notice, as a means of improving station load factors. This system aims at securing a constant load on the plant by the automatic adjustment of a thermal storage or kindred load, according to the variation in the lighting or power load. The principle is to use two independent feeders, with one common return for both, one of these feeders being maintained at standard voltage for the usual loads, while the other feeder supplies power at a variable voltage for thermal storage and similar purposes where intermittent working is of no consequence, *e.g.* some forms of pumping. The voltage on the 'change-circuit' is automatically varied so as to maintain the sum of the loads, *i.e.* the total load on the station, at approximately full load continuously. The cost of generating the energy used in filling up the hollows is little more than the fuel cost (§ 269), so what the author of the system calls the 'out-of-bounds load' can be supplied very cheaply.

From the supplier's point of view electric lighting (other than in streets) is by no means a satisfactory 'load,' owing to the limited hours of use. Plant lying idle is costing as much in capital charges, for interest and depreciation, as when it is fully loaded. Consequently, by the bait of a low tariff for other purposes, undertakers seek to encourage the use of electrical energy in more profitable directions, to the advantage both of the supplier and consumer. In the domestic field, these applications of electricity include electric fans and motors, heating air or water, cooking and minor domestic apparatus. These have a far better diversity factor than lights.

265. Some Practical Examples.—In very small lighting installations the maximum demand may amount to 80 or 100 % of the wattage of lamps installed; and, on the other hand, it may amount only to 33 % or so of the wattage installed in a large installation. In assessing primary charges under the pre-war 'telephone' lighting-tariff (§§ 272, 273) at Marylebone (London), the maximum demand assumed was 70 % of the wattage installed for lighting, *excluding* convenience lights (*i.e.* lamps in cupboards, cellars, pantries, and so on). Probably it is not far wrong to assume 66 % maximum demand on the first 10 lamps in a domestic lighting installation and 33 % thereafter, or, say, 50 % of the total lighting wattage installed in an average middle-class home. According to Mr. Seabrook (*Journ. I.E.E.*, 48, p. 394), it has been found in Chicago that the average residence percentage of maximum demand to watts installed is—

90 %	in a	300 W	installation.
64 „	„	500 W	„
48 „	„	1 000 W	„
46 „	„	2 000 W	„

The prediction of demand and energy consumption is discussed in § 576, Vol. 2, in connection with the planning of the installation. In churches, theatres, shops, and offices, the whole of the lights may be in use at once, and the maximum demand consequently equal to the maximum possible. Where motors are used for pumping or other domestic uses, the work can generally be done during daylight hours, when the lights are off, and the M.D. will not be affected—unless, of course, the power taken by the motor is greater than that taken by the lamps, in which case the former determines the M.D. Where electric heating and cooking are used the lighting and power loads inevitably overlap, and the M.D. is raised. In such cases the power load will generally be much greater than the lighting load, and the M.D. must be worked out according to the apparatus installed and the probable hours during which both light and power will be in use together. The domestic M.D. for lighting supply is generally about 8 P.M., but if electric cooking be practised the maximum evening demand is shifted to 6 or 7 P.M., according to the hour of dining, and it is often found that the actual maximum demand occurs just before breakfast in winter, when a quantity of heating and cooking apparatus is in use in addition to a certain amount of lighting. In India the domestic M.D. generally occurs at about 8 P.M., whether the load is lighting only or mixed lighting and power. Reference may be made to the examples in § 275 and §§ 607, 608, Vol. II.

It will be instructive here to give a working example going beyond the bounds of a private installation; say, for a small town in the tropics. The conditions assumed are set out alongside

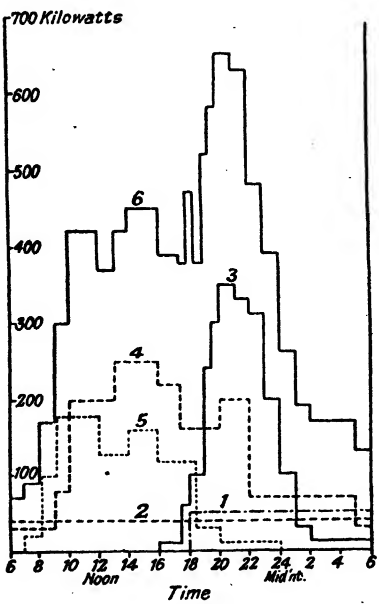

FIG. 49.—Load curves for a small town.

(i) *Public Lighting.*—50 kW steady load for an average of 12 hrs. a night throughout the year—6 P.M. to 6 A.M.

(ii) *Pumping.*—40 kW steady load throughout the 24 hrs. all the year round.

(iii) *Private Lighting.*—550 kW of lights installed; maximum demand 350 kW between 8 and 9 P.M. Consumption equal to 2 hrs.' use of all lamps daily throughout the year. Practically no all-night load. Maximum load variable.

(iv) *Fans.*—350 kW of fans installed; maximum demand 250 kW between 1 P.M. and 4 P.M. A good all-day load and a fair all-night load for 6 months in the year.

(v) *Motors.*—400 kW installed; maximum load 180 kW between 9 A.M. and noon; a good load all day and practically no night load.

Fig. 49, which shows the 'load curve' (kilowatts plotted against time) for each of the component loads, and also the total load imposed upon the station by the sum of the individual loads.

Load (i) will be represented by a straight line at 50 kW from about 6 P.M. to 6 A.M.; its individual load factor is 50 %. Load (ii) will be represented by a straight line at 40 kW throughout the 24 hrs.; its load factor will be 100 %. The curve representing load (iii) has been drawn of the approximate shape it would be in practice, the load beginning at about 4 P.M., rising rapidly to a maximum at 8 P.M., and thereafter dropping down to a very small night load, the whole curve corresponding to the consumption assumed; its load factor is only 13 %

Load (iv) yields a much more uniform curve than the previous one; it will be lowest in the early morning, will be at its maximum in the early afternoon, will drop somewhat during the hours when people are out of doors, will rise again about the dinner-hour, and will then drop to the steady all-night load; its load factor during the six-month working season to which the curve relates will be 40 %, whereas it will be practically zero during the rest of the year. Load (v), the commercial motor load, will come on in the early morning, will probably drop somewhat at midday, and will, for the most part, stop about 6 or 7 P.M.; its load factor will be 35 %. By adding the ordinates of all the curves hour by hour the total load curve (vi) is obtained, showing a maximum load *on the plant* of 650 kW. As the values assumed are maxima, the average values will be considerably lower, especially during the season when fans are not running. The daily load curve, of which Fig. 49 is an example, varies of course from day to day. Many engineers have their daily load curves drawn out on cardboard and then cut out and stacked vertically in a box, like a card index catalogue; the resulting mass of cards, when compressed close, gives a solid graphical representation of the conditions obtaining over any period.

TABLE 37.—*Illustrating Conditions of Supply.*

Nature of Load.	Kilowatts Connected.	Max. Demand. kW.	Average Demand and Hours of Use.	Units per Annum. kWh.
(i) Public lights . .	50	50	50 kW for 12 hours for 365 days	219 000
(ii) Pumping . .	40	40	40 kW for 24 hours for 365 days	350 000
(iii) Private lights . .	550	350	2 hours' use all lights per day	400 000
(iv) Fans	350	250	100 kW for 24 hours for 180 days	430 000
(v) Motors . . .	400	180	125 kW for 12 hours for 365 days	532 000
Total . .	1 390	870	—	1 931 000

From the curves in Fig. 49 much information can be extracted. In the first place, the area of each to the base line is a measure of the units consumed. In the figure as reproduced, the horizontal scale is 0·075 in. to 1 hr. and the vertical scale is 0·075 in. to 20 kW, so that each 0·075 in. square (*i.e.* 0·005 64 sq. in.) corresponds to 20 kWh; in practice larger and more convenient scales are used. The ratio of the area under each curve to the total area of the rectangle in which it is contained is the load factor of that particular curve, giving the results enumerated above. The peak of the aggregate curve shows the number of kilowatts the plant must be capable of giving, and the ratio of the area of that curve to its rectangle gives the load factor of the plant on the particular day for which it is drawn. If similar curves are made for average summer and winter conditions, the annual consumption and load factor can be found from the various areas. Table 37 gives the probable results under the conditions set forth.

It will be observed that the total in the M.D. column is 870 kW, whereas in Fig. 49 it is only 650 kW; this is due to the fact that in practice the various maximum demands are not simultaneous, or, in other words, *to the diversity factor of the various loads.* For that matter they would not even occur on the same day, except by coincidence. With the assumed steady street lighting and pumping the load factor over the whole year will be an exceptionally good one, *viz.* 1 931 000 × 100 / 650 × 365 × 24 = 34 %; it will be higher than this on the curve, but there all the maximum loads are assumed to occur at different times on the same day, which would hardly be likely to happen. Actual computation shows that the total load curve in Fig. 49 has an area of 11·3 sq. ins., while the containing rectangle is 21·7 sq. ins. The ratio between these shows a daily load factor for this one day of 52 % or 8 160 units generated in one day against a possible 15 600. The total units *per annum* shown in Table 37 are less by about 36 %, *viz.* 1·9 million against 3 million.

The diversity factor for this particular day will be 870 / 650 = 1·34 or, if expressed by the first method explained in § 262 as a percentage, 75 %. This too will vary from day to day.

Reference to Fig. 49 shows that the plant is only fully loaded from about 6-10 P.M. It would pay to take additional load at a very low rate if these hours were excluded by agreement. In the U.S.A. a large business has been worked up in charging batteries for electric automobiles (Chapter 36, Vol, 3) during the hours of light load. It is said that 65 million units per annum are used for this purpose.

Elsewhere arrangements are made so that pumping loads, or water heating, are carried out at all hours of the day *except just at the peak load;* in this way they may add greatly to the number of units usefully sold without causing any addition to be made to the size of the generating plant. Furthermore, the actual cost of these units to the supplier is merely the *extra* cost of fuel required to produce them, and therefore far below the total average cost of all the units sold, so that such off-peak supply is doubly profitable. Bearing in mind the fact that the boilers are under steam in any case, all the casual losses due to external radiation, heat rejected in the flue gases and so on, occur in any case, and do not increase appreciably with the extra demand; therefore the cost of this extra fuel will be far less than the average cost of fuel per unit recorded in the station tables.

266. Industrial Load Curves.—Fig. 50 shows a load curve such as will be more or less typical of a water-power plant supplying electro-chemical or metallurgical industries. In this are shown four separate load curves and their summation.

No. 1 takes about 2 000 kW from 6 A.M. to 6 P.M.

Nos. 2 and 3 take about 3 000 and 4 000 kW respectively throughout the 24 hrs. on some continuous process.

No. 4 represents the local load of the town and of the continuous factories in lighting and other subsidiaries, rising to a maximum of 1 800 kW.

Here the load factor of the whole supply is about 86 %—even this is sometimes exceeded in such works—and the diversity factor of the 4 separate loads is

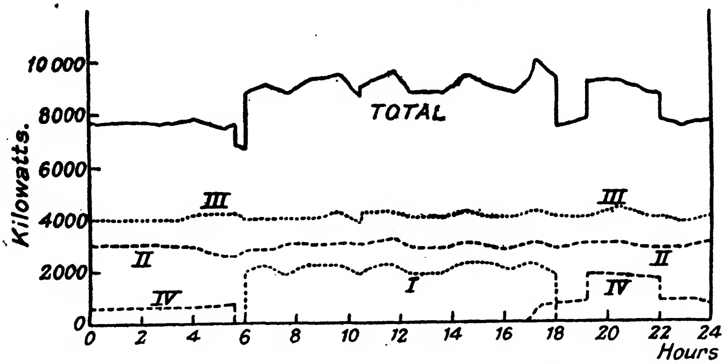

Fig. 50.—Load curve typical of electro-chemical or metallurgical industries.

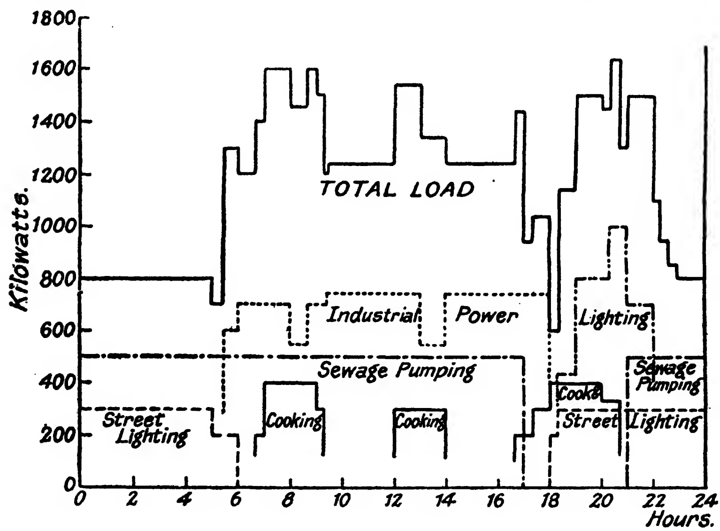

Fig. 51.—Load curve with excellent diversity and load factor.

11 700 / 10 000 or 1·17. The individual load factors are so high that there is not much room for diversity.

The curve in Fig. 51 is an ideal one, with a diversity factor and load factor such as the station engineer seldom realises except in his dreams; but nevertheless it represents an ideal towards the attainment of which he can do a great deal. Only the peaks of the several loads are shown, and the summation curve is therefore only approximate. Inspection, however, shows the combined peak load to be about 1 640 kW at the time when all the various lighting loads overlap with cooking at 8 P.M., or perhaps 7 P.M. in actual fact. The individual peaks are—

Street lighting	300
Cooking	400
Industrial power	740
Private lighting, etc.	1 000
Sewage pumping	500
Total	2 940

The diversity factor is therefore 2 940 / 1 640 or 1·8 combined with a load factor of nearly 75 °/₀.

266a. Load-Duration Curves.—As applied to an individual consumer, a feeder, transmission line, substation or power station, as the case may be, a 'load-duration' curve shows the total time for which the load has reached the various values represented by the ordinates of the curve. The curve may show, for example, that the load of a particular consumer reaches 5 kW for 4 500 hrs. per annum (or say 1 200 hrs. during a certain quarter, or 500 hrs. during a certain month, according to the period considered), 10 kW for 2 000 hrs. per annum, 20 kW for 1 000 hrs. per annum, and 30 kW for 300 hrs. per annum. The technical problems and the economic aspects of supplying such a consumer would be different from those of supplying another consumer whose demand reached 5, 10, 20 and 30 kW for say 4 500, 3 000, 2 500 and 1 500 hrs. per annum. The areas under their respective load-duration curves are proportional to the annual kWh consumptions of the consumers, and these areas also form a measure of the load factor of each consumer. Further, they afford an indication of the probable diversity factor (§ 262) of various consumers.

Though the total kWh per annum (area under the load-duration curve) be the same for each of a number of consumers, and though the maximum kW be the same for each, there is a better chance of being able to supply them all through a given size of feeder, or from a given substation, with some combinations of shapes of load-duration curves than with others. The study of load-duration curves is often of great assistance in determining the permissible loading of circuits, economic distribution of load between generating sets, and so on. It is laborious to plot load-duration curves from the charts of recording wattmeters, and to avoid this, load-duration meters* have been devised with trains recording the number of times the load exceeds 10, 20, 30 . . . 120 °/ₒ of rated full-load during the 15 min. periods of a month or other convenient term. The shape of a load-duration curve is often similar to that of the flow-duration curve in Fig. 48*a*, § 209.

267. Bibliography (see explanatory note, § 58).

A Study in Load Factors, by Councillor Denny, *El. Rev.*, Vol. 86, p. 675, is based on an experiment made by the Glasgow Corporation, and shows clearly the improvement which can be effected in load factor by cultivating domestic demands for electricity (*see also* Chapters 26, 30).

I.E.E. Papers.

Domestic Load Building. W. A. Gillott, Vol. 61, p. 197.

Much information on maximum demand, diversity factor, and load factor is to be found (generally in relation to supply tariffs) in the *Journal of the I.E.E.* and in the electrical press.

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* Articles on load-duration curves and meters by W. Borgquist, *E.T.Z.*, Vol. 58, pp. 449, 455, describe a type of meter largely used in Sweden and give numerical examples of the uses of load-duration curves.

CHAPTER 12.

ELECTRICITY COSTS AND TARIFFS.

268. 'Undertakers' and the Sale of Energy.—Where a public company or local authority, known in British law as 'undertakers,' is supplying energy under an 'order' within any 'area of supply,' it is generally cheaper to purchase from the undertakers rather than to generate from private plant (*see*, however, § 185), notwithstanding the fact that the undertakers must make a profit on their sales. For, in the first place, the supplier can lay down a large plant at a much lower capital cost per horse-power or kilowatt than a private person can lay down a small plant; secondly, he can keep his plant working at a better load factor (§ 264) than any private person, owing to the diversity of uses to which different consumers will put the power and the different times at which their various maximum demands (§ 265) will occur, *i.e.* the good diversity factor (§ 264) of the load. Even so, the actual works cost of generating a unit varies greatly in different undertakings, from about 0·25 up to 3d. or 4d. (Table 38*a*, § 269); and the selling price varies accordingly. The above considerations will have more force still as the National policy of the Central Electricity Board is carried to its logical conclusion. By closing down inefficient generating stations, or keeping them in some cases as reserves for use at peak load times only, and by interconnecting 'selected stations' with the lowest generating costs,* the position of public supply must eventually be materially strengthened, even if the politicians' 'cheap and abundant' parrot-cry is not entirely substantiated. This policy, including also the standardisation of frequency throughout Great Britain, has already had some good results, though the supply industry undoubtedly suffers from the layman's inability to understand why a unit should cost twice as

* At present (1938) some 150 efficient power stations account for 95 °/₀ of the total kWh generated per annum, and of this amount, about half is generated by 15 'selected stations.'

much on one side of the street as it does, under another company, on the other side. The most important item in the costs is the price of fuel (Tables 25, 26, § 194), and it is therefore often tacitly assumed that a hydro-electric plant will always be able to supply energy cheaper than a steam plant; this, however, is not necessarily the case, as the capital cost of water-power development is generally comparatively high (Table 35, § 216).

269. Analysis of Cost of Public Supply.—(1) '*Works Costs' and 'Fixed Costs.'*—In order to realise the great variations in the working expenses of different undertakings, reference may be made to the tables published periodically by the *Electrical Times*, analysing the costs in hundreds of British power stations (*vide* Table 38 here and Table 26, § 194). There are certain general considerations applicable to every generating station. Thus, certain items of cost (known as 'works costs') vary approximately with the output of the plant from time to time, *viz.* fuel, oil, water; engine-room stores; and (to some extent) wages, repairs, and maintenance. Naturally, if the output increases greatly, the cost of these items *per unit generated or sold* drops somewhat, but on the whole it is fairly constant in any particular case; and in charging for energy supplied each consumer should pay his share of these charges according to his consumption. Owing to the absence of fuel charges, which usually amount to between 30 and 50 °/ₒ of the works costs in a steam station, the 'works costs' of a water-power plant are generally lower. The other items of cost ('fixed charges') are independent of the output of the plant, *viz.* rent, rates, and taxes; management expenses; interest and depreciation; these involve the payment of a fixed sum, whether the output is large or small, more or less in proportion to the total size and capacity of the plant. As the output in units increases, the cost of these items per unit diminishes; double the units, and the share of the cost of each is halved. Now, as the size of the plant ultimately depends on the maximum power required by the various consumers, it will be evident that each consumer should pay an annual sum sufficient to cover his share of these 'standing charges' or 'fixed charges,' according to his demand, in addition to his share of the variable costs (*see also* § 260). In the case of hydro-electro plant nearly the whole of the costs are fixed, the capital charges being generally by far the most important; consequently in these plants the cost price of a unit varies almost inversely as the total output; if the plant is standing idle it is costing almost as much as when working continuously at full load, so that, in order to fill in the hollows in the load curve and improve the load factor, it pays to sell energy from such an undertaking at a very low price during certain restricted 'off-peak' hours (§ 217). The various tariffs for the sale of energy are based on these two factors of variable costs and fixed costs. One other consideration may be briefly touched upon. The works costs can never fall below a certain minimum, even if the consumption falls to *nil;* for fuel and lubrication, etc., continue to be used in order that the plant may be able to take up its burden at a moment's notice. It follows, therefore, that the true *extra* cost of generating units is less than the full average works cost, and that it is both practicable and a paying proposition to sell power during restricted 'off-peak' hours, for the sole purpose of levelling up the load curve (*see* Figs. 49, 50, 51) at the bare cost of the *additional* fuel only, or even below it. For units so sold, by increasing the total output, diminish the cost per unit of the fixed charges. (*Cf.* § 264, 'Wilkinson Change-circuit System.')

(2) *Effect of Size of Plant and Load Factor on 'Works Costs.'*—For reasons explained in connection with Table 26, § 194, it is no longer possible to analyse works costs on the basis of plant capacity and load factor as effectively as in the past. The operation of the 'Grid' has replaced hundreds of power stations operating as separate entities by a relatively small number of stations operating under conditions determined by the load factor, load distribution and reserve capacity of the interconnected system as a whole. For this reason, although Table 38*a* has been added for purposes of general comparison (*see* page 352, § 194, on this point), Table 38 is based on data relating to 1932, and affords a more reliable indication of relative costs in more or less independent generating plants than can be obtained from any later analysis of this type.

The figures in Table 38 have been calculated from the invaluable 'Tables of Costs and Records' which the *Electrical Times* has now published for many years. Typical groups of plants of various sizes at various load factors have been taken, and the various items which make up the works costs (*i.e.* capital charges being excluded) have been averaged for each group; the highest and lowest costs of each group are also given. Undertakings purchasing energy in bulk are of course excluded in the

Table, as also those of intermediate size between the limits of our typical groups. The average load factor of the 338 undertakings analysed in the *Electrical Times* in 1932, *including* those purchasing in bulk, was 27·3 %; it was substantially higher for local authorities (28·8 %) than for companies (23·6 %). Only 10 undertakings exceeded 40 % L.F., the highest having 47 %; on the other hand, no less than 43 undertakings were below 20 % and 9 below 15 %—a state of affairs which could only be pronounced highly unsatisfactory. These figures compared with an overall average of 20 % in 1915 and of 18·6 % in 1922, as given in our fourth edition; so that the probable rise we forecast was very marked in the more efficient undertakings. The striking rise in load factors resulting from 'Grid' operation is apparent from a comparison of the preceding figures with those given in Table 38*a*. There are now (1938) several power companies whose 'undertaking load factor' (calculated as shown in the footnote to Table 38*a*) is 60 % or higher. As explained in § 194 (page 353) base load sets in 'selected stations' operate practically continuously at their most economical load, or say 75 % load factor calculated on their rated capacity.

Even before the 'grid' came into being a large proportion of the total electricity supply of the country was generated by a relatively small number of high-capacity, high-efficiency stations, so that the average works costs per kWh for the whole country was much lower than the average of the costs in individual stations. Economical generation in a single station delivering many hundreds of millions of kWh per annum is of far greater importance than the high costs in a number of the smallest stations. The favourable influence of bulk generation at minimum cost has been greatly extended by the working of the 'grid' (see footnote in § 268).

Data relating to 105 stations were used in compiling Table 38, which serves as a useful guide to the amount and distribution of works costs in plants operating independently. In these stations, in 1932, fuel accounted for roughly one-third to one-fifth of the total works cost, the mean percentages in the groups entered (8 entries in Table 38) being 28·1 %, with a maximum of 37·5 % and a minimum of 17·3 % (*cf.* Tables 25, 26, § 194). Bearing in mind the trend towards generating a higher proportion of the total kWh in the largest stations, it will be seen from Table 38*a* that fuel is likely to represent from 30 to 50 % of the total works

TABLE 38.—*Works Costs per Unit (kWh) in Great Britain.*

Based on the Tables in the *Electrical Times*, 1st December, 1932.
(Excluding cases where energy is purchased in bulk.) *See also* Table 26, § 194, and Table 38*a*.

Plant Installed (Approximate).	Output per Annum.	Load Factor.	Fuel.	Oil, Waste, Water, Stores.	Wages.	Repairs and Maintenance.	Rent, Rates and Taxes.	Management, Salaries, Office and Legal Expenses.	Total Works Costs.	L.A. = Level Authority. Co. = Company.
Kilowatts.	Million of Units.	%.	Pence per Unit.							
Up to 400	0·42	18	·57	·13	·53	·42	·25	·58	2·48	Mean of 4 L.A.'s
	0·31	18	·66	·12	·65	·58	·52	1·30	3·83	„ 21 Co.'s
	0·19	17	2·06	·12	·41	·88	·47	2·29	6·23	Highest of group.
	0·53	25	·39	·07	·28	·92	·05	·41	2·12	Lowest of group.
1 000 (600-1 700)	2·4	25	·56	·04	·24	·30	·21	·32	1·67	Mean of 19 L.A.'s
	1·4	21	·38	·05	·27	·30	·32	·61	1·93	„ 8 Co.'s
	1·7	20	·41	·02	·25	·26	·71	·71	2·36	Highest of group.
	3·5	30	·29	·05	·13	·18	·17	·22	1·04	Lowest of group.
10 000 (8 000-15 000)	25	32	·26	·01	·06	·17	·10	·12	0·72	Mean of 32 L.A.'s
	22	29	·36	·01	·07	·10	·31	·23	1·08	„ 3 Co.'s
	22	24	·41	·02	·09	·08	·68	·34	1·62	Highest of group.
	26	31	·14	·01	·05	·07	·03	·08	0·38	Lowest of group.
33 000 to 52 000	93	32	·18	·01	·05	·14	·09	·09	0·56	Mean of 12 L.A.'s
	99	31	·17	·01	·06	·29	·17	·12	0·82	Highest of group.
	93	35	·14	—	·03	·07	·05	·04	0·33	Lowest of group.
100 000 to 180 000	366	34	·16	·01	·06	·13	·14	·07	0·57	Mean of 5.
	398	35	·16	·01	·11	·21	·10	·08	0·67	Highest of group.
	509	39	·13	—	·03	·10	·10	·06	0·42	Lowest of group.
London Power Company 296 600 (1931)	881	36	·16	—	·02	·03	·05	·03	0·29	Largest in G.B. Lowest costs.
For Comparison with Above.										
7 500	14·6	29	·19	·01	·04	·03	·03	·02	0·32	Lowest prior to 1914
9 000	10	20	·38	·01	·17	·13	·08	·12	0·89	Lowest in 1922, as in 4th edition, during post-war inflation.

TABLE 38*a*.—*Approximate Analysis of Costs per Unit Sold.*

NOTE.—The figures given are the *averages* for a number of stations in each group calculated from figures given in the *Electrical Times* tables, February 3, 1938. (*See also* Table 26 (§ 194) and Table 38.)

Max. Load or Undertaking.	Output (Sold) per Annum.	Load Factor.*	Generation. Fuel.	Generation. Salaries and Wages.	Generation. Repairs-Maintenance and Stores.	Generation. Energy Bought, C.E.B. or Bulk and Gen.	Distribution.	Rents, Rates and Taxes.	Management, Salaries, Insurance, etc.	Total Working Costs.	Interest, Loan Repayment and/or Sinking Fund.	Total Costs.	L.A. = Local Authority. Co. = Company.
kW.	Million -kWh.	%.	Pence per Unit (kWh).										
200 (80-350)	0·4	20·6	—	—	—	1·28	·20	·29	·55	2·32	·66	2.89	Mean of 4 L.A.'s
	0·36	24·6	—	—	—	1·10	·30	·22	·36	1·99	—	—	,, 4 Co.'s
	0·27	23·8	·48	·64	·38	—	·22	·40	·93	3·06	—	—	,, 5 ,,
800 (400-1 200)	1·68	28·5	—	—	—	0·86	·30	·20	·31	1·66	·79	2·44	Mean of 10 L.A.'s
	1·84	26·3	·41	·15	·14	—	·16	·15	·34	1·36	·88	2·24	,, 2 ,,
	1·45	24·0	—	—	—	1·14	·18	·22	·39	1·93	—	—	,, 10 Co.'s
	1·18	23·4	·49	·24	·22	—	·15	·41	·71	2·22	—	—	,, 8 ,,
8 500 (6 000-12 000)	21·9	33·6	—	—	—	0·56	·11	·09	·15	0·97	·31	1·26	Mean of 11 L.A.'s
	26·9	35·9	·34	·05	·04	—	·10	·08	·12	0·73	·26	0·99	,, 5 ,,
	19·1	32·9	—	—	—	0·69	·13	·13	·31	1·27	—	—	,, 8 Co.'s
	25·7	37·6	·30	·06	·06	—	·09	·12	·12	0·77	—	—	,, 5 ,,
32 000 (25 000-40 000)	87·9	34·3	—	—	—	0·49	·10	·06	·08	0·73	·20	0·94	Mean of 10 L.A.'s
	86·4	39·0	·19	·02	·02	—	·05	·07	·05	0·42	·22	0·64	,, 4 ,,
	142·7	48·7	—	—	—	0·35	·02	·04	·05	0·47	—	—	,, 3 Co.'s
	75·6	33·2	·24	·03	·02	—	·11	·12	·06	0·58	—	—	One Co.
98 000 (65 000-120 000)	260	36·6	—	—	—	0·41	·07	·04	·06	0·58	·18	0·76	Mean of 6 L.A.'s
	333	36·2	·16	·02	·03	—	·07	·05	·09	0·32	·24	0·57	,, 2 ,,
	260	29·6	—	—	—	0·65	·11	·15	·18	1·09	—	—	,, 2 Co.'s (Lond.)
	456	52·6	·11	·02	·01	—	·02	·04	·05	0·25	—	—	One Co.
345 000 (154 000-580 000)	561	34·4	—	—	—	0·36	·07	·06	·05	0·55	·17	0·72	Mean of 2 L.A.'s
	1992	—	·13	·02	·02	—	·02	·04	·02	0·24	—	—	,, 2 Co.'s (Lond.)

$$\text{* Load Factor} = \frac{(\text{No. of kWh generated } plus \text{ purchased in bulk}) \times 100}{(\text{Max. simultaneous load on generators and bulk supply, in kW}) \times 8\,760} = x \text{ per cent.}$$

cost as generation becomes more restricted to 'selected stations.' For 1930-31, the average works cost of generation *only* (not distribution) was given by the Electricity Commissioners as 0·260d. per unit; while the average revenue per unit sold was 1·38d. in that year. The corresponding figures for 1935-36 were 0·174d. and 1·125d. per kWh (*see* Table 29*c*, § 197). The working expenses, excluding capital charges, are given as 0·642d. / kWh for 1935-36, made up as follows: Cost of energy, excluding inter-purchases, 0·256d.; transmission and distribution, 0·086d.; management, 0·122d.; rates, etc., 0·178d.; total 0·642d. / kWh.

270. The Sale of Electrical Energy by Meter; Flat Rate.—The only method of ascertaining the value of the supply, and charging for it, which is readily understood by the public, is that of sale by meter at a fixed price or 'flat rate' for each and every unit consumed; consequently this method is in more general use than any other system of charging. It has the disadvantage, from the central station point of view, that it does not encourage the most profitable type of consumer, *i.e.* the consumer who, by using energy when the average demand is small, is most profitable to the central station (directly), and hence of greatest benefit (indirectly) to the consumers as a whole. Consequently there is sometimes provision for modifying the flat rate according to the load factor; and also according to the power factor, which when low similarly operates to increase the cost of supply, owing to the increased capital costs in plant and mains to deal with wattless currents. The supply meter registers on its dials the actual number of units supplied; sometimes these units are charged for at a flat rate of (say) 2d., 4d., or 6d.; sometimes discounts are given either to very large consumers or to all who pay prompt cash; again, two meters are sometimes installed, one for registering energy used for lighting, and the other for registering energy used for other purposes, different rates being charged in the two cases (§ 275, *A* and *B*). The technical features of various types of supply meters are discussed in §§ 113-117, and the correct method of reading meter dials is explained in § 113. Meter testing is dealt with in § 1 035, Vol. 3. Most supply companies arrange to test meters specially on consumer's request, the cost of the test being borne by the consumer if the meter proves to be accurate within the limits laid down by law, *i.e.* if the error does not exceed ± 3 °/₀ between $\frac{1}{10}$ full load and full load and under normal supply conditions in meters of less than 3 A capacity, or ± 2 % in larger meters. It is laid down in the Electricity Supply (Meters) Act, 1936, that all consumers' meters must be certified by a Meter Examiner appointed by the Electricity Commissioners, after the meters have been tested with approved apparatus and by approved methods by the supply authorities.

271. Minimum Quarterly Charge.—The Electric Lighting Orders granted by the Board of Trade since 1890 generally provided for a minimum quarterly charge to consumers, for any amount up to 20 kWh, of twenty times the authorised maximum price per unit. The intention of this provision was to ensure to undertakers a reasonable return from each consumer in respect of the capital expenditure incurred to enable the desired supply to be available at all times to all consumers. In the case of large undertakings supplying industrial districts, lighting consumers now represent so small a fraction of the total load that it is generally possible to supply them without insisting upon payment of a minimum quarterly charge. It should be borne in mind, however, that every consumer may justly be expected to yield a fair return upon the capital expenditure involved in rendering supply available to him, and that this capital expenditure has increased (actually, though not relatively; Table 25, § 194), due to the general rise in costs, whereas the use of high efficiency incandescent lamps and the operation of the Summer Time Act (§ 612, Vol. 2) have reduced greatly the energy consumption of the average lighting installation. These factors bear particularly heavily upon the smaller electricity undertakings, which mainly supply a lighting load and operate at low load factor, and in such cases it is economically essential to impose a minimum quarterly charge or to secure by other means a reasonable return for the facilities provided.

Domestic and shop-lighting consumers are the ones principally affected by minimum-charge regulations and that mainly during the summer months. In typical cases, the occupiers of small houses and flats with, say, 400 W of lamps installed, consume about 30 kWh during the 3 months April 1 to June 30 with Summer Time in operation. Circumstances vary, but in few, if any, cases would the revenue from the sale of 30 kWh cover the legitimate standing charges on a 400 W installation in addition to the actual cost of the energy consumed, even when the price per unit is 50 % above the pre-war figure. To allow for this, the Electricity Commissioners recommend that a minimum quarterly charge be allowed on the following basis :—

(*a*) In respect of each of the two winter quarters, for any amount up to 15 units, fifteen times the authorised maximum price per unit;

(*b*) In respect of each of the two summer quarters, for any amount up to 10 units, ten times the authorised maximum price per unit.

Common sense, however, should be exercised by undertakers. In one instance brought to our notice a separate underground connection had been made to a garage by a consumer who afterwards sold the estate. Obviously the consumption in a garage must be extremely small, however desirable. The undertakers demanded both a minimum charge of 13s. 4d. per quarter and a quarterly meter rent; with the result that the connection was made by an overhead line.

272. Tariffs Based on Maximum Demand.—(*a*) *Fixed Price per Kilowatt and per Lamp.*—The considerations discussed in §§ 259, 270 have led to the introduction of various tariffs based entirely or mainly on the maximum demand of each consumer, with the twofold object of increasing the profits of the undertaking and diminishing the price per unit paid by the consumer. These two apparently inconsistent aims can only be reconciled when the result of such a tariff is both to enhance the output and improve the load factor of the station; the latter consideration involves the encouragement of the use of power for fans, motors, heating, refrigeration, etc., during hours when lights are not required.

Whereas lighting was the main, if not the only duty of the early central stations, and industrial power has become the principal factor during recent years, it is now realised that domestic applications (other than lighting) are capable of being developed so as to constitute the greatest load on the station, as well as the most desirable from the standpoint of high average load factor; (*see El. Rev.*, Vol. 86, p. 675).

A special indicator is used to record the maximum demand (§ 117). A warning device or 'current limiter' is sometimes added, which rings either a bell or a buzzer when the load is such that there is a danger of a previously recorded maximum demand being exceeded.

The simplest tariff based on maximum demand is that which makes a fixed charge per kW of maximum demand, regardless of the consumption in kWh and of the purposes to which the current is applied. This charge may be so much per annum per kW, this being a common basis of charging where industrial loads are supplied from hydro-electric stations or from overland power transmission systems. Alternatively, it may be per quarter, per month, or per week in the case of small power users and for domestic supply. In the latter case the charge frequently takes the form of a fixed weekly payment per lamp of specified type and candle-power (§ 275, *E*). Obviously this is simply a fixed charge per week per kW of maximum demand, though it is referred to a basis more easily understood by, and hence more appealing to, the class of consumer to whom it applies, *viz.* artisans, tenement dwellers, and so on. So far as the authors are aware, this is the only form in which the 'fixed charge per kW' tariff is applied in Great Britain, but this form of tariff is used considerably abroad in connection with heavy power supply from hydro-electric stations. In the latter case, the load factor of the industry concerned is known, or can be determined with reasonable accuracy, so that, in making a fixed charge per month per kW, the supply engineer is really making simply a lump charge for a certain number of units at a price per unit which he considers profitable. In street lighting contracts a fixed charge per lamp per annum is frequently agreed upon, but the total annual consumption is then known within very close limits, and the remarks in the previous sentence apply with particular force. In domestic supply, however, the load factor is a much more variable factor, and there is considerably greater risk of current being used recklessly. The use of a 'current limiter,' cutting off supply or actuating a trembling contact in the event of the demand exceeding a predetermined maximum, prevents more lights being used at once than are contracted for by the consumer's payment. On the other hand, the cost of a limiter is at least comparable with that of a meter. As regards preventing lamps being kept alight needlessly, this can be done more or less satisfactorily by making the consumer pay for lamp renewals and by refusing to renew contracts in the case of flagrant offenders. The longevity and cheapness of modern filament lamps makes the 'pay-for-renewals' arrangement less effective than formerly as a safeguard against current wastage.

(*b*) *Standing Charge plus Low-unit Charge.*—A more effective method of preventing waste, and certainly a more rational tariff, consists in charging a fixed annual sum per kW of maximum demand, plus a small additional charge per kWh actually consumed, as registered by meter, but still regardless of the purpose to which the current is applied. This method of charging, which is practically the 'telephone' system mentioned in § 273, involves providing a meter, which it is the chief object of the previous tariff to avoid in the case of very small consumers. The present tariff encourages the long-hour consumer, for every additional unit used adds little to the bill, and reduces the *average* price per kWh. Suppose, for instance, a purely lighting installation, with a maximum demand of 2 kW, to be working under this tariff; the owner could introduce a motor or other apparatus, also taking 2 kW, and so long as it was not used during lighting hours, his fixed annual charge would be unaltered, the maximum demand remaining at 2 kW. He would only have to pay for the additional units used by the motor at the low rate of charge presupposed (§ 275, *D*).

The fixed or standing expense incurred by keeping the supply system ready for service, includes the interest and redemption charges on the capital investment, rents, rates, insurance, etc., and a proportion of the wages and coal bills. Hitherto, where maximum demand tariffs have been used, it has been customary to recoup the standing expenses by a fixed charge per kW of maximum demand, but it has been shown by J. R. Blaikie (*Jour. I.E.E.*, Vol. 59, p. 701) that there is much to be said in favour of different fixed charges for industrial and residential consumers. Large factory loads, demanding supply during well-defined hours 6 days a week, involve much lower capital charges per kW and considerably lower coal and wages costs (apart from the saving due to higher load factor) than do small residential demands which may require supply at any time, throughout the week (*see*, however, the note in § 271 regarding the favourable effect of wholesale utilisation of electricity for domestic purposes). Proposals for tariffs discriminating between consumers requiring supply for 7 days a week and those requiring supply for 6 days a week are given in the paper *loc. cit.*

Wright's System.—In this older system of charging, the consumer pays a high price per unit metered until his consumption corresponds to 1 (or 2) hrs.' daily use of his maximum demand during the period for which the account is rendered; this charge s equivalent to the fixed charge in the preceding paragraph; for all units used over this amount he pays at a low rate. For example, if the maximum demand recorded by the indicator (§ 117) is 2 kW, then an average of 2 units a day (*i.e.* 180 kWh per quarter of 90 days), equal to 1 hr's. use per diem of the maximum demand, must be paid for at the high rate. If the actual consumption as shown on the meter averages 5 units a day during the period in question, the balance, or 3 units a day, will be paid for at the low rate.

Restricted Hour Tariffs.—Methods of charging which depend on the time at which the maximum demand occurs have also been tried, with a view to improving the diversity factor of the power station. In this case two-rate meters (§ 116 (ii)) are used, in which a clock or time switch regulates the hours at which each tariff is operative (§ 374, 622). In many places the introduction of a two-rate tariff has led to important increases in demand during off-peak periods.

273. Rateable Value (Norwich) System; Floor Area; Glasgow, Metropolitan, Telephone, and Point-five Tariffs.—A detailed discussion of types of residence tariffs, *i.e.* charges for electricity supplied for domestic purposes, is to be found in a paper delivered some years ago by Mr. A. H. Seabrook (*Jour. I.E.E.*, Vol. 48, pp. 376 *et seq.*). That author laid stress upon the fact that the Hopkinson principle (of making distinct charges for M.D. and kWh consumed, to cover standing and running costs respectively) is the only scientifically correct basis of charge, though it is by no means universally applied, owing to the difficulty of framing a simple tariff thereon. Mention has already been made (§ 272) of the fixed charge per kW or 'contract demand' tariff and of the Wright maximum demand system. Other tariffs based on the Hopkinson principle and finding more or less extensive application in Great Britain are the rateable value tariff, the Glasgow system, the Metropolitan system, and the telephone system.

The *Rateable Value* tariff consists of a fixed annual payment, based upon the rateable value of the consumer's premises, supplemented by a low charge per kWh of metered consumption. This system of charging is generally known as the *Norwich system* from the town of its origin. Consumers in private houses, may, for example, have the option of paying a flat rate of 4½d. per kWh for all purposes, or, alternatively, of paying 12 °/ₒ on the rateable value of the premises, plus 1d. per unit; in the case of business houses the fixed charge is based on the lamps installed, and may be, say, 5s. to 7s. 6d. per lamp per annum.

A census of towns using the rateable value system in 1922, for domestic purposes, showed an average consumption of 36 units (kWh) per £1 of R.V., with a maximum of 65 at Leigh and a minimum of 15·6 at Stafford. In a 10-roomed house with a family of 5, the consumption in 1935 was 11 kWh per £1 of R.V. for lighting and 3·5 kWh per £1 R.V. for an electric washer and ironer; no electric cooker, fires or water heaters are used in this installation. The higher kWh figures mentioned above are donbtless due to electric cooking, heating and water-heating. Generally the R.V. tariff is designed to attract such loads, but even without them it is often profitable to the consumer to adopt the R.V. basis. The unit (kWh) charge under R.V. tariffs is now (1938) as low as 0·33d. in some supply areas.

Though the rateable value tariff may be held to have justified itself in practice, it is obviously an empirical tariff; there is no definite relation between the rateable value of premises and the maximum demand of the electricity consumer occupying those premises. The percentage of the rateable value taken as the fixed charge differs from town to town (*see also* § 275, *F*). The following are a few cogent arguments from an article discussing the characteristics of the rateable value tariff:—

The most tempting feature of the rateable value tariff, from the central station point of view, is its simplicity. The fundamental assumption is that rateable value is a reasonably accurate measure of the electricity-consuming capacity of private premises, and the fundamental weakness of the system is that it is not necessarily or even generally anything of the kind. Houses of similar size and quality shelter families of very different sizes and habits, so that rateable value bears neither theoretical nor actual relationship to the current consumption of a household. In some cases the percentage charge on rateable value is increased, and in other cases decreased, as the rateable assessment increases. In any event, if a different percentage of R.V. is to be charged in the case of different-sized houses (as seems desirable), and if allowance is to be made for the effect of specially large or small gardens on rateable value (as seems essential), the R.V. tariff at once loses its merits of simplicity and power of being easily understood by the layman. The method generally employed (at the time of initiating the new tariff) in determining the percentage of rateable value to be taken as the fixed charge, is to analyse previous accounts, and see what percentage of rateable value will, in conjunction with, say, ½d. per unit, give the same revenue from lighting as the previous flat rate (say, 4d. a unit). This amounts to securing the station's revenue and supplying all additional units at ½d. It is a simple, if tedious, method of arriving at a suitable *average* percentage on rateable value, but there is nothing to secure (1) that this percentage will not be far wide of the mark in individual cases; and (2) that the percentage decided by reference to previous accounts will be at all suitable under the new conditions which it is desired to bring about by the new tariff. Generally the percentage charge is 10, 12½, or 15 °/₀ on rateable value, but it makes a considerable difference to consumers, and so, ultimately, to the station's prospects, which percentage is adopted. The average price per kWh fluctuates enormously with rateable value and with total consumption per annum, wherever the rateable value tariff is applied; this cannot be fair to either supply authority or consumer. Perhaps the most disturbing feature is the considerable difference in average price per unit paid by consumers taking the same amount of energy, but using it in houses of different rateable value. Nor can this discrepancy be justified by attributing it to differences in load factor, for sometimes the difference is in one direction and sometimes in the other. District, size of garden, and assessor's whim are a few of the factors determining the rateable value. Number and position of windows, nature of surroundings, number and habits of household are factors influencing the consumption of electricity for lighting and other domestic purposes. Where is the connecting link between these groups of factors? On the average for a whole district the rateable value tariff may be equitable, and in most cases where it is working it *is* equitable as between supply authorities and consumers as a body; but is this altogether unconnected with the fact that the tariff has only been in vogue a few years, and that when it was put into force it was deliberately arranged to give what might be called 'average equity'? In other words, is not the tariff very largely artificial—with just that basis of reason sufficient to make it plausible and workable for the nonce? The rateable value tariff must already be responsible for grave anomalies between the current consumption and bills of individual consumers, and such anomalies cannot be good for the development of the industry as a whole. The maximum demand system in a modified form is, in the writer's opinion, the best and fairest possible. Every consumer is entitled to special consideration of his case, for, after all, it is to meet the electrical engineer's difficulties and limitations that any departure at all from the flat rate is required. It is, at this date, quite easy to estimate what will be the average maximum demand for any proposed equipment, and so to determine a fixed charge which shall be fairer to the consumer than the R.V. charge can be, whilst being, for the district as a whole, equally satisfactory to the station (*El. Rev.*, Vol. 77, pp. 443 *et seq.*).

Floor Area Tariffs.—The levying of a fixed charge per unit (sq. ft.) base area of house or, more logically, per unit of total floor area, plus a low charge per kWh consumed, is an approved system of charging. Like many other systems it embodies a strong element of empiricism and probably, in practice, it is approximately equivalent to a R.V. tariff, because floor area is usually a primary factor in determining R.V. assessments.

Modified Norwich System.—Instead of taking the rateable value of the premises, a system sometimes adopted (as *e.g.* in Cawnpore, India) is to assess the fixed charge on the number of living rooms in the house. In the assessment, 'convenience' rooms such as bathrooms, lavatories, dressing rooms, entrance halls, kitchens, etc., are not taken into account. A 'room' is taken as a single one when not exceeding (in Cawnpore) 400 sq. ft.; every 300 sq. ft. over this counts as another room. Outdoor areas served by fans are similarly assessed on an area basis. The tariff is only applicable to the supply paid for by one consumer in one building through one service and one meter. There is a fixed charge per month of Rs. 9½ * for premises, assessed as 'one-room'; Rs. 11 for 'two-room'; Rs. 12½ for 'three-room' and so on, with a small

* Say 14s.

unit charge as well. The disadvantage of this tariff lies in the necessity of measuring up a town; but, once this is done, it is simple and more equitable than a rateable value pure and simple.

The *Glasgow system* charges a fixed number of hours' use of the M.D. at a primary rate, and all further consumption at a lower secondary rate. When the system was first enforced in Glasgow, it was found that the average domestic consumer used his lighting M.D. for 800 hrs. per annum, so the tariff charged 800 hrs.' use of the M.D. at 3d. per kWh, and all additional units at 1d. The system is only a slight modification of the Wright system (§ 272), and, like the latter, it overcharges the consumer for any heating and cooking consumption unless the latter be metered separately.

The *Metropolitan system* consists of a fixed primary charge (based on the kW capacity and nature of lighting and other apparatus installed) plus a certain charge per kWh till the amount of this charge equals the primary charge. Thereafter all units are supplied at a lower price. For example, the fixed primary charge may be £5 per annum, the first energy charge 2d. and the second 1d. per kWh. Then the consumer's minimum bill is £5; if he uses 600 kWh per annum he pays a further £5 for them, *i.e.* a total of 4d. per kWh on the average; thereafter he obtains additional units at 1d. Under these conditions the average price is: 8d / kWh for 200 kWh per annum, 4d. for 600 kWh, 2·8d. for 1 000 kWh, 1·9 for 2 000 kWh per annum, and so on. This system of charging does away with double metering and double wiring. The chief object of the two rates of charging for energy seems to be that consumers using only small domestic appliances pay for all current at the lighting rate, whereas if they install heaters or cookers they get on to the lower energy rate, to which they are entitled.

The *Telephone system* was so named because it consists (like the telephone charges formerly in force in this country) of a fixed annual payment in advance, plus a small unit charge for service actually utilised, *i.e.* per kWh consumed. The fixed charge is based on a certain percentage, say, 70 °/ₒ of the connected lighting load, not counting convenience or decorative lighting, and not counting wattage installed for other than lighting purposes. The secondary charge is low, say 1d. or $1\frac{1}{2}$d. per kWh. The standing charges are based solely on the lighting installation, and it is insisted that only electric lighting be used on the premises. By exempting 'convenience' lamps from standing charges, the installation of such lamps is not checked. The system encourages liberal and long-hour consumption of energy, is easy to understand, and needs only a single meter, whilst being applicable to all classes of domestic supply. The advantages and working of the system are dealt with fully in Mr. Seabrook's paper (*loc. cit.*).

'Point-five' tariffs have as their object the encouragement of electric heating and cooking. As matters stand at present, any system of charging can claim to be a point-five tariff, so long as it provides additional units for heating and cooking at 0·5d. per kWh. This charge may be, and generally is, supplemented by a fixed charge or minimum payment in some form or other, so that the average price per kWh is generally considerably higher than 0·5d.; but, as explained in § 615, Vol. 2, the important point is that the charge which varies with the use of the apparatus, *i.e.* the energy charge for 'additional' units, be low, so as to encourage liberal consumption and make the wastage of a few units of negligible importance to the consumer; the central station can afford to supply them at low price, once the standing charges have been covered.

274. **Tariffs taking Power Factor into Account.**—The ill-effects of low-power factor in A.C. circuits have been discussed in § 155. As these effects increase the costs of producing and distributing a given quantity of energy (kWh as distinct from kVAh, § 154), it is justifiable to increase the average charge per kWh used by a consumer if the power factor of his load is less than unity. The object of the adjustment should be approximately to make the increased charge equal to the increased cost of supply. This is rational and, indeed, necessary on economic grounds. There is, however, no justification for increasing the charge beyond this point. As explained in § 156, the low power factor is caused mainly by the lagging reactive current essential to the operation of induction motors. The user of such motors ought to pay the extra cost entailed by the supply of the reactive current, if he takes it from the mains, but there should be no implication that he is to be 'penalised' as though he were committing an offence. The reactive component must be supplied from some source, and it is a purely economic problem whether it be generated at the central station, transmitted and charged for, or generated at the user's expense near the place where it is required. In many cases the latter

course is the cheaper, and there is a financial inducement for the consumer to install power factor correcting devices (§§ 159-161), and so to reduce the average cost per kWh of the energy he uses.

Any tariff taking power factor into account involves the use of special metering arrangements for the determination of some quantity, additional to kWh, which depends upon the power factor. Generally an additional instrument such as a kVAh or a kVArh meter is required, for the determination of kVA demand, or the calculation of average power factor (§ 116*a*). If two single-phase meters are used to measure a 3-phase supply, then an approximate value of the kVArh can be obtained from the difference of the meter registrations (§ 110) and, hence, the average power factor can be computed. In the case of large installations the cost of two or three metering instruments can be afforded, but this is not so where small consumers are concerned, and these are often the worst offenders in respect of low-power factor.

One method of dealing with low-power factor is to charge for the true energy (kWh) metered according to a sliding scale, the price per kWh increasing as the P.F. decreases. This method demands that the supplier should know the cost per kWh delivered at various power factors (which varies with the location of the consumer because of the transmission losses occasioned by low P.F., § 155); also, the method depends upon the consumer accepting the method for the determination of his average power factor.

A better method of taking power factor into account consists in making a fixed charge per kVA of maximum demand (instead of per kW, § 272 *b*) plus a unit charge per kWh consumed. If the supply voltage be constant, the maximum demand of small single-phase supplies in kVA can be measured by means of thermal indicator such as described in § 117, which is calibrated for the declared voltage. Thermal indicators can be used for 3-phase balanced loads by measuring the maximum demand in 1-phase, but they are not suitable for unbalanced loads. The accurate measurement of kVA demand in a 3-phase supply calls for the use of a true kVA meter (§§ 116A, 117). The kVA demand system of charging is not quite exact in equating the average rate per kWh to the cost of supply since it allows only for the increase in fixed costs occasioned by low-power factor, and not for the increase in running or working costs. Though the increase in standing charges is the main factor, the other is not negligible (§ 155).

Professor Arno (Milan) has devised a special meter, the reading of which is determined by two-thirds of the kWh consumption and one-third of the kVAh consumption. The consumer is charged so much per composite 'unit' as thus recorded, hence the actual charge per kWh increases as the kVA consumption rises (*i.e.* as the P.F. decreases). It can be shown that with this method of charging the increase in the average rate per kWh can be made to correspond to the additional cost of supply due to low-power factor. In its original form the Arno method is not very suitable commercially, but the principle underlying it has recently been applied in two part tariffs for power supplies in which the consumers bill consists of a component proportional to his kWh consumption and a second component proportional to the kVArh consumption. If the rates per kWh and per kVArh be properly fixed, the tariff operates in close conformity with the Arno principle over a wide range of power factors. The rate per kVArh under this tariff is usually of the order of ⅓ that of the rate per kWh.

Many other tariffs * have been devised for taking power factor into account, but there are so many factors involved that costly metering equipment and elaborate accountancy are required to arrive with certainty at a close approximation to the equitable charge. Thus if the consumer will consent to the arrangement in his supply contract, it is sufficiently accurate to use the maximum demand system (§ 272 *b*), correcting the indicated maximum demand according to the formula; $kW_c = kW_i \times P/Q$; where kW_c = corrected max. demand used to calculate the standing charge, at so much per kW; kW_i = actual max. demand as indicated by the demand indicator; P = assumed basic or standard power factor, say 0·7, 0·8, or 0·85, according to circumstances; and Q = consumer's power factor as measured periodically, at the undertaker's discretion, under conditions of normal load. The standing charge per kW thus varies inversely with the consumer's power factor and the unit charge per kWh is the same for all power factors. If a fairly low value of P (say 0·8) be taken as the basic power factor (the standing charge per kW being adjusted accordingly) the average consumer will be able to maintain a power factor higher than P, thus securing a reduction in the charge per kW. This amounts to offering a bonus for high-power factor, rather than imposing a penalty for low-power factor, and is to be recommended for psychological reasons. Present practice, however, tends to the measurement of the power factor upon which the kWh rate is adjusted by integrating instruments as described above, rather than by the use of indicating or recording power factor meters.

275. Actual Tariffs in the United Kingdom; Examples of Charges.—It would serve no useful purpose to attempt anything like a complete statement of the great variety of tariffs actually in force in this country, especially as the *Electrical Times* has done so,† but the following typical examples, chosen at random,

* *See* 'The Improvement of Power Factor,' by Gisbert Kapp, *Jour. I.E.E.*, Vol. 61, p. 89; and, for American practice, *Nat. El. Light Assoc. Bull.*, Sept. 1921, pp. 520, 551.

† 'Electricity Tariffs and Voltages of Supply Undertakings in the United Kingdom.' Sixth edition, 1932.

are interesting and instructive. A few special tariffs for specific purposes have been given at the end of the tabulated list.

Note.—Section 22 (1) of the Electricity (Supply) Act, 1922, repealed Subsection 2 of Section 31 of the schedule to the Electric Lighting (Clauses) Act, 1899, under which a consumer had hitherto had the option of requiring undertakers to charge him for the actual amount of energy supplied or for the electrical quantity contained in the supply. The effect of this repeal was to remove what had been an obstacle to the general adoption of multi-part tariffs, and thus to permit tariffs to be introduced suitable for the varied demands on an undertaking and for encouraging the more extensive utilisation of electricity. If, however, the consumer and the undertakers had entered into an agreement as to a special method of charge, a course expressly provided for by the Act of 1899, and that agreement was for a definite period and allowed a definite length of notice to be given before either party could terminate it, it is practically certain that the contract would have been held good. The provision for termination by one month's notice was 'in the absence of an agreement to the contrary.' The point is of importance as the alteration in the law referred to holds good only in the United Kingdom and not in overseas countries which have followed British law.

EXAMPLES OF TARIFF CHARGES.*

A. Flat Rates by Meter (§ 270).

Lighting.

(1) Winchester. 6½d. per unit.
(2) Battersea. 3¾d. per unit.
(3) Finchley. 3d. per unit.

Power.

(4) Southport. 2d. per unit.
(5) Kensington. 1d. per unit.
(6) St. Pancras. ¾d. per unit.

Heating.

(7) Scarborough. 1½d. per unit.
(8) Coventry. 1¼d. per unit.
(9) Kensington. 1d. per unit.

Cooking.

(10) Aberdare. 1½d. per unit.
(11) Scarborough. 1d. per unit.
(12) St. Pancras. ½d. per unit.

Power, Heating and Cooking.

(13) Llanelly. 1¾d. per unit.
(14) Westminster. 1d. per unit.
(15) Hastings. ¾d. per unit.

By Slot (Prepayment) Meter.

(16) Warmley. 9d. per unit.
(17) Newcastle-on-Tyne. 5d. per unit.
(18) Coventry. 4½d. per unit.

B. Meter Rates with Discounts or Rebates (§ 270).

Lighting.

(19) Malvern. First 200 units / quarter, 6½d.; down to 4d.
(20) Prescott. 6d. per unit, with discount from 5 °/ₒ to 18 °/ₒ.
(21) Edinburgh. 3½d. per unit, with rebate from 1 °/ₒ to 12 °/ₒ.

* It must not be assumed that the actual tariffs cited are still in force. Changes (usually downwards) have been frequent during recent years, but the examples given are representative of the range of changes in the United Kingdom, and the later examples of the effects of various tariffs are instructive.

Power.

(22) Prescott. $1\frac{1}{2}$d. per unit, less variable discount.

(23) Ashton-under-Lyme. For 5 000 units per week, 0·7d. per unit; diminishing to 0·35d. per unit over 40 000 units; with coal clause; also 20 °/₀ off all units used between 6 p.m. and 6 a.m.; also discount of $2\frac{1}{2}$ °/₀ for prompt payment.

C. *Maximum Demand Tariffs* (§ 272).

Lighting.

(24) Liverpool. £2 per quarter / kVA of M.D., plus 2d. per unit.

(25) Cardiff. First 1 000 units per annum per kW of M.D. $3\frac{1}{2}$d. per unit; remainder $1\frac{1}{16}$d.

(26) York. $6\frac{1}{2}$d. per unit until the amount of energy consumed equals that required for use of consumer's M.D. for 91 hrs. / quarter; excess at 1d. per unit.

All Purposes.

(27) Bristol. $1\frac{1}{2}$d. per unit up to the number equivalent to the use of the M.D. for 300 hrs.; excess at $\frac{3}{4}$d. per unit; discounts from 1 °/₀ to 10 °/₀.

Power.

(28) Liverpool. Fixed charge of £1 7s. 6d. per quarter per kW of M.D., plus 0·5d. per unit.

(29) Shipley. Standing charge of 7s. 6d. per month per kW of M.D., plus $\frac{1}{2}$d. per unit; coal clause.

(30) Cardiff. First 1 400 units per annum per kW of M.D. $1\frac{1}{16}$d. per unit; balance at 3s. 8d. per unit.

D. *Fixed Charge per H.P. or kW, Plus Charge by Meter* (§ 272).

(31) Torquay. Standing charge of 12s. per H.P. per quarter, plus $\frac{3}{4}$d. per unit.

(32) Canterbury. £6 per annum per kVA, plus $\frac{1}{2}$d. per unit; £4 with similar unit charge when over 200 H.P. and 50 000 units per annum.

(33) Bournemouth. 'Business Tariff,' £15 per kW plus $\frac{3}{4}$d. per unit.

(34) Bangor. £2 per H.P. per annum, plus 2d. to $1\frac{1}{2}$d. per unit.

E. *Fixed Charge per Lamp* (§ 272).

(35) Aberdare. 3s. 6d. per quarter per 32 W lamp plus $1\frac{1}{2}$d. per unit.

(36) Barnes. 2d. per week per 20 W. lamp.

(37) Bangor. 'Residence Contract System'; primary charge of 8s. per 30 W assessed lamp, plus $1\frac{1}{2}$d. per unit.

F. *Rateable Value* (*R. V.*) *Systems* (§ 273). *See also* I. below.

(38) Norwich. Fixed annual charge of $12\frac{1}{2}$ °/₀ on R.V., plus $\frac{3}{4}$d. per unit.

(39) Aberdeen. Fixed annual charge of $7\frac{1}{2}$ °/₀ on R.V., plus $\frac{1}{2}$d. per unit.

(40) Accrington. Fixed annual charge of 15 °/₀ on R.V., on the first £100 and 10 °/₀ on the excess, plus 0·6d. per unit.

(41) Manchester. Fixed annual charge of $12\frac{1}{2}$ °/₀ on R.V. up to £130 and 10 °/₀ on excess, plus $\frac{1}{2}$ °/₀d. per unit.

(42) Aylesbury. Fixed charge of 10d. for each 10 sq. ft. of base area of house, plus 1d. per unit.

(43) Bradford. Domestic. Half-yearly fixed charge of $8\frac{3}{4}$ °/₀ on R.V., plus 1d. per unit; but all energy in excess of 10 units per £ of such R.V. at $\frac{1}{2}$d.

(44) Central Sussex. Fixed charge per quarter, up to 800 sq. ft. 7s. 6d. summer and 15s. winter, increasing for larger areas, plus 1d.

G. Flat Rate, Subject to Load Factor and / or Power Factor (§ 270).

(45) Sunderland. Power at e.h.t., 1d. per unit for all up to 20 °/₀ L.F.; 0·4d. per unit between 20 °/₀ and 40 °/₀ L.F.: 0·25d. per unit above 40 °/₀ L.F.; with discount of ½ °/₀ for each 1 °/₀ improvement in L.F.

(46) Chesterfield. Power over 50 kW £5-10 per kVA of M.D. per annum plus 0·375d. per unit, with coal clause; 5 °/₀ discount for P.F. improvement from 80 °/₀ to 100 °/₀; discount of 5 °/₀ to 17 °/₀ according to L.F. also.

H. Restricted Hours Rates (§ 272).

(47) Blackburn. Lighting from sunset to 11 p.m., 6½d.; balance 3d. per unit.

(48) Blackpool. Industrial heating, off-peak, ¾d.

(49) Brighton. Water Heating, 1s. 3d.

(50) Burton. Sliding scale ranging from 1½d. for 5 000 units per quarter to 0·9d. per unit for 125 000.

I. Fixed Charge per Room (§ 273).

(51) Alton. Domestic tariff. Fixed charge of 6s. 8d. per quarter in summer and 3s. 4d. in winter per room, plus 1¾d. per unit.

(52) Amble. Residential tariff. Fixed charge of 18s. per room per annum, plus 1d. per unit.

(53) Stoke-on-Trent. 'All-in' tariff. Fixed charge of 5s. per quarter per room, plus from 1d. to ¾d. per unit.

(54) Cardiff Rural. 'All-in' tariff. Fixed charge of 8s. 6d., plus 1s. 3d. per quarter for each living-room in winter; 11s. 6d., and 2s. 6d. per quarter for each living-room in summer; plus 1d. per unit.

J. Two-Rate Systems (Clock Meter ; Time-Switch, etc.).

(55) Ashton-under-Lyme. From 4 p.m. to 11 p.m., first 500 units per quarter, 4d. per unit, diminishing to 2d. per unit over 10 000. Other hours, 2d.

(56) Barnstaple. From 4 to 10 p.m., 8d. per unit; rest, 4½d.

K. Prepayment ; Slot Meter, etc. (*See also* last list in A, Flat Rates *supra.*)

(57) Barnoldswick. All purposes, 7d.

(58) Birkenhead. All purposes, 4½d.

(59) Brighton. Lighting, 4½d.

L. Bulk Supply (to Distributors).

(60) Barnsley. Sliding scale. £3 18s. per kVA of M.D. per annum, plus 0·6d. per unit up to 200 000 units per annum, diminishing to 0·4d.; based on coal at 15s. per ton, subject to adjustment; and less 2½ °/₀ for prompt payment.

(61) Sheffield. £4 per annum per kVA of M.D., plus ½d, and subject to a coal clause.

M. Special Tariffs for Particular Applications.

Shop-Window Lighting.

(62) Barnes; Barrow. 1d. per unit.

(63) Reading. 2d. per unit.

(64) Aldershot. 3d. per unit.

(65) Cheltenham. £6 per kW per annum, plus 1d.

Cinematographs.

(66) Generally about 2d. per unit, varying according to whether there are daily matinees.

Flood-Lighting.

(67) St. Marylebone. 2d. per unit.

Signs.

(68) Manchester. 1½d. per unit, restricted hours, plus rental of time-switch.

(69) Ashford. £1 per 30 W per annum.

Churches.

(70) Birmingham. 30 % discount of heating rate where 60 % of the demand is on Sunday.

Water-Heating.

(71) St. James and Pall Mall. ½d. per unit, off-peak.

(72) Kensington and Knightsbridge. ½d. per unit, off-peak.

(73) Aylesbury. ¾d. per unit.

(74) Brighton. 1s. 3d. per unit, restricted hours.

Central Heating.

(75) St. Marylebone. ½d. per unit or 1s. 3d. off-peak.

Thermal-Storage Heating, Thermostatically Controlled.

(76) Liverpool. Up to 500 units per quarter, 0·5d. per unit; all over, 0·3d.

(77) Brighton. ½d. per unit (low-temperature).

(78) Birmingham. ½d. per unit between 8 p.m. and 7 a.m.

(79) Burnham. 1d. per unit.

(80) Buxton. ¾d. per unit.

Incubators.

(81) Warrington. 1d. per unit.

Vehicle Battery Charging.

(82) Birmingham. 1½d. and 1d. per unit.

(83) Hackney. 1d. and 2d. per unit.

Bakers' Ovens.

(84) Barnes. First 500 units / quarter, 1d.; rest 0·9d.

(85) Birmingham. After 8 p.m., 0·6d. per unit; in daytime, 0·75d. per unit.

(86) Liverpool. Commercial cooking and baking, 5s. 8d. per unit; restricted in winter.

Cooking.

(87) Blackburn. 1½d. per unit.

(88) Bristol. 1d. per unit.

(89) Westminster. ½d. per unit.

Refrigerators.

(90) Aylesbury. 1¾d. per unit.

(91) Lichfield. 1d. per unit.

Farm Tariffs.

South-Wales Power. Fixed charge of 3s. 6d. per quarter per 1 000 sq. ft. floor area of outbuildings, plus 1d. per unit; with discount of 2½ % for prompt payment.

South Somerset. 7s. 6d. per quarter per H.P. connected, plus 2d. per unit for first 500 units and 1½d. for the balance.

South-East Yorkshire. All purposes. Fixed charge based on acreage (min. £5), plus 1d. per unit; first 50 acres, 2s. per acre, down to 6d. per acre over 300.

EXAMPLE OF CHARGES BY VARIOUS TARIFFS.—By way of practical example, the cost of these tariffs may be worked out for a hypothetical installation containing a variety of apparatus. In this connection it must be remembered that the tariffs mentioned above are not the only ones available in the places concerned; in some cases the full tariff schedule is very complex, so that the actual charge made might vary considerably from the following estimates. Assume the installation data to be as follows:—

(*a*) Fifty 40 W lamps = 2 kW or 2 units per hr. if all alight simultaneously.
Maximum demand, 7 to 9 P.M., 1·7 kW.
2½ hrs.' average use of all lamps per day.
Units per day, 3 in summer, 7 in winter.

(*b*) Cooking equipment—one 3 kW oven; one 1½ kW grill; 3 1 kW hot plates.
Maximum demand, 7½ kW at any time between 7 A.M. and 9 P.M.
Working hours, 14-16 hrs. a day intermittently.
Units per day, 15, average all year round.

(*c*) Four heaters of ½ kW each = 2 kW.
Maximum demand, 2 kW any time between 7 A.M. and midnight (winter only).
Working hours, 18 per diem for 7 months.
Average load, 1½ kW.
Units per day, 27.

(*d*) One 10 B.H.P. motor, used for industrial purposes, taking 9 kW at full load.
Working hours, 8 A.M. to noon and 1 P.M. to 6 P.M = 9 hrs. per diem.
Maximum demand, 9 kW at any time during those hours.
Average load, 5 kW or 5 units per hr.
Units per day, 45 all the year round.

(*e*) Water-heater, in circuit only off-peak, taking 2 kW. working for 20 hrs. daily all the year.

(*f*) *Whole installation.*
Total load connected, 2 + 7½ + 2 + 9 + 2 = 22½ kW.
Maximum demand. The lights and the large motor do not overlap, so the maximum demand will be the sum of the M.D. of motor and cooking apparatus in summer, plus heaters in winter, *i.e.* 16½ kW in summer and 18½ kW in winter. The water-heater is "off-peak."

The units consumed will be:—

	Per Month.				Per Annum.
	Summer.		Winter.		
Lighting per day 3 or 7	90		210		1 800
Cooking „ 15	450	3 000	450	3 810	5 400
Heaters „ 27	—		810		5 670 (7 months)
Motors „ 45	1 350		1 350		16 200
Water-heater „ 40	1 200		1 200		14 400
Total	3 090		4 020		43 470

Let it be assumed, furthermore, that the house consists of seven assessed rooms (omitting all service rooms, etc., vide Tariffs I.); that its base area is 1 500 sq. ft.; and that its rateable value is £70 per annum.

The annual bill on these hypotheses, subject to the limitations noted and based on the tariffs specified below, will be as follows:—

	£ s. d.	£ s. d.
At Flat Rates, A.		
Lighting, A 3; 1 800 units at 3d.	22 10 0	
Remainder, A 15; 41 870 units at ¾d.	130 16 10	
Rent of 2 Meters at £1 p.a.	2 0 0	
Average price per unit, 0·86d. *Total*		155 6 10
By Maximum Demand System, C.		
Lighting, C 25; M.D. = 1·7 kW.		
First 1 700 units at 3½d.	24 15 10	
Remaining 100 units at 1$\frac{1}{16}$d.	0 8 10	
Rent of 1 Meter	1 0 0	
Light	26 4 8	
Power, C 27; M.D. 18½ kW.		
18½ × 300 = 5 550 units at 1½d.	34 13 9	
Remaining 35 570 ,, ,, ¾d.	111 3 1	
Rent of 1 Meter	1 0 0	
Power	146 16 10	
Average price per unit, 0·95d. *Total*		173 1 6
By Rateable Value System, F 38.		
12½ °/ₒ per annum on £70 R.V.	8 15 0	
43 470 units at ¾d.	136 4 4	
Rent of 1 Meter	1 0 0	
Average price per unit, 0·81d. *Total*		145 19 4
By Floor Area, F 42.		
1 500 sq. ft./10 = 150 × 10d.	6 5 0	
43 470 units at 1d.	181 12 6	
Rent of 1 Meter	1 0 0	
Average price per unit, 1·04d. *Total*		188 17 6
By Assessed Rooms' (in part), I 51; and Flat Rate.		
Summer rate, 7 rooms at 13s. 4d. half-year	4 13 4	
Winter ,, ,, ,, ,, 6s. 8d. ,,	2 6 8	
Lighting, cooking and heater units, 12 870 at 1¾d. per unit	93 16 10	
Motor and water-heater power, at flat rate, 30 600 units at 1d.	127 10 0	
Rent of 2 Meters	2 0 0	
Average price per unit, 1·27d. *Total*		230 6 10

By a Diversity of Systems.	£ s. d.	£ s. d.
Lighting, E 35; the equivalent of 62 32W lamps at 3s. 6d. per quarter	43 8 0	
1 800 at 1½d.	11 5 0	
Cooking, A 11; 5 400 units at 1d.	22 10 0	
Heating, A 9; 5 600 „ „ 1d.	23 6 8	
Motor, D 31; standing charge on 10 H.P.	24 0 0	
16 200 units at ¾d.	50 12 6	
Water-heating, M 74; 14 400 units at 1/3d.	20 0 0	
Rent of 3 Meters	3 0 0	
Average price per unit, 1·1*d.* *Total* . . .		198 2 2

275a. Grid Tariffs.—The Electricity Supply Act, 1926, makes provision in section 11 for the price to be charged by the Central Electricity Board for energy 'supplied directly by them to authorised undertakers,' in accordance with such tariff as may be fixed by the Board. The tariff shall be so framed as to include and show separately—

(*a*) a fixed kilowatt charges component,

(*b*) a running charges component.

These components are 'to be ascertained in accordance with such principles as may be approved by the Electricity Commissioners,' so as to enable the Board to pay its way, with a margin, but without making a profit. (The expressions (*a*) and (*b*) above are repeated, somewhat confusingly, in section 51 and the seventh schedule, which are not directly concerned with section 11.)

Taking as an example the actual tariff for the South-east and East England areas, 'the price to be paid for electricity so supplied in each calendar year shall be the sum of the charges A., B., C. following.'

A. *Service Charge.* No charge for the first point of supply; but 'in respect of each additional point of supply on an existing main transmission line of the Board, such annual or other sum (if any) as may be fixed by the Board having regard to' all the circumstances.

B. *Fixed Kilowatt Charge in Respect of each Point of Supply.*

	£ s. d.
For each kW of M.D. on the Board, being part of the basic demand	3 10 0
For each kW of M.D. being part of the first standard increment	3 5 0
For each kW of M.D. being part of the second standard increment	3 0 0
For each kW of M.D. in excess of the basic demand and two standard increments	2 15 0

It is laid down that 'maximum demand on the Board' means twice the largest number of kilowatt-hours supplied and taken at this tariff during any half-hour in Jan., Feb., Nov. and Dec. 'Basic demand' means the maximum demand of the undertaking in the year 1932, or 2 000 kW, whichever is the greater.

'Standard increment of demand' means an increase of the M.D. of the undertaking over the basic demand, in accordance with a scale laid down, and depending upon the magnitude of the basic demand; it varies inversely with the size of the basic demand.

Thus, for example, take an undertaker whose basic demand in 1932 was 12 500 kW. If in 1940 he made a demand of 20 000 kW, he would pay for it as follows:—

12 500 kW (basic) at £3 10s.
2 000 kW (first standard increment) at £3 5s.
2 000 kW (second ,, ,,) ,, £3.
3 500 kW (balance remaining) at £2 15s.

For a smaller undertaking with a basic demand of less than 3 000 kW, the standard increment would be 3 000 kW; while for a larger one, with a basic demand exceeding 22 000 kW, the standard increment would be 1 000 kW.

The fixed kW charge is subject to variation according to power factor. If in any year this is less than 0·85 lagging during the half-hour of M.D., the fixed charge shall be increased in that year at the rate of 4s. 6d. for each 0·1 below 0·85 and pro rata for fractions. A further variation is made according to the average of the rates levied on the selected stations in the area, based on 4s. 3d. in the £.

C. *Running Charge.* For each kWh supplied and taken during the year the sum of 0·21d. is charged. This, however, is subject to variation according to the total cost of fuel consumed and the calorific value; 11 500 B.Th.U. per lb. and 16s. per ton being the standard figures for the purpose. The variation is 0·0008d. for each penny above or below 16s.

276. Bibliography (*see* explanatory note, § 58).

COSTS, TARIFFS, ETC., IN BRITISH AND COLONIAL SUPPLY STATIONS.

Electricity Tariffs and Voltages (*Electrical Times*).
Tables of Costs and Records (Supplement to the *Electrical Times*).
Electrician Electrical Trades Directory (Benn Bros.).
Manual of Electrical Undertakings. E. Garcke (Electrical Press).

BOOKS.

Electrical Engineering Economics, by D. J. Bolton (Chapman & Hall).
Costs and Tariffs in Electricity Supply, by D. J. Bolton (Chapman & Hall).

I.E.E. PAPERS.

Small Electricity Supply Undertakings, P. A. Spalding. Vol. 48, p. 237.
Residence Tariffs, A. H. Seabrook. Vol. 48, p. 376.
Tariffs for Electrical Energy, with particular reference to Domestic Tariffs, W. W. Lackie. Vol. 49, p. 147.
Electricity Supply of Large Cities, G. Klingenberg. Vol. 52, p. 123.
Electric Supply; Present Conditions and the Hopkinson Principle, J. R. Blaikie. Vol. 59, p. 701.
Multi-Part Tariffs for Domestic Electricity Supply, J. W. Beauchamp. Vol. 59, p. 714.
Electric Supply Tariffs, their Simplification by Discrimination, G. Wilkinson and R. McCourt. Vol. 63, p. 844.
Electric Supply Tariffs, H. M. Sayers. Vol. 63, p. 850.

Industrial, Agricultural and Domestic Applications of Electricity, including Illumination and Tariffs, Professor Parker Smith. Vol. 65, p. 351.

Load-levelling Relays and Metering Problems, W. Holmes. Vol. 67, p. 296.

Recent Developments in Electric Meters, J. L. Carr. Vol. 67, p. 859.

Electric Supply Tariffs and Methods of Charge, J. W. Beauchamp. Vol. 68, p. 152.

An Analysis of the Costs of Electricity Supply, and its Application in Relation to Various Types of Consumers, E. H. E. Woodward and W. A. Carne. Vol. 71, p. 852.

An Analysis of the Costs of Electricity Supply and Distribution in Great Britain, J. M. Kennedy and D. M. Noakes. Vol. 73, p. 97.

Private Plant and Public Supply Tariffs, J. A. Sumner. Vol. 77, p. 310.

The Measurement of Large Supplies of Electrical Energy for Costing Purposes, W. Casson and A. H. Gray. Vol. 78, p. 681.

Tariffs for Domestic and Business Premises, B. Handley. Vol. 79, p. 505.

The Prices for Electric Supply, M. Walker. Vol. 79, p. 510.

Modern Factors Affecting Electricity Costs and Charges, J. A. Sumner Vol. 81, p. 429.

Electricity Demand and Price, D. J. Bolton. Vol. 82, p. 185.

MISCELLANEOUS.

Every supply authority issues its own schedule of tariffs and supply conditions; a representative selection of these (§ 275) may be studied with advantage. They have not the force of law, as in the case of the 'Regulations' of the Electricity Commissioners; in fact it is doubtful if they are always *intra vires.*

The Annual Reports of the Electricity Commissioners and the Central Electricity Board also contain much useful information.

Modern Factors Affecting Electricity Costs and Charges. J. A. Sumner, Vol. 81, p. 429.

PART III.—TRANSMISSION AND CONTROL.

CHAPTER 13.

INSULATED WIRES AND CABLES.

277. **Applications of Insulated Conductors.**—Insulated conductors are used for the wiring of practically all installations, indoors and outdoors. Outdoors permanent (fixed) circuits can sometimes be provided more cheaply by bare conductors than by insulated cables, but, against the cost of insulation on the latter, there must be set the cost of the poles (or brackets) and insulators required by bare conductors; also, the obstruction caused by, and the risk of accidental contact with, bare wires in works' yards and similar situations. The last-named consideration applies in yet greater degree to interior installations, and almost the only uses for bare circuits indoors are as contact wires for travelling cranes and in carrying low-voltage current for electro-chemical and electro-metallurgical purposes. Insulated cables are also used for the transmission and distribution of electricity (generally underground) wherever accommodation cannot conveniently be provided for overhead lines, or where the use of the latter would be dangerous. In the early days of electricity supply, bare distributing cables were stretched on insulators in underground conduits (*e.g.* the Crompton system at Hove and elsewhere) and a few examples of this practice may still be in existence. The same principle was used extensively in the contact rails of the now obsolete conduit-tramway system (§ 634, Vol. 3) but there a bare conductor is essential, in order that continuous sliding contact may be made, and the conductor itself is rigid. The relatively small copper conductors required for general distribution service need closely-spaced supports in order that the conductor may not sag into contact with the conduit; for this reason and because the system cannot easily be insulated for high pressures, insulated cables are now standard.

Bare conductors are used mainly for overhead transmission and their characteristics and constants are therefore dealt with in §§ 307-309 where, also, there are discussed certain features of high voltage cables associated with power transmission over considerable distances. Special features of colliery cables are discussed in § 820, Vol. 3.

278. Low and Medium Voltage Wires and Cables.—For installation work insulated stranded copper wires should be used. The size of the copper conductor will depend primarily on the current to be carried. If, however, the length of any particular circuit is considerable, the loss of volts due to the resistance of the copper must also be taken into account (§§ 24, 286); otherwise the lamps and apparatus may not get their correct pressure even when the wire is carrying much below its maximum safe current. It is generally specified (following the I.E.E. wiring rules) that the loss of volts in the conductors, from the entrance of the supply up to any apparatus, when the whole installation is switched on, shall not exceed 2 % of the supply pressure plus a fixed allowance of 1 V, *i.e.* say, 3¼ V on 110 V circuits and 5½ V on 220 V circuits. As will be seen when dealing with branch circuits (Chapter 22) these are generally so laid out that a single size of wire can be safely used throughout for lighting or fans—not for heating—but the cables leading to the distribution boards require to be worked out carefully. On power and heating circuits the drop in volts is not of so much importance, and the size of conductors is then determined by their permissible rise of temperature; this, with rubber insulated cables, should be limited to 20° F. whatever the purpose for which current is used, while with paper or fibre insulated cables a rise of 50° F. is allowable (§ 291).

279. British Standard Sizes of Insulated Annealed Copper Conductors.—Formerly there were thirty-two standard sizes of conductors from 0·001 to 1 sq. in. nominal area; with three exceptions these were stranded wires and in most cases the size of the individual wires was quoted in S.W.G. numbers (*see* Table 39). In order to simplify and cheapen manufacture, the number of standard sizes was reduced to twenty-five (between the same limits of nominal area) by the B.S.S. No. 7, 1922. At the same time, the sizes of the individual wires were specified in inches throughout. However, a vast amount of conductors of the

TABLE 39.—*Old and New British Standard Sizes for Insulated Annealed Copper Conductors.*

Old Standard.		New Standard.	
Number and S.W.G. and / or Dia. in Ins. of Individual Wires.	Nominal Area in Sq. In.	Nominal Area in Sq. In.	Number and Dia. in Ins. of Individual Wires.
1 / 20 (·036″)	0·001 0	0·001 0	1 / ·036
—	—	0·001 5	1 / ·044
1 / 18 (·048″)	0·001 8	—	—
3 / 22 (·028″)	0·001 8	—	—
—	—	0·002 0	3 / ·029
7 / 25 (·020″)	0·002 2	—	—
3 / 20 (·036″)	0·003 0	0·003 0	3 / ·036
7 / 23 (·024″)	0·003 1	—	—
1 / 16 (·064″)	0·003 2	0·003 0	1 / ·064
7 / 22 (·028″)	0·004 2	—	—
—	—	0·004 5	7 / ·029
7 / 21½ (·030″)	0·004 9	—	—
7 / 20 (·036″)	0·007 0	0·007 0	7 / ·036
7 / 19 (·040″)	0·008 6	—	—
—	—	0·010 0	7 / ·044
7 / 18 (·048″)	0·012 5	—	—
—	—	0·014 5	7 / ·052
7 / 17 (·056″)	0·017 0	—	—
7 / 16 (·064″)	0·022 1	0·022 5	7 / ·064
—	—	0·030 0	19 / ·044
19 / 18 (·048″)	0·033 8	—	—
7 / 14 (·080″)	0·034 6	—	—
—	—	0·040 0	19 / ·052
19 / 17 (·056″)	0·045 9	—	—
19 / 16 (·064″)	0·060 0	0·060 0	19 / ·064
19 / 15 (·072″)	0·075 0	0·075 0	19 / ·072
19 / 14 (·080″)	0·093 7	—	—
—	—	0·100 0	19 / ·083
37 / 16 (·064″)	0·116 8	0·120 0	37 / ·064
19 / 13 (·092″)	0·125 0	—	—
37 / 15 (·072″)	0·150 0	0·150 0	37 / ·072
37 / 14 (·080″)	0·182 4	—	—
37 / ·083″	0·200 0	0·200 0	37 / ·083
37 / ·092′	0·250 0	0·250 0	37 / ·093
37 / ·104″	0·300 0	0·300 0	37 / ·103
61 / ·092″	0·400 0	0·400 0	61 / ·093
61 / ·104″	0·500 0	0·500 0	61 / ·103
61 / ·112″	0·600 0	0·600 0	91 / ·093
91 / ·101″	0·750 0	0·750 0	91 / ·103
127 / ·101″	1·000 0	1·000 0	127 / ·103

old standard sizes are still in service; and the comparison between the old and new standards in Table 39 (p. 501) will therefore be found useful.

280.—I.E.E. Regulations regarding Insulated Wires and Cables.—The I.E.E. Regulations embody many clauses relating to permissible types of construction for insulated wires and cables. The main purport of most of these clauses is that flexible cords and cables (excepting fittings wire) shall conform to B.S.S. Nos. 480 and 7 respectively. A few extracts are given below from the tenth edition of the I.E.E. Regulations, but reference should be made to the complete text. Tables 40-40 J give the physical constants and current carrying capacities of cables of various types and size.

304. Voltage Drop.—The sizes of conductors shall be so selected that, for lighting, the drop in voltage from the consumer's terminals in a public supply (or from the busbars of the main switchboard controlling the various circuits in a private generating plant) to any and every point on the installation does not exceed 1 volt plus 2 % of the voltage at the consumer's terminals (or at the busbars as the case may be) when the conductors are carrying the maximum demand under the normal conditions of service.

NOTE.—Tables 5 to 12 and Table 20 show the total length of conductor in circuit that will give a voltage drop of 1 volt when the respective maximum currents are being carried.

305. Voltage Drop on Earthed Concentric Wiring.—Where a direct-current supply is given to earthed concentric wiring the potential difference between any two positions in the external conductors shall not exceed:—

(i) Seven volts, if the internal conductors are connected to the positive pole of the system; or

(ii) One-and-a-half volts, if the internal conductors are connected to the negative pole of the system.

NOTE.—Regulation 305 is framed with a view to minimizing the risk of electrolytic action, and alternating-current installations are therefore exempt from its provisions.

306. Minimum Size.—The smallest size of conductor for sub-circuit wiring shall have a nominal cross-sectional area not less than 0·0015 square inch except for fittings wire [*see* Regulation 1305 (B)].

307. Insulation and Protective Covering.—(A). Every cable, flexible cable and flexible cord, shall comply as regards its insulating material and protective covering with the requirements of Section 13.

(B). Flexible cables and flexible cords provided with a protective braiding of natural or artificial silk or of glacé cotton shall not be used where they are subject to the risk of mechanical damage.

(C). "Medium insulation" (*see* Regulation 1312) flexible cords may be used only for pendant lighting fittings and for the internal wiring of lighting fittings.

(D). "High insulation" (*see* Regulation 1311) twin and triple, twisted flexible cords without further braiding may be used only for fixed wiring and for fixed lighting fittings (including pendants): in all other positions and for all other purposes where flexible cords are used, "high insulation" flexible cords made up to a circular section and finished as specified in Regulation 1313 shall be employed.

Table 40.—*Dimensions, Weight, and Resistance of Solid and Stranded Circular Copper Conductors.*

(From Table 4, *I.E.E. Regulations*, 10th Edn.)

Nominal Cross-Sectional Area. 1.	Number and Diameter (in.) of Wires forming Conductor. 2.	Overall Diameter. 3.	Standard Weight per 1 000 Yards. 4.	Standard Resistance per 1 000 Yards. at 60° F. (15·6° C.) 5.
sq. in.		inch	lbs.	ohms
0·001	1/·036	0·036	11·77	23·59
0·001 5	1/·044	0·044	17·58	15·79
0·002	3/·029	0·062	23·37	12·36
0·003	3/·036	0·078	36·02	8·019
0·003	1/·064	0·064	37·20	7·463
0·004 5	7/·029	0·087	54·39	5·281
0·007	7/·036	0·108	83·81	3·427
0·01	7/·044	0·132	125·2	2·294
0·014 5	7/·052	0·156	174·9	1·643
0·022 5	7/·064	0·192	264·9	1·084
0·03	19/·044	0·220	340·4	0·8468
0·04	19/·052	0·260	475·5	0·6063
0·06	19/·064	0·320	720·3	0·4002
0·075	19/·072	0·360	911·6	0·3162
0·1	19/·083	0·415	1 211·0	0·2380
0·12	37/·064	0·448	1 403·0	0·2056
0·15	37/·072	0·504	1 776·0	0·1625
0·2	37/·083	0·581	2 360·0	0·1223
0·25	37/·093	0·651	2 963·0	0·097 38
0·3	37/·103	0·721	3 635·0	0·079 39
0·4	61/·093	0·837	4 886·0	0·059 08
0·5	61/·103	0·927	5 994·0	0·048 16
0·6	91/·093	1·023	7 290·0	0·039 61
0·75	91/·103	1·133	8 942·0	0·032 29
0·85	127/·093	1·209	10 175·0	0·028 38
1·0	127/·103	1·339	12 481·0	0·023 14

Table 40A.—*V.I.R. Cables and Paper Cables.* 1 / ·036″ *to* 7 / ·029″. *Current Rating* (*subject to Voltage Drop*) *for Vulcanized-Rubber-Insulated or Impregnated-Paper-Insulated Cables* * *run:* (i) *Bunched, and enclosed in one conduit, troughing, or casing* (*Col.* 3 *or Col.* 5 *according to the type and number so run*); (ii) *Bunched, and open* (*Col.* 3 *or Col.* 5 *according to the type and number so run*); (iii) *Separated, and open* (*Col.* 3 *only*).

(From Table 5, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Not more than: Four Single-Core Cables, or Two Twin (or Concentric) Cables, or One Three-Core Cable.		Not more than: Eight Single-Core Cables, or Four Twin (or Concentric) Cables, or Two Three-Core Cables.	
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	Current Rating (subject to Voltage Drop), for D.C., or Single-phase or 3-phase A.C.	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 3: *Lead plus Return*, for D.C., or Single-phase A.C.; *Lead only*, for balanced 3-phase A.C.	Current Rating (subject to Voltage Drop), for D.C., or Single-phase or 3-phase A.C.	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 5: *Lead plus Return*, for D.C., or Single-phase A.C.; *Lead only*, for balanced 3-phase A.C.
1.	2.	3.	4.	5.	6.
Sq. in.		Amps.	Feet	Amps.	Feet
0·001	1 / ·036	3	40	3	40
0·001 5	1 / ·044	5	36	5	36
0·002	3 / ·029	5	47	5	47
0·003	3 / ·036	10	35	8 †	42
0·003	1 / ·064	10	37	8 †	46
0·004 5	7 / ·029	15	34	12 †	42

Note.—The above table applies to cables employed in the wiring of buildings but does not apply to every condition under which cables may be used. (Braided vulcanized-rubber-insulated cables run open are required under Regulation 403 to be spaced on insulators.)

In conditions of abnormally high ambient air temperature, the Notes to Tables 40B and 40F should be consulted for vulcanized-rubber-insulated and impregnated-paper-insulated cables respectively.

The lower limit set to the size of conductor by the permissible voltage drop is dealt with in Regulation 304.

* Including tough-rubber-protected cables and lead-covered cables, but excluding (for use with alternating current) single-core cables armoured with wire or tape of magnetic material and such ferrous-sheathed cables as are prohibited under Regulation 308.

† These figures (8, 8, 12) may be increased to 9, 9, and 13·5 amperes respectively, where a diversity factor can properly be applied to the circuit which feeds the cables forming the group of final sub-circuits.

Table 40B.—*V.I.R. Cables* [*see also Table* 40C]. 7 / ·036″ *to* 127 / ·103″. *Current Rating* (*subject to Voltage Drop*) *for Vulcanized-Rubber-Insulated Cables* * *run*: (i) *Bunched, and enclosed in one conduit, troughing, or casing* (*Cols.* 3 *and* 4 *or Col.* 7 *according to the type and number so run*); (ii) *Bunched, and open* (*Cols.* 3 *and* 4 *or Col.* 7 *according to the type and number so run*).

(From Table 6, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Not more than: Two Single-Core Cables.†				Not more than: Four Single-Core Cables, or Two Twin Cables or One Concentric Cable.		
		Current Rating (subject to Voltage Drop).		Approximate Length in Circuit (*Lead plus Return*) for 1-volt Drop with Current Rating in Col. 3 or Col. 4.		Current Rating (subject to Voltage Drop).	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 7.	
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	D.C.	Single-phase A.C.	D.C.	Single-phase A.C.	D.C., or Single-phase or 3-phase A.C.	*Lead plus Return*, for D.C.	*Lead plus Return*, for Single-phase A.C.; *Lead only*, for balanced 3-phase A.C.
1.	2.	3.	4.	5.	6.	7.	8.	9.
Sq. in.		Amps.	Amps.	Feet	Feet	Amps.	Feet	Feet
0·007	7 / ·036	**24**	**24**	33	33	**19**	41	41
0·01	7 / ·044	**31**	**31**	39	39	**25**	49	49
0·014 5	7 / ·052	**37**	**37**	45	45	**30**	56	56
0·022 5	7 / ·064	**46**	**46**	55	55	**37**	69	69
0·03	19 / ·044	**53**	**53**	61	60	**42**	76	76
0·04	19 / ·052	**64**	**64**	71	70	**51**	89	89
0·06	19 / ·064	**83**	**83**	83	80	**66**	104	104
0·075	19 / ·072	**97**	**97**	90	86	**78**	113	113
0·1	19 / ·083	**118**	**118**	98	92	**94**	123	120
0·12	37 / ·064	**130**	**130**	103	94	**104**	129	123
0·15	37 / ·072	**152**	**152**	112	97	**122**	140	127
0·2	37 / ·083	**184**	**184**	123	98	**147**	154	128
0·25	37 / ·093	**214**	**214**	132	98	**171**	165	128
0·3	37 / ·103	**240**	**240**	145	97	**192**	181	128
0·4	61 / ·093	**288**	**288**	162	90	**230**	202	119
0·5	61 / ·103	**332**	**332**	172	82	**266**	215	107
0·6	91 / ·093	**384**	**366**	181	79	—	—	—
0·75	91 / ·103	**461**	**425**	185	69	—	—	—
0·85	127 / ·093	**512**	**463**	190	64	—	—	—
1·0	127 / ·103	**595**	**520**	200	59	—	—	—

* † For footnotes, see p. 506.

308. Cables Unsuitable for Alternating Current.—The following types of cables shall not be used for alternating current except in connection with earthed concentric wiring in which the sheath forms one conductor:—

(A). Single-cored cables armoured with wire or tape of magnetic material or encased in a sheath of magnetic material.

(B). Single-cored cables encased in brass, copper, or equally hard incorrodible metal, and having a conductor of nominal cross-sectional area greater than 0·1 square inch.

NOTE.—Where single-core, unarmoured, lead-covered cables are used, attention is drawn to the current ratings shown in the Tables appropriate to the conditions of running.

309. Identification of Cables by Colour.—Where colours are used to distinguish the conductors of cables those set out in Regulations 310 and 311 shall be employed (the polarities indicated are those up to the lamp or other current-using appliance when the switch is closed).

NOTE.—*See* Regulation 1301 (L) for the identification by colour of switchboard connections.

310. D.C. Cable Colours.—Distinctive colours (if any) for the cables of direct-current systems of supply shall be as follows:—

(A). Two-conductor circuits connected to a two-wire system of wiring. Red for positive or switch wire. Black for negative.

(B). Two conductor circuits connected to the "middle wire" and one "outer" conductor of a three-wire system of wiring. Red for "outer." Black for "middle-wire."

(C). Two-conductor or three-conductor circuits connected to a three-wire system of wiring except as in clause (B) above. Red for positive or switch wire. Black for "middle-wire." White for negative or switch wire.

Note to Table 40B.

NOTE.—Table 40B applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used. (Braided vulcanized-rubber-insulated cables run open are required under Regulation 403 to be spaced on insulators.)

The above table refers to situations where the ambient air temperature does not exceed 100° F. (37·7° C.). Where the ambient air temperature is abnormally high the current ratings given in the table shall be multiplied, and the lengths for 1-volt drop divided by the appropriate factor, as follows:—

Ambient air temperature .	105° F.	110° F.	115° F.
Factor	0·86	0·68	0·45

The lower limit set to the size of conductor by the permissible voltage drop is dealt with in Regulation 304.

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* Including tough-rubber-protected cables and lead-covered cables, but excluding (for use with alternating current) such of the following cables as are prohibited under Regulation 308:—

(*a*) Single-core armoured or ferrous-sheathed cables.

(*b*) Single-core cables above 0·1 sq. in. encased in brass, copper, etc.

† For one twin cable see Columns 7 to 9.

Table 40c.—*V.I.R. Cables* [*see also Table* 40b]. 7 / ·036″ *to* 37 / ·093″. *Current Rating* (*subject to Voltage Drop*) *for Vulcanized-Rubber-Insulated Cables* * *run :* (i) *Bunched, and enclosed in one conduit, troughing, or casing* (*Col.* 3 *or Col.* 6 *according to the type and number so run*) ; (ii) *Bunched, and open* (*Col.* 3 *or Col.* 6 *according to the type and number so run*).

(From Table 7, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Not more than Six Single-Core Cables, or Three Twin Cables, or One Three-Core or Four-Core Cable, or Two Concentric Cables.			Not more than Ten Single-Core Cables, or Five Twin Cables, or Two Three-Core or Four-Core Cables, or Three Concentric Cables.		
		Current Rating (subject to Voltage Drop).	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 3.		Current Rating (subject to Voltage Drop).	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 6.	
Nominal Cross-Sectional Area	Number and Diameter (in.) of Wires.	D.C., or Single-phase or 3-phase A.C.	*Lead plus Return*, for D.C.	*Lead plus Return*, for Single-phase A.C. ; *Lead only*, for balanced 3-phase A.C	D.C., or Single-phase or 3-phase A.C.	*Lead plus Return*, for D.C.	*Lead plus Return*, for Single-phase A.C. ; *Lead only*, for balanced 3-phase A.C.
1.	2.	3.	4.	5.	6.	7.	8.
Sq. in.		Amps.	Feet	Feet	Amps.	Feet	Feet
0·007	7 / ·036	**17**	47	47	**14**	55	55
0·01	7 / ·044	**22**	56	56	**19**	65	65
0·0145	7 / ·052	**26**	64	64	**22**	75	75
0·0225	7 / ·064	**32**	79	79	**28**	92	92
0·03	19 / ·044	**37**	87	87	**32**	102	102
0·04	19 / ·052	**45**	101	101	**38**	118	118
0·06	19 / ·064	**58**	119	119	**50**	138	138
0·075	19 / ·072	**68**	129	129	**58**	150	150
0·1	19 / ·083	**83**	140	137	**71**	163	160
0·12	37 / ·064	**91**	147	140	**78**	172	164
0·15	37 / ·072	**106**	160	147	**91**	187	170
0·2	37 / ·083	**129**	176	147	—	—	—
0·25	37 / ·093	**150**	189	144	—	—	—

* Including tough-rubber-protected cables and lead-covered cables, but excluding (for use with alternating current) such of the following cables as are prohibited under Regulation 308 :—

(*a*) Single-core armoured or ferrous-sheathed cables.
(*b*) Single-core cables above 0·1 sq. in. encased in brass, copper, etc.

Note to Table 40c.

The above table applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used. (Braided vulcanized-rubber-insulated cables run open are required under Regulation 403 to be spaced on insulators.)

It refers to situations where the ambient air temperature does not exceed 100° F. (37·7° C.). Where the ambient air temperature is abnormally high the current ratings given in the table shall be multiplied, and the lengths for 1-volt drop divided, by the appropriate factor as follows :—

Ambient air temperature .	105° F.	110° F.	115° F.
Factor	0·86	0·68	0·45

The lower limit set to the size of conductor by the permissible voltage drop is dealt with in Regulation 304.

Table 40d.—*V.I.R. Braided Cables on Cleats.* 19 / ·083″ *to* 127 / ·103″. *Current Rating (subject to Voltage Drop) for Single-Core, Unarmoured, Vulcanized-Rubber-Insulated, Braided and Compounded Cables* * *(with or without tape) run open on cleats as defined in Note (a) below.*

(From Table 8, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Current Rating (subject to Voltage Drop) for Cables run under the conditions defined in Note (A) below.			Approximate Length in Circuit for 1-volt Drop.		
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	D.C.	Single-phase A.C.	Three-phase A.C.	*Lead plus Return*, for D.C., with Current Rating in Col. 3.	*Lead plus Return*, for Single-phase A.C., with Current Rating in Col. 4.	*Lead only*, for balanced 3-phase A.C., with Current Rating in Col. 5.
1.	2.	3.	4.	5.	6.	7.	8.
Sq. in.		Amps.	Amps.	Amps.	Feet	Feet	Feet
0·1	19 / ·083	**138**	**138**	**137**	84	76	76
0·12	37 / ·064	**154**	**154**	**153**	87	77	77
0·15	37 / ·072	**176**	**176**	**174**	96	80	80
0·2	37 / ·083	**210**	**210**	**208**	106	81	81
0·25	37 / ·093	**243**	**243**	**238**	116	77	78
0·3	37 / ·103	**275**	**275**	**272**	126	74	75
0·4	61 / ·093	**341**	**340**	**330**	137	58	60
0·5	61 / ·103	**393**	**390**	**378**	145	54	56
0·6	91 / ·093	**445**	**435**	**422**	156	52	54
0·75	91 / ·103	**520**	**490**	**470**	164	49	51
0·85	127 / ·093	**563**	**520**	**500**	172	48	50
1·0	127 / ·103	**630**	**560**	**537**	189	48	50

* Including single-core, unarmoured, tough-rubber-protected cables; but excluding (for use with alternating current) such cables as are prohibited under Regulation 308.

Note to Table 40D.

The above table applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used.

It applies to two or three cables run spaced as shown in Note (A) below. Where four or more cables are so spaced the current ratings are reduced to 90 per cent. of those set out in Col. 3 or Col. 4 above for direct-current or alternating-current (either single-phase or three-phase) loading respectively.

For two or three smaller cables (7 / ·036″ to 19 / ·072″ inclusive) so spaced the current ratings are those given in Col. 3 or Col. 4 of Table 40B, and for four or more such smaller cables the current ratings are 90 per cent. of those given in Col. 3 or Col. 4 of Table 40B, for direct-current or alternating-current (either single-phase or three-phase) loading respectively.

Table 40D refers to situations where the ambient air temperature does not exceed 100° F. (37·7° C.). Where the ambient air temperature is abnormally high the current ratings given in this table shall be multiplied, and the lengths for 1-volt drop, divided by the appropriate factor as follows :—

Ambient air temperature .	105° F.	110° F.	115° F.
Factor	0·86	0·68	0·45

The lower limit set to the size of conductor by the permissible voltage drop is dealt with in Regulation 304.

NOTE (A). CABLES RUN UNDER DEFINED CONDITIONS.

The current ratings and corresponding lengths (approximate) in circuit for 1-volt drop set out in Tables 40D, E and H, apply to cables run under the conditions defined below :—*

(1) The circuit comprises two single-core cables carrying direct current or single-phase alternating current, or three single-core cables carrying three-phase alternating current.

(2) Where the cables are lead-covered, the lead sheaths are electrically bonded together, at each end of the cable run, with bonds of negligible resistance.

(3) The cables are remote from iron, steel, or ferro-concrete.

(4) The cables are supported horizontally, one above the other, on cleats on a vertical wall, and are separated from one another and from the wall by the following distances :—

Nominal Cross-Sectional Area of Conductor. 1.	Approximate Vertical Distance between Cable Centres. 2.	Approximate Horizontal Distance of Cable Centres from Wall. 3.
Sq. in.		
0·1 to 0·3 inclusive	Twice the diameter of the finished cable	1½ inches
0·4 to 1·0 inclusive	3½ inches	2½ inches

* For cables run under certain other conditions see Appendix 5, *I.E.E. Regulations*, 10th Edn.

TABLE 40E.—*V.I.R. L.C. Cables on Cleats.* 19 / ·083″ to 127 / ·103″ *Current Rating (subject to Voltage Drop) for Single-Core, Unarmoured, Vulcanized-Rubber-Insulated, Lead-Covered Cables, run open on cleats as defined in Note (A) below Table* 40D.

(From Table 9, *I.E.E. Regulations,* 10th Edn.)

Conductor.		Current Rating (subject to Voltage Drop) for Cables run under the conditions defined in Note (A) below Table 40D.			Approximate Length in Circuit for 1-volt Drop.		
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	D.C.	Single-phase A.C.	Three-phase A.C.	*Lead plus Return,* for D.C., with Current Rating in Col. 3.	*Lead plus Return,* for Single-phase A.C., with Current Rating in Col. 4.	*Lead only,* for balanced 3-phase A.C., with Current Rating in Col. 5.
1.	2.	3.	4.	5.	6.	7.	8.
Sq. in.		Amps.	Amps.	Amps.	Feet	Feet	Feet
0·1	19 / ·083	**138**	**138**	**137**	84	75	75
0·12	37 / ·064	**154**	**150**	**149**	87	77	77
0·15	37 / ·072	**176**	**171**	**169**	96	80	81
0·2	37 / ·083	**210**	**205**	**202**	106	79	81
0·25	37 / ·093	**243**	**239**	**234**	116	76	78
0·3	37 / ·103	**275**	**268**	**260**	126	74	76
0·4	61 / ·093	**341**	**321**	**309**	137	60	62
0·5	61 / ·103	**393**	**366**	**350**	145	56	59
0·6	91 / ·093	**445**	**400**	**383**	156	55	58
0·75	91 / ·103	**520**	**442**	**421**	164	53	56
0·85	127 / ·093	**563**	**464**	**439**	172	53	56
1·0	127 / ·103	**630**	**490**	**463**	189	53	56

The above table applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used.

It applies to two or three cables run spaced as shown in Note (A), Table 40D. Where four or more cables are so spaced the current ratings are reduced to 90 per cent. of those set out in Col. 3 or Col. 4 above for direct-current or alternating-current (either single-phase or three-phase) loading respectively.

For two or three smaller cables (7 / ·036″ to 19 / ·072″ inclusive) so spaced the current ratings are those given in Col. 3 or Col. 4 of Table 40B, and for four or more such smaller cables the current ratings are 90 per cent. of those given in Col. 3 or Col. 4 of Table 40B, for direct-current or alternating-current (either single-phase or three-phase) loading respectively.

Table 40E refers to situations where the ambient air temperature does not exceed 100° F. (37·7° C.). Where the ambient air temperature is abnormally high the current ratings given in this table shall be multiplied, and the lengths for 1-volt drop divided, by the appropriate factor as follows:—

Ambient air temperature .	105° F.	110° F.	115° F.
Factor	0·86	0·68	0·45

The lower limit set to the size of conductor by the permissible voltage drop is dealt with in Regulation 304.

Table 40F.—*Paper L.C. Cables [see also Table 40G]. 7 / ·036″ to 127 / ·103″. Current Rating (subject to Voltage Drop) for Impregnated-Paper-Insulated, Lead-Covered Cables * run :* (i) *Bunched, and enclosed in one troughing or casing (Cols.* 3 *and* 4 *or Col.* 7 *according to the type and number so run)* ; (ii) *Bunched, and open (Cols.* 3 *and* 4 *or Col.* 7 *according to the type and number so run).*

(From Table 10, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Not more than : Two Single-Core Cables.†				Not more than : Four Single-Core Cables, or Two Twin Cables, or One Concentric Cable.		
		Current Rating (subject to Voltage Drop).		Approximate Length in Circuit (*Lead plus Return*) for 1-volt Drop with Current Rating in Col. 3. or Col. 4.		Current Rating (subject to Voltage Drop).	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 7.	
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	D.C.	Single-phase A.C.	D.C.	Single-phase A.C.	D.C., or Single-phase or 3-phase A.C.	*Lead plus Return*, for D.C.	*Lead plus Return*, for Single-phase A.C. ; *Lead only*, for balanced 3-phase A.C.
1.	2.	3.	4.	5.	6.	7.	8.	9.
Sq. in.		Amps.	Amps.	Feet	Feet	Amps.	Feet	Feet
0·007	7 / ·036	**28**	**28**	27	27	**22**	34	34
0·01	7 / ·044	**42**	**42**	27	27	**34**	34	34
0·0145	7 / ·052	**57**	**57**	28	28	**46**	35	35
0·0225	7 / ·064	**75**	**75**	32	32	**60**	40	40
0·03	19 / ·044	**87**	**87**	35	35	**70**	44	44
0·04	19 / ·052	**104**	**104**	41	41	**83**	51	51
0·06	19 / ·064	**135**	**135**	48	46	**108**	60	60
0·075	19 / ·072	**157**	**157**	52	50	**126**	65	65
0·1	19 / ·083	**191**	**191**	57	53	**153**	71	70
0·12	37 / ·064	**210**	**210**	60	55	**168**	75	72
0·15	37 / ·072	**246**	**246**	65	56	**197**	81	74
0·2	37 / ·083	**296**	**296**	72	57	**237**	90	75
0·25	37 / ·093	**343**	**343**	78	57	**274**	97	75
0·3	37 / ·103	**385**	**385**	85	57	**308**	106	75
0·4	61 / ·093	**464**	**464**	95	53	**371**	119	70
0·5	61 / ·103	**540**	**540**	100	48	**432**	125	63
0·6	91 / ·093	**624**	**590**	105	46	—	—	—
0·75	91 / ·103	**738**	**670**	109	41	—	—	—
0·85	127 / ·093	**815**	**725**	116	39	—	—	—
1·0	127 / ·103	**932**	**795**	121	37	—	—	—

Excluding (for use with alternating current) such single-core armoured cables as are prohibited under Regulation 308.

† For one twin cable, see Columns 7 to 9.

Note to Table 40F.

The above table applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used.

It refers to situations where the ambient air temperature does not exceed 120° F. (48·8° C.). Where the ambient air temperature is abnormally high the current ratings given in this table shall be multiplied, and the lengths for 1-volt drop divided by the appropriate factor as follows :—

Ambient air temperature	125° F.	130° F.	135° F.	140° F.	145° F.	150° F.
Factor	0·95	0·88	0·82	0·75	0·68	0·60

The lower limit set to the size of conductor by the permissible voltage drop is dealt with in Regulation 304.

311. **A.C. Cable Colours.**—Distinctive colours (if any) for the cables of alternating-current systems of supply shall be as follows :—

(A). Two-conductor circuits of a two-wire system of wiring connected to one phase. Red for switch wire or one conductor. Black for 'neutral' or other conductor.

(B). Two-conductor or three-conductor circuits of a three-wire system of wiring connected to one phase, except as in clause (A) above. Red for one con ductor or switch wire. Black for 'middle wire.' White for other conductor or switch wire.

(C). Three-conductor circuits connected to a two-phase three-wire system of wiring. Red for one phase. Black for 'common return.' White for other phase.

(D). Three-conductor circuits connected to a three-phase three-wire system of wiring. Each conductor red, white, and green, respectively.

Note.—In a three-phase three-wire system of wiring it is permissible to use parti (red/white or natural) instead of green for impregnated-paper-insulated conductors in conformity with B.S.S. No. 480.

(E). Four-conductor circuits connected to a two-phase four-wire system of wiring. Red for one phase. White for other phase.

(F). Four-conductor circuits connected to a three-phase four-wire system of wiring. Red, white, and green, for the three phases. Black for 'neutral.'

Note.—Attention is drawn to the requirement in Regulation 1318 (C) that the covering of an earth continuity conductor in a flexible cord or flexible cable shall be coloured brown.

Note.—In a three-phase four-wire system of wiring it is permissible to use parti (red/white or natural) instead of green for impregnated-paper-insulated conductors in conformity with B.S.S. No. 480.

1305. **Standard Sizes of Conductors.—(A).** The sizes of conductors set out in Table 4 [Table 40] are recognized as standard. (The Table shows the nominal and calculated cross-sectional areas, dimensions, weight and resistance of each such standard conductor.)

Note.—The standard sizes and resistances of conductors for flexible cables and flexible cords are set out in Tables 13, 14, 15 [Tables 41, 41a, pp. 522, 523].

TABLE 40G.—*Paper L.C. Cables [see also Table 40F], 7 / ·036″ to 37 / ·093″. Current Rating (subject to Voltage Drop) for Impregnated-Paper-Insulated, Lead-covered Cables * run:* (i) *Bunched, and enclosed in one troughing or casing (Col. 3 or Col. 6 according to the type and number so run)*; (ii) *Bunched, and open (Col. 3 or Col. 6 according to the type and number so run).*

(From Table 11, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Not more than Six Single-Core Cables, or Three Twin Cables, or One Three-Core or Four-Core Cable, or Two Concentric Cables.			Not more than Ten Single-Core Cables, or Five Twin Cables, or Two Three-Core or Four-Core Cables, or Three Concentric Cables.		
		Current Rating (subject to Voltage Drop).	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 3.		Current Rating (subject to Voltage Drop).	Approximate Length in Circuit for 1-volt Drop with Current Rating in Col. 6.	
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	D.C., or Single-phase or 3-phase A.C.	*Lead plus Return,* for D.C.	*Lead plus Return,* for Single-phase A.C.; *Lead only,* for balanced 3-phase A.C.	D.C., or Single-phase or 3-phase A.C.	*Lead plus Return,* for D.C.	*Lead plus Return,* for Single-phase A.C.; *Lead only,* for balanced 3-phase A.C.
1.	2.	3.	4.	5.	6.	7.	8.
Sq. in.		Amps.	Feet	Feet	Amps.	Feet	Feet
0·007	7 / ·036	**20**	39	39	**17**	45	45
0·01	7 / ·044	**29**	39	39	**25**	45	45
0·014 5	7 / ·052	**40**	40	40	**34**	47	47
0·022 5	7 / ·064	**52**	46	46	**45**	53	53
0·03	19 / ·044	**61**	50	50	**52**	58	58
0·04	19 / ·052	**73**	59	59	**62**	68	68
0·06	19 / ·064	**94**	69	69	**81**	80	80
0·075	19 / ·072	**110**	74	74	**94**	87	87
0·1	19 / ·083	**134**	81	79	**115**	95	93
0·12	37 / ·064	**147**	86	82	**126**	100	95
0·15	37 / ·072	**172**	93	85	**148**	108	98
0·2	37 / ·083	**207**	103	86	—	—	—
0·25	37 / ·093	**240**	111	85	—	—	—

The above table applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used.

It refers to situations where the ambient air temperature does not exceed 120° F. (48·8° C.). Where the ambient air temperature is abnormally high the current ratings given in this table shall be multiplied, and the lengths for 1-volt drop divided by the appropriate factor as follows :—

Ambient air temperature	125° F.	130° F.	135° F.	140° F.	145° F.	150° F.
Factor	0·95	0·88	0·82	0·75	0·68	0·60

The lower limit set to the size of conductor by the permissible voltage drop is dealt with in Regulation 304.

* Excluding (for use with alternating current) such single-core armoured cables as are prohibited under Regulation 308.

TABLE 40H. *Paper L.C. Cables on Cleats*, 19 / ·083″ *to* 127 / ·103″. *Current Rating* (*subject to Voltage Drop*) *for Single-Core, Unarmoured, Impregnated-Paper-Insulated, Lead-Covered Cables, run open on cleats as defined in Note* (A), *Table* 40D.

(From Table 12, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Current Rating (subject to voltage drop) for cables run under the conditions defined in Note (A) Table 40D.			Approximate Length in Circuit for 1-volt Drop.		
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	D.C.	Single-phase A.C.	Three-phase A.C.	*Lead plus Return*, for D.C., with Current Rating in Col. 3.	*Lead plus Return*, for Single-phase A.C., with Current Rating in Col. 4.	*Lead only*, for balanced 3-phase A.C., with Current Rating in Col. 5.
1.	2.	3.	4	5.	6.	7.	8.
Sq. in.		Amps.	Amps.	Amps.	Feet	Feet	Feet
0·1	19 / ·083	**219**	**216**	**212**	50	46	46
0·12	37 / ·064	**242**	**242**	**238**	52	46	51
0·15	37 / ·072	**275**	**275**	**268**	58	48	49
0·2	37 / ·083	**325**	**322**	**316**	66	50	51
0·25	37 / ·093	**378**	**375**	**362**	71	48	50
0·3	37 / ·103	**424**	**408**	**395**	77	48	50
0·4	61 / ·093	**515**	**480**	**454**	86	40	42
0·5	61 / ·103	**593**	**538**	**503**	91	38	40
0·6	91 / ·093	**675**	**585**	**544**	97	37	40
0·75	91 / ·103	**788**	**642**	**598**	102	36	39
0·85	127 / ·093	**860**	**676**	**628**	106	36	39
1·0	127 / ·103	**958**	**718**	**669**	117	36	39

The above table applies to cables employed in the wiring of buildings, but does not apply to every condition under which cables may be used.

It applies to two or three cables run spaced as shown in Note (A) Table 40D. Where four or more cables are so spaced the current ratings are reduced to 90 per cent. of those set out in Col. 3 or Col. 4 above for direct-current or alternating-current (either single-phase or three-phase) loading respectively.

For two or three smaller cables (7 / ·036″ to 19 / ·072″ inclusive) so spaced the current ratings are those given in Col. 3 or Col. 4 of Table 40F, and for four or more such smaller cables the current ratings are 90 per cent. of those given in Col. 3 or Col. 4 of Table 40F, for direct-current or alternating-current (either single-phase or three-phase) loading respectively.

Table 40H refers to situations where the ambient air temperature does not exceed 120° F. (48·8° C.). Where the ambient air temperature is abnormally high the current ratings given in this table shall be multiplied, and the length for 1-volt drop divided, by the appropriate factor as follows :—

Ambient air temperature	**125° F.**	**130° F.**	**135° F.**	**140° F.**	**145° F.**	**150° F.**
Factor	**0·95**	**0·88**	**0·82**	**0·75**	**0·68**	**0·60**

The lower limit set to the size of conductor by the permissible voltage drop is dealt with in Regulation 304.

TABLE 40J.—*Bare Copper Conductors. Current Rating (subject to Voltage Drop) of Bare Solid Copper Conductors of Circular Cross-Section, run with a spacing of 3 inches between Centres of Conductors.*

(From Table 20, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Current Rating (subject to Voltage Drop).			Approximate Length in Circuit for 1-volt Drop.		
Diameter.	Approximate Cross-Sectional Area.	D.C.	Single-phase A.C.	Three-phase A.C.	*Lead plus Return*, for D.C., with Current Rating in Col. 3.	*Lead plus Return*, for Single-phase A.C., with Current Rating in Col. 4.	*Lead only*,* for balanced 3-phase A.C., with Current Rating in Col. 5.
1.	2.	3.	4.	5.	6.	7.	8.
In.	Sq. in.	Amps.	Amps.	Amps.	Feet	Feet	Feet
$\frac{3}{8}$	0·11	**230**	**230**	**230**	50	41	37
$\frac{1}{2}$	0·20	**320**	**320**	**310**	63	43	38
$\frac{5}{8}$	0·31	**430**	**430**	**400**	73	40	36
$\frac{3}{4}$	0·44	**550**	**540**	**490**	83	37	33
1	0·79	**820**	**800**	**700**	99	30	27

NOTE.—The current ratings given in this table may be increased by 20 per cent. where the conductors are painted dull black.

This table does not apply to bus bars and connections on switchboards, the requirements for which are contained in B.S.S. No. 159 [see Regulation 303 (B)].

(B). Fittings wire shall have a stranded conductor of 3 / ·020 in. (0·000 9 sq. in. nominal cross-sectional area) and shall consist of tinned copper wire. The conductor shall be insulated with vulcanised rubber having a radial thickness of not less than 0·030 in. and an outer protection of cotton braiding suitably compounded.

1306. **Maximum Size of Single Wire.**—All conductors, except earth continuity conductors (see Table 19), of cables having a nominal cross-sectional area exceeding 0·003 sq. in. (1 / ·064 in.) shall be stranded.

281. Grade of Cables.—(i) *Megohm Grades.*—Electrical wires and cables are sold as being of a certain 'grade' of insulation resistance (§ 71). Three grades are standardised in the I.E.E. Regulations, two of these, known as 600 and 2 500 megohm grades being suitable for cables in which the voltage of the conductor to earth does not exceed 250 V, the third, known as the 660 V grade, for cables in which the conductor pressure to earth lies between 250 and 660 V. Table 40K gives the normal

* For the conductor having the greatest impedance.

TABLE 40K.—*Insulation Resistance of Cables.*

(From Table 16, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Minimum Insulation Resistance of a Mile Length at 60° F. (15·6° C.).			
		Vulcanised-Rubber-Insulated Cables.			Impregnated-Paper-Insulated Cables.
		250-volt Grade.*		660-volt Grade.†	
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	600-megohm Grade.	2 500-megohm Grade.		
1.	2.	3.	4.	5.	6.
Sq. in.		Megohms	Megohms	Megohms	Megohms
0· 001	1 / ·036	2 000	5 000	5 000	140
0· 001 5	1 / ·044	2 000	5 000	5 000	140
0· 002	3 / ·029	1 250	4 500	4 500	140
0· 003	3 / ·036	1 250	4 500	4 500	140
0· 003	1 / ·064	2 000	5 000	5 000	140
0· 004 5	7 / ·029	1 250	4 500	4 500	140
0· 007	7 / ·036	900	4 000	4 000	140
0·01	7 / ·044	900	4 000	4 000	140
0· 014 5	7 / ·052	900	4 000	4 000	140
0· 022 5	7 / ·064	900	3 500	3 500	130
0·03	19 / ·044	750	3 500	3 500	125
0·04	19 / ·052	750	3 000	3 000	115
0·06	19 / ·064	750	3 000	3 000	100
0· 075	19 / ·072	600	3 000	3 000	85
0·1	19 / ·083	600	3 000	3 000	80
0·12	37 / ·064	600	3 000	3 000	75
0·15	37 / ·072	600	3 000	3 000	60
0·2	37 / ·083	600	2 500	2 500	55
0·25	37 / ·093	600	2 500	2 500	50
0·3	37 / ·103	600	2 500	2 500	50
0·4	61 / ·093	600	2 500	2 500	50
0·5	61 / ·103	600	2 500	2 500	45
0·6	91 / ·093	600	2 500	2 500	40
0·75	91 / ·103	600	2 500	2 500	40
0·85	127 / ·093	600	2 500	2 500	35
1·0	127 / ·103	600	2 500	2 500	35

* For (*a*) direct-current systems for voltages not varying from earth potential by more than 250 V; (*b*) three-phrase systems, with neutral point earthed, for voltages not more than 500 V between phases.

† For voltages not varying from earth potential by more than 660 V.

insulation resistances per mile for cables of various sizes of these three grades, and it will be seen that the nominal insulation resistance values apply to cables of the larger sizes.

Thus, in the 600 megohm grade cables, from about 19 / ·072 in. (19 / 15 S.W.G.) upwards will actually have this resistance per mile; smaller cables of this grade, insulated to the same specification, will have higher actual insulation resistance, up to 1 200 or even 2 000 megohms per mile in the smallest sizes. This is due to the fact that the reduction in wire diameter, and hence in its leakage surface in contact with the insulation, more than compensates for the reduced radial thickness of insulation.

(ii) *Association and Non-Association Cables.*—Two qualities of cable are manufactured in Great Britain, known as 'Association' and 'Non-Association' cables, respectively, according to whether the dielectric complies with the specification of the 'Cable Makers' Association' or not. The higher quality is recommended as preferable; each coil should have the 'C.M.A.' label attached. It may be added, however, that certain manufacturers who do not belong to the C.M.A. make cables to the specification of that body, and that some of the special 'tropical' brands of cable have been found more serviceable abroad than C.M.A.; in some instances the same manufacturers supply both qualities and recommend the non-Association 'tropical' quality as preferable to the other.

As regards the rubber insulation of cables, it is sometimes specified that it shall stand dry heat at 270° F. for 2 hrs., and moist heat at 320° F. for 4 hrs. without its qualities or elasticity being impaired.

(iii) *C.M.A. Standard Cables.*—New standard cables were introduced by the C.M.A. as from January 1, 1937. The need for the C.M.A. standards is explained substantially as follows:—

The B.S.I. standards relate to standard sizes of conductors, thicknesses of dielectric, lead, armouring wires, etc., and also tests for rubber insulated cables. They are purely quantitative and do not deal with the quality or durability of the insulating material used as dielectric or with the suitability or quality of protective coverings.

External appearances and the results of initial tests may be very deceptive in the case of rubber insulated cables. Two cables may look exactly alike and comply with the same acceptance tests, yet a few years after installation one may be as sound as ever and the other deteriorated to such an extent as to make it a source of trouble and danger.

Formerly, the C.M.A. standard cables were always insulated with one layer of pure rubber adjacent to the tinned conductor and two layers of vulcanised rubber superimposed thereon. As a result of improvements in rubber compounds and processes of vulcanisation, together with the attainment of much greater efficiency in the tinning of individual wires of conductors, the layer of pure rubber can now be safely and advantageously omitted. Therefore, in the new C.M.A. standard cables the layer of pure rubber is omitted.

Further, because the insulation resistance test affords little or no indication of the reliability of a rubber insulated cable, the C.M.A. has discontinued classification by megohms and designates its standard cables by the voltages at which they are designed to operate.

The following excerpts from a brochure issued by the C.M.A. relate to the new standards :—

The new standard dielectric for 'C.M.A.' grade cables is a vulcanised rubber compound applied in three layers. For 'Nonazo' class cables similar rubber compounds are used, but not of such high quality.

In the new standards, the maximum size of 'C.M.A.' grade cables in 250 V grade is 19 / ·064 in. (0 ·060 sq. in.), larger sizes being made only in 660 V and higher voltage grades.

In the 'Nonazo' class the maximum sizes are 19 / ·064 in. for single-core cables; and 7 / ·064 in. (0·022 5 sq. in.) for twin and 3-core flat lead covered and flat tough rubber sheathed cables.

Besides the new standard C.M.A. flexible cords with three-layer vulcanised rubber dielectric, there are standard twin and 3-core unkinkable domestic flexible cords.

282. Purpose and Testing of Tinning on Copper.—Rubber insulated wires are always tinned, and it is not always realised that the function of tinning is no less to protect the rubber from the catalytic oxidising effect of copper than to protect the latter from sulphur in the rubber.

The standard tinning test laid down by the I.E.E. Regulations requires that any part of the conductor shall satisfy the following

Samples of the tinned wire, taken from the standard conductor, either before or after vulcanisation, shall be selected and bent into circles of diameter between 24 and 30 times the diameter of the wire. After cleaning by immersion in benzine and rubbing with a pad of clean cotton wool or filter paper to remove any grease, the samples shall be dried in air and the part to be immersed in the test solution shall not be handled.

Each sample shall then be immersed in test solutions, as stated below, and maintained at a temperature of approximately 60° F. (15·6° C.). The cycle of operation shall be performed 6 times. Each cycle shall consist of:—

First.—Immersed for 1 min. in hydrochloric acid as defined below. Washed in clean water and wiped dry.

Second.—Immersed for 30 sec. in sodium-polysulphide solution as defined below. Washed in clean water and wiped dry.

The sample shall then be examined under a hand lens to ascertain if copper exposed through openings in the tin coating has been blackened by the action of the sodium-polysulphide. The sample shall be considered to have failed if, by such blackening, exposed copper is revealed.

The hydrochloric acid solution shall have a specific gravity at 60° F. (15·6° C.) of 1·088.

A portion of hydrochloric acid solution having a volume of 180 cu. cm. shall be considered to be exhausted when there has been immersed in it the following number of test samples:—

Diameter of Wire.	Maximum Number to be tested in 180 cu. cm. of Acid Solution.
Up to and including 0·044 inch	20
Above 0·044, up to and including 0·083 inch	12
Above 0·083 inch	8

The sodium-polysulphide solution shall have a specific gravity at 60° F. (15·6° C.) of 1·142 and shall be made in the following manner:—

Dissolve about 25 grms. of pure sodium-sulphide crystals (Na_2S_1, $9H_2O$) in distilled water and make up to 100 cu. cms., add powdered sulphur in excess of the quantity required to saturate the solution, about 25 grms. per 100 cu. cms., and boil for about one hour with occasional stirring.

Cool and filter the solution and then dilute with distilled water to a specific gravity of 1·142 at 60° F. (15·6° C.).

Good tinning should have a slightly golden tint. Blackening means that the tinning is imperfect, but silver-white appearance is also to be regarded with suspicion. Imperfectly vulcanised rubber adheres to the metal.

Silvery brightness of the tin coating after vulcanisation casts suspicion on the quality of the rubber. It has nothing to do with the purity of the tin or its application to the wire. A low-grade foreign wire may often be detected by this feature alone. During vulcanisation of the (inferior) rubber, acid products—due to the method of preparing the 'pure' rubber layer or to reactions in organic loading constituents, other than rubber—may be formed which slightly 'pickle' the tin and prevent formation of tin sulphides. A high-grade rubber compound takes longer than an inferior compound to vulcanise, and due to this and to the absence of 'pickling' there is formed the slightly golden film of tin sulphide which is regarded by cable inspectors as probable indication of excellence (Beaver *Jour. I.E.E.* Vol. 53, p. 70).

283. Class of Cables.—The term 'class' in regard to cables refers to the protecting covering over the dielectric, which may be of any of the grades mentioned in the preceding paragraph.

Pure rubber strip wound in two or three layers with staggered joints and covered with tape and braiding forms a type of insulation which is only suitable up to 100 V or so, and is obviously not moisture-proof. Vulcanised india-rubber (V.I.R.) cables are standard for ordinary work, and it is usually sufficient if the cable is externally 'taped and braided.' It is frequently remarked that, when there is any difference in durability, black-finished rubber cables always last longer than red-finished ones. The difference is attributed by Beaver to the presence of resin in the ozokerite compound with which the braiding is saturated. The natural colour of ozokerite is black. The operation of dyeing it red is facilitated by presence of resin, but resinous matter is absorbed with avidity by rubber, to the great detriment of the latter. The presence of resin is not essential, but its exclusion involves extra cost. Unless it is certain that attention has been paid to this point, there is sound justification for preferring black-finished cable.

Vulcanised india-rubber cables are often lead-covered, and copper is sometimes used as protective covering (§ 556, Vol. 2). Where extra mechanical strength is required, 'armoured' cable is used, the protection consisting of galvanised iron wire or tape, single or multiple. Round-wire armouring is generally used on small sizes of cable and also where the armouring has to carry weight, as in cables suspended vertically in pit shafts. Metal tape probably affords better mechanical protection than is given by round wires; wires of special inter-locking section are sometimes used and these combine flexibility with a high degree of mechanical protection. Armouring may be used in combination with braiding (within or without the armouring, or both), or over a lead sheath. Impregnated tape between lead and steel reduces the risk of cutting or deforming the lead by the armour and prevents electrolytic action between the two metals. Impregnated hemp or jute may be used to protect the armouring. Wherever paper or other hygroscopic dielectric is used, lead sheathing is essential (besides impregnation of the paper, § 287), and great care must be taken to ensure that the ends of the cable are sealed and the joints moisture-proof. Paper-insulated cables are seldom used for house wiring or for small sizes of branch wiring; their use for high-tension work is practically standard (§§ 287, 288). Vulcanised bitumen is a waterproof insulating material, often considered treacherous in its mechanical properties, but greatly improved during recent years. It is largely used in mining work (§ 819, Vol. 3), and to a limited extent for general distribution mains. It may be lead sheathed and armoured or it may be used unsheathed or as a sheathing for paper-insulated cables. Special forms of protection have been devised for a variety of purposes. Thus there are fireproof cables; special trailing cables for serving portable underground machines, where rough usage is inevitable; acid-proof cables, and so on. The use of asbestos as a fire-resisting covering for cables is not without risk, since the asbestos may serve as a wick for oil in case of switchboard fires or explosions.

Tough Rubber Protected Cables, sometimes known as 'Cab-tyre sheathed' cables consist of single or multiple core V.I.R. cables with a substantial sheathing of tough rubber compound similar to that used for cab tyres, and chosen for its mechanical properties and chemical inertness. This sheathing will stand a great deal of rough usage and all conditions due to steam, oil, acid, alkali, etc., which are likely to be encountered in practice. Besides its use in industrial service of all kinds, this class of cable is suitable for general wiring work. It is useful in making connections to lift cars and in wiring to cookers in kitchens. It can be run in plaster unprotected, and in general wiring it eliminates condensation, leakage, and corrosion troubles, particularly if used in conjunction with special terminal and connecting boxes in which the wire is taken down through an outer vessel and up into an inner 'bell,' the mouth of which is sealed by insulating oil in the outer vessel when the whole is assembled.

The I.E.E. Wiring Regulations contain clauses relating to the installation of tough-rubber-protected cables, stating the conditions under which they may be used without the further protection of casing or conduit.

British standard dimensions for armouring, bedding, braiding, serving, cab-tyre sheathing, etc., on insulated copper conductors for power and light service are given in B.S.S. No. 7.

284. Flexible Cables.—Modern practice, as embodied in the 10th edition of the I.E.E. wiring regulations, distinguishes between flexible cables and flexible cords, commonly known simply as 'flexibles.' These latter (see next paragraph) are defined in the wiring rules (§ 4 *supra*) as flexible cables in which each conductor is of no greater cross-section than 0·007 sq. in., beyond and

TABLE 41.—*Flexible Cables, other than Flexible Cords: Dimensions, Current Rating, and Resistance.*

(From Table 13, *I.E.E. Regulations*, 10th Edn.)

Nominal Cross-Sectional Area of Conductor.	Number and Diameter of Wires forming Conductor.				Current Rating (subject to Voltage Drop) for Vulcanised-Rubber-Insulated Cables.		Resistance of Conductor per 1 000 Yards at 60° F. (15·6° C.).		
	Diameter, 0·010 inch.	Diameter, 0·012 inch.	Diameter, 0·018 inch.	Diameter, 0·029 inch.	Two-Conductor.	Three-Conductor.	Standard.	Maximum allowable for Plain Wires.	Maximum allowable for Tinned Wires.
1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Sq. in.					Amps.	Amps.	Ohms	Ohms	Ohms
0·01	140 / ·010	97 / ·012*	—	—	25	22	2·29	2·34	2·39
0·014 5	195 / ·010	—	60 / ·018*	—	30	26	1·64	1·68	1·71
0·022 5	296 / ·010	—	91 / ·018*	—	37	32	1·08	1·11	1·13
0·03	—	266 / ·012	117 / ·018*	—	42	37	0·847	0·864	0·881
0·04	—	368 / ·012	163 / ·018*	—	51	45	0·606	0·618	0·631
0·06	—	557 / ·012	248 / ·018*	—	66	58	0·400	0·408	0·416
0·075	—	705 / ·012	313 / ·018	121 / ·029*	78	68	0·316	0·323	0·329
0·1	—	—	416 / ·018	160 / ·029*	94	83	0·238	0·243	0·247
0·12	—	—	482 / ·018	186 / ·029*	104	91	0·206	0·210	0·214
0·15	—	—	610 / ·018	235 / ·029*	122	106	0·163	0·166	0·169
0·2	—	—	810 / ·018	312 / ·029*	147	129	0·122	0·125	0·127
0·25	—	—	1 017 / ·018	392 / ·029*	171	150	0·097 4	0·099 3	0·101
0·3	—	—	—	481 / ·029	192	—	0·079 4	0·081 0	0·082 6
0·4	—	—	—	646 / ·029	230	—	0·059 1	0·060 3	0·061 4
0·5	—	—	—	792 / ·029	266	—	0·048 2	0·049 1	0·050 1

NOTE.—The cross-sectional areas of the conductors in the above table are given in nominal figures, an addition having been made to the number of wires in order to give resistances as nearly as possible corresponding to those for the same cross-sectional areas in Table 40.

A flexible cable shall be so supported that there is no appreciable mechanical stress on any socket or terminal fitted thereto [see Regulation 312 (C)].

An earth continuity conductor, whether insulated or not, forming part of a flexible cable, is not regarded as a conductor for the purposes of Table 41.

* For trailing cables and similar purposes.

TABLE 41A.—*Flexible Cords: Dimensions, Rating, Resistance and Weight Standard.*

(From Tables 14 and 15, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Minimum Thickness of Dielectric for 250-volt Circuits.			Current Rating (subject to Voltage Drop) for Twin Flexible Cords.	Resistance * per 1 000 Yards at 60° F. (15·6° C.).			Maximum Permissible Weight supported by Twin Flexible Cord [see Regulation 602(E)].
		'High Insulation.'		'Medium Insulation.'			Maximum Allowable for—		
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	Pure Rubber.	Vulcanised Rubber or Pure and Vulcanised Rubber.	Vulcanised Rubber.		Standard.	Plain Wires.	Tinned Wires.	
1.	2.	3.	4.	5.	6.	7.	8.	9.	10.
Sq.in.		In.	In.	In.	Amps.	Ohms	Ohms	Ohms	lbs.
0·000 6	14 / ·007 6	0·020	0·033	0·028	2	39·7	40·5	41·3	3
0·001	23 / ·007 6	0·020	0·034	0·029	3	24·2	24·6	25·1	5
0·001 7	40 / ·007 6	0·020	0·035	0·030	5	13·9	14·2	14·4	10
0·003	70 / ·007 6	0·020	0·036	0·031	10	7·94	8·10	8·26	10
0·004 8	110 / ·007 6	0·020	0·038	0·032	15	5·05	5·15	5·25	10
0·007	162 / ·007 6	0·020	0·039	—	20	3·43	3·50	3·57	10

NOTE.—The above table does not apply to earth continuity conductors, whether insulated or not.

The minimum thickness of protection on tough-rubber-protected flexible cords is 0·05 in., except for 0·000 6 square inch and 0·001 square inch cords insulated as in Columns 4 or 5 for pendant lighting fittings up to 250 volts, in which case a minimum thickness of 0·03 in. is permissible.

* The figures given for resistance refer to straight single cores. Where the cores are twisted into twin or multicore cords an allowance must be made for the extra length due to laying up.

over which the designation is flexible cable. The dimensions, rating, and resistance of flexible cables are given in Table 41.

285. Flexible Cords.—For hanging pendant lamps, and for connecting up portable apparatus to wall plugs, etc., the ordinary wires shown in Table 40 are too stiff; and special flexible wires ('flexibles') are used, consisting of many strands of very fine copper wire.

Over the dielectric there is generally a covering of either cotton or silk, and two or three separate wires are then twisted together to form a twin or triple flexible. Where subject to rough use the two wires are padded to a circular shape and then covered by an outside protective layer of braiding; this class is known as 'workshop flexible.' Circular flexibles, either silk or rubber-covered, are also made for use with portable electric fires, vacuum cleaners and the like.

The standard sizes for flexible cords together with their electrical characteristics are given in Table 41A.

The requirements of the I.E.E. Regulations regarding flexible cords should be studied in the original. Tables 41B and C give particulars of the insulation resistances and test voltages for flexible cords.

TABLE 41B.—*Insulation Resistance of Vulcanised-Rubber-Insulated Flexible Cords.*

(From Table 17, *I.E.E. Regulations*, 10th Edn.)

Conductor.		Minimum Insulation Resistance of a Mile Length at 60° F. (15·6° C.).	
Nominal Cross-Sectional Area.	Number and Diameter (in.) of Wires.	'High Insulation.'	'Medium Insulation.'
1.	2.	3.	4.
Sq. in.		Megohms	Megohms
0·000 6	14 / ·007 6	1 250	300
0·001	23 / ·007 6	1 250	300
0·001 7	40 / ·007 6	1 250	300
0·003	70 / ·007 6	1 250	300
0·004 8	110 / ·007 6	1 250	300
0·007	162 / ·007 6	900	300

TABLE 41C.—*Test Voltages for Flexible Cords.*

(From Table 18, *I.E.E. Regulations*, 10th Edn.)

Kind. 1.	Insulating Material. 2.	Test Voltage and Frequency. 3.	Nature of Test. 4.
		volts	
'High insulation'	Pure Rubber	1 500, at 25–100~	Between conductors, in dry state.
'Medium insulation'	Vulcanised Rubber	1 500, at 25–100~	(Between conductors, in dry state.)
'High insulation'	Vulcanised Rubber or Pure and Vulcanised Rubber	1 000, at 25–100~	In water, after 24 hours' immersion.

It is sound policy to assume a low current-carrying capacity for flexibles (particularly in the smaller sizes), because individual strands often break at many points, particularly in leads supplying vacuum cleaners (§ 525), flat irons, and other portable apparatus. The resulting local reduction in effective copper section increases the current density and local heating at the point affected.

Useful information on the mechanical testing of flexibles for wearing quality, etc., is to be found in Report No. 32529 of the Electrical Testing Laboratories to the National Electric Light Association (U.S.A.); *see also Electricity*, Vol. 34, p. 772.

286. Drop of Volts in Cables.—In the tables in § 280 are given the approximate lengths of each size of wire in which, with the current in the preceding column flowing, there will be a drop of 1 V. If the current is halved the length for the same drop of pressure will be doubled, and so on, in inverse proportion.

For example, using 3 / ·029 in. wire, if the current carried is the maximum allowable, *viz.* 7·8 A, the drop is 1 V in about 31 ft. Therefore, if the pressure of the supply in question is 220 V, and we arrange for 4 V drop in the branch wires (out of the 5½ V allowable, § 278), we are limited to 124 ft. of wire, *i.e.* 62 ft. run of lead and the same of return.

Generally the length of wire and the current are known and it is required to find the size of wire which must be used. Thus, the pressure being 110 or 220 V, we may generally allow up to 2 or 4 V drop respectively in the branch wiring; now by Ohm's Law the total resistance of the conductor will be E / I, E being the *drop* in volts allowed; then if we know the total length (lead plus return) and the resistance of that length (by the above calculation) the resistance per 1 000 yards can be found at once by simple proportion, and from this the nearest size of wire can be selected from the wire table (col. 8), as in examples (Table 41D on following page).

TABLE 41D.—*Examples in Selecting Size of Conductor, on the Basis of Assumed Voltage Drop.*

Drop Allowed E.	Current I.	$R = E / I$.	Length Lead and Return.	Proportional Resistance per 1 000 Yds.	Nearest Size from Col. 6 of Table 40.
V.	Amperes.	Ohms.	Yds.	Ohms.	
2	5	0·4	40	10	3 / ·036″
4	5	0·8	60	13·4	3 / ·029″
2	7	0·28	50	5·7	7 / ·029″
2	7	0·28	80	3·5	7 / ·036″
2	13	0·15	30	5	7 / ·036″

Care must be taken to see that the cable selected on the basis of voltage drop is not too small for the current it has to carry; this may be ascertained by reference to Tables 40A-J. Also, if the size comes out smaller than 3 / ·029 ins. (3 / 22 S.W.G.), that wire is the smallest which should ordinarily be used. Of two sizes, in cases of doubt, it is better to use the larger, especially if the current is near the maximum allowable by the Table or if the air temperature is liable to exceed 80° F. In the case of mains and sub-mains, where extensions may cause an increase of current, it is also best to be liberal in the size used.

287. Insulating Materials for High-Pressure Cables.—General information concerning insulating materials is to be found in Chapter 2, § 70, *et seq.* The notes here given relate to the characteristics of various insulating materials as affecting the use of the latter in high-voltage cables (*see also* §§ 281, 283 for low-voltage cables, and § 288 for extra high-pressure cables). The inductance and capacity of cables are discussed in §§ 310, 311.

Air under pressure (§ 78) has been used experimentally as dielectric for high-voltage 'cables'; with a ¼-in. conductor inside a 4-in. iron tube, and air at 120 lbs. per sq. in., it is possible to transmit energy at 60 000 V (J. S. Highfield, *El. Rev.*, Vol. 91, p. 919).

Rubber is too costly for use as insulating material on high-pressure cables; it has a high insulation resistance, but has lower break-down pressure than paper, and both the insulation resistance and dielectric strength of rubber depend greatly on its composition and degree of vulcanisation. The proportion of pure rubber in the mixture is generally from 30-60 %. Rubber insulation is liable to attack by ozone and nitric acid formed from the atmosphere in the neighbourhood of e.h.t. conductors ; a sheathing of bitumen between rubber and conductor eliminates this risk. The lower specific inductive capacity of paper as compared with rubber is an advantage in cable construction.

The general properties of *vulcanised bitumen* include a tendency to break short at low temperatures, particularly under shock, and to soften and permit decentralisation of conductors when heated in service. However, manufacture of these cables has improved greatly during recent years. Two- and three-core bitumen cables are generally found more reliable than single-core cables, and A.C. cables give less trouble than D.C. cables of this type. Vulcanised bitumen is immune from attack by acids, but alkalis cause a certain amount of surface attack. From an extensive investigation, C. J. Beaver concludes that the softening of bitumen by saponification is attributable to leakage current, moisture (in so far as the latter is required to render braiding conducting), and heat, the effect increasing with the time these conditions endure. Saponification troubles occur only on negative cables, since it is only there that alkali is produced electrolytically. The incorporation of 5-10 °/₀ of high-grade vulcanised rubber in vulcanised bitumen is said to give a material free from any softening trouble, even under severe conditions of practice, and superior to either ingredient alone. The principal use of bitumen cables is as distributors in mining and other industrial service; a bitumen sheathed cable with bitumen "wormings" between the component conductors, which are themselves insulated with bitumen is practically moisture-proof. The bitumen should be forced into the interstices between the strands of each conductor to prevent 'creeping' of moisture from a defective point.

Paper insulation is employed in most cables for pressures of 3 000 V or higher, owing to its good mechanical and electrical properties. Suitable paper stands heating in service better than rubber ; also it is cheaper than rubber and has a very high breakdown pressure (about 200 kV (R.M.S.) per cm., as a commercial maximum, with 120 to 150 kV as the basis for guarantees), though its insulation resistance is low, say 70-100 megohms per mile in large and 150-300 megohms per mile in small paper cables. Unusually high insulation resistance in paper-insulated cables does not necessarily indicate over-heating of the latter in manufacture and is not a reasonable basis for rejection, though it is sometimes laid down as such in specifications. In this country, pure manilla paper is considered best for insulating purposes; on the Continent, paper containing a proportion of wood pulp is often used, on the ground that it absorbs impregnating oil more freely. Probably the cheapness of the impure paper is a major consideration. Paper-insulated cables may be impregnated (under heat and vacuum) after the paper is applied, or the paper strip may be impregnated before being wound on the cable. In the latter case a more viscous impregnant may be used, the heating period for drying out the cable may be reduced, and no difficulty is found in excluding air bubbles. The impregnating compound should not set stiff or hard but should be oily in nature so that the paper is not torn when the cable is bent. Break-down by ionisation results if voids are caused by the paper absorbing filling material from the interstices of the strand, or by the impregnant not flowing to fill up bends. Paper itself is very hygroscopic, and no impregnation renders it waterproof to the extent required for insulating purposes; hence it is most important to protect all joints and ends during laying, and to keep them perfectly sealed when in service.

Varnished cambric (*Empire cloth*) is used, particularly in America, as insulation for cables which may be exposed to oil or acid as in the case of connecting-cables in power-houses, switch-boards, accumulator rooms, etc. In these applications the cable can be used with a simple braiding and the ends need not be sealed. Though much less hygroscopic than paper, varnished cambric must be lead sheathed if it is to be used underground. For underground service paper insulated cables are generally to be preferred.

British Standard thicknesses of dielectric, sheathing, and armouring for various types and classes of cable are specified fully in B.S. Specification No. 7.

288. Extra High-pressure Cables.—The object of using very high pressures for transmission purposes is to reduce the weight of metal required to conduct the power in question. However, this idea must not be carried too far, particularly in insulated cables. The electrostatic strain on the insulation surrounding a charged conductor increases with the pressure to which the latter is charged, and also increases with the curvature of the conductor, *i.e.* is greater for a small wire than for a larger wire charged to the same pressure. The minimum permissible conductor radius in a high-tension cable is $r = (V / S)$ cms., where V = R.M.S. volts p.d. between conductor and sheathing, and S = maximum safe dielectric stress in R.M.S. volts per cm. (*see also* § 72). This assumes that the conductor is circular in section. If it be stranded, the sharp curvature of the outer-strand conductors themselves will intensify the electrostatic stress, but this may be overcome by pressing a lead sheathing on to the stranded conductor so as to give it a smooth cylindrical surface. If the minimum radius r, determined by consideration of electrostatic stress, be greater than the radius dictated by consideration of electrical conductivity and mechanical strength, the weight and cost of the conductor may be kept down by adopting a tubular section of external radius r. A rigid tube of metal would be of very limited applicability, but flexibility may be maintained by using a ring of small conductors laid on to a lead-tube core, to keep them in position, and sheathed with lead to obtain a smooth circular periphery. By using a paper tube as mandrel for the outer ring of conductors, and placing an ordinary stranded conductor inside the paper tube, the 'split conductor' needed by the Merz-Price protective gear (§ 359) can be obtained without increasing the overall conductor diameter (as compared with the previously mentioned lead-tube core construction).

There is no special difficulty in insulating cables for pressures up to 20 000 V between cores, and 3-core, 33 000 V cable is a standard commercial product. If required, 3-core, 44 000 V or 66 000 V cable can be supplied under satisfactory guarantees. For underground transmission at higher pressures between phases it is probably cheaper and safer to use single-core cables (*see also* §§ 289, 290*a*). The Gennevilliers (Paris) system uses considerable lengths of 33 000 V single-core cable, with 60 000 V between phases.

A typical British 3-core cable for operation at 33 000 V between phases has three stranded conductors, each of 0·2 sq. in. section and covered with ¼ in. layer of paper; round the three cores is another ¼ in. layer of paper, outside which comes the lead sheathing, a jute bedding, double armouring, and the outer serving of jute. There is thus ½ in. of paper between cores and between each core of the lead sheath. The cable is about 4 ins. diameter overall and weighs 72 lbs. per yard.

289. E.H.T. Cables, Special Types.—(i) *Graded Insulation.* —Where a charged cylindrical conductor is surrounded by a uniform thickness of a homogeneous insulating material, the electrostatic stress on the latter is much more intense on the inner layers, adjacent to conductor, than on the outer layers. In other words, the 'potential gradient' is not uniform, and the inner layers of insulation may be broken down or deteriorated by overstrain (*see*, however, § 72). One way of overcoming this difficulty is to use successive layers of different insulating materials having different specific inductive capacities. The complete insulation then consists of a number of concentric tubular condensers connected in series, and the distribution of pressure through the insulation is determined by the electrostatic capacity (§§ 46, 60, 79, 107 ii) of the several layers. Theoretically, the total electrostatic stress could be distributed uniformly through the whole thickness of insulation by this means, but in practice the method involves grave difficulties. In the first place, consideration of manufacturing cost limits us to, say, three or four layers of insulation, so that the resultant pressure gradient curve consists necessarily of a number of 'steps.' The chief difficulty, however, is to obtain even a few insulating materials of suitable electrical and mechanical properties, which can be used in the first place and relied upon to preserve their properties unchanged, and not to attack each other chemically in the course of twenty or thirty years. The intersheath method is more flexible and probably more reliable.

(ii) *Intersheaths.* — An alternative method of maintaining definite potentials at certain depths in the insulation, thus ensuring that the electrostatic stress across intervening parts shall not exceed a predetermined maximum, consists in laying on thin metallic sheathings from time to time during the application of the insulation, which is itself of the same material throughout. There are thus obtained a series of concentric electrodes in the insulation, which can be 'anchored' at any desired potential; the potential gradient in the outer layers of insulation may be higher than in the inner layers because the outer layers are cooler and therefore of higher insulation resistance (§ 71) and lower dielectric loss. The potentials of the 'intersheaths' may be fixed by condensers connected between them, or by tapping connections from transformer or generator windings at suitable points, or, in the case of high-tension constant current on the Thury system (§ 317), by small natural or artificial leakage currents, tappings being taken from the connections of the series-connected generators. The intersheaths themselves may be of lead; they can then be applied easily with smooth interior and exterior surface, and the cable can be tested thoroughly after each intersheath is applied—which is an important manufacturing advantage. The intersheaths may also be used for maintenance tests in service; or they may be of copper wire and used for power transmission (§ 319). Intersheaths have not, so far as the authors are aware, come into use to any extent; the principle is sound, but the necessity for feeding the intersheaths at intervals is a practical objection.

As described by Beaver (*Jour. I.E.E.* Vol. 53, p. 57), a single cable designed for use in a 3-phase line, for a working pressure of 100 kV per phase and a breakdown pressure of 250 kV per phase, consists of an inner lead tube of 0·27 in. bore and 0·06 in. radial thickness, on which is a single layer of nineteen 15 S.W.G. wires sheathed by an outer lead tube of 0·05 in. radial thickness. The first layer of paper insulation is 0·545 in. in thickness, and is covered by a 0·05 in. lead intersheath. The second layer of paper is 0·565 in. thick, and the outer lead sheath is 0·16 in., bringing the overall diameter of the cable to 3·27 ins. The maximum stress in the dielectric at the working pressure is 52 kV per cm., giving a factor of safety of about 2½. By accepting a lower factor of safety, the overall diameter could be reduced yet further.

The difficulties encountered in manufacturing intersheath cables have been overcome, and sample 100 000 V cables have given satisfactory results on test. The conditions calling for grading (either by graded insulation or by intersheaths) are: (1) working pressures exceeding 60 kV; (2) maximum stresses above 60 kV per cm.; (3) where cable diameters, without grading, would exceed, say, 3 ins. For most practical purposes one intersheath will suffice. The saving possible by using graded cable is greater the higher the working pressure and the smaller the conductor to be insulated. In the present state of practice, such cables as considered above are required only for short-distance interconnecting with e.h.t. transmission lines in city areas or round about power-houses, railways, etc. Should long intersheath cables come into use, their considerable capacity current (§ 311) will necessitate 'feeding' the intersheaths at intervals along the line, unless, of course, the Thury constant current system (§ 317) is employed.

(iii) *Screened Type 3-Core E.H.T. Cables.*—In 3-core cables of the ordinary type, three paper insulated conductors are made up with a centre filling and served with an external belt of paper tapes and finally lead sheathed. When such cables are used for pressures much exceeding 22 kV, the non-uniform electric stress in the centre zone between the cores tends to impair the insulation and ultimately to lead to breakdown. Further, expansion and contraction of the lead sheath, due to load changes, tends to the formation of air voids in the spaces between the cores and the sheath, which cause further stress distortion. In the H type of 3-core cable, each core is served with a metallic screen or sheath over the paper insulation in the form of either a copper tape or a layer of aluminium-coated paper. The three cores are made up into the complete cable in such a way that the screens are mutually in contact and are also all in contact with the lead sheath. By this means the concentric zone round each core is maintained at earth potential, with the result that the direction of the electric stress in the insulation of the cores is radial, and harmful tangential stresses in the paper tape insulation are avoided. The screened type cable also has better heat dissipating properties than the ordinary belted type.

In the S.L. type cable, manufactured by Messrs. W. T. Henley's Telegraph Works Co. Ltd., each insulated core is covered with a lead sheath over the metal screen. The three single-core cables are laid up, warmed, and armoured. This type of cable has a favourable distribution of electric stress, as in the H-type, and the further advantage of readier dissipation of heat; also, its construction allows it to be bent easily. The capacitance of screened cables is greater than those of the belted type for equivalent duty, but this circumstance is not, as a rule, of great importance.

(iv) *Oil-Filled and Gas-Filled Cables.*—Experience and research have shown that breakdown of cables for very high pressures is due largely to the ionisation of minute air spaces in the insulation under electric stress. To prevent the formation of these air spaces the oil-filled type of cable has been developed. In this type the lead sheath is connected to oil reservoirs which give a pressure head sufficient to force oil into the interstices of the paper tapes of the insulation. By this means the insulation of the cable is continuously impregnated with oil under pressure during any cycles of temperature change which may arise, due to variations of load. An alternative type of high-pressure cable is one in which compressed air or inert gas is used instead of oil. As the dielectric strength of a gas increases rapidly with the pressure, it is practicable, by increasing the pressure in the voids, to obtain a breakdown voltage equal to or greater than that of oil. The gas-filled cable is simpler in construction and installation than the oil-filled type, particularly when gradients are met with, as, in these conditions, obtaining correct pressure head for oil-filled cables is often a matter of some difficulty. Nitrogen is generally used (*see also* § 290*a*).

290. Cable Construction, Jointing, and Laying.—The conductors in cables are generally stranded and of circular cross-section, either of rope form (two conductors being placed side by side, or three at the apices of a triangle), or tubular, as in concentric cables. Single-core cables are easier to make, lay, and joint than 3-core cables, but the eddy current losses in the sheaths are heavier and if single-core A.C. cables be armoured the inductance becomes excessive. Probably the largest 3-core cable yet built is a 3 × 0·5 sq. in., 11 000 V cable connecting a 12 000 kVA generator to the bus bars in the Neepsend station. The use of tubular or ring-formed conductors to reduce electrostatic stress is discussed in § 289. Individual cores may be split into two concentric sections lightly insulated from each other and of circular form (or elliptical form in 3-core cables), the object being to use the split-conductor protective system (§ 359); separate 'pilot' wires are then unnecessary. The elliptical form of conductor saves space as compared with circular cores, without unduly increasing electrostatic strain. Up to 1 000 V or so, sector-shaped cores effect important saving in size and weight of 3-core cables, particularly when the copper section is relatively large. In high-tension cables the additional insulation required by the enhanced electrostatic stress at the corners of the sector outbalances the saving otherwise to be derived from the geometrical form of the sectors. The economic possibilities of aluminium conductors are reviewed in §§ 308, 331; as an aluminium conductor is about 29 °/₀ larger in diameter than the copper conductor of equal conductivity, the extra insulation and armouring required is a serious consideration.

Insulating materials and their 'grading' are discussed in §§ 287, 289. A point of some importance in laying out new distribution schemes is the possibility of saving money by installing cables which can subsequently be operated at higher pressure than at first, the change being made when demanded by increase in the load supplied. The question whether an existing cable can safely be run at higher pressure than was originally contemplated, depends upon the factor of safety then allowed, and upon the history of the cable in service, *i.e.* the average and maximum current densities at which it has been worked and the pressure surges to which it has been exposed. As explained in § 298 A.C. cables must withstand higher maximum pressures (apart from surges) than D.C. cables working at the same effective pressure. Also the maximum dielectric stress (§ 289) must be kept down in A.C. cables to avoid serious heating by dielectric losses (§ 312).

Single or double armouring may be used, according to local conditions, if the cable is to be laid directly in the ground; and it is then a sound precaution to place a row of tiles or the like over the cable before filling in. Round wires are generally used for armouring, fewer being required, though they are heavier than segmental wires. Tape armouring tends to pull open under tension (as in pit-shaft cables). The conductivity of the armouring should be at least 50 °/ₒ of that of the largest conductor enclosed in mining cables, § 819, *et seq.*, Vol. 3; in single-armoured cables the armouring may have 25 °/ₒ of the conductivity of the largest conductor, and a copper sheath within but separated from the armouring is then frequently employed. To resist corrosion by water, armour may be galvanised and covered by an impregnated serving. Electrolytic corrosion of cables by stray earth-current is discussed in § 907, Vol. 3.

In the 'solid' system of laying cables, the cables are placed on bridges or separators in a cast-iron or stoneware trough, which is then filled with hot bitumen or compound and closed by a cover-plate. On this system unarmoured cables are generally employed. Draw-in conduit systems are not satisfactory in the tropics, but are much used in England; the facility with which fresh cables may be laid or existing ones withdrawn for repair is an important advantage. Pounding of heavy traffic on roads is apt to injure cables laid near the surface; in such cases flexibility should be secured either by laying the cable 'direct' or by laying it on the solid system in a flexible wooden troughing.

Cables laid directly in the ground or on the solid system have better facilities for cooling than cables which are drawn into ducts. The drawing-in process necessarily involves some risk of damaging the cable. The cost of trenching and tunnelling when laying cables may often be greatly reduced by using the Mangnall-Irving 'thrust borer.' This is an hydraulic machine which drives a hole of any desired diameter (up to 12 ins. as a maximum under favourable circumstances) on a predetermined alignment through the earth between two access pits which may be, say, 40 ft. apart. The soil is displaced (*not* removed) and the hole is thus left with a consolidated surface which will allow a cable to be drawn through without undue resistance. If desired, pipes can be left in the hole as it is bored (*El. Rev.*, Vol. 90, p. 545).

Joints in cables may be made in junction boxes or, permanently, in the run of the cable itself. In the latter case the general aim is to make the joint electrically as similar as possible to the cable itself. Insulating material, such as impregnated paper strip or rubber tape, may be built on to jointed conductors, or the conductors may be held apart by porcelain or other separators, a lead casing being then wiped on to the lead sheathing at each side of the joint and filled with molten insulating compound. The latter should be kept warm for a time, and there should be a reserve of hot compound in the extended top or funnel of the casing to make up for contraction as the mass cools. Sharp edges or points of solder on the joint, air-bubbles or films, and inclusion or ingress of moisture are particularly to be guarded against, especially in h.t. cables.

290a. Gas-Filled Cables.—Reasons for using compressed gas-filling in h.t. cables are noted briefly in § 289 (iv). Further information on the subject is to be found in papers by C. J. Beaver and E. L. Davey* and A. N. Arman.† An 'impregnated pressure' cable ‡ designed for 200 kV operation has a dielectric similar to that of the solid type, in which oil or compound is used, and after the cable is installed, dry nitrogen is admitted, filling all the interstices with gas at 200 lb. / sq. in. The article cited gives test data and particulars of the jointing arrangements. The lead sheath is reinforced against the internal pressure by a wrapping of overlapping copper tapes.

291. Heating of Cables.—The heating of various types of cables under various service conditions is important because it

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* International Conference on Large H.T. Systems, Paris. Paper No. 204, 1937.

† *Jour. I.E.E.*, Vol. 81, p. 625. ‡ *El. Rev.*, Vol. 121, p. 700.

determines the maximum current which may safely be carried by the cable. The current carrying capacities of vulcanised rubber insulated and paper insulated cables of various types under stated conditions, and subject to the voltage drop being within permissible limits, are given in Tables 40A—J, in footnotes to which there are stated the corrections to be applied if the ambient air temperatures exceed stated values.

Subject to any later recommendations which may be based on improvements in materials and further research on the complex subject of the heating of insulated cables under various conditions of service, the data in Tables 40A—J should be used in planning all new installations.

The notes and examples in the succeeding small type paragraphs, are, however, retained from the fourth edition of this book because they illustrate clearly the influence of the various factors involved; also, they may serve as a useful check on other recommendations. Table (A) below is based on Table 40 in the fourth edition of this book and gives data then cited as being supplied by the National Physical Laboratory; these figures are now reproduced only for the purpose of the notes with which they are associated, and except for the necessary addition of Table (A), the following notes are as on pp. 411 *et seq* of our fourth edition:—

The Henley Manual gives tables of current-carrying capacities of insulated cables (for pressures up to 6 000 V) based approximately on the following data:—

(*a*) *For situations where the air temperature does not exceed 80° F.:* The safe carrying capacities for *two single cables* laid together are: For rubber cables erected in air, wood casing, exposed or buried conduit; and for paper, lead-sheathed cables in ducts underground; as shown in Table (A). For bitumen insulated cables in ducts underground, about 0·9 times the values for rubber-insulated cables (assuming that the bitumen cable is not allowed to reach a total temperature higher than 110° F.).

The safe current for *one single cable* or for *one multi-core cable* is obtained approximately by multiplying the value for two single cables by a factor as follows:—

For one single cable multiply by 1·1.
For one concentric (or twin) cable multiply by 0·93.
For one 3-core cable multiply by 0·88.
For one 4-core (or twin concentric) cable multiply by 0·82.

If *several cables are laid together*, multiply the safe current for one cable by 0·9 for two cables; by 0·85 for three cables; and by 0·8 for four cables.

If the *cable is installed otherwise than stated above*, multiply the value so far obtained for the safe current by a factor as in Table (B).

(*b*) *For situations where the air temperature exceeds 80° F.* In addition to the correction factors given above, which must be applied successively in so far as they are applicable, the safe current value now obtained must be multiplied by a factor to allow for the higher initial temperature of the air, as in Table (C).

TABLE (A).—*Former Basic Values of Current Carrying Capacity for Insulated Cables.*

As explained in the text these data are reproduced (from Table 40 in the fourth edition of this book) only for the purposes of the accompanying notes. These values of current carrying capacity (subject to voltage drop) were given in the eighth edition of the I.E.E. Wiring Rules. They relate to single cables run in pairs and touching one another, and refer to situations where the maximum temperature of the air does not exceed 80° F. (26·7° C.) The currents are those corresponding to a temperature rise of 20° F. for rubber insulated (50° F. for paper insulated) cables above the temperature of the surrounding air.

No. and Dia. of Wires.	Maximum Current.		No. and Dia. of wires.	Maximum Current.	
	Rubber Insulated Cables.	Paper or Fibre Insulated Cables.		Rubber Insulated Cables.	Paper or Fibre Insulated Cables.
	Amps.	Amps.		Amps.	Amps.
1 / ·036″	4·1	4·1	19 / ·072″	97	157
1 / ·044″	6·1	6·1	19 / ·083″	118	191
3 / ·029″	7·8	7·8	37 / ·064″	130	210
3 / ·036″	12·0	12·0	37 / ·072″	152	246
1 / ·064″	12·9	12·9	37 / ·083″	184	296
7 / ·029″	18·2	18·2	37 / ·093″	214	343
7 / ·036″	24	28	37 / ·103″	240	385
7 / ·044″	31	42	61 / ·093″	288	464
7 / ·052″	37	57	61 / ·103″	332	540
7 / ·064″	46	75	91 / ·093″	384	624
19 / ·044″	53	87	91 / ·103″	461	738
19 / ·052″	64	104	127 / ·093″	512	815
19 / ·064″	83	135	127 / ·103″	595	932

TABLE (B).—*Factors Allowing for Method of Installation of Cables.*

Method of Installation.	Rubber Cable.	Paper, Lead-sheathed Cable or Bitumen Cable.
Cleated to wall	1·0	0·9
In underground duct	1·1	1·0
Solid system	1·2	1·1
Direct in dry soil	1·3	1·2
,, ,, wet ,, ...	1·4	1·3
Under water	1·5	1·5

TABLE (C).—*Factors Allowing for Temperature of Surrounding Air.*

Initial Air Temperature.	Rubber Cables.	Paper Cables.	Bitumen Cables.
° F.			
90	0·87	0·93	0·82
100	0·71	0·85	0·58
110	0·50	0·76	—
120	—	0·65	—
130	—	0·54	—
140	—	0·38	—

Example.—What is the safe current for four, 3-core paper cables laid solid in a situation where the initial air temperature is 110° F.? Each core is a 7 / ·064 conductor.

From Table (A), the safe current for two single paper cables of this size is 75 A. Multiplying this value successively by 0·88 because 3-core cables are concerned; by 0·8 because four cables are laid together; by 1·1 because the cables are laid solid; and by 0·76 because the initial temperature is 110° F., we have: Safe current = 75 × 0·88 × 0·8 × 1·1 × 0·76 = 44 A (approx.).

It should be noted that the air temperature in the shade is no guide to the temperature 2 or 3 ft. below ground where the surface is exposed to the full sun and may reach 160° F. or higher temperature.

The heating in a buried cable on load varies with the method of laying, with the thermal properties of the insulating materials, and with the current density in the cable (*see also I.E.E. Report*, § 293). If the temperature rise be excessive the insulating material deteriorates and the cores in vulcanised bitumen cables may be decentralised. The maximum temperature should not exceed 120° F. for rubber cables; 150° F. for paper cables; and 110° F. for bitumen cables. In practice, trouble due to overheating generally takes the form of pulling-out at joints, and of broken or crumpled sheathing, due to the forces of expansion and contraction; direct injury by the actual temperature attained is seldom experienced. In emergency, the carrying capacity of cables laid in ducts can be increased by forcing cool air through the ducts by blowers situated at alternate manholes, the warm air escaping at the intermediate manholes. Cables supplying cyclic loads (*i.e.* loads which demand current for relatively short periods followed by periods of little or no demand) may carry considerably higher current than would be permissible continuously; the actual safe current can only be determined by plotting the heating and cooling curves of the cable from tabulated experimental data, or by direct measurement of the steady temperature reached after a prolonged series of duty cycles.

292. Submarine Cables.—There are a number of cases in which electric power cables (as distinct from telegraph and telephone cables) are laid in sea-water, across bays, channels, estuaries, etc. The following notes are instructive:—

Two cables were laid (in 1915) a distance of 13 000 ft. across the Golden Gate (San Francisco) to deliver 18 000 H.P. at 11 000 V. Each cable has three copper cores (of 350 000 circ. mils * area at the shore ends and 250 000 circ. mil * for the deep-water sections), insulated by rubber and varnished cambric, and enclosed in a 5/32-in. lead sheath. Two layers of jute form a cushion for the steel armouring, which in turn is covered by jute and a layer of sand and asphaltum. The overall diameters of the shore end and deep-water sections of the cable are 4½ ins. and 4 ins., the weights being 22 and 19 lbs. per ft. respectively. Since the tide runs at 6 knots and the water is over 200 ft. deep (from which depth the cable could not safely be hoisted for repair), each power cable is carried by a 1⅝-in. stranded steel messenger cable. The two cables are bound together by a continuous winding of two galvanised wires, soldered every 12 ins. (to prevent unwrapping should the wire break), and wound in a number of turns at one point every 20 ft. The messenger cable relieves the cable and joints from all tension. There are eleven splices in each completed cable. The safe carrying capacity of the cables is 350 A or 400 A in emergency. The specification required a test pressure of 30 000 V, 60 cycles between cores for 30 mins.; the actual break-down pressure is 1C0 000 V between cores (*see also El. Rev.*, 78, 443).

More recently a 25 000 V cable has been laid 3½ mls. under the sea, at a maximum depth of 125 ft., between Palsjö (Sweden) and Marienlyst (Denmark). This cable supplies about 5 000 kW, 3-phase A.C., and uses impregnated paper insulation, a fact which involved very great care in making joints at sea whilst laying the cable. The twin copper cores (0·019 sq. in. each) are insulated for 35 000 V, and the cable is lead-sheathed, and armoured by special Z-shaped wires. The overall diameter is 3·6 ins., and the weight 19 lbs. per ft. run. Iron coupling boxes 5 ft. in length transmit strain in the armouring across the lead-sheathed joints, of which there are eight. A steel cable is laid alongside to protect the power cable from damage by anchors.

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* In the U.S.A. the standard unit in which to express the sectional area of wires is the *circular mil* (circ. mil or C.M.). The term circular mil denotes the area of a circle 1 mil or 0·001 in. in diameter; hence 1 circ. mil = 0·785 4 sq. mil = $7{\cdot}854 \times 10^{-7}$ sq. ins. = $5{\cdot}067 \times 10^{-4}$ sq. mm. The sectional area of a round wire in circ. mils is numerically equal to the square of its diameter expressed in mils (*i.e.* in thousandths of an inch). Conversely, the diameter of the wire in mils = $\sqrt{}$(Area in circ. mils). Thus 350 000 circ. mils = 0·274 9 sq. in., and is equivalent to a solid round wire of $\sqrt{350\,000}$, *i.e.* 590 mils or 0·59 in. diameter. Similarly, 250 000 circ. mils = 0·196 4 sq. in., and is equivalent to a round wire of 0·5 in. diameter. For easy reference:—

1 circ. mil. = $7{\cdot}854 \times 10^{-7}$ sq. ins.
1 sq. in. = 1 273 240 circ. mils (approx.).

As will be gathered from these particulars, any waterproof cable of suitable mechanical strength can be used under water, the chief problem being to provide for laying and recovering it without mechanical injury. The stiffness of adequately armoured cables makes them difficult to handle; for this reason and because of the high capacity of the cable (§ 311) the length of submarine power cables is limited to a few miles. The cable may be carried on the cable-laying ship by a drum capable of rotation about a vertical axis, or it may be coiled in figure-of-eight formation on deck. The external covering of compounded jute is mainly useful in preventing damage during laying. It is difficult to make splices whilst laying the cable, and splices are always a source of electrical and mechanical weakness; they may be avoided, in cables of 2 mls. or so in length, by using cable insulated with rubber compound and with no lead sheathing.

The construction of a cable of this type laid, in 1922, between N. Brothers and Rikers Islands, East River (N.Y.) is: Two No. 0 A.W.G. stranded conductors, each insulated with $\frac{12}{64}$ in. of 30 °/$_{o}$ rubber compound and covered by one rubber filled tape. The insulated conductors are twisted with paraffined jute fillers, and over this is a rubber filled tape and two layers of asphalted jute. The latter serves as bedding for a layer of No. 6 A.W.G. galvanised steel wire armour (drawn through asphaltum compound before application); outside this is a layer of No. 4 A.W.G. galvanised steel wire wound in the opposite direction. The complete cable is 2·92 ins. outside diameter and weighs 31·8 lbs. per yard.

293. Bibliography (*see* explanatory note, § 58).

REGULATIONS, ETC.

Board of Trade Regulations (Electric Lighting Acts, 1882 and 1888); Publication 2 C (P) (Stationery Office).

Electricity Commissioners' Regulations (Under Sec. 4 of Electric Lighting Act, 1888); Publication El. C. 12 (Stationery Office).

Electricity Commissioners' Regulations as to Extra High Pressure (Electricity (Supply) Acts, 1882-1919); Publication El. C. 13 (Stationery Office).

H.O. Electricity Regulations for Factories and Workshops (Stationery Office).

Mines and Quarries Form No. 11 (Coal Mines Act, 1911). Regulations as to installation and use of Electricity (Stationery Office).

I.E.E. Wiring Rules (Spon).

B.S. SPECIFICATIONS.

No. 7. Insulated Annealed Copper Conductors for Electric Power and Light.

No. 91. Electric Cable Soldering Sockets.

No. 94. Watertight Glands for Electric Cables.

No. 356. Brass Armouring Wire for Electric Cables.
No. 446. Braided Cables with Copper Conductors for Overhead Transmission Lines.
No. 480. Metal-Sheathed Paper-Insulated Plain Annealed Copper Conductors for Electricity Supply, including Voltage Tests.
No. 608. Varnished Cambric Insulated Annealed Copper Conductors for Electricity Supply, including Voltage Tests.

BOOKS.

The Indian Electricity Rules, 1922; 'The Law Relating to Electrical Energy in India and Burma,' by J. W. Meares (5th Edition; Thacker Spink, Calcutta, 1937).

Underground Cable Systems. G. W. Stubbings (Chapman & Hall).

Electric Cables. F. W. Main (Pitman).

Theory of Electric Cables and Networks. A. Russell (Constable).

Electric Mains and Distributing Systems. J. R. Dick and F. Fernie (Benn Bros.).

High Voltage Cables. L. Emanueli (Chapman & Hall).

Dielectric Phenomena in High Voltage Cables. D. M. Robinson (Chapman & Hall).

I.E.E. PAPERS.

Insulation of Cables. M. O'Gorman. Vol. 30, p. 608.

Dielectric Strength of Insulating Materials and Grading of Cables. A. Russell. Vol. 40, p. 6.

Cables. C. J. Beaver. Vol. 53, p. 57.

Research on the Heating of Buried Cables. Vol. 59, p. 181; Vol. 61, p. 517; Vol. 64, p. 161.

The Rating of Cables for Intermittent or Fluctuating Loads. S. W. Melsom and H. C. Booth. Vol. 61, p. 363.

The Use of Single-Core Sheathed Cables for A. C. W. Cramp and N. S. Calderwood. Vol. 61, p. 477.

Permissible Loading of British Standard Paper-Insulated Cables. (B.E.R.A. Report.) Presented to I.E.E., March, 1923.

Ionization in Cable Dielectrics. P. Dunsheath. Vol. 73, p. 321.

The Thermal Resistance and Current-Carrying Capacity of Three-Core Screened and S.L.-Type Cables. H. Waddicor. Vol. 76, p. 195.

Copper Losses in Large Cables at Power Frequencies (E.R.A. Report). Vol. 76, p. 299.

The Breakdown Mechanism of Impregnated Paper Cables. D. M. Robinson. Vol. 77, p. 90.

The Breakdown of Cables by Thermal Instability. L. G. Brazier. Vol. 77, p. 104.

CHAPTER 14.

TRANSMISSION OF POWER: OVERHEAD AND UNDERGROUND.

294. D.C. and A.C. Calculations.—In this chapter examples are first worked out by approximate formulæ which give, near enough for practical purposes, the results required; then the more ordinary, but less simple, methods of working are explained. Transmission of power by continuous current is practically confined to feeders, except where the Thury high-pressure, constant current, series system is employed (§ 317). The calculation for the size of the conductors for D.C. working is quite straightforward (*see* § 296), there being then no question of power factor or self-induction. With alternating current, on the other hand, complications are introduced by the fact that the pressure and current are seldom in phase; causes of low-power factor and typical values for the P.F. at each end of transmission lines are given in §§ 156, 157.

It must always be remembered that, although laboratory tests are capable of exact calculation, the size of conductors in transmission lines must be one that is manufactured, and, even so, a variation of 2 °/₀ is permissible in the resistance and weight. Again, the exact length of the conductors (which in hilly country is by no means the scaled length on a map), their spacing and temperature, and the actual maximum load to be carried, are all approximations when the calculations are made. So also is the power factor of the load, which is speculative until consumers' requirements are definitely known. On this account some of the calculations following are really carried unnecessarily far, although only slide-rule results. If numerical examples are not worked out fairly closely, they may not be clear.

295. General Formulæ for Copper.—The approximate sectional area of the conductor, in square inches, required for any transmission line, may be found by the following formula, *viz.* :—

$$\text{Area} = \frac{kW \times D \times n}{V^2 \times L \times P.F.}, \text{ where}$$

kW = kilowatts delivered at *end* of line;
D = route yards in length of line; *not* lead and return;
V = voltage at point of use;
L = percentage loss of V (as 5 or 10, not as a decimal);
n = a constant as follows :—

(i) D.C. or 1-phase, 2-wire system . . . . . $n = 4{\cdot}9$, say 5

(ii) D.C. or 1-phase, 3-wire system; V measured across outers; for outer conductors . . . . . $n = 4{\cdot}9$, say 5

Note.—The neutral is generally taken half the size of the outers (*see* Chapter 20).

(iii) D.C. or 1-phase, 3-wire system; V measured between outer and neutral; for outer conductors . . $n = 1{\cdot}25$

(iv) 3-phase mesh or star system; V measured between any 2-phase wires. . . . . $n = 2{\cdot}5$

(v) 3-phase star system; V measured between outer and neutral . . . . $n = 0{\cdot}833$

$P.F.$ = power factor of the load *at the receiving end* (§ 157).

Some engineers work out their lines from the generator end, assuming the power required there and the percentage loss of the power and pressure of the generator; in the case of small powers this can be done, but in a complicated scheme it is obviously preferable to work out the power required at the point of utilisation, and to decide on the pressure at the lamps and motors, and then to work backwards to the plant. Where transformers are involved the latter part of § 313 shows the advantage of this method. Having found the cross-sectional area of the conductor, a reference to the table of cables (§ 280) or solid wires (§ 307), as the case may be, will show which standard size is nearest to the required size, and this should be taken. Then the weight of the conductors in lb. per yd. will be 11·56 times the area in sq. ins., and this, multiplied by D, the length of the line, will give the total weight of each wire. There will of course be two such wires for D.C. and single-phase 2-wire supply, and three such for 3-phase 3-wire lines.

From the cross-sectional area the resistance can be found from the tables; the values given are for annealed copper in Table 40 (§ 280) and hard-drawn copper in Table 44 (§ 307). Alternatively the resistance of either annealed or hard-drawn wire per yard may be found from the expression in § 62, and this multiplied by the route length, D, will give the resistance, R, of each wire. The values are in each case true at 60° F., but in ordinary calculations it is not necessary to make corrections for temperature. The loss of power in watts in each wire will then be I^2R and the *total* loss will be $2I^2R$ for D.C. or single-phase and $3I^2R$ for 3-phase circuits. The loss of pressure will be IR in each wire, in phase with the current. In applying this formula to overhead lines there is not likely to be any question of the conductor being too small to carry the current, but in the case of underground cables a reference should be made to Tables 40 A—J, § 280, to see that the cable (according to its class and method of installation) is not overloaded. The current (I amperes), corresponding to W watts delivered, is given by—

For direct currents, I = Watts delivered / V.
For single-phase, I = Watts delivered / $V \times$ P.F.
For 3-phase, I = Watts delivered / $V \times 1{\cdot}73 \times$ P.F.

The Electricity Commissioners' Regulations concerning the minimum strength of overhead lines are summarised in § 324. Hard-drawn copper wire has a breaking stress of from 25 tons per sq. in. in large sizes to 29 tons in the smaller sizes used for overhead lines. In practice it is seldom advisable to use a smaller wire than No. 6 S.W.G.

296. Direct Current Transmission.—In order to compare transmission by A.C. with that by D.C., an identical example is worked out for each in this and the following paragraphs.

Assume that it is required to deliver 1 000 kW at a point 8 000 yds. from the generator, at a pressure V of 6 285 V at the delivery end, the loss in transmission being 5 °/₀ of the power delivered. Then the initial pressure will be 6 600 V and the power at the generator will be 1 050 kW. The current will be 1 000 × 1 000 / 6 285 (or 1 050 × 1 000 / 6 600) = 159 A, and the volts lost in the line 6 600 − 6 285 = 315 V, which is 5 °/₀ of 6 285 V. In D.C. practice these pressures would only be used with the Thury system (§ 317), but they have been assumed here because 6 600 V is a standard in A.C. work and it serves for comparison purposes.

A useful rule for D.C. circuits, involving fewer factors than the general formula in § 295, may be given here, *viz.*:—

$$\text{Area of conductor} = \frac{\text{Current} \times D \text{ in route-yards}}{20\,000 \times \text{Lost volts in line}}.$$

This gives the area = 159 × 8 000 / 20 000 × 315 = 0·202 sq. in. The constant in the denominator should, strictly speaking, be 20 800 for annealed copper and 20 380 for hard-drawn wire, at 60° F., but such accuracy is not necessary in commercial calculations. The preceding general formula will be found to give a similar result.

Working out the problem in the usual way, the *total* resistance of the line must be $= E / I = 315 / 159 = 1{\cdot}98\ \Omega$. As the *total* length is 16 000 yds., the resistance will be 0· 000 123 5 Ω per yd. or 0· 217 Ω per mile. From § 62 it then follows that the cross-sectional area for hard-drawn wire will be 0· 000 024 53 / 0· 000 123 5 = 0· 198 sq. ins., agreeing with the result obtained above. The weight of this conductor will (in round numbers) be 0·2 × 11·56 = 2·31 lbs. per yd. (§ 62), 18 500 lbs. for each wire and 37 000 lbs. for the line; say 16½ tons.

Direct current high-tension transmission by the Thury system is dealt with below in § 317, and extra high-tension transmission generally in § 315.

297. Single-phase A.C. Transmission by General Formula.—With the single-phase A.C. 2-wire system, the same *virtual* or R.M.S. pressure (§ 31), and unity P.F., the above calculations give practically accurate results at ordinary frequencies, neglecting the self-inductance of the line and assuming (as may safely be done in ordinary cases) that the conductor is not large enough to cause a loss through skin effect (§ 38).

With lower P.F. the current in the circuit is increased, and more copper is needed to keep the loss of power the same.

Thus, assume that with the same effective delivery pressure, *viz.* 6 285 V, it is again required to deliver 1 000 kW with a loss of 5 °/₀ of the power delivered, the length of the line being unchanged, but the P.F. to be 0·9 instead of unity. Then the current will be 1 000 × 1 000 / 6 285 × 0·9 = 177 A, *i.e.* the current in the D.C. example divided by the P.F.; and the 'apparent power' delivered to the circuit will be 6 285 × 177 / 1 000 = 1 110 kVA (§ 56). The area of the conductor will be 0· 221 sq. in., found either by dividing the D.C. value by the P.F. (*i.e.* 0· 198 / 0·9) or by the general formula in § 295. The weight will now be 0· 221 × 11·56 = 2·55 lbs. per yd. or 41 000 lbs. for the whole line, lead and return. This is 1·11 times the amount required for D.C. or for single-phase current at unity P.F. The factor 1·11 applies to any single-phase transmission at 0·9 P.F.

With a P.F. of 0·8 the calculations may be similarly worked out, and the results will be: Current 199 A; area of conductor 0· 248 sq. in.; total weight 46 000 lbs. or 1·25 times the weight required for D.C. or single-phase current at unity P.F.

The actual loss in the above cases would be a little more than 5 °/₀, owing to the self-induction of the line, but the result is near enough for all practical purposes.

298. Area and Weight of Conductor to give same Strain on Insulation.—It must be remembered that the *maximum* pressure corresponding to a virtual or R.M.S. pressure of 6 600 V is 6 600 × $\sqrt{2}$ or 9 400 V (§ 31); therefore the insulators in the case of A.C. overhead lines would have to be larger, or the insulation of the underground cable of higher quality, in an A.C. supply of the same virtual pressure as a corresponding D.C. supply.

To give the same strain on the insulation in the example of §§ 296, 297, which would actually be the fairer method of comparison, the virtual pressure with single-phase A.C. would have to be only 4 670 V at the generating end ($4\,670 \times \sqrt{2} = 6\,600$), so the current and size of conductor would be proportionately increased. The actual figures may be worked out from the formula given above, and they will show the D.C. system in its most favourable light (*see also* § 317).

On the other hand, if there is a fault in the insulation which can just be broken down by an alternating pressure of R.M.S. value E, it will generally be broken down by a D.C. pressure much lower than $E \times \sqrt{2}$, owing to the sustained stress produced by the D.C. pressure (the break-down voltage of insulation is lower with prolonged application of the pressure, § 72). This is an argument in favour of testing insulation by D.C. voltage (§ 1027 *et seq.*, Vol. 3), but the latter does not subject the insulation to sustained capacity current, hence the dielectric loss (§ 312) —that due to leakage through the ohmic resistance—is lower and the heating of the dielectric is correspondingly reduced. For these conflicting reasons, the ratio between D.C. and A.C. pressure strain is not a physical constant.

299. Single-phase Overhead Lines; Inductance, Reactance, Impedance.—Although the method employed in the example of § 297 is accurate enough for ordinary work, the effect of induction and of the current and pressure being out of phase may be followed up further. Assuming that overhead lines are being used, so that 'capacity' may be neglected (§ 304 *et seq.*), the apparent resistance or 'impedance' of conductors carrying alternating currents is made up of two components, *viz.* ohmic resistance, R, which is an absolute function of the material and temperature of the conductor; and reactance, S, which depends on the working conditions. These components may be considered as vectors at right angles, and the total impedance may be found graphically by completing the right-angled triangle (*see* Fig. 10 in § 44). Expressed algebraically:—

$$\text{Impedance} = \sqrt{(\text{resistance}^2 + \text{reactance}^2)}$$
$$= \sqrt{\{R^2 + (2\pi n)^2 \times (L\,/\,1\,000)^2\}},$$

where n is the frequency in complete periods per second and L is the self-inductance in millihenries (mH).

In the example in § 297, the pressure at the receiving end is 6 285 V and the energy component of the drop in the line will by hypothesis be 5 °/₀ of this or 315 V. (This is not the actual drop, as will be seen presently, for the reactance causes a wattless or inductance drop as well.) This equals IR (§ 295), and the current I (with a P.F. of 0·9) is 177 A. Therefore $R = 315 / 177 = 1{\cdot}77\ \Omega$ for the whole 16 000 yds. (Note here that the power lost $= I^2R = 177^2 \times 1{\cdot}77$ or 56 kW.) This resistance is equivalent to 0· 000 111 Ω per yd., giving a cross-sectional area of 0· 000 024 53 / 0· 000 111 or 0· 221 sq. in. as before (§ 297). The diameter of such a conductor, of solid copper, would be 0·53 in. In practice this would be an inconvenient size to handle and difficult to obtain, and two parallel wires each of half the equivalent cross-section would be used; but for the purpose of the example this may be waived.

Of the three factors shown under the square root sign in the above expression for impedance, the first, R, is calculated as shown in the preceding example. The product of the other two factors is the (reactance)^2, and of these $(2\pi n)^2$ at the standard frequency of 50 cycles is 98 800, or, in round numbers, 100 000. The self-inductance of the line, L, must be found from the formula * :—

$$\text{Millihenries per mile} = 0{\cdot}\,080\ 5 + 0{\cdot}\,741 \log [(d - r) / r],$$

where d = distance between centres of conductors, in ins.; and r = radius of conductor, in ins. In the case of overhead lines $(d - r)$ may be taken as d, since r is relatively small.

In the example considered, the diameter of the wire is 0·53 in., so the radius is 0·265 in., and the distance between conductors may here be taken as 12 ins. In practice the spacing would be at least 24 ins. if not 30 ins. (*see* § 327).

Then $L = 0{\cdot}\,080\ 5 + 0{\cdot}\,741 \log (12 / 0{\cdot}\,265) = 0{\cdot}\,080\ 5 + (0{\cdot}\,741 \times 1{\cdot}\,657) = 1{\cdot}\,306$ mH per ml. or 11·9 mH for 16 000 yds. From this value of L, we have that $(L / 1\ 000)^2 = (11{\cdot}9 / 1\ 000)^2 = 0{\cdot}\,000\ 141$. This gives the reactance,† S as $\sqrt{(98\ 800 \times 0{\cdot}\,000\ 141)} = 3{\cdot}72\ \Omega$, and the impedance $= \sqrt{(1{\cdot}77^2 + 3{\cdot}72^2)} = 4{\cdot}12\ \Omega$. The energy and induction components of the voltage may now be tabulated as follows, bearing in mind that with a power factor ($\cos \phi$) of 0·9, the wattless or induction factor (§ 157) will be $\sqrt{(1 - 0{\cdot}9^2)}$ or $0{\cdot}\,436 = \sin \phi$. Both these factors are used in Table 42, and this will make their significance clear.

It will be noticed that if the impedance drop of 730 V is added to the delivery pressure 6 285 V the result is 7 015 V, whereas the actual generator pressure is only 6 860 V; this is due to the change of phase caused by self-induction in the line, as the graphical construction in § 300 will demonstrate. Ordinarily the discrepancy may be neglected, at least in preliminary estimates. The P.F. at the generator end of the line is lower than at the

* An alternative form is: mH per mile $= 0{\cdot}160\ 9\ \{0{\cdot}5 + 4{\cdot}\,605 \log [(d - r) / r]\}$.

† Or ohmic value of self-inductance, which $= 2\pi \times$ periods $\times$ henries. The E.M.F. of self-inductance = reactance × current.

TABLE 42.—*Voltage Components and Power in Single-Phase Overhead Line.*

	Voltage.		Power.
	Energy Component.	Induction Component.	
At delivery end—			
Energy component 0·9 of 6 285 V	5 650	—	Power = 5 650 × 177 = 1 000 kW as presumed.
Induction component 0·436 of 6 285 V	—	2 740	
In line—			
Resistance loss IR = 177 × 1·77 V	315	—	Line loss of power = 315 × 177 = 56 kW.
Reactance loss IS = 177 × 3·72 V	—	660	
Total . .	5 965	3 400	Power generated 5 965 × 177 = 1 056 kW.

Impedance drop = $\sqrt{(315^2 + 660^2)}$ = 730 V.
Generator pressure = $\sqrt{(5\,965^2 + 3\,400^2)}$ = 6 860 V.

receiving end, owing to this self-induction. The power put into the line is seen from Table 42 to be 1 056 kW, and this equals $I \times E \times$ P.F. or 177 × 6 860 × P.F. Therefore the P.F. of the whole circuit is 0·87, not 0·9, when the line is taken into account The ratio between 6 860 and 7 015 V, *viz.* 0·97, gives the P.F. of the line alone. Assuming the power to be given by a single generator with an efficiency of 93 %, the power required to drive it would be (1 056 / 0·746) × (100 / 93) = 1 520 B.H.P. The output of the generator, however, would be expressed as 1 210 kVA, *i.e.* kW / P.F. or 1 056 / 0·87. It will be seen from § 313 that, if the pressure at the generating station is stepped up by means of transformers, both the P.F. of the line and the kVA output of the generator would be affected; the former being lowered, and the latter raised.

300. Graphical Construction for Single-phase Lines; Power Factor of Line.—In order to ascertain the conditions in the same line graphically the following construction (Fig. 52) may be followed; it is *not* to scale, and in working out results by this method a very large sheet of paper is required:—

Fix on any arbitrary scale for representing volts and amperes respectively. Draw vector *OE* to represent the voltage at the receiving end of the line, *viz.* 6 285 V in the example considered. Next draw the vector *OI* to represent the current in magnitude and direction, the angle ϕ between *OE* and *OI* being that for which the power factor of the load is the natural cosine; in this case the angle is 25¾° for P.F. 0·9. For the present neglect the dotted construction. The drop of pressure, 315 V, due to the ohmic resistance of the line (*i.e.* 177 × 1·77) will be in phase with the current, and is represented by *ER*, drawn parallel to *OI*, to the same volt scale as *OE*. The inductive drop is at right angles to the ohmic drop, and this, calculated as above, is represented by *RS* drawn at right angles to *ER* to the same scale; its value here is 177 × 3·72 or 660 V. Then *ES* gives the impedance drop, 177 × 4·12 or 730 V. Finally, *OS* gives the voltage at the sending end of the line, 6 860 V on the same scale. As the resultant or impedance drop *ES* is in this case (though not always) out of phase with the receiving voltage, it is not exactly equal to the difference (6 860 − 6 285), but it may safely be taken so in ordinary work. The dotted construction in this figure is explained later (§ 305) in connection with capacity.

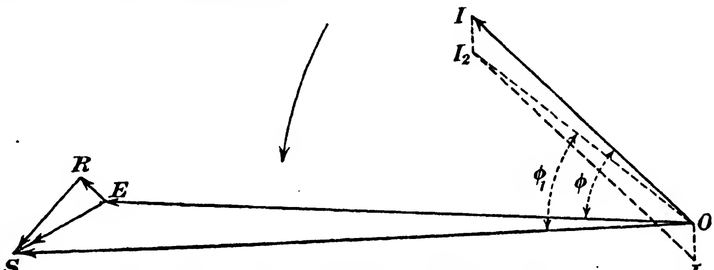

FIG. 52.—Graphical construction for single-phase line.

301. Three-phase Transmission by General Formula.

—In order to facilitate comparison between the several systems, the same problem as before (§§ 296, 297) is considered, but with 3-phase supply. It is assumed that 1 000 kW is to be delivered at the end of a 3-phase, 3-wire line 8 000 yds. long, the delivery pressure being 6 285 V (virtual), and the loss in transmission being 5 °/ₒ of the power delivered.

Using the general formula in § 295, the area of each conductor in sq. ins. will be: (1 000 × 8 000 × 2·5) / 6 285 × 6 285 × 5 × P.F. = 0·101 / P.F. This gives the following values for the area and weight of the conductors with various power factors:—

	P.F. Unity.	P.F. 0·9.	P.F. 0·8.
Area of each conductor, sq. in.	0·101	0·112	0·126
Weight, lbs. per yard = area × 11·56	1·167	1·295	1·455
Total weight 24 000 yds. . .	28 000	31 000	35 000
Percentage of total weight for continuous current (§ 296) . .	75 °/ₒ	83°/ₒ	94°/ₒ
Current in each conductor, amperes	92	102	115

The current = Watts delivered / (V × $\sqrt{3}$ × P.F.) = (1 000 × 1 000) / (6 285 × 1·73 × P.F.) = 92 / P.F. As the line loss is 5 %, 1 050 kW will be put into it and the initial pressure will be (1 050 × 1 000) / ($\sqrt{3}$ × current × P.F.), or about 6 600 V in each case. For rough working this is all the information required, but in the next paragraph the matter is considered in greater detail on different lines, as in the case of single-phase transmission.

It may be noted that, as pointed out in § 298, a larger area and weight of conductor would be required to subject the insulation only to the same *maximum* pressure as in the D.C. example; this would give the D.C. system an advantage, and the Thury series system utilises it (*see* § 317).

302. Three-phase Transmission Lines; Inductance, Reactance, and Impedance.—The pressure between any two conductors in the preceding example is 6 285 V at the receiving end, and the pressure between any one wire and the neutral point will therefore be 6 285 / $\sqrt{3}$ or 3 630 V. We shall consider one of the three conductors in the first place. Each conductor will deliver one-third of the total power or 333·3 kW.

Taking as example the case where the power factor is 0·9, the *apparent* energy delivered by each branch will be 333·3 / 0·9 = 370 kVA, and the current in the branch will be 370 × 1 000 / 3 630 = 102 A, as found by another method in the preceding paragraph. Now, as the loss of power is to be 5 % of that delivered, the 'energy component' of the drop in pressure in each branch, or $I \times R$, will also be 5 % of the pressure to neutral; 5 % of 3 630 is 181 V. (The line current is in phase with this component of the total drop of pressure in the wire, so the loss of energy in each conductor will be $I \times E$ = 102 × 181 or 18·5 kW, showing the actual energy loss in the three branches to be 18·5 × 3 = 55·5 kW.) Now the ohmic resistance of each branch must be (Volts lost) / Current = 181 / 102 = 1·78 Ω for the 8 000 yds. of wire. (Note again that the loss in the branch is also equal to I^2R = 102² × 1·78 or 18·5 kW as before.) We then have the resistance per yd. = 1·78 / 8 000 = 0· 000 222 Ω. Area of conductor = 0· 000 024 53 / 0· 000 222 = 0· 111 sq. in. (about 3 / 0 S.W.G.). Weight = 1·29 lb. per yd. = 10 300 lbs. per branch or 30 900 lbs. for the line, *i.e.* 83 % of the amount required for D.C.

We may now ascertain the inductance and reactance of the line, with 12-in. spacing between wires as before, noting again that the actual spacing would be greater (§ 327). The diameter of the wire is 0· 376 in. or radius 0· 188 in. Self-induction = 0· 080 5 + 0· 741 log (12 / 0· 188) = 1·42 mH per ml. or 6·45 mH for 8 000 yds. (§ 299). Then $(L / 1\,000)^2$ = (6·45 / 1 000)² = 0· 000 041 6, so that—

Reactance at 50 cycles = $\sqrt{(98\,800 \times 0{\cdot}\,000\,041\,6)}$ = 2·02 Ω for each wire,
and Impedance = $\sqrt{(1{\cdot}78^2 + 2{\cdot}02^2)} = \sqrt{7{\cdot}16}$ = 2·69 Ω.

Now, although there is actually but one current in the wire and one pressure between any two points, it makes matters clearer if, as in the case of single-phase, the pressure is resolved into two components at right angles, an energy component and a 'wattless' induction component. The power factor cos ϕ being 0·9, the 'induction factor' sin ϕ (§ 157) will be $\sqrt{(1 - 0{\cdot}9^2)}$ or 0·436. The various voltages, etc., in one wire will be as shown in Table 43.

TABLE 43.—*Voltage Components and Power in 3-Phase Overhead Line.*

	Voltage, between Phase Conductor and Neutral.		Power.
	Energy Component.	Induction Component.	
At delivery end— Energy component 0·9 of 3 630 V . . .	3 268	—	Power delivered 3 268 × 102 = 333·3 kW per branch or 1 000 kW altogether.
Induction component 0·436 of 3 630 V . . .	—	1 583	
In line— Resistance or energy loss IR = 102 × 1·78 V .	181	—	Power lost 181 × 102 = 18·5 kW per branch or 55·5 kW altogether.
Reactance loss 102 × 2·02 V	—	208	
Total	3 449	1 791	Power generated = 3 449 × 102 = 352 kW per branch or 1 056 kW altogether.

Impedance drop = $\sqrt{(181^2 + 208^2)}$ = 276 V; which also = (2·69 × 102) V.
Generator pressure = $\sqrt{(3\,449^2 + 1\,791^2)}$ = 3 885 V to neutral; and 3 885 × $\sqrt{3}$ = 6 730 V between phase wires.

The power required to drive a single generator to give the output required, assuming an efficiency of 93 %, would here be (1 056 / 0·746) × (100 / 93) = 1 530 B.H.P. The output of the generator would be specified as 1 200 kVA, *i.e.* 1 056 kW / 0·88, the denominator being the P.F. shown in the next paragraph.

303. Graphical Solution for 3-phase Lines; Power Factor of Line.—Here, again, the effect of self-induction in the line is to alter the power factor, or the phase relation of current and pressure, as shown in the graphical solution in § 300. The total power at any point in a 3-phase line is $I \times E \times \sqrt{3} \times$ P.F. and is in this case 1 056 kW at the generator end of the line; at this point, I = 102 A; and E = 6 730 V, therefore the P.F. is 0·88 at the generator end of the line, compared with 0·9 at the load end.

Graphically, taking Fig. 52 again, *OE* will be 3 630 V and the angle *OI* will be unchanged, *viz.* $23\frac{3}{4}°$. The vector *ER* will be 181 V and *RS* will be 208 V, as shown in Table 43; *ES*, the impedance drop, will be found to be 276 V (*vide* Table 43), and *OS* will scale 3 885 V. If the impedance drop 276 V is added arithmetically to the initial pressure 3 630 V, the result is 3 906 V, not 3 885 V as obtained by vectorial addition. The difference is due to the slight alteration of phase in the line itself, owing to its self-induction, and may be neglected.

The graphical method of dealing with 3-phase problems illustrated in Fig. 53 is due to B. Welbourn, and the method of drawing and using the diagram is as follows:—

The equilateral triangle *BHJ* is drawn to scale, each side representing the pressure between phases at the loaded end. Then *AB*, *AH*, *AJ* represent the pressure to neutral (= line pressure / $\sqrt{3}$). Draw *AC*, representing to scale the

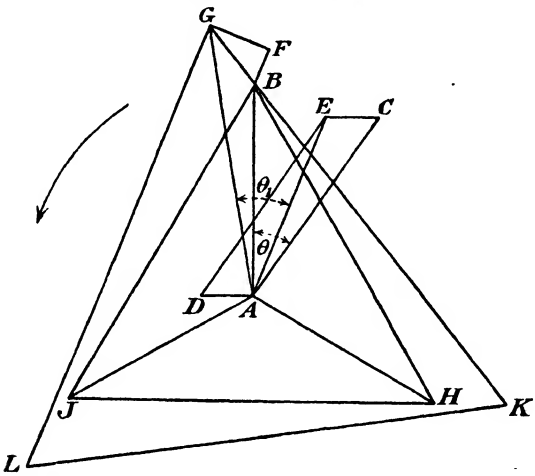

FIG. 53.—Graphical construction for three-phase line.

full-load current, lagging behind *AB* by the angle ϕ. Draw *AD* at right angles to *AB* to represent the capacity current to the same scale as *AC*. Compound *AC* and *AD* to find the resultant current, *AE*, in the line. The resistance drop in one wire is in phase with the current *AE*, and is given by *AE* × *R*; its value is represented, to the same scale of volts as before, by *BF* drawn parallel to *AE*. Next draw *FG* to the same scale and at right angles to *BF*, to represent the E.M.F. of self-induction or reactance drop in one wire. Join *AG*, which gives the pressure to neutral at the generating end; this multiplied by $\sqrt{3}$ gives the pressure between phases at that point. The sides of the equilateral triangle *GLK*, completed from the centre *A* and vertex *G*, also give this. Cos ϕ_1 is the power factor at the generating end, and the kW delivered to the line is given by the product (pressure *GL* × $\sqrt{3}$ × current *EA* × cos ϕ_1).

304. Capacity and Capacity Reactance.—Capacity, *i.e.* electrostatic capacity, has exactly the opposite effect to inductance, that is to say, it causes the current to *lead on* the impressed

E.M.F. instead of to *lag behind* it. Capacity in a circuit implies that the conductors or apparatus act like a condenser, which of course will not pass a continuous current. With an alternating impressed E.M.F., energy is stored up in the condenser in the form of electrostatic stress, as the E.M.F. rises, but when the wave of E.M.F. dies away this stored energy returns to the circuit, as a current leading 90° out of phase; this is called the capacity current or charging current (§ 46). If both inductance and capacity are present they tend to neutralise one another.

In the foregoing examples the existence of capacity has been ignored; in short overhead lines its effect is usually of no practical importance, but in long lines and in all underground cables it must be taken into account.

The deliberate introduction of variable capacity into transmission systems, in order to balance the inductive effect of motors, etc., and improve the P.F., is discussed fully in §§ 159-62. As there explained, artificial improvement of the P.F. of a transmission system is generally a sound financial proposition, since the cost of the necessary equipment is much less than that of the generating and distributing plant otherwise rendered idle by wattless current.

Of the three factors, resistance, reactance, and 'condensance' or capacity reactance, all expressed in ohms, the two former may be considered in *series* in a line or cable, while the latter, due to capacity, is in *parallel* with the other two, as already stated in § 46. It will be seen in the examples following that, although the charging current due to capacity is often important, the effect of capacity on the total impedance of an overhead line is negligible. Capacity is expressed in microfarads (μF) or millionths of the true unit, *viz.* the farad.

305. Capacity and Charging Current of Overhead Lines, Single-phase.—The capacity of two overhead wires side by side, and relatively far from the ground, is $[0{\cdot}019\,4 / \log (D / r)]$ μF per ml., where D is the distance between the centres of the wires, in ins.; and r is the radius of each wire, in ins.; the dielectric is air, and the actual capacity varies somewhat according to atmospheric conditions.

In the single-phase line of § 299, D is 12 ins. and r is 0·265 in., so $\log (D / r) = 1{\cdot}66$. Then capacity $C = 0{\cdot}019\,4 / 1{\cdot}66$ or 0·011 7 μF per ml. run of line or 0·053 μF for the whole length of 8 000 yds.

The capacity current or charging current $I_c = 2\pi \times$ frequency $\times E \times C / 10^6$ or, at the standard frequency of 50 periods, $I_c = 0{\cdot}000\ 314\ EC$, where E is the pressure between wires at the generator end and C is in microfarads.

In the example chosen, $I_c = 0{\cdot}000\ 314 \times 6\ 860 \times 0{\cdot}053 = 0{\cdot}114$ A for the whole line or 0·025 A per ml. run. This means that in order to charge the line to full pressure, *when no power is being used,* the generator must be giving $(I \times E)$ apparent watts or $6\ 860 \times 0{\cdot}114 = 785$ apparent watts. In this particular instance capacity and its consequences may be neglected, but it is worked out to show the method.

Where the charging current is of sufficient importance, as in cables, it has to be considered in connection with the main current; the main current is lagging behind the impressed E.M.F. by an angle depending on the power factor, while the charging current is leading the E.M.F. by 90°. To obtain the magnitude and phase relation of the actual or resultant current, vectorial addition is the simplest method.

This is shown in dotted lines in Fig. 52. There OS and OE are the pressures at the transmitting and receiving ends of the line respectively, and OI is the lagging energy current. The charging current OI_c is drawn to the same scale, leading, at right angles to OE. (Actually OS should be used, but OE and OS are always so nearly parallel in a scale drawing that no error will result.) Then by compounding OI and OI_c the resultant current OI_2 is found. In the subsequent construction ER should then be parallel to OI_2 instead of OI. The angle ϕ_1 will give the P.F. at the generating end.

The capacity reactance or condensance is $(1 / 2\pi n \times C)\ \Omega$, where C is expressed in farads. In this case, the capacity reactance $= 1 / (2\pi \times 50 \times 0{\cdot}053 \times 10^{-6}) = 1 / 0{\cdot}000\ 016\ 6 = 60\ 000\ \Omega$. It may also be expressed as $E / I_c = 6\ 860 / 0{\cdot}114$; or as (Apparent watts) / (Charging current)^2, *i.e.* $785 / (0{\cdot}114)^2$. The same result is obtained in each case. These relations in fact are merely an extension of Ohm's law applied to alternating capacity currents. It is obvious that this apparent resistance, in *parallel* with the impedance as determined in § 299 (*viz.* 4·12 Ω), will not affect its value appreciably.

306. Capacity and Charging Current of 3-phase Line.—In 3-phase lines the Y-capacity of the line is the same as that of one wire to the neutral point, which is $[0{\cdot}038\ 8 / \log (D / r)]\ \mu F$ per ml.

Thus, in the case already considered in § 302, D is 12 ins. and r is 0·188 in. Log $(12 / 0{\cdot}188) = 1{\cdot}81$, so the capacity is $0{\cdot}038\ 8 / 1{\cdot}81$ or $0{\cdot}021\ 4\mu F$ per ml., *i.e.* $0{\cdot}097\mu F$ for the whole 8 000 yds.

The capacity current or charging current in each conductor at 50 cycles will now be $[0{\cdot}000\ 314 \times (E / \sqrt{3}) \times$ capacity in $\mu F]$, E being the line pressure and $(E / \sqrt{3})$ the volts to neutral at the generating end. Then $I = 0{\cdot}000\ 314 \times 6\ 730 \times 0{\cdot}097 = 0{\cdot}118$ A, which again is negligible, representing only $(0{\cdot}118 \times 3\ 885 \times 1{\cdot}73)$ or 1 380 apparent watts from the generator. The graphical solution in

§ 300 would be modified in the manner explained in the preceding paragraph, if it were necessary. The capacity reactance here is 1 / 0·000 030 4 or 6 730 / 0·118 or 790 / ($0·118^2 \times 1·73$) = 33 000 Ω, and here again it is in *parallel* with the impedance of 2·69 Ω (§ 302), and is of negligible effect.

307. Constants of Hard-drawn Copper Wire.—The capacity of a line varies with the size of the wires, and the charging current with the frequency of the supply; tables will be found in many books giving the values for American wire gauges and 40, 60, or 100 cycles. Table 44 gives the various constants of hard-drawn copper wire in S.W.G. and British standard units; *i.e.* the frequency in cols. 10 *et seq.* is 50 cycles.

NOTES ON TABLE 44.

Columns 1-4 require no explanation.

Column 5 is based on an ultimate strength of 25 tons per sq. in. except in the case of No. 10 wire (27½ tons).

Column 6 is dealt with in § 327, on the dip and stress of overhead wires.

Columns 7 and 8 give the resistance per yd. and mile of wire respectively based on 2 °/ₒ higher resistance than annealed copper (*see* Table 40, § 280). The increased resistance to A.C., due to skin effect, is negligible at 50 cycles with all these sizes (§ 38), being much less than the permissible variation of 2 °/ₒ. All these columns are therefore applicable both to D.C. and A.C. transmission.

Columns 9 et seq. relate to A.C. transmission only. Col. 9 gives the nominal spacing between centres of conductors (§ 327), which of course necessarily varies considerably in a completed line; this factor enters into the calculation of all the subsequent constants, and interpolation will, if necessary, give intermediate values.

Column 10 gives the self-induction, L, of a line at each spacing, in millihenries (mH), *i.e.* (Henries / 1 000), per ml. of wire. It is based on the formula already given in § 299, neglecting the $(-r)$ in the last factor, *viz.*,

$$L = [0·080\,5 + 0·741 \log (D / r)] \text{ mH per ml.}$$

Therefore in calculating out a single-phase line either the value of L must be multiplied by the total length of wire (lead and return), as in the example in § 299, or by 2 to give the inductance of 1 ml. run of the whole line. In 3-phase calculations (*vide* example in § 302) a single wire is taken with respect to the neutral point, and the value of L in the table must be multiplied by the *route length* of the line in miles.

Column 11 gives the reactance, in ohms per ml. of wire, at 50 cycles, *i.e.* $2\pi nL$, or $314L$, where L is in henries or (mH / 1 000) (*see* examples in § 299 (single-phase) and § 302 (3-phase)). The value in cols. 10 and 11 differ so little that they are only given for alternate gauges; interpolation between the two neighbouring values *for the same spacing* will give the figures if necessary, but, as the impedance is given all through, these columns will not be required often.

For any other frequency the figures must be multiplied by (Actual frequency / 50). Thus for No. 3 S.W.G. and 18-in. spacing, the reactance per ml. at 60 cycles will be 0·628 Ω per ml.; at 125 cycles 1·31 Ω.

Column 12 gives the total impedance at 50 cycles in ohms per ml. of wire, *i.e.* $\sqrt{\{\text{resistance}^2\ (\textit{col. 8}) + \text{reactance}^2\ (\textit{col. 11})\}}$.

TABLE 44.—*Constants of Hard-drawn Copper Wire* (50 *Cycles in Cols.* 10 *to* 16).

FOR EXPLANATORY NOTES *see* pp. 555 and 558.

Size of Wire. S.W.G.	Dia. of Wire. In.	Area of Wire. Sq. In.	Weight of Wire. Lbs. per Ml.	Tensile Strength. Lbs.	Permissible Tension. Lbs. (For Factor of Safety = 3.)	Resistance, at 60° F. Ohms per Yd.	Resistance, at 60° F. Ohms per Ml.	Spacing Between Centres. Ins.	Inductance. Millihenries per Ml.	Reactance. Ohms per Ml. of Wire.	Impedance. Ohms per Ml. of Wire.	Single-Phase. Capacity. Microfarads per Ml. Run.	Single-Phase. Charging Current, at 10 000 V Between Wires. Amperes per Ml. Run.	Three-Phase. Capacity, 1 Wire to Neutral (= Y-Capacity of Whole Line). Microfarads per Ml. Run.	Three-Phase. Charging Current, at 10 000 V Between Wires (= 5 775 V to Neutral). Amperes per Ml. Run.
1.	*2.*	*3.*	*4.*	*5.*	*6.*	*7.*	*8.*	*9.*	*10.*	*11.*	*12.*	*13.*	*14.*	*15.*	*16.*
7/0	0·500	0·196	3 995	11 000	3 670	0·000 125 0	0·220	12	1·32	0·415	0·470	0·011 5	0·036 1	0·023 0	0·041 7
								18	1·46	0·459	0·509	0·010 5	0·033 0	0·021 0	0·038 0
								24	1·55	0·487	0·534	0·009 7	0·030 5	0·019 5	0·035 2
								36	1·68	0·528	0·572	0·009 0	0·028 2	0·018 0	0·032 6
6/0	0·464	0·169	3 441	9 500	3 170	0·000 144 9	0·255	12	—	—	0·494	—	—	0·022 6	0·040 9
								18	—	—	0·530	—	—	0·020 5	0·037 2
								24	—	—	0·555	—	—	0·019 3	0·034 9
								36	—	—	0·593	—	—	0·017 7	0·032 0
5/0	0·432	0·147	2 983	8 200	2 740	0·000 167 1	0·294	12	1·37	0·431	0·522	0·011 1	0·034 8	0·022 2	0·040 2
								18	1·50	0·471	0·555	0·010 1	0·031 7	0·020 2	0·036 6
								24	1·59	0·499	0·579	0·009 5	0·029 8	0·019 0	0·034 4
								36	1·73	0·544	0·618	0·008 7	0·027 3	0·017 5	0·031 6
4/0	0·400	0·126	2 558	7 000	2 340	0·000 194 9	0·343	12	—	—	0·558	—	—	0·021 8	0·039 5
								18	—	—	0·590	—	—	0·019 7	0·035 6
								24	—	—	0·612	—	—	0·018 7	0·033 8
								36	—	—	0·650	—	—	0·017 2	0·031 1

TABLE 44 (*continued*).

1.	2.		4.	5.	6.	7.	8.	9.	10.	11.	12.	13.	14.	15.	16.
3 / 0	0· 372	0· 109	2 212	6 100	2 030	0· 000 2256	0· 397	12	1·42	0· 446	0· 598	0· 010 7	0· 033 6	0· 021 4	0· 038 8
								18	1·55	0· 487	0· 628	0· 009 7	0· 030 4	0· 019 5	0· 035 2
								24	1·64	0· 515	0· 650	0· 009 2	0· 028 8	0· 018 4	0· 033 3
								36	1·78	0· 559	0· 684	0· 008 5	0· 026 7	0· 017 0	0· 030 8
2 / 0	0· 348	0· 095	1 935	5 300	1 760	0· 000 258 0	0· 454	12	—	—	0· 640	—	—	0· 021 1	0· 038 2
								18	—	—	0· 670	—	—	0· 019 3	0· 034 9
								24	—	—	0· 694	—	—	0· 018 1	0· 032 8
								36	—	—	0· 726	—	—	0· 016 8	0· 030 4
1 / 0	0· 324	0· 082	1 678	4 600	1 540	0· 000 297 7	0· 524	12	1·46	0· 459	0· 698	0· 010 3	0· 032 4	0· 020 7	0· 037 5
								18	1·59	0· 499	0· 724	0· 009 5	0· 029 8	0· 019 0	0· 043 4
								24	1·69	0· 532	0· 747	0· 008 9	0· 028 0	0· 017 9	0· 032 4
								36	1·82	0· 572	0· 776	0· 008 2	0· 025 8	0· 016 5	0· 029 8
1	0· 300	0· 071	1 439	4 000	1 340	0· 000 347 1	0· 611	12	—	—	0· 770	—	—	0· 020 4	0· 037 0
								18	—	—	0· 794	—	—	0· 018 7	0· 033 8
								24	—	—	0· 814	—	—	0· 017 6	0· 031 8
								36	—	—	0· 840	—	—	0· 016 3	0· 029 1
2	0· 276	0· 060	1 218	3 350	1 120	0· 000 410 2	0. 722	12	1·52	0· 478	0· 866	0· 010 0	0· 031 4	0· 020 0	0· 036 2
								18	1·64	0· 515	0· 888	0· 009 2	0· 028 8	0· 018 4	0· 033 3
								24	1·74	0· 547	0· 906	0· 008 6	0· 027 0	0· 017 3	0· 031 2
								36	1·87	0· 587	0· 931	0· 008 0	0· 025 2	0· 016 1	0· 029 1
3	0· 252	0· 050	1 015	2 800	935	0· 000 492 0	0· 866	12	—	—	0· 994	—	—	0· 019 6	0· 035 5
								18	—	—	1· 012	—	—	0· 018 0	0· 032 6
								24	—	—	1· 030	—	—	0· 017 0	0· 030 8
								36	—	—	1· 052	—	—	0· 015 8	0· 028 6
4	0· 232	0· 042	860	2 350	782	0· 000 580 1	1· 021	12	1·57	0· 494	1· 134	0· 009 6	0· 030 1	0· 019 2	0· 034 8
								18	1·70	0· 534	1· 152	0· 008 8	0· 027 6	0· 017 7	0· 032 0
								24	1·79	0· 564	1· 166	0· 008 4	0· 026 4	0· 016 8	0· 030 4
								36	1·92	0· 605	1· 187	0· 007 8	0· 024 5	0· 015 6	0· 028 2
5	0· 212	0· 035	718	1 950	650	0· 000 694 8	1· 223	12	—	—	1· 322	—	—	0· 018 9	0· 034 2
								18	—	—	1· 338	—	—	0· 017 4	0· 031 4
								24	—	—	1· 352	—	—	0· 016 5	0· 029 8
								36	—	—	1· 368	—	—	0· 015 3	0· 027 6
6	0· 192	0· 029	589	1 620	540	0· 000 847 0	1· 491	12	1·63	0· 512	1· 576	0· 009 2	0· 028 9	0· 018 5	0· 033 4
								18	1·76	0· 554	1· 591	0· 008 5	0· 026 7	0· 017 1	0· 030 9
								24	1·86	0· 584	1· 602	0· 008 0	0· 025 2	0· 016 1	0· 029 1
								36	1·98	0· 622	1· 615	0· 007 5	0· 023 6	0· 015 1	0· 027 2
10	0· 128	0·012 9	262	800	267	0· 001 906 0	3· 354	12	1·76	0· 553	3· 400	0· 008 5	0· 027 7	0· 017 1	0· 031 0
								18	1·89	0· 594	3· 410	0· 007 9	0· 024 8	0· 015 8	0· 028 6
								24	1·98	0· 622	3· 415	0· 007 5	0· 023 6	0· 015 1	0· 027 2
								36	2·12	0· 656	3· 425	0· 007 0	0· 022 0	0· 014 1	0· 025 4

Note.—The old B.O.T. Regulations required a factor of safety of 5, as in our fourth edition. This has now been reduced by the Electricity Commissioners to 3, as in the present table; which, under the worst conditions, is sufficient in practice. The new Regulations are referred to in § 324.

Thus for a single-phase line the figure must be multiplied by the length of wire in miles (lead + return), while for 3-phase the impedance of one wire is found from the table by multiplying by the route length. For other frequencies the value can be worked out from the formula by obtaining the reactance in the manner explained above.

Columns 13 and 14 relate to single-phase transmission; the former gives the capacity per ml. run of line, so when multiplied by the route length will give the capacity of the whole line. The formula and an example are given in § 305.

Column 14 gives the charging current per ml. run of line, at 50 cycles and 10 000 V between wires; *see* example in § 305. For any other frequency or pressure the figures should be multiplied by (Frequency / 50) or (Pressure / 10 000) as the case may be. Thus the charging current of a line 110 mls. long, consisting of two No. 3 S.W.G. wires spaced 18 ins. apart, at 60 or 125 cycles respectively and 6 600 V, will be $0{\cdot}028\,2 \times 110 \times [60 \text{ (or } 125) / 50] \times (6\,600 / 10\,000) = 2{\cdot}46$ or 5·13 A, as the case may be.

Columns 15 and 16 refer to 3-phase lines. Col. 15 gives the capacity per ml. of 1 wire to the neutral point, which is also the Y-capacity of the whole line per ml. run. Col. 16 gives the charging current per ml. run of line at 50 cycles and 10 000 V between wires, or 5 775 V to neutral. It is the charging current of a corresponding single-phase line $\times 2 / \sqrt{3}$. An example is given in § 306. For other frequencies and pressures multiply by (Frequency / 50) and by (Line pressure / 10 000) or (Pressure to neutral / 5 775).

308. Constants of Hard-drawn Aluminium Wire.—If required, a table corresponding to Table 44, but for hard-drawn aluminium wires, can be prepared by aid of the following notes:—

MODIFICATIONS REQUIRED TO ADAPT TABLE 44 FOR ALUMINIUM.

Columns 1-3 are applicable regardless of the material.

Column 4. The figures in this column must be multiplied by 0·305 to give the weight per ml. of aluminium wire, *e.g.* the weight of No. 1 S.W.G. wire is about $1\,439 \times 0{\cdot}305 = 439$ lbs. per ml.

Columns 5 and 6. The ultimate tensile strength and the permissible tension for aluminium wires are about 0·53 the values given for copper wires of the same gauge size (*not* of the same conductivity).

Columns 7 and 8. The resistance values for hard-drawn aluminium are about 1·63 times those for copper wires of the same gauge size.

Column 9. In any particular line the spacing between aluminium conductors is generally greater than it would be using copper wires; this, however, does not affect the use of the table.

Columns 10 and 11. The values given for copper apply also to aluminium (or any other non-magnetic material) for the same size and spacing.

Column 12. The values for aluminium will be calculated from $\sqrt{\{\text{resistance}^2\ (\textit{new col. 8}) + \text{reactance}^2\ (\textit{col. 11. Table 44})\}}$.

Columns 13-16. The values for copper apply also to aluminium for the same size and spacing of wires.

For data concerning the mechanical constants of aluminium wire *see* § 331.

309. Constants of Steel Wires.—Steel conductors offer economic advantage in the case of short or medium-length lines

TABLE 45.—*Constants of Steel Conductors.*

Size and Description of Conductor	Cross-section Circ. Mils.* (sq. ins. in brackets).	Temperature Coefficient of Resistance per 1° C., at 20° C.	Test Frequency, Cycles / Sec.	Test Current, Amperes.	Steady Temperature Rise Above Air at 20° C., in °C.	True (D.C.) Resistance† (Single Conductor) Ohms / Mile. (A).	Effective (A.C.) Resistance† (Single Conductor) Ohms / Mile. (B).	Skin Effect Ratio (= B / A).	Internal Inductance (Single Conductor) Millihenries per Mile.	Internal Inductance Ratio.‡
⅝" High-strength strand	99 960 (0· 078 5 sq. in.)	0· 003 38		5	0·2	5·84	5·87	1· 006	1·35	13·1
				15	1·8	5·87	5·94	1· 011	1·48	14·3
				25	4·6	5·93	6·03	1· 016	1·61	15·6
			25	5	0·2	5·82	5·83	1· 002	1·36	13·2
				15	1·6	5·85	5·86	1· 001	1·49	14·5
				25	—	5·96	5·99	1· 005	1·65	15·9
½" Siemens-Martin strand	177 600 (0· 139 4 sq. in.)	0· 003 33	60	5	0·2	3·36	3·40	1· 012	1·42	13·8
				15	1·2	3·38	3·43	1· 015	1·52	14·7
				25	2·8	3·40	3·47	1· 021	1·63	15·8
			25	5	0·2	3·36	3·37	1· 004	1·47	14·2
				15	1·2	3·37	3·39	1· 006	1·55	15·0
				25	3·0	3·39	3·41	1· 007	1·66	16·0
⅜" Siemens-Martin strand	99 960 (0· 078 5 sq. in.)	0· 003 48	60	5	0·4	5·40	5·44	1· 008	1·40	13·6
				15	2·4	5·44	5·49	1· 011	1·58	15·3
				25	6·6	5·52	5·62	1· 017	1·73	16·7
			25	5	0·4	5·41	5·42	1· 002	1·40	13·5
				15	3·0	5·45	5·47	1· 004	1·58	15·3
				25	6·4	5·53	5·57	1· 006	1·73	16·8
¼" Siemens-Martin strand	46 900 (0· 036 8 sq. in.)	0· 003 09	60	5	0·6	12·22	12·25	1· 002	1·46	14·1
				15	5·4	12·46	12·54	1· 006	1·65	15·9
				25	17·8	12·91	13·04	1· 009	1·85	17·9
			25	5	0·6	12·17	12·20	1· 001	1·47	14·2
				15	7·4	12·49	12·51	1· 002	1·65	15·9
				25	18·2	12·94	13·02	1· 006	1·88	18·2
⅜" Standard strand (relatively soft)	109 400 (0· 085 9 sq. in.)	0· 005 70	60	5	0·2	3·62	3·91	1· 080	3·24	31·4
				15	2·0	3·62	4·37	1· 207	4·69	45·4
				25	5·0	3·73	5·63	1· 512	6·33	61·3
			25	5	0·2	3·60	3·73	1· 036	3·90	37·7
				15	2·0	3·64	4·07	1· 117	6·19	59·9
				25	5·6	3·70	4·62	1· 250	8·54	82·7

* 1 circ. mil. = 0· 785 4 sq. mil. ; 10 000 circ. mils. = 0· 007 85 sq. in. See footnote to § 292.
† At the steady temperature attained by the wire when carrying the stated current, in air at 20° C.
‡ The internal inductance ratio = (internal inductance) / (internal inductance assuming unit permeability).

carrying relatively small amounts of energy at relatively high voltage, so that the pressure drop and power loss in the line are not above the permissible limit. Steel conductors can also be used in short or medium-length lines in which the minimum size of conductor is fixed by considerations of corona loss, and not by the effective resistance of the line. On long spans across rivers, valleys, etc., it may be necessary to use steel to secure sufficient mechanical strength in the line (§ 331). The harder grades of steel have higher tensile strength and higher ohmic resistance than softer steel; on the other hand, their magnetic permeability is lower, hence the skin effect (§ 38) and internal inductance are less than in the softer steel. The effective resistance to A.C. is lower at 25 than at 50 cycles / sec. (§ 135) and is generally lower in soft than in hard steel at all currents up to 25 A in a $\frac{3}{8}$ in. stranded conductor. The data in Table 45 are from tests made to the order of the Indiana Steel and Wire Co. (*see also El. Wld.*, Vol. 80, p. 872.)

310. Insulated Cables; Inductance, Reactance, and Impedance.—The coefficient of self-induction, L, of insulated cables is found by the same formula as is given (§ 299) for overhead lines, *viz.* $L = \{0{\cdot}080\,5 + 0{\cdot}741 \log [(d - r) / r]\}$mH per ml., and the reactance and impedance are determined in the same way as before. Here r is of the same order of magnitude as the distance between wires, d, and becomes important; though the value of d increases with the pressure, owing to the greater thickness of dielectric required. For cables with conductors of 0·03 sq. in. (equivalent roughly to No. 6 S.W.G. solid or 7 / 15 stranded) the impedance may be taken as equal to the resistance, and this holds good for all smaller sizes. For a cable of 0·25 sq. in. the ohmic resistance may be multiplied by the following factors to give the impedance at 50 cycles, *viz.:* 660 V cable, 1·18; 2 200 V, 1·20; 3 300 V, 1·21; 6 600 V, 1·23; 11 000 V, 1·27. It is better to obtain actual figures from the manufacturers in all cases where the impedance must be taken into account.

311. Paper-insulated Cables; Capacity and Charging Current.—In the case of overhead wires the dielectric was air; in cables it may be bitumen, india-rubber, paper, etc. (§ 287), and the capacity varies directly as the permittivity or specific capacity of the material (Table 7, p. 78). The capacity of *concentric* paper-insulated cables is about $[0{\cdot}1\text{-}0{\cdot}12 / \log (D / d)]\ \mu F$ per ml., where D is the diameter over the insulation surrounding the inner conductor and d is the diameter of inner conductor. The charging current is found as for 2-wire aerial lines (§ 305). For 3-phase, 3-core (*shaped-conductor*), paper-insulated cables, made in accordance with B.S.I. Report No. 7, 1922 (amended 1927), for a mesh system (*i.e.* with equal insulation 'core-to-core' and 'core-to-lead'), the *Henley Manual* gives a table from which Table 46 has been calculated.

TABLE 46.—*Electrostatic Capacity of 3-core Paper-insulated Lead-covered Cables with Shaped Conductors and Equal Insulation Core-to-core and Core-to-lead.*

Note.—C = Capacity per ml., one wire against others bunched and earthed
= also, the wire to earth capacities for single-phase circuits.
C_y = star or Y-capacity, *i.e.* the working capacity per ml. for 3-phase circuits.

For cables with *circular conductors*, the capacities will be about 10 °/₀ less than shown below.

For cables with *less insulation core-to-lead* than core-to-core, as used for *star systems with earthed neutral*, the capacities will be about 15 °/₀ greater than shown below.

Conductor.		Capacity per Ml. of Cable, for Voltage (between Conductors).									
Nominal Area. Sq. In.	No. of Wires and Dia. In.	660 V.		2 220 V.		3 300 V.		6 600 V.		11 000 V.	
		C. μF.	Cy. μF.	C. μF.	Cy. μF.	C. μF.	Cy. μF.	C. μF.	Cy. μF.	C. μF.	Cy. μF.
0·0225	7 / ·064	0·44	0·53	0·39	0·47	03·5	0·42	0·30	0·37	0·23	0·28
0·030	19 / ·044	0·49	0·60	0·42	0·51	0·39	0·47	0·32	0·39	0·25	0·30
0·040	19 / ·052	0·56	0·69	0·46	0·56	0·42	0·51	0·35	0·42	0·28	0·33
0·060	19 / ·064	0·67	0·81	0·53	0·63	0·49	0·60	0·39	0·47	0·32	0·39
0·075	19 / ·072	0·76	0·91	0·58	0·70	0·53	0·63	0·42	0·51	0·35	0·42
0·100	19 / ·083	0·84	1·02	0·65	0·79	0·58	0·70	0·46	0·56	0·37	0·46
0·120	37 / ·064	0·90	1·09	0 70	0·86	0·63	0·77	0·49	0·60	0·40	0·49
0·150	37 / ·072	0·95	1·16	0·76	0·91	0·69	0·83	0·55	0·67	0·44	0·53
0.200	37 / ·083	1·00	1·21	0·83	1·00	0·77	0·93	0·60	0·72	0·49	0·60
0·250	37 / ·093	1·05	1·28	0·90	1·09	0·83	1·00	0·65	0·79	0·53	0·63

The charging current is found from the formula already given for 3-phase aerial lines (§ 306).

Thus for a 3-core cable, 10 mls. long, having conductors 0·1 sq. in. (about equivalent to the No. 3/0 solid wire in §§ 302, 306) the charging current at

6 600 V and 50 cycles will be [0·000 314 × (6 600 / $\sqrt{3}$) × 0·56 × 10] = 6·7 A. This is no longer negligible; it represents 6·7 × 6 600 × 1·73 / 1 000 = 76·8 kVA from the generator solely to charge the line to full pressure.

Welbourn (*Jour. I.E.E.*, Vol. 53, p. 95) estimates that about 2 500 kVA of plant would be required merely to charge a 30-ml. network of 30 000 V cable in a system operating at 50 cycles; taking into account also the cost of transformers, switch-gear, etc., it is doubtful whether higher pressures than 33 000 V are commercially justifiable in 3-core, 50-cycle cables.

The question of charging currents is of particular importance in 'intersheath' cables (§ 289). The capacity between intersheath and outer lead sheath is larger than in an ordinary cable, but the capacity currents on inner and outer surfaces of the intersheath are in opposite directions, so that the net intersheath current is relatively small. The capacity current in the outer sheath equals, however, the sum of the capacity currents in all the intersheaths and in the conductor itself. At 100 kV, 50 cycles, the charging current in the intersheath cable specified in § 289 is: (*a*) in conductor, 3·9 A; (*b*) in intersheath, 7·4 A; (*c*) in lead sheath, 11·3 A per ml. Though only 0·05 in. in thickness, the intersheath will carry the charging current for more than 3 mls. of cable when that current is fed from one end, or for 6 ml. feeding from both ends. Only short lengths of intersheath cable are likely to be used in the near future, but there is no great difficulty in arranging to feed in charging current at intervals when that becomes necessary.

312. Dielectric Loss in Cables.—In all cables there is some leakage of current between cores and between cores and earth through the ohmic resistance of the insulation; this resistance is however so high, when the cable is in good service condition, that the leakage current is extremely small and the I^2R loss in the insulation (as distinct from that in the conductor) is insufficient to heat the insulation appreciably. On the other hand, if the insulation be damp, the leakage current and the heating caused thereby increase to a dangerous extent. In D.C. cables the leakage current is the only loss in the dielectric, but the charging current has also to be considered where cables carry alternating current. Every cable is in effect a condenser and, if its power factor were zero, the charging current would be quite 'wattless.' Actually, energy is dissipated by dielectric hysteresis (§ 60) and the P.F. of the cable is, say, 2 or 3 % (lower sometimes *), so that there is a small watt-component in the charging current, and this component heats the dielectric (*see also* § 71A).

The power absorbed by the dielectric of a cable increases with the square of the applied voltage and, after decreasing as the temperature rises to 35° C., it thereafter increases rapidly with temperature; for example, the dielectric loss in certain 13 200 V, 3-core cables at 60 cycles was about 0·75 kW / ml. at 50° C.; 2·25 kW at 70° C.; and 6·25 kW at 100° C. The dielectric loss in modern 33 000 V, 3-core cables at 50 cycles, 60° C. is about 1¾-2 kW per ml.

313. Calculations for Three-Phase Line with Transformers.—Where extra high pressure is used on the transmission line it is generally stepped up at the generating station and down again at the receiving end. About 3 % (more or less) is lost in each transformation at full load, and in working out a system on the lines of § 302 this must be taken into account. If the transformation ratio is, say, 25 to 1, then, when the pressure is either raised or lowered, the inverse ratio must be applied to the current; this can be done subsequently, as it simplifies matters if the line pressure is used in the calculations throughout.

For example, assume that 3 000 kW are to be delivered at the end of a 3-phase line 15 mls. long, with a line loss of about 10 %, the power factor of the load being 0·85 and the pressure at the receiving end 1 000 V between lines. Then with a transformer ratio of 25 to 1 the equivalent line pressure will be 25 000 V and the pressure to neutral will be 14 430 V. The energy delivered by each branch will be 1 000 kW, and the current (1 000 × 1 000 / 0·85 × 14 430), or say 82 A.

Proceeding as in §§ 302, 306 the nearest size of wire will be No. 4 S.W.G., and each branch may be assumed to have the following approximate characteristics: Resistance = 16·05 Ω; inductance = 25·62 mH; reactance = 9·66 Ω; capacity = 0·264 μF. These data may either be worked out or taken from Table 44, assuming suitable spacing.

The transformers at both ends are assumed to have the following characteristics: Efficiency, 97 %; copper loss, 1 %; hysteresis, 1¼ %; reactance, 3¼ %;

* Low P.F. is particularly important in high-voltage, high-power cables because each 1 % of the total kVA then represents a large amount of energy and therefore appreciable heating of the dielectric, the break-down strength of which decreases as the temperature rises. It is now possible to make 44 000 V, 3-core cables with a P.F. not exceeding 1 % at temperatures up to 55° or 60° C. The P.F. of air-core telephone cables, in which paper is used only as a mechanical spacer to hold the wires apart, may be as low as 0·2 %.

TABLE 47.—*Voltage Components, Current and Power in 3-Phase Overhead Line with Transformers.*

	Voltage.		Current.	Power.
	Energy.	Induction.		
	V	V	A	
Secondary circuit—				
Energy component 85 % of 14 430 V	12 265	—	—	Total power at end 12 265 × 82 × 3 = 3 017 kW.
Induction component 52 % of 14 430 V	—	7 503	—	
Current	—	—	82	
Step-down transformers—				
Resistance loss 1 % of 14 430 V	144	—	—	Loss 80 kW.
Reactance loss $3\frac{1}{2}$ % of 14 430 V	—	505	—	
Hysteresis loss $1\frac{1}{2}$ % of 82 A .	—	—	1·2	
Data at high-tension side of transformer	12 409	8 008	83·2	Power to transformers 3 097 kW.
Line—				
Resistance loss (16·05 × 83·2) V	1 336	—	—	Loss 334 kW.
Reactance loss (9·66 × 83·2) V .	—	804	—	
$\sqrt{(13\,745^2 + 8\,812^2)} = 16\,329$ V at terminals of step-up transformer	13 745	8 812	83·2	Power to line 3 431 kW.
Step-up transformers—				
Resistance loss 1 % of 16 329 V	163	—	—	Loss 94 kW.
Reactance loss $3\frac{1}{2}$ % of 16 329 V	—	572	—	
Hysteresis loss $1\frac{1}{2}$ % of 83·2 A .	—	—	1·3	
$\sqrt{(13\,908^2 + 3\,984^2)} = 17\,030$ V at generator terminals . .	13 908	9 384	84·5	Power, 3 525 kW.

magnetising current, 4 %. As the power factor of the load (cos ϕ) is 0·85, the induction factor (sin ϕ) will be 0·52.

The working may now be set out as in Table 47, from which it will be seen that the pressure between lines at the generator terminals is 17 030 × $\sqrt{3}$ or 29 450 V and the current 84·5 A ; if the ratio of the transformation is 25 to 1, then the actual values will be 1 180 V and 2 110 A. The efficiency of transmission is (Power delivered / Power generated) = 3 017 / 3 525 or $85\frac{1}{2}$ %. The P.F. of the whole circuit will be (kW delivered / kVA generated) = 3 017 / 4 320 or 0·7.

This method of calculation is applicable to any installation of transformers on an A.C. system.

314. Star and Delta Connections of Generator.—Hitherto we have dealt with a 3-phase 3-wire line and the conditions in it, but largely by reference to the pressure from any phase wire to the neutral point. Now, as any two wires act as the return for the third, at both ends of the line the phase wires must in some manner be interconnected. For instance, at the generating end there are the coils on the generator; if the pressure is stepped up or down there are the coils on the transformers; at the receiving end there may be the stator coils of a motor, or the phases may be used as separate single-phase circuits. Either the star or the delta arrangement may be used (§ 143).

First consider the coils of a generator and the wires leading from them, in the example of 3-phase transmission with P.F. 0·88 at the generator end discussed in §§ 301-303.

With *star connection* one end of each generator coil connects on to one wire of the line, so the current must obviously be the same in coil and wire, *viz.* 102 A. The other ends of the three coils are all joined together at the neutral point (which may or may not be 'earthed'), so the pressure developed in each coil will be the pressure from line wire to neutral, *viz.* 3 885 V. The power generated in each coil is $IE \cos \phi$ *i.e.* $102 \times 3\,885 \times 0{\cdot}88 = 352$ kW, or 1 056 kW for the whole generator.

With *delta connection* the ends of the generator (or transformer) coils are connected in delta (Δ) or triangle, and the neutral point may be considered as in the middle of the triangle; the line wires take off from the junction points (as shown in Fig. 36, § 143). It will be seen that each line wire is being supplied with current by two generator coils, and the current in each coil will be (Line current $/ \sqrt{3}$) $= 102 / 1{\cdot}73$ or 58·8 A. As each generator coil is connected directly between two line wires the pressure developed in it must be the full line pressure or 6 730 V. Here also the power generated in each coil is $IE \cos \phi$, *i.e.* $58{\cdot}8 \times 6\,730 \times 0{\cdot}88 = 352$ kW or 1 056 kW for the whole generator.

315. Extra High Voltage Transmission.—It will be seen from the general formula in § 295 that the sectional area of conductor required to transmit any stated amount of power for a given distance with specified loss varies inversely with the square of the voltage between lines. In other words, the cost of the conductors themselves varies inversely with the square of the transmission voltage. This statement holds good in practice, at least up to the voltage at which corona (§ 316) requires the use of a larger conductor than would otherwise be needed. Alternatively, the amount of power which can be transmitted by conductors of stated size increases with the square of the voltage between lines. Thus, according to requirements, we can use smaller conductors or fewer circuits in the transmission system by working at higher voltages. The cost of towers and of wayleaves is reduced by reducing the number of circuits but, on the other hand, higher voltages involve greater outlay upon insulators and more costly towers, if the spacing between conductors has to be increased. In practice it is generally found that the cost of transmission lines for pressures higher than, say, 66 000 V increases in direct proportion with the line voltage. As the carrying capacity increases with the square of the line voltage there is a wide margin in favour of higher voltages wherever the amount of power and the distance of transmission justify the higher cost of transformers and switchgear for the higher pressure. The relative merits of different voltages must be determined by comparing detailed estimates for the alternative schemes, and an allowance (varying with circumstances) must be made for the fact that the security of supply is reduced when working at higher voltage over fewer circuits.

In Great Britain 132 kV is the maximum pressure used for long distance transmission, and, excepting in certain parts of the United States, this pressure has generally been found high enough for the economic transmission of power from the source of supply to the industrial areas in which it is absorbed and for the interconnection of power stations.

The United States, with enormous industrial demands at long distances from equally large water-power projects, is the home of 'super-transmission' schemes. An interesting pioneering measure was the conversion, by the Southern Californian Edison Co., of its two 150 kV, 55 000 kW, 3-phase circuits from the Big Creek hydro-electric development to Los Angeles (240 mls.) for operation at 232 kV, thus increasing the power capacity of the lines.

Tests by the General Electric Co. (Schenectady) in 1921 demonstrated that power could be transformed to 1 100 kV at 60 cycles / sec. and transmitted at this pressure, using tubular conductors of 4 ins. dia. to avoid corona (§ 316). The spark-over distance between points at 1 000 kV is about 105 ins. This investigation is mainly of interest as regards pressure testing and the determination of physical laws. It demonstrates, however, that power transmission at commercial frequencies is feasible at much higher pressures than yet used. Probably power could be transmitted 1 000 mls. with equipment representing a mere extension of present-day practice, but the cost of tubular conductors and of the insulators required would be abnormally high, and it is, at present, generally possible to sell within a radius of 200 or 300 mls. all the hydro-electric power which can economically be developed. Save for this general consideration, however, there is nothing to indicate that existing transmission pressures and distances will not be greatly exceeded (§§ 318, 319).

Reference should here be made to the possibility of the transmission of direct current at high pressures by the use of inverted grid-controlled mercury arc rectifiers. This possibility is based upon a recent development of the arc rectifier whereby it can be used to convert D.C. into A.C. of any required frequency by the action of polarised grids in the arc path. An account of this development will be found in a paper by J. E. Calverley,* and it will be dealt with in Ch. 17 of the fifth edition of Vol. 2 of this work.

316. Corona Discharge.—The term 'corona' is generally applied to the discharge which takes place from a charged body in air when the electrostatic stress is sufficient to ionise the layers of air in contact with the body, thus rendering them electrically conducting. At higher values of the electrostatic stress there occurs a brush discharge or, if the stress be high enough, flash-over to an adjacent body. Corona discharge occurs from overhead transmission conductors at high pressures (rarely below 100 kV between phases with usual sizes and spacings of conductors), and it is also liable to occur from the sharp edges of charged metal in oil-immersed apparatus, and in air films in or between layers of solid dielectric. In the latter case, as in cables, it quickly deteriorates the insulating material by its heating and chemical effects and so leads to break-down.

In high-voltage cables and coil insulation air films must be eliminated at all costs (§ 79). In switchgear, transformers, mercury rectifiers, and other apparatus where corona might give trouble, the discharge may be eliminated by the use of well-rounded parts (so as to reduce the electrostatic stress, § 288) or the possible source of corona may be separated from the danger space (*e.g.* a space filled with air and oil vapour) by an earthed metallic screen. The factors determining the occurrence of corona on overhead transmission lines are shown in the formula below; increasing the distance between conductors is a costly and relatively ineffective method of reducing the loss; in any particular case the voltage and frequency are fixed, and atmospheric conditions are beyond control; the only remaining method of reducing the loss is to increase the diameter of the conductor, *e.g.* by the use of steel-cored copper cable or aluminium (§ 331). Corona leads to corrosion of conductors by causing the formation of nitrous acid, and the power dissipated by the discharge may be a serious factor.

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* "The Grid-controlled mercury arc rectifier and the principles involved." J. E. Calverley. A paper read before the East Midland Centre of the I.E.E. and reprinted in the *English Electric Journal*, Dec. 1933, p. 185; *see also Electrician*, Vol. 112, p. 365.

The following data are due to F. W. Peek:* The *disruptive critical voltage* of air (at which voltage corona actually commences in practice, due to dirt and irregularities on the surface of the conductor) is given by—

$$e = gMr\delta \log_e \frac{S}{r},$$

where e = disruptive critical voltage, in kV (R.M.S.) to neutral;
g = disruptive pressure gradient of air;
= 21·1 kV (R.M.S.) per cm. for all conductors and commercial frequencies at 25° C. and 76 cms. barometric height;
M = 1·0 for polished wires; 0·98-0·93 for rough or weathered wires; 0·87-0·83 for 7-strand conductors;
r = radius of conductor, in cms.;
δ = an air density factor = $3{\cdot}92\, b / (273 + t)$, where b = barometric height in cms.; t = temperature in °C.;
S = distance between centres of conductors, in cms.;
log = $2{\cdot}303 \log_{10}$.

The *power loss by corona* is given by—

$$P = \frac{344}{\delta} f \sqrt{\frac{r}{S}} (E - e)^2 \times 10^{-5},$$

where P = power loss, in kW per km. per conductor;
f = cycles per sec.;
E = R.M.S. pressure between line and neutral, in kV; and the other symbols have the same meanings as before.

(*Note.*—1 in. = 2·54 cms.; 1 ml. = 1·61 km.)

Within the range of the tests (47-120 cycles) the power loss by corona varies directly with the frequency. At zero frequency (D.C.) the loss is from ¼-½ the loss at 60 cycles for the same *maximum* voltage.

The above formulæ relate to fair weather conditions. To determine the power loss in foul weather, take e = 80 °/₀ of the fair weather value. The operating voltage should not exceed e or the corona loss will be very high during fog, rain, or snow, or when the conductor surface is rough.

317. Thury Constant-current System.—The Thury system of direct-current transmission employs the same general principles as are applied in constant-current series-arc circuits (§§ 446, 595, 611, Vol. 2), but much higher pressure and power are now involved. A number of series-wound generators (§ 138) are connected in series to supply a number of loads also in series, the loads being generally motors driving auxiliary generators in substations, and the voltage of the main generators being varied to maintain the current constant. This system has been used fairly extensively on the Continent, where constant currents from 50 up to 450 A are used in various installations with maximum circuit pressures up to 100 kV. The Moutiers-Lyons scheme is the most important

* *Trans. Amer. I.E.E.*, Vol. 30, p. 1889; Vol. 31, p. 1051; Vol. 32, p. 1767.

yet erected.* In England, the Metropolitan Electric Supply Co. adopted a Thury transmission designed for 10 000 kW and a maximum pressure of 100-120 kV, using single-conductor, lead-sheathed cables with core section 0·125 sq. in. and ½ in. of paper insulation, to serve an area of 300 sq. mls. or so in Western London. This transmission provided an economical solution to the problem of supplying an undeveloped but rapidly growing district in which overhead transmission was not considered permissible, and underground A.C. transmission was not, at that time, practicable under comparable conditions of economy. Later developments in high-voltage cable construction, and the need for unifying operation on the basis of 3-ph., 50-cycle work, resulted in the abandonment of this Thury transmission.

Though the P.D. between points in the windings of a generator or motor in a Thury circuit may be limited to, say, 3 000 or 5 000 V, the line pressure at this point may be 100 000 V above earth pressure; hence it is necessary to carry the bedplate of the machine on insulators and to place the cement foundation block on insulators and surround it by a filling of asphalt and bitumen. Insulating couplings are necessary between generator and prime mover; and commutators for high pressures are costly and need much attention. Advantages and disadvantages may be thus summarised:—

Advantages.—Economy in distribution due to use of high pressures (§ 315). Possibility of using higher pressure than with A.C. for given insulation strain (§ 298). Inductance, capacity, phase displacement, and voltage surge problems are eliminated, and dielectric loss in cables reduced practically to zero. The only loss of importance is that due to ohmic resistance of the line; the percentage value of this loss is not serious when the constant current for the power available is so chosen that the circuit is normally worked near the limit of practicable voltage. (At present the limiting voltage for D.C. cables is about 150 kV to earth or 300 kV between extreme conductors.) On the other hand, since the current is constant, ohmic losses in the line are also constant, so that the efficiency of a Thury transmission on light loads is low. The aim must be low current and high voltage, *i.e.* minimum ohmic loss and maximum useful load to reduce the percentage importance of the loss.

The earth can be used as return path in a Thury circuit, or it can be 'tapped' to replace the function of a broken-down section of a metallic circuit.

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* Much information concerning this, as well as a detailed treatment of the principles, advantages, and disadvantages of the Thury system, is to be found in *General Electric Review*, Vol. 18, p. 1026 *et seq.;* other papers which may be consulted are: *Jour. I.E.E.*, Vol. 38, p. 407; Vol. 39, p. 848; Vol. 51, pp. 443, 640.

The ohmic loss in the earth path is small, but there is a certain liability to electrolytic trouble near the earth plates. Instead of being used as an active conductor, the earth may be used as neutral to limit the voltage, line to earth, to half the total pressure. One or more generators can be connected in series with a Thury circuit at any convenient point, say where there is a waterfall which might be so small as not to justify development on any other system (§ 187). One of the most important advantages of the Thury system is that it provides a flexible and efficient means of interconnecting heterogeneous generating systems (§ 186). By using motor generators consisting of constant-current series motors and A.C. or D.C. generators as may be required, any number of A.C. or D.C. networks can be interconnected, energy being transferred from one to another through the Thury circuit and motor generators; this arrangement has been proposed as a possible solution to the problem of co-ordinating electricity supply in London.

No transformation of pressure is required in a Thury circuit, and no general switchboards are required. The switches used are very simple, machines being short-circuited when idle, and tapped into the circuit when working. The series circuit is never opened, and in place of automatic circuit-breakers there are relays shifting the brushes to zero in case of generator break-down or accidental open-circuit. There is nothing in a Thury station corresponding to the synchronising of A.C. generators, and the load is shared automatically by all the series generators even with 10 % difference in the speed of the sets.

Disadvantages.—The constant current of the circuit cannot be subdivided, and rotary machines are required to yield A.C. or D.C. for distribution purposes. The insulation of the generator and motor frames is a serious problem. A 500 H.P. motor in a 200 A, D.C. circuit would have to be insulated in its windings for about 3 000 V (to allow for 50 % overload); the frame, however, would have to be insulated from earth for the full line voltage, which might be 100 000 V. High-power, high-voltage machines offer difficulties in the way of commutation; about 5 000 V per commutator is the upper limit at present, so that twenty commutators are required for 100 000 V line pressure. Speed-governors or brush-shifting gear or both are required on constant-current generators to provide for voltage regulation.

Though the commutators, generators, and motor governors and frame insulation are costly items in a Thury system, the cost of transmission conductors is less than for A.C. systems (§ 334), particularly where cables are concerned, and to an even greater degree where the earth is used as one conductor. It is not considered likely that the Thury system will ever compete with long-distance, overhead 3-phase transmission as at present developed, but the constant-current D.C. system is undoubtedly the best where transmission must be effected over considerable distance by underground cable; also it has very valuable application in linking together power schemes which have or have not the same voltage, frequency, etc.

An application of medium-voltage constant-current distribution for electric motor circuits is described in § 678 (Vol. 3). In this connection, the system offers great advantages.

318. Quarter-wave and Half-wave Transmission Lines.—A 'quarter-wave' transmission line is one of such length that the time taken for an alternating current to flow from one end to the other equals one-quarter period of the A.C. concerned; similarly, a 'half-wave' line is of such length that the time occupied equals one-half period of the current. If the velocity of flow be equal to the velocity of light (say, 186 000 mls. per sec.), and if A.C. at 50 cycles per sec. be used, the length of a quarter-wave line is about $186\,000 / (\frac{1}{4} \times \frac{1}{50}) = 930$ mls.; and that of a half-wave line is about 1 860 mls. In terms of the inductance and capacity of the line the length of the quarter-wave line is $1 / (4f\sqrt{LC})$ mls., and of the half-wave line $1 / (2f\sqrt{LC})$ mls., where f = cycles per sec., and LC = inductance and capacity per ml. If the product LC be increased (*e.g.* by the addition of reactance coils to the circuit and the use of underground cables) the route length of a quarter- (or half-) wave line may be reduced to a few hundred miles. Lines of these electrical lengths have distinctive properties of considerable value from the point of view of power transmission; and it has been suggested that such lines could be used to advantage for the transmission of power over relatively short distances, the line being then 'loaded' as above, or over very long distances, only the natural inductance and capacity of overhead lines being then in circuit. The following notes indicate the possibilities and limitations of the two systems* (*see also* §§ 135 (1) and (4)):—

The method at present standard for the transmission of A.C. power consists in the delivery of a variable current (according to the load) at constant voltage. In order to maintain constant voltage at the load, the voltage at the input end of the line must be increased as the load increases, so as to compensate for the higher pressure drop in the line. Where a large amount of power has to be transmitted for long distances a wide range of voltage regulation is required at the supply end, and the power loss in the line is a serious consideration.

The Quarter-wave System.—A quarter-wave line is in resonance (§ 47) on open circuit and the characteristics of the circuit are such that, neglecting resistance, constant current input is required for the maintenance of constant voltage at the delivery end. In practice it would be necessary to increase the current input somewhat to compensate for the higher ohmic loss at higher loads

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* For a detailed investigation of the characteristics of long transmission lines, *see Theory and Calculation of Transient Electric Phenomena and Oscillations*, by C. P. Steinmetz (McGraw, Hill Co.). The notes here given are from papers on the basic equations of quarter-wave and half-wave lines, with numerical examples, abstracted from *Rev. Gén. d'Électricité* in *El. Rev.*, Vol. 87, pp. 250 *et seq.*

but, fundamentally, the system is one of constant current input and its application would require the use of constant-current alternators (which are not standard machines). As the pressure along the line varies with the load delivered, it is impracticable to tap energy from a quarter-wave line at any intermediate point; the system is only applicable to 'through' transmission of energy from point to point. The route length of a quarter-wave line, with only the inductance and capacity of air lines in circuits, is about 750-900 mls. using 50-cycle current, and 1 500-1 800 mls. using 25-cycle current.

The Half-wave System.—A half-wave line may be regarded as two quarter-wave lines placed end to end. With constant voltage supply at the input end there is, neglecting resistance, constant voltage at the delivery end and constant current at the centre of the line. Maximum voltage in the line is at points about one-quarter the total length of the line from each end and is there equal to the station voltage which would be required in an ordinary A.C. system for transmission over this quarter distance. In other words, the half-wave system makes possible transmission over four times the length of an ordinary transmission line with the same maximum voltage in the circuit.

As the voltage at intermediate points varies with the load the half-wave system is limited to 'through' transmission from end to end, except that supply can also be taken at or near the centre from the constant-current portion of the line. With only the inductance and capacity of overhead lines, the route length of a half-wave line is about 1 500-1 800 mls., using 50-cycle current (3 000-3 600 mls. for 25 cycles), but the route length could easily be reduced to 300 mls. by the use of reactance coils of reasonable dimensions in the case of lines for 10 000 kW or so. For higher power, up to, say, 50 000 kW, extra capacity is also required in the circuit; this could be provided by using condensers and or some underground cable, but it would generally be sufficient merely to subdivide the line conductors.

The half-wave system could be used with standard (constant-voltage) alternators. Its advantages, compared with a plain transmission, are: (1) Elimination of the effects of inductance and capacity on the voltage regulation required at the supply station; the station voltage is higher than the delivered voltage only by the amount of the ohmic (*IR*) drop. (2) Longer distance transmission feasible with the same maximum line voltage. (3) Lighter conductors and better voltage regulation for given variations in load kW and P.F. Its disadvantage is that energy cannot be tapped intermediately except at the centre point and there only by special constant-current equipment.

319. Six-Phase Underground Transmission at 100-150 kV.—The system proposed by A. M. Taylor (*Jour. I.E.E.*, Vol. 61, p. 220) employs single-core cables with intersheaths (§ 288) which are utilised for power transmission as well as to relieve the pressure gradient on the insulation near the main core. Two star-connected transformer-secondaries are arranged so as to yield a 6-phase supply, the terminals of which (in sequence) are connected to the central, intermediate, and outer cores of one cable *A*, and to the corresponding cores of a second cable *B*. The intermediate point of the 6-phase system, between the points connected to the outer cores, being earthed, and the system being operated at 60 000 V, the P.D. between the central and intermediate cores (and between the intermediate and outer cores) is 30 000 V, whilst that between the outer core and the lead sheathing is 17 800 V. This system has not materialised commercially.

320. Interconnection of Transmission Systems.—For the reasons outlined in § 186 it is becoming increasingly common to interconnect A.C. transmission systems so that power can be transferred from one to another at will.* The voltage and power factor conditions in the interconnecting line are both important; their relation is discussed fully in a paper by L. Romero and J. B. Palmer (*Jour. I.E.E.*, Vol. 60, p. 287), from which the following points are extracted:—

To obtain any desired division of load between two interconnected A.C. power stations it is necessary to adjust the steam (or water or gas, etc.) supply to the prime movers. Mere adjustment of generator fields, or the raising by other means of the voltage at the 'sending' end of the interconnector, only causes wattless kVA to flow through the circuit, the kW remaining constant except for the additional copper loss in the interconnector (§ 155). Adjustment of voltage, in addition to prime mover control, is sometimes necessary.

When current flows through a circuit having resistance and reactance (such as the interconnector, with or without transformers) there is an impedance drop (IZ) which causes the voltage at the two ends of the circuit to differ in magnitude or phase or both.

If the station voltages are *constant and equal*, the mean P.F. of transmission remains at a constant leading value, and the power factors at the station ends of the interconnector vary (slightly) in opposite directions as the load varies or reverses. Power up to the capacity of the line may be transmitted in either direction without varying the voltage or mean P.F. This method might be used to connect two stations each with a load at or near unity P.F., but most stations are unable to take a bulk supply at leading or unity P.F. without serious disturbance to their operating conditions.

If the station voltages are *constant and unequal*, the P.F. of the transmission varies from lag towards lead as the load increases. This method is suitable only for transmitting power in one direction because a reversal of power would flow at a low leading P.F.

If the station voltages are *varied with load*, by induction regulators (§ 406, Vol. 2), boosting transformers (§§ 395, 406, Vol. 2) or other means, the P.F. may be kept constant at any desired value within the available range of voltage variation. This method is necessary in most cases. The use of a boosting device makes possible control of the transmission P.F. without varying the bus bar voltage. Formulæ for determining the P.F. of the line current with given load and voltage boost, or the boost required to transmit a stated load at given P.F., are to be found in the paper (*loc. cit.*).

* In the great interconnected transmission networks of the United States, some of the power is transmitted 500 or 600 mls. when there is a local shortage of coal or water. The same problems are now met with in the British 'Grid.'

321. Synchronising Effect of Parallel Transmission Lines.—If two alternators be connected each to one of a pair of transmission lines, which are electrically independent but physically parallel to each other on the same poles or towers, the two circuits have a synchronising effect which tends to hold the generators in synchronism or in anti-phase, according to the arrangement of the line conductors.* In order that the paralleling of apparatus in a sub-station may be helped (instead of being hindered) by the synchronising effect of the transmission lines, the conductors of one line should be placed in phase sequence 1—2—3 down one side of the tower, those of the other line being in sequence 3—2—1. That is to say, similar phases in the two lines should be *diametrically opposite* to each other and not in the same relative positions on each side of the tower. This diametrical relation must, of course, be retained at each transposition of the wires.

322. Wayleaves.—Before any overhead transmission line can be erected it is necessary (in Great Britain) to obtain permission (*a*) from the Ministry of Transport; (*b*) from the owner of the ground traversed. Fortunately, it is now much easier than in the past to obtain the requisite official and private consent. The abolition of the absolute power of veto formerly possessed by local authorities is an important reform.

Under the provisions of the General and Special Acts or Orders relating to the supply of electricity, the consent of the Minister of Transport is necessary before Authorised Undertakers may place any electric line above ground, except within premises in the sole occupation or control of the Undertakers, and except so much of any service line as is necessarily so placed for the purpose of supply. In cases where the Local Authority are not themselves the Undertakers, the further consent of such authority was formerly necessary under the provisions of § 14 of the Electric Lighting Act, 1882, and § 10 of the Schedule to the Electric Lighting (Clauses) Act, 1899, or corresponding provision in any Special Act or Order. The position, however, has been modified by § 21 of the Electricity (Supply) Act, 1919, and where the consent of the Minister is obtained to the placing of any electric line above ground in any case, the consent of the Local Authority is not required; but the Minister before giving consent is required to afford the Local Authority an opportunity of being heard. The section last quoted has in its turn been amended by the sixth schedule to the Electricity (Supply) Act, 1926; while section 44 of the same modifies the procedure. A local authority now includes a County Council; and the two enquiries necessitated by sections 21 and 22 of the 1919 Act may be amalgamated into one. It also falls to the Minister of Transport to give consents in connection with way-

* This phenomenon and the reason for it are discussed in *Gen. El. Rev.*, Vol. 25, p. 146, and *Electricity*, Vol. 36, p. 588.

leaves for electric lines whether above or below ground under the provisions of § 22 of the Act of 1919.

As previously indicated, overhead lines, whether erected by Authorised Undertakers or without statutory authority, are subject to Regulations prescribed by the Electricity Commissioners for securing the safety of the public and for the protection of the lines and works of the Postmaster-General (§ 324 and § 1048, Vol. 3).

323. Steel, Wooden, and Concrete Poles.—*Steel Poles.*—For transmission lines, built-up steel lattice poles are the most satisfactory on all counts. For comparatively unimportant or light lines, however, tubular tramway poles are often used, and serve their purpose. These latter are generally used in towns, where lattice poles would take up too much room. Tubular 'Hamilton' telegraph poles have also been extensively used, but in the gauges of metal generally employed for telegraph purposes they are not satisfactory; a much higher factor of safety is required in power lines than will suffice for telegraphs.

On one important point engineers and buyers can ensure their steel poles having the longest possible life, namely, by excluding high-tensile steel, of which poles are sometimes made. Most chemists will agree that high-tensile steels tend to corrode more quickly than either wrought-iron or mild steel; and this is probably due to the higher percentage of manganese and carbon present in high-tensile steel. Mild steel with a tensile strength not exceeding 24-28 tons per sq. in. will give the best results in the direction of the minimum tendency to corrode. Engineers would do well to specify the steel of which their poles are made to fall within this figure (E. J. Fox, *Jour. I.E.E.*, Vol. 52, p. 320).

Wooden Poles, used on several important transmission schemes in India, have proved uniformly unsatisfactory; possibly with proper treatment better results would have been obtained, at any rate at high altitudes, where there are no white ants. In this country they are used to a considerable extent. A compound pole of A-form, built up from two single poles and spread about 1 in 8, is roughly $4\frac{1}{2}$ times as strong as a single pole. Where more room is required the H-form is used, with cross-bracing to give stability. At angles, H-poles or three-legged structures should always be used with stays (§ 326) in both alignments rather than a single stay in the resultant. Concrete foundations may be necessary in bad ground, and if a concrete sheathing be carried up the pole above ground level, rotting at the latter is prevented. The most favourable season for cutting trees for poles is the beginning of winter, when the sap is dormant. The cubic content of a tree may be roughly obtained by the formula:—

$$\text{Cub. content} = \text{length in feet} \times (\text{quarter girth inches}^2) / 144.$$

Notes on preservative processes for timber are given in § 86. Statistics from a variety of sources show that creosoting under pressure gives the longest life to timber, *viz.* 20-25 years for poles in temperate climates. The life of poles treated with copper sulphate, zinc chloride, or mercury chloride is given as 12-15 years. The life of wooden poles as hitherto used in India has been 5 or 6 years. Untreated poles last 10 or 12 years in England and by proper creosoting a life of 30 years or more, up to 50 years is attainable.

Concrete Poles.—Reinforced concrete poles have been used in a number of cases (particularly in America), as being stronger and more durable than wood, whilst eliminating the constant supervision and repainting required by steel. Concrete poles are heavy, which is a serious matter where transport is difficult; their use is principally in low- and medium-pressure distribution schemes. In some cases a portable pole-making plant and local aggregates may be used with advantage. Tubular construction saves weight with little loss of strength, and provides a convenient duct for cables. A 25-ft. pole tapering from 16 ins. to 7 ins. with 2½-in. walls and twelve ¼-in. steel reinforcing rods, weighs about 2 500 lbs., and if set 6 ft. in the ground will withstand safely a pull of 1 000 lbs. applied at the top.

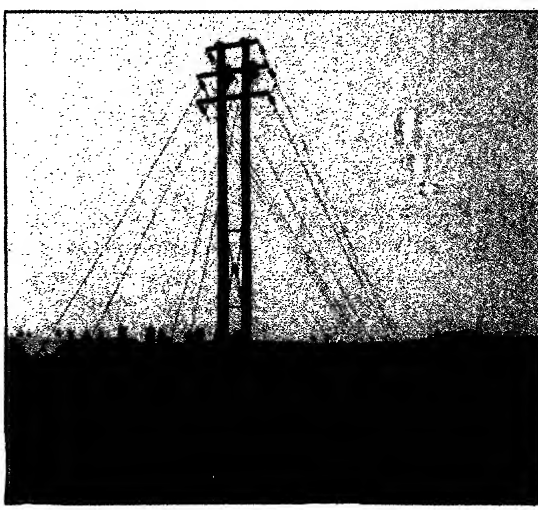
324. Poles and Wires; Requirements of Regulations.—The first requirement of an overhead line is that it shall be set out properly before erection begins. The position of every pole should be determined; it should be ascertained that the wires in a span will not come too near the ground, especially in the case of tortuous distribution lines in hilly country; the angles should be noted; the nature of the ground where poles and stays must go should be investigated; the height and strength of special poles should be taken out.

In early editions of this work the Board of Trade Regulations for overhead lines were referred to. The Board has made way for the Electricity Commissioners and the Regulations have been revised (1934). In theory the Regulations prescribed by the Commissioners, under the power conferred by the existing 'Regulations for securing the safety of the public,' are specially made for each undertaking, and become a part of the Special Order; in fact the new Regulations, like the old ones, are now in standard form. It should be noted that the Regulations of the El. Com. for Overhead Lines (El. C. 53) *remain in force* at present, as specifically stated in the new (1934) Regulations in the para. 'Short Title and Application,' and are therefore *not* classed as superseded 'prior Regulations.' The definitions from the 1934 code are set forth in § 5 *supra.*

Johnson & Phillips, Ltd.

MEDIUM-VOLTAGE AND HIGH-VOLTAGE OVERHEAD POWER LINES.

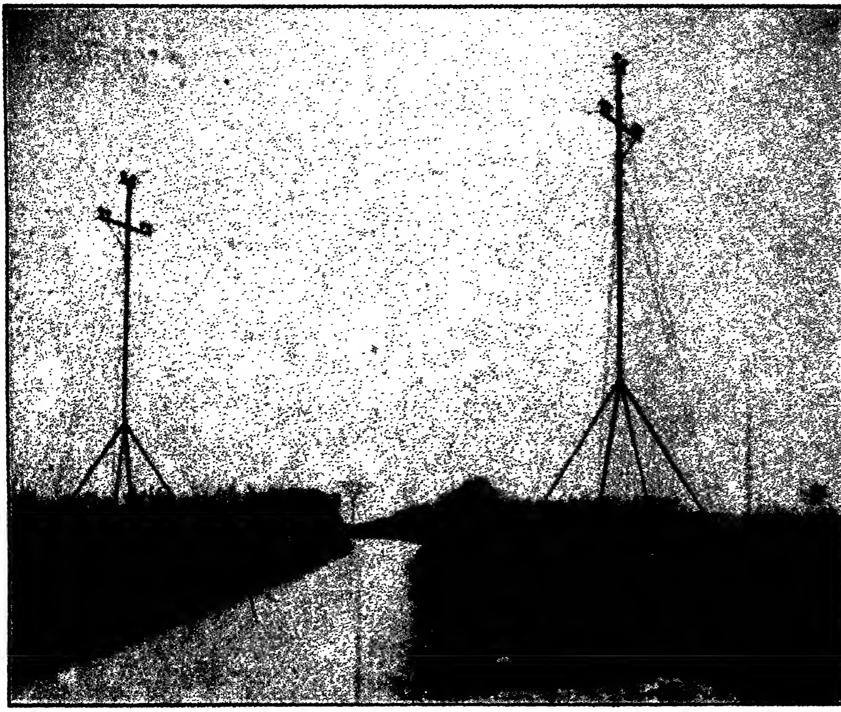
Current is supplied through 3 300 V overhead feeders and delivered, through pole-type transformers, to the 430 V overhead distributors. The copper conductors, ranging from 37/13 to 7/14 S.W.G. are carried by cantilever channel cross-arms, and are all single-circuit lines with a 7/14 S.W.G. earth wire below. The triangular spacing of the conductors is 2 ft. 6 ins. The creosoted wooden poles are A, H and single-type, 34 ft. long overall, from 7 in. to 8½ in. diameter at 5 ft. from the butt, and at average spans of 50 yds.



Johnson & Phillips, Ltd.

A double-circuit, 3-phase, 11 000 V line running from a terminal pole to which current is conveyed by two 11 000 V underground cables; the cable cores are connected to the lines in the inverted pole-type trifurcating boxes. The conductors are of 1 S.W.G. copper spaced 4 ft. 4 ins. horizontally on the top and bottom cross arms and 5 ft. 4 ins. on the centre arm; below them is a 7/14 S.W.G. galvanised steel earth wire. The vertical spacing between conductors is 1 ft. 6 ins. The poles are 36 ft. long, 9½ ins. dia. (at 5 ft. from butt); the span is 80 yds. and the minimum clearance from ground at maximum summer sag is 20 ft.

[To face p. 576.



Callender's Cable and Construction Co., Ltd.

A 33 000 V TRANSMISSION LINE ON 'KAY' POLES.

This type of pole is particularly suitable for cross-country transmission. It is preferably made of high-tensile steel tubes which may be painted or, better, wrapped with hessian impregnated with a bitumen compound. The foundations consist of buckled plates to which the tubes are bolted, and the connection between the four base tubes and the upright is made by a cast-iron block with five projections which slip into the appropriate tubes and require no bolt or other fastening. The ties are of galvanised steel rope. The foundation plate carries only the difference between the thrust of the tube and the pull of the wire, hence these poles can be used on marshy ground. They are easily transported and easily erected, and passage between the legs is not obstructed by bracing.

[*To face p.* 577.

The following summary may be taken as substantially correct both for pressures (*a*) not exceeding 650 V, D.C., and 325 V, A.C., and (*b*) exceeding those values.

Line conductors will be of copper or aluminium ordinarily, though steel or other conductors for specially long spans would no doubt be allowed. As regards breaking load, elongation, and elasticity the conductors at the time of erection will have to comply with the latest specification of the British Standards Institution (see § 336). Minimum values are as in Table 47*a*. The minimum permissible size, except for service lines, must be such as to have an actual breaking load of at least 1 237 lbs. equivalent to No. 8 S.W.G. copper; for service lines, the figure is 816 lbs. = No. 10 S.W.G.

TABLE 47*a*. — *Minimum Elongation, Breaking Load and Elasticity of Solid Conductors of Copper and Aluminium. (See* B.S.S. 125 and 215 *for complete data.)*

Material.	Diameter (approx.). in.	Elongation in 10 ins. %.	Breaking Load.	Young's Modulus of Elasticity. Lbs. per sq. in.
Copper . .	0·204 0·400	1·81 2·55	26·5 tons / sq. in. 22·9 tons / sq. in.	18×10^6
Aluminium .	0·093 0·211	1·80 2·60	190 lb. 804 lb.	$9{\cdot}9 \times 10^6$

In calculating the factor of safety the actual breaking load is taken. It is assumed that the wires are covered with ice to a radial thickness of $\frac{3}{16}$ in. (for the higher pressures $\frac{3}{8}$ in.) and are simultaneously subjected to a wind of 50 m.p.h. or 8 lbs. per sq. ft. of the projected area. (See footnote * on page opposite.) Under these conditions and allowing for the elasticity, the stress in the conductor at 22° F. (5·5° C.) must not exceed half the breaking load.

The minimum computed height from the ground of any line conductor, at a temperature of 122° F. (50° C.), is fixed at 19 ft. across a public road or 17 ft. elsewhere; and for pressure over 650 and under 66 000 V 22 ft.; beyond that, 23 ft. The conductors must not be accessible without a ladder or the like. In the case of the higher pressures, approved means for rendering a falling wire dead must be provided; and at all pressures above 250 V D.C. or 125 V A.C. approved means must be provided to prevent 'danger' from a falling wire. The conditions are somewhat more stringent along or across public roads or canals, or upon factory or other premises. Any auxiliary and earth wires or service lines are generally subject to similar restrictions. Lines crossing or near other overhead lines must be specially protected against accidental contacts, at the expense of the last comer.

Poles or supports (§ 323) of creosoted wood, iron, steel or reinforced concrete are permissible; for the higher pressures the supports must be consecutively numbered and must carry a 'danger' notice. The factors of safety allowed are $2\frac{1}{2}$ for iron or steel and $3\frac{1}{2}$ for wood or concrete under the same conditions as to ice and wind pressure as for wires. For lattice and other compound poles, such as A and H poles, special conditions of calculation are laid down. In the case of the higher pressures a continuous earth wire must be provided, connecting up all metal not alive,* and earthed at least four times in every mile; and the design must be such that the leakage on a contact occurring with live metal shall be at least double that required to operate the safety devices for rendering the line dead.*

Regular inspection and efficient maintenance is, as heretofore, insisted upon.

All materials used must, at the time of erection, conform with the latest specifications of the B.S.I. and with the Post Office Technical Instructions (No. XIII.) for the construction of aerial lines, as far as applicable.

No limiting span is laid down; it is clear that if the restrictions are complied with the distance between supports is immaterial. In certain cases the Regulations may be modified with the consent of the Electricity Commissioners. There are no detailed instructions (such as were found in the B.O.T. Regulations) for guarding against corrosion; but it must be guarded against both statutorily and as a matter of common sense.

In practice, it is seldom advisable to use conductors smaller than No. 5 or No. 6 S.W.G. Long spans are generally preferable in transmission lines, except where crossing streets or other places where the public have a right of way; there the span should be as short as possible. It is good practice to duplicate each wire on transmission lines crossing roads; the two wires are then bound together, and the chance of breakage is reduced to a minimum. Earthing metal towers or other accessible supports is not always an easy matter in dry districts. A continuous earth wire (§ 347) is useful for the purpose. Cases have occurred where poles have been made 'alive' by leakage and have caused serious accidents to men and horses. During erection and repair, line wires should always be earthed. Neglect of this precaution has been responsible for cases of shock to linesmen from electrostatic charges on the line.

The Regulations require a liberal factor of safety (see above) in transmission conductors, and assume that a wind pressure of 8 lbs. (as against the B.O.T. 25 lbs.) per sq. ft. of projected area will be operative. This is equivalent to a wind velocity of 50 M.P.H., Table 48. Such a velocity is comparatively rare even in tropical countries, and is seldom reached away from the coast. A map showing the maximum wind pressures which may be expected in India, prepared by the Meteorological Department,† shows only narrow strips at the head of the Bay of Bengal and the Indian Ocean liable to such pressure, though in cyclones much greater

* The terms 'live,' and 'dead' in their electrical sense are defined in the 1934 Regulations, see § 5; 'danger' is defined in the factory and workshop regulations (q.v.).

† Frontispiece to *The Law Relating to Electrical Energy in India and Burma*, J. W. Meares (Thacker Spink, Calcutta).

force occurs; over most of that coast from 25 to 20 lbs. per sq. ft. is the most to be anticipated. Actually, such a pressure is rarely experienced at any distance from the coast, but provision must be made for abnormal conditions. The United States and Canadian recommendations allow a maximum stress of 30 000 lbs. per. sq. in. for copper (14 000 lbs. for aluminium) at 0° F. with a ½-in. coating of ice and a wind pressure of 8 lbs. per sq. ft. projected area of conductor. In the Himalayas a stranded 7 / 10 S.W.G. cable has been observed when enlarged to 4 ins. diameter over a whole span.

TABLE 48.—*Velocity and Force of Wind.*

Mls. per Hour.	Ft. per Second.	Force in Lbs. per Sq. Ft.	Common Appellation.
1	1·47	0·005	Hardly perceptible.
2	2·93	0·020	Just perceptible.
4	5·87	0·079	Gentle pleasant wind.
8	11·75	0·315	Pleasant brisk gale.
16	23·45	1·25	
20	29·34	1·97	Very brisk.
25	36·67	3·07	
30	44·01	4·42	High wind.
35	51·34	6·03	
40	58 68	7·87	
45	66·01	9·96	Very high.
50	73·35	12·30	
55	80·7	14·90	
60	88·02	17·71	Storm.
65	95·4	20·85	
70	102·5	24·10	Great storm.
75	110·0	27·70	Hurricane.
80	117·36	31·49	
100	140·66	50	Tornado.

Table 48, abstracted from Nystrom's, shows the relation between wind velocity and pressure on a plane surface normal to the wind.

The relation between the velocity, V ft. per sec., and the pressure, P lbs. per sq. ft., is given by $P = 0{\cdot}\,002\,29\,V^2$. If x be the angle of incidence of the direction of the wind with the plane of the surface, the effective value of P is $0{\cdot}\,002\,29\,V^2 \sin x$.

There are various ways of ensuring that a broken line wire is earthed before it reaches the ground. Where there is an earthed 'neutral' as in 3-wire D.C. or 3-phase, 4-wire A.C. circuits) it may be split into two conductors carried below the other wires and cross-connected. A falling live wire must then strike the neutral and open the circuit-breaker. Alternative methods are to fix earthing brackets on, or immediately below, the wires at each end of each span; or to suspend a loop under the outers from the neutral at the top. Protection is just as necessary on overhead service lines; a man has been killed by touching the broken end of a service line attached to a house and apparently 'dead,' but actually 'alive' through a fan in the house, the fan being still connected to the unbroken service line.

The safest arrangement where different sets of overhead lines have to cross (leaving trolley wires out of consideration) is to make the crossing at a support and at right angles. Guard brackets, earthed on the pole, can then be thrown out between the two sets. Even where all the lines belong to the same person, the not uncommon practice of running high and low-tension lines on the same supports should not be encouraged. Though it is obviously bad engineering, service lines or tappings are sometimes taken off aerial lines otherwise than at a point of support; this is prohibited.

Among the devices for protecting overhead lines from breakdown may be mentioned the 'pernax' bird-guards, which have been favourably reported on by the National Physical Laboratory.

325. Strength of Poles.—First consider the effect of wind pressure on the whole structure, on the basis of the old Board of Trade requirements. The general procedure illustrated by the examples in this and the succeeding paragraphs is the same whatever the regulations in the locality concerned; it is only necessary to substitute the appropriate loads, factors of safety, etc.

Wind pressure on *wires* = $0{\cdot}6 \times (d / 12) \times L \times n \times 25 = 1{\cdot}25dLn$ lbs., where d = diameter of wire in inches; L = length of span in feet; and n = number of wires. Denoting by H the average height of wires above ground in feet, the moment (W) of wind pressure on the wires is given by $W = 1{\cdot}25\ dLnH$ lb.-ft.

The wind pressure on *pole* = $0{\cdot}6 \times$ (Mean diam. / 12) $\times$ Exposed height $\times$ 25 = $1{\cdot}25 \times$ Mean diam. in inches $\times$ Height in feet. The moment of this pressure is:

$$P = 1{\cdot}25 \times \text{Mean diam. (ins.)} \times \text{Height (ft.)} \times \tfrac{1}{2}\,\text{Height (ft.)}$$
$$= 0{\cdot}65 \times \text{Mean diam. (ins.)} \times \text{Height.}^2$$

the height being expressed in feet.

Then, allowing a factor of safety of 10 for wooden poles or 6 for steel poles, the poles must have a breaking stress not less than $10(W + P)$ or $6(W + P)$ respectively. The later Regulations greatly reduce the actual strength required.

In the 3-phase transmission line worked out in § 302, there are three No. 3 S.W.G. wires, of 0·372 in. diameter. Assume that the ground permits spans of 500 ft., and that metal poles of 6 ins. average diameter are set with 30 ft. out of ground. Suppose also that a fourth No. 3 S.W.G. wire is used as continuous 'earth-wire' (§ 347). Then wind pressure on wires = $1·25 \times 0·372 \times 500 \times 4 =$ 930 lbs., and if the average height of the wires be 28 ft. the moment of wind pressure = $930 \times 28 = 26\,000$ lbs.-ft. = W. The wind pressure on pole = $1·25 \times 6 \times 30 = 225$ lbs., and the moment of this pressure = $225 \times 30 / 2 = 3\,380$ lbs.-ft. = P. The total bending moment to which the pole is subjected by wind pressure of 25 lbs. per sq. ft. = $W + P = 26\,000 + 3\,380 = 29\,380$ lbs.-ft., hence the pole (unless stayed all round) ought to have a breaking stress not less than $6 \times 29\,380$ or say 176 000 lbs.-ft., which is equivalent to 6 300 lbs. applied 28 ft. above ground level. Obviously no single pole of the assumed dimensions would give the requisite strength, hence a lattice or built-up structure would be necessary. (It may be noted that the Hamilton poles used for telegraph work have the following breaking loads, *viz.* ABC, 1 250 lbs.-ft.; CDE, 3 600 lbs.-ft. For steel tramway poles *see* § 910, Vol. 3.)

326. Stays and Stay Wires.—Galvanised steel stranded wire is used for stays, and a breaking stress of about 30 tons per sq. in. may be assumed; but for special work it can be produced up to 100 tons per sq. in. Stays may be needed either to strengthen the line at angles or terminal points, or to bring up construction on straight lengths to the required strength where the poles are not strong enough. They also serve to prevent the wires blowing together in a wind. They should be fixed to the post, if possible *above* the line wires or at the resultant point between them, not below. It is evidently better at an angle to fix a stay in each alignment, rather than one only, in the resultant direction. Again, stays should be carried well away from the pole, for a stay at right angles would be in the best possible position. Finally, the stay wire must run straight to the anchor, with no angle at ground level; it is best to undercut the hole for the anchor and to cut a slot in the ground for the stay wire. Where a wash-out is liable to occur in heavy rain four stays are sometimes advisable, two across and two along the line, to limit the trouble in case of a breakage of the line.

Taking first the case of a *terminal* stay, assume as in the previous paragraph that a line of three No. 3 / 0 wires (breaking load 6 100 lbs.) is terminated on a pole, and that the stay is to carry the load. If the wires have been erected to have a factor of safety of 5, the tension which three such wires will exert on a terminal post will be 3 × 6 100 / 5 = 3 660 lbs. The tension to be taken by the stay would then be (3 660 / sin θ), where θ is the angle which the stay makes with the post. Thus, if fixed at right angles, in continuation of the line wire, the tension is evidently 3 660 lbs.; at 45° it is 5 180 lbs.; at 30°, 7 320 lbs. If the factor of safety of the stay is 5, it should have a breaking load of 25 900 lbs. for 45° and 36 600 lbs. for 30°. Iron stay wire may be taken as having a breaking load in lbs. of about 3½ times its weight per mile, so that the stranded wire used should be equal to 7 800 lbs. and 11 000 lbs. per mile in the two cases. For steel, one-third or less of these weights per mile would be sufficient, according to the material used. In this and the following instances the roughest calculation suffices; there is no necessity to ascertain the exact angles dealt with. The following values of the sine will be accurate enough:—

Angle	90°	75°	60°	45°	37½°	30°	22½°	15°	10°	5°
Value of sine	1	·96	·87	·71	·61	·5	·38	·26	·17	·08

In the case of an *angle* stay, the resultant load, R, caused by the wires (*i.e.* the *line* wires) on the post is: $R = 2T \sin(\theta / 2)$, where T is the tension of the wires and θ is the *supplement* of the angle contained by the line wires. Thus, suppose the three No. 3 / 0 wires all make a horizontal angle of 120°, where the line changes its direction at a certain angle pole, then θ is 60°. The tension of the three wires is, as before, 3 660 lbs., so $R = 2 \times 3\,660 \times \sin(60 / 2)$. As sin 30° = 0·5 the resultant load at this angle is the working load on the wires or 3 660 lbs., so a single resultant stay will be of the same size as the terminal stay already worked out above.

For other angles in the line the weight per mile of the terminal stay as previously determined should be multiplied by the following factors:—

Angle of Wires at Angle Post.	Supplement.	Multiplier for Stay Wire.
90°	90°	1·4
120°	60°	1·0
140°	40°	0·68
150°	30°	0·52
160°	20°	0·35
170°	10°	0·17

These factors are of course equally applicable to any other line for which a terminal stay has been calculated. If a stay can be fixed in each alignment, instead of one in the resultant, each component may be of half the size of the single stay. The straining screws should not be weaker than the stay wires attached to them. As the stay is connected to the 'earthed' pole it is sometimes advisable, especially in the hills, to insulate the accessible part of it by means of a tramway 'strain insulator.' The pole may of course accidentally become 'alive' through a fault on the line and a bad earth, but accidental contact with a live stay wire is much more probable.

327. Dip and Stress of Wires; Spacing.—As regards the wires, the old B.O.T. rules now superseded by those of the Electricity Commissioners, viz. El. C. 39 (1924) and El. C. 53 (1931) assumed that the dip would be such that the wire was subject to $\frac{1}{5}$ breaking stress *under the worst conditions*. This is in fact seldom the case, but the elasticity of the wire and the 'give' on the posts may counterbalance abnormal conditions to a considerable extent. Where snow is experienced the over-all diameter of a wire may be increased up to 3 or even 4 ins.; but in many cases, as in Indian hill stations, a high wind does not accompany the conditions for 'binding' snow. In such cases, if the wire is strained so that it will be subject to $\frac{1}{5}$ breaking stress at the probable minimum temperature, snow may be disregarded; and where snow never falls a somewhat lower factor, or smaller dip, may be allowed. The current Regulations, however, demand a factor of safety of 2 under specified conditions of temperature and ice (§ 324).

Thus, to continue the example of 3-phase transmission from the preceding paragraph, the breaking stress of a No. 3 / 0 S.W.G. hard-drawn wire may be taken as 6 100 lbs., and to allow a factor of safety of 5 we must take a working stress, S, of 1 220 lbs. (*see* col. 6 of Table 44, § 307) at the minimum temperature expected. The span L being 500 ft. and the weight, w, of 1 ft. of wire being 0·42 lb., the dip or sag D is given by: $D = L^2 \times w / 8 \times S = 500 \times 500 \times 0{\cdot}42 / 8 \times 1\,220 = 10{\cdot}8$ ft.

Suppose the minimum temperature to have been taken as 22° F., and that a maximum temperature of 100° F. occurs. Then the new dip will be $\sqrt{[D^2 + L^2 (T \times \frac{3}{8}k)]}$, where T is the rise of temperature and k is the coefficient of expansion. For copper $k = 0{\cdot}000\,009\,6$ per 1° F. Hence dip at maximum temperature $= \sqrt{[(10{\cdot}8^2 + 500^2)(78 \times \frac{3}{8} \times 0{\cdot}000\ 009\ 6)]} = \sqrt{(116{\cdot}5 + 70{\cdot}5)} = 13{\cdot}7$ ft. If the lowest wire were placed 27 ft. above ground at the pole, the height in centre of span would then be only about $13\frac{1}{4}$ ft., so that, unless the ground dipped down, a longer pole would be necessary.

The distance of the wires apart, or spacing, is regulated by two main factors: (i) the pressure, (ii) the dip; the latter depends on the weight of conductor and the span, as explained above, and the length of span is in turn dependent on the nature of the country. It is purely a commercial question whether high towers and long spans are preferable to short posts and spans. It has been shown in § 302 that the power lost in the line by reactance is proportional to the distance apart of the wires, and in long lines this must not be lost sight of. Short spans at low pressure should have the wires at least 1 ft. 6 ins. apart, and the distance must be increased with the pressure and the dip. Up to 10 000 V, with short spans, 2 ft. 6 ins. is sufficient. In long spans the wires should be arranged so that no two are in the same horizontal plane, because of their liability to blow together in a wind. For pressures over 20 000 V, the *minimum* distance in inches should be $= 6 + 0{\cdot}001\,25 \times$ volts. A useful dip and stress table will be found in Glover's *Vade Mecum.* A case has been cited in America where a heavy short-circuit, and the consequent repulsion due to the excessive current, caused a pair of wires to separate under great tension, and to fly together when the circuit-breaker acted. See § 338 under 'Mechanical Effect.'

It may be necessary to increase the spacing of wires to avoid corona discharge, but it is more effective to increase the diameter of the wires (§ 316).

328. Temperature Rise of Overhead Conductors.—The temperature rise (which affects the sag, § 327) of a *solid* copper conductor in still air is given approximately by—

$$t = 19{\cdot}8\rho I^2 / (d^3 \times 10^6);$$

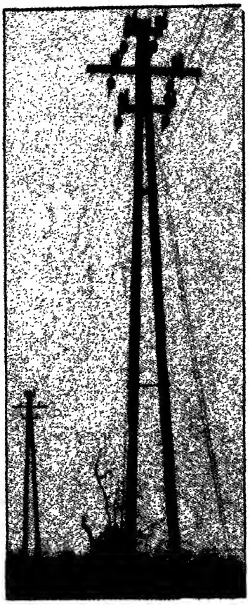
where t = temperature rise, in °C.; ρ = specific resistance of hard-drawn copper, in microhms per cm. cube (§ 62), at temperature $(t + t_a)$°C.; t_a = air temperature, in °C.; I = current, in amperes; d = diameter of conductor, in inches (Table 44, § 307). Until t is known the appropriate value of ρ cannot be determined, hence it is necessary to assume a limiting temperature $(t + t_a)$, calculate t from the formula, and repeat the calculation with a different assumed limiting temperature if the difference between the latter and the temperature rise is not approximately equal to the actual air temperature.

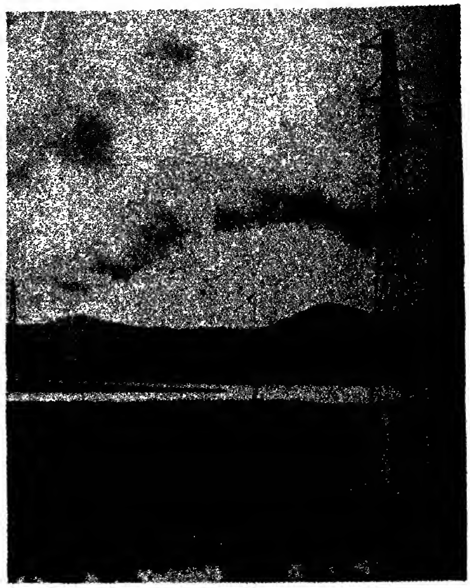
The inverted formula $I = \sqrt{(td^3 \times 10^6 / 19{\cdot}8\rho)}$ can be used directly to determine the current corresponding to a specified temperature rise above stated atmospheric temperature. For *stranded* conductors the diameter of the solid wire of equal copper section should be taken for d in the above formulæ; the current for stated temperature rise will be about 8 °/₀ greater than thus determined from the formula.

In *steel-cored* and *aluminium* cables the temperature rise is less than in copper conductors of equal resistance because the radiating surface is greater.

In practice the size of conductors used in an overhead line is generally determined by considerations of power or voltage drop and not by temperature rise.

329. Long Spans in Transmission Line.—Where practicable long spans, supported on built-up towers, are preferable to





British Aluminium Co., Ltd.

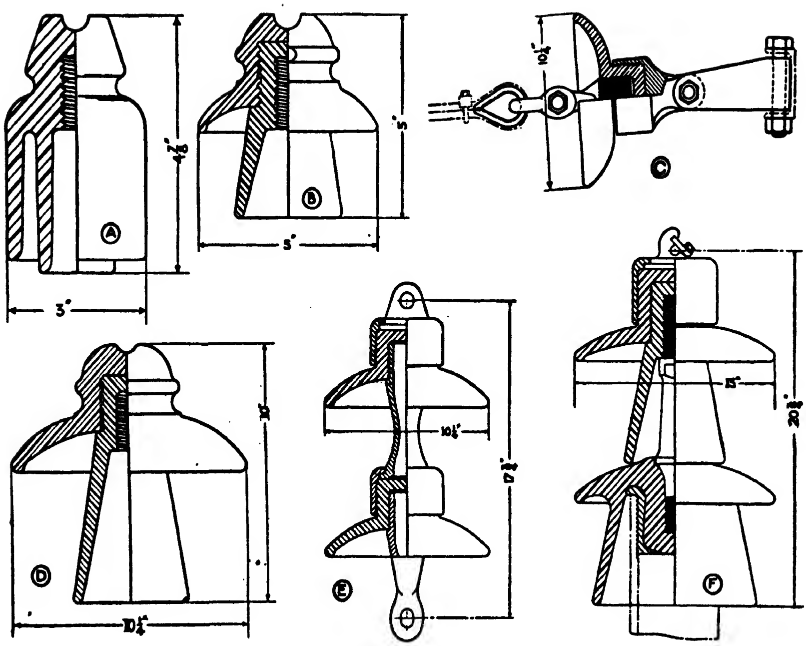
ALUMINIUM CONDUCTORS ON WOOD POLES.

A 6 000 V,. 3-phase, double-circuit transmission line on A type poles. For equal conductance the aluminium is 20 to 25 % cheaper than copper. The diameter of the conductors is 28 % greater and the strength 18 % less than with copper, but this is of little importance on spans up to 200 ft. Little difference is involved in the height or strength of poles required.

STEEL-CORED ALUMINIUM CONDUCTORS ON STEEL TOWERS.

A 154 000 V, 3-phase, single-circuit transmission line with 1 100 ft. span. The aluminium wires are stranded round a core of steel wires, providing a cable which is stronger, lighter, and cheaper than copper cable of equal conductance. This makes possible long spans, reduces the number of towers and insulators, and thus increases the security of the line. The long spans permissible are particularly useful where a river or marshy ground has to be crossed.

[To face p. 584.



TYPICAL 'KALANITE' INSULATORS FOR POWER TRANSMISSION LINES.

(By Callender's Cable & Construction Co., Ltd.)

	Flash-over Test.	
	Wet	Dry
(A) Low tension insulator . .	20 000 V	40 000 V
(B) 6 600 V straight line insulator	40 000 V	65 000 V
(C) 6 600 V end strain insulator .	40 000 V	65 000 V
(D) 33 000 V straight line insulator	85 000 V	120 000 V
(E) 33 000 V suspension insulator .	85 000 V	120 000 V
(F) 66 000 V straight line insulator	145 000 V	200 000 V

The lower petticoat of the insulator shown at (F) covers the cross arm and so reduces the liability to short-circuiting by birds.

[*To face p.* 585.

short ones on ordinary poles, for high-pressure transmission lines, for every support is a potential source of trouble and every insulator of leakage. Where the ground is level the dip renders it necessary to have very tall masts, but in hilly country it is often possible to use Nature's supports and to run from spur to spur; in such cases the amount of the dip is hardly limited. If the wires in an exceptionally long span are run vertically one below the other there is no danger of them blowing together and short-circuiting the line.

For example, consider a span of 2 000 ft. consisting of three No. 3 / 0 S.W.G. wires. In calculating a 500-ft. span in § 327 the effect of wind pressure in increasing the stress was neglected; this must now be taken into account, so in the formula $D = L^2 \times w / 8 \times S$ (§ 327) the factor w will now be $\sqrt{(W^2 + P^2)}$, where W is the weight of the wire in lbs. per ft., and P = (0·05 × Wind pressure in lbs. per sq. ft. × Diam. of wire in ins.). Then the equivalent $w = \sqrt{[0{\cdot}42^2 + (0{\cdot}05 \times 25 \times 0{\cdot}375)^2]} = \sqrt{(0{\cdot}176 + 0{\cdot}216)} = 0{\cdot}626$ lb. per ft. The dip, with a factor of safety of 5 at minimum temperature and 25 lbs. wind pressure, will then be $(2\,000 \times 2\,000 \times 0{\cdot}626) / (8 \times 1\,220) = 256$ ft.; or, with a factor of safety of 4, 206 ft.; and with a factor of safety of only 3, the dip would still be 155 ft.

Obviously such spans on level ground would involve impracticably tall supports, except in such cases as a river crossing, where the alternative would be an under-water cable (§ 292); instances, however, may be seen at Buffalo and elsewhere in the U.S.A., the tension on the wires being regulated by a pulley and weight inside the steel pole structure. In crossing a valley, on the other hand, these dips would be no obstacle, and the extra height gained under the wires by lowering the factor of safety would offer no advantage. The extra dip at the maximum temperature will not seriously affect the problem in the case of long spans—*see* formula in § 327. If on such a span silicon bronze wire of the same size, with a breaking stress of 110 000 lbs. per sq. in., were used instead of copper, the dip would be reduced to about half the figure given above; and in the case of only a few isolated spans, the extra loss of pressure could be ignored (*see* Table 49, in § 331).

330. Insulators.—Porcelain insulators are used for the most part, though glazed stoneware and glass are also extensively used in some countries. For low-tension work the insulators differ little from those used on telegraph lines, with double or triple petticoat, except that for large wires the mechanical strength must be greater. For high-tension circuits up to 50 000 V, or even 70 000 V, insulators of the same general type (*i.e.* pin supported) are used, but these are very much larger in order to secure mechanical strength sufficient to carry heavy lines and in order to increase the leakage path and the flash-over distance from the wire to the spindle and earth. For yet higher pressures, and up to 250 kV, suspension type insulators are used; these generally resemble inverted saucers or truncated cones, the under-surface being often corrugated, *i.e.* made with 'petticoats.' Such insulators are used mechanically and electrically in series to suspend the line from the cross-arm of the pole. The connection between successive insulators may be in the form of a pin cemented into the upper insulator which engages with a metal cap attached to the top of the insulator below ('cap' insulators); or the porcelain pieces may be formed with two tunnels at right angles through which pass stranded steel wire links providing the mechanical coupling between adjacent insulators (Hewlett insulators).

A number of typical insulators are illustrated opposite page 585; these are made of 'Kalanite,' a proprietary hot-moulding (§ 75) insulating material which is much tougher than porcelain and consequently not subject to malicious damage by stone-throwing, etc. The dielectric strength of Kalanite is said to be equal to that of porcelain, but its resistance to the passage of A.C. is about 28 °/$_o$ that of porcelain. The leakage current through a Kalanite insulator is about three and a half times as great as that through a porcelain insulator, but the actual amount of energy so dissipated is negligible in both cases at normal transmission frequency. The energy dissipated by the Kalanite, however, increases directly with frequency and, whereas vitreous insulators offer high resistance to the passage of high-frequency current, it is claimed that Kalanite permits lightning, switching, or other high-frequency surges to go safely to earth.

The characteristics and requirements of porcelain as an insulator are discussed in § 74, II(*c*), and the testing of insulators is dealt with in § 1033, Vol. 3. The design and manufacture of insulators for extra high pressures are highly specialised problems in which great advances have been made during recent years. It is now recognised that the main problem of design is not to provide a leakage path of maximum length on the surface of the insulator, but to shape and arrange the parts of the insulator, so that it and the surrounding air are subjected to as low, and as nearly uniform, potential stress as possible. A mechanical difficulty, where there are cemented joints between steel and porcelain, is to obtain secure fixing without risk of cracking by expansion or contraction stresses (the coefficients of expansion of steel and cement are higher than that of porcelain).

C. E. Elder (*Jour. I.E.E.*, Vol. 52, p. 304) recommends that pin-type insulators should be secured to their pins by hemp twine packing, without any cement; the pin should have a rough-cut thread to grip the twine, and the latter should be of such size that only one layer is required; also, the twine should be spun loosely enough to bed well into the threads, and a felt wad should be inserted at the bottom of the hole.

A string of Hewlett insulators consists essentially of a chain of steel links insulated from each other by spacing pieces of porcelain; the mechanical strength of the suspension is unaffected by breakage of the porcelain, and there is little risk of the metal links being melted by arcing.

The use of cement in cap-type suspension insulators can be avoided by screwing the pin into a specially shaped nut which is held inside the insulator by a piece of porcelain of spherical form; the latter is inserted in the cavity before the insulator is baked and cannot subsequently be withdrawn (*see Sc. Abstr.*, B, 201, 1922).

The best modern pin-type insulators for high-pressure lines are designed with full recognition of the importance of securing uniformity in the electrostatic field, and these insulators are characterised by the absence of the very wide-spread hood which formed a feature of older designs. The same principle is taken into consideration in the design of suspension insulators. Where they are applicable pin-type insulators have the advantage that a shorter pole or tower can be used than with suspension insulators for the same clearance above ground.

At the pressures for which suspension insulators are used, and particularly above 100 kV, the uniformity or otherwise of the division of potential between the units of a string of insulators is an important factor. Even if only two insulators be used in series the P.D. across the one nearer the line is greater than that across the other, and, as the number of insulators in series is increased, the departure from uniform division of potential becomes more marked.

With more than five insulators in series there is still from 20-30 % of the total voltage across the insulator nearest the line, and if this be a higher P.D. than one insulator can carry safely (as it may well be in the case of extra high pressure lines) we reach a limit beyond which it is impossible to insulate the line because the addition of another insulator to the chain does not appreciably reduce the P.D. across the line-end unit. Fortunately, this difficulty can be overcome. The division of potential between the units of the string is determined by the relative magnitude of the capacity of the insulator itself and its capacity to earth. By increasing the capacity of the line-end insulator, the P.D. across the latter can be reduced. In this respect cap-type insulators are preferable to Hewlett insulators because of their greater capacity (say 30 $\mu\mu$F compared with 15 $\mu\mu$F). In some cases the cap is extended by metallising the adjoining surface of the porcelain (by the Schoop-spray or similar process), thus further increasing the capacity of the insulator; the objection to this is that the end insulators are not standard, and, therefore, involve extra cost and the risk of being used in the wrong position. The use of cap insulators in series with Hewlett insulators offers another means of graduating the capacity, and, therefore, the potential of the insulation as a whole. Instead of increasing the capacity of the end insulators the division of potential may be equalised by reducing the capacity of the links with regard to earth. This may be done by using oil-soaked hardwood or other insulating material instead of metal links, provided that sufficient mechanical strength can be obtained.

In America a number of extra high pressure lines (up to 220 kV between phases) are insulated by strings of standard suspension insulators, electrostatic flux shields being provided at each end of the string. These consist of large metal rings, one earthed and one connected to the line, placed concentric with the string of insulators, and serving as electrodes between which is established a uniform electrostatic field. The stress across the individual insulators is equalised by this means, and any flash-over or arcing occurs between the guard rings, well away from the insulators.

The flash-over voltage in fog or mist generally determines the number of suspension insulators needed in a chain; the flash-over voltage of the chain being satisfactory, there is generally no risk of break-down by puncture.

In the case of some three-part insulators mentioned by W. T. Taylor (*Jour. I.E.E.*, Vol. 46, p. 538), the flash-over voltages for a single insulator and for 2, 3, 4, 5, and 6 in series were, respectively: *Dry Test*—90, 160, 220, 274, 310, and 340 kV. *Standard Precipitation Wet Test*—56, 90, 130, 175, 220, and 265 kV. Three insulators of this type in series are considered ample for a 60 000 V line, and six insulators for a 104 000 V line.

Insulators should have the same mechanical factor of safety as the wires which they support, so that the breaking load of a terminal insulator is the same as that of the wire with which it is used. Thus a No. 3/0 wire has breaking load 6 100 lbs. and working load 1 220 lbs.; for a terminal insulator to carry this load, with a factor of safety of 5, its *breaking* load should be not less than 6 100 lbs. The Electricity Commissioners Regulation, No. 7 of both El. C. 39 and E.C. 53, dealing with supports generally—this includes the insulators—says that 'The supports, in conjunction with stays or struts if provided, shall withstand the longitudinal, transverse and vertical loads due to the ice loadings and wind pressure hereinafter (*see* § 324) specified without damage and without movement in the ground. In no case shall the strength of a support in the direction of the overhead line be less than one-quarter the required strength in a direction transverse to the line.'

Where the wire is not terminated, but makes an angle or change of direction at the insulator, sin $(\theta / 2)$ must not be greater than $(R / 2T)$. In the present case R, the permissible load on the insulator, with the required factor of safety, is 1 220 lbs.; T, the working load on the wire, is the same; so $R / 2T = 0{\cdot}5$. Therefore, when the wire makes an angle of 120°, the supplement θ being 60°, sin $(\theta / 2) = 0{\cdot}5$. As in the case of stays (§ 326), this angle is equivalent to a terminal point. At any more severe angle a stronger insulator is required; thus at 90°, where θ is also 90°, sin $(\theta / 2)$ is 0·71 and is greater than $(R / 2T)$, whereas at any less angle than 60° the insulator has a higher factor of safety than 5. Where a large solid copper wire makes a considerable angle, as at a corner pole, it is advisable to break up the angle by using two insulators; otherwise there is considerable danger of breakage occurring.

It is not unusual for an overhead line to break down from the deposition of salt, blown inland during storms. In the autumn of 1927 a series of such failures was reported on inland lines, subsequent to an abnormally severe S.W. gale, which lasted for 30 hours and reached a maximum velocity of 90 m.p.h., with an average of 60 to 70 m.p.h. During the gale the atmosphere was abnormally dry, but later it became humid and heavy rain followed. Failures of insulation occurred in coastal areas during the gale, but were not experienced inland until some hours after its cessation. Investigation showed that:—

(1) During the gale, large quantities of sea water were raised into the air.
(2) The spray was at once deposited on the insulators near the coast, causing their failure.
(3) The dry air travelling inland, caused the water to evaporate and so become charged with salt particles.
(4) The salt particles were sufficiently damp to adhere to insulators, but not so damp as to form conducting surfaces.
(5) When the air became humid, the salt absorbed the moisture and formed conducting paths over the insulators.
(6) The heavy rain washed the salt off the insulators and the disturbances ceased.

In another case, with very similar conditions, an abnormal number of breakdowns occurred during the humid period and ceased when the rain fell. All the faults were located in a leeward direction from a rocky beach and occurred first at points nearest to the sea. It is stated that where 3-petticoat insulators have been used, instead of 2-petticoat, there has been less trouble or none. The Lothians Electric Power Co. has stated that during such storms their 11 kV lines, protected by 'Pernax' guards, were unaffected, whereas a similar line, ten miles from the coast, and not so protected, flashed over several times.

331. Conductors other than Copper.—The use of aluminium as a material for overhead conductors has been mentioned in §§ 63, 308. The diameter of an aluminium wire is 28 °/₀ greater than that of a copper wire of equal conductivity, so the wind pressure and weight of snow are increased. According to the British Aluminium Co., the coefficient of linear expansion is 0· 000 013 6 per 1° F., so the dip increases more rapidly than with copper (§ 327), and the spacing between wires must be greater. For long spans the difference in deflection between aluminium and copper wires may be so great as to require a higher pole or tower when the former metal is used. As greater care is necessary for stringing aluminium than copper wire, and also for its general handling, it costs more to erect. Mechanical connectors are often used in place of soldered joints.

Cadmium-copper wires (§ 909, Vol. 3)* offer the advantage of high tensile strength with relatively high conductivity. For very long spans bronze and even steel (§ 309) wires are often used. Particulars of the materials mentioned are given in Table 49. As to aluminium steel-cored cables, *see* § 917 (Vol. 3).

As mentioned in §§ 64, 309 iron conductors may be used economically for the transmission of relatively small amounts of power at high voltage, as in rural electricity supply. A typical American installation uses No. 8 S.W.G. galvanised iron wires for the transmission of 95 kVA at 22 000 V, 3-phase ($2\frac{1}{2}$ A per phase) for a distance of 31 mls.; the power loss in the line is about 9 °/₀. The charging current of lines of these physical dimensions (whether of iron or copper) is a serious factor, and it is advantageous to secure induction motor loads along the line, as well as at the end, if possible (§ 158). Line loss is a minimum when the current at the load end has a lagging component about equal to half the charging current (*El. World*, Vol. 70, pp. 715, 1 252).

* *See also* 'Copper-Cadmium Wire for Electrical Transmission,' by W. C. Smith, *El. World*, Vol. 79, p. 223.

TABLE 49.—*Constants of Aluminium, Cadmium-Copper, Bronze, and Steel Conductors (see also* §§ 63, 307-309).

	Conductivity; Copper = 100.	Breaking Stress. Lbs. per Sq. In.	Weight of Equivalent Conductor; Copper = 100.	Coefficient of Expansion per 1° F.	Percentage Increase in Resistance per 1° F.
Copper, hard drawn	100	56 000	100	0·000 009 6	0·238
Cadmium-copper (0·7 % Cd)	93·5	73 000	107	—	—
" " (1·1 % Cd)	90	100 000	111	—	—
Silicon bronze (1)	97	63 000	103	0·000 01	0·1
" " (2)	80	76 000	125		
" " (3)	45	110 000	222		
Phosphor bronze	26	101 000	384		
High carbon steel	11	125 000	910	0·000 006	0·2
Aluminium	61	30 000	48	0·000 011	0·217

332. Cost of Overhead Lines.—Table 50, from the Electricity Commissioners' Report for 1931-32, gives the actual cost of certain high-tension rural lines of steel and aluminium. The same Report gives an analysis of the cost of 9 miles of low-tension underground distribution at 400 / 230 V consisting of 4-core 0·06 sq. in. paper-insulated lead-covered and jute-served cables laid direct in the ground, *viz.* cost of cable per mile £389, and of other materials and labour £204. Services off this cost on the average £4 13s. 4d. In some cases, the Commissioners found the cost of underground distribution less than that of overhead lines.

TABLE 50.—*Cost of* 11 000 *V Overhead Lines, on Wooden Poles, in Bedford Rural Demonstration Area.*

Conductor.	Technical Details and Approximate Cost.				
	Size of Conductor.	Kilowatt Capacity of Line.	Route Length.	Total Cost.	Average cost per Mile.
		kW	Miles	£	£
Galvanised Steel	2 × 7/12 S.W.G.	100	1·65	395	239
" "	3 × 7/12 S.W.G.	150	27·11	9 045	333
Steel-cored aluminium	3 × 0·05 sq. in.	1 000	31·36	11 758	375
Steel-cored aluminium	3 × 0·025 sq. in.	500	4·83	1 606	333

The transmission system of the Ganges hydro-electric scheme cost:—

37 000 V lines, double-circuit, 2 000 kW, £660 per mile.
11 000 V „ single-circuit, for district branches, about £300 per mile; kW not stated.

While the above figures may be useful as a general guide, careful estimates must be made for each case on its merits. For underground cables a quotation should be obtained from the makers, and the cost of trenching and laying added. In the case of overhead lines, the price of bare copper wire fluctuates between about £60 and £85 per ton in normal times. Ordinary light metal poles cost from £3 to £12 or more, and built-up towers for long spans may cost ten times as much. For maintenance *see* § 1015, Vol. 3.

333. Economical Section of Conductor; Kelvin's Law.— In the majority of actual cases a certain percentage loss of the delivered power is assumed from experience, and the pressure of transmission is settled according to the length of the line. Strictly speaking, these factors should be ascertained by the application of Kelvin's Law,* so that the annual cost of wasted energy in the line (I^2R watts) *plus* the annual allowance for interest and depreciation of the line shall be a minimum.

Thus, take the case of D.C. transmission calculated in § 296. The full-load current was 159 A. The probable load factor in any case can be approximately gauged from other working undertakings; assume it to be 31 °/₀, and the *average* current will then be 50 A. Take the resistance per mile of any wire of about the size required, say 0·25 Ω per ml.; then for a mile of line (lead and return) the resistance is 0·5 Ω. The power lost in this would (on the average) be ($50^2 \times 0{\cdot}5 / 1\,000$) or 1·25 kW, equivalent to 11 000 kWh per annum per mile of *line*. From the rough estimates the probable output of the station in units and the total annual cost of the plant [interest, depreciation, fuel (if any), and establishment] will be known, giving the cost of each unit generated. In this case take the cost per unit as 0·66d., a fair figure for water power on the assumed conditions. Then the cost of the 11 000 units lost in transmission per mile would be £30 5s. Now lay out a diagram (Fig. 54) with resistance (inversely proportional to cross-sectional area) of copper horizontally and cost vertically, and mark the point where £30 5s. and 0·25 Ω per ml. meet. Draw a straight line through this

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* Lord Kelvin's original statement was: 'The economical cross-sectional area is that for which the annual cost of energy lost just equals the annual interest on the capital invested.' Hopkinson's modification (which is particularly applicable to feeders for public electricity supply) provides for the ratio of the gross annual revenue derived from the conductor to the total gross annual expenditure on it and on the energy supplied through it, to be at the maximum.

from the origin. Next take any three sizes of wire somewhere near the mark and find the approximate cost of a mile run, *i.e.* in this case 2 mls. of wire. Taking this at £75 a ton, or say 8d. a lb., we get the following :—

7/0 S.W.G.	Weight of 2 mls. = 8 000 lbs.	Cost = £266
5/0 „	„ „ = 6 000 „	„ = £200
3/0 „	„ „ = 4 400 „	„ = £147

Taking 10 °/₀ of these costs for the charges on the line, mark off the points where these annual costs correspond with the ohms per mile of the wire thus :—

7/0 S.W.G.	Ohms per mile = 0·22.	Annual cost = £26 12s.
5/0 „	„ „ = 0·29.	„ „ = £20
3/0 „	„ „ = 0·39.	„ „ = £14 14s.

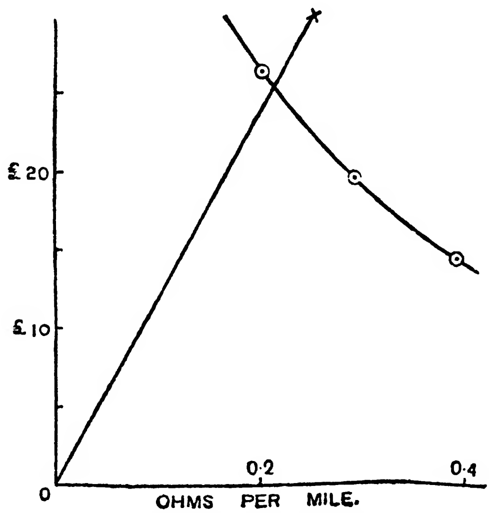


FIG. 54.—Graphical example of Kelvin's Law.

Draw the curve through these three points, and where this curve is intersected by the straight line the combined costs will be a minimum. The resistance per mile corresponding to this point, *viz.* 0·22 Ω per ml., will give the most economical size of wire to use.

In the case of 3-phase lines, the same data may be more easily obtained and plotted for a single conductor than for the three wires.

In the case of overhead lines results near enough for practical purposes will be obtained by considering the annual charges on the copper alone, though strictly speaking the cost should be increased for large sizes owing to the greater cost of the poles.

In the case of insulated cables the total cost should be used as a basis for the calculation, instead of the cost of the copper alone.

At 20 kV working pressure, the commercial considerations entailing the selection of such a voltage also determine to some extent the size of cable most commercially economical from the transmission and distribution point of view. In the case of distribution to a number of areas in various stages of development, the most economical section will be 0·1 to 0·15 sq. in. at 20 kV. Where a large amount of power has to be transmitted from a generating station to a main distributing centre, and the cable will be more or less fully loaded, it may be best to use, say, a 0·25 sq. in. cable, working at 33 kV. The considerations then to be taken into account are: (*a*) the limit of current density fixed by working temperature and largely dependent on method of laying and number of cables in proximity to one another; (*b*) the broad aspect of the whole scheme in which cable considerations are simply an item (C. J. Beaver).

It is evident that where water power is in question the generating cost per unit will usually be lower than with steam; if, however, the available power is limited, and can all be sold, every unit lost in the line is a direct loss of revenue to the undertaking at the actual rate of sale, and the average *selling* price per unit should then be taken instead of the prime cost.

334. **Cables *v.* Overhead Lines.**—Underground cables are in general (though not always—*see* § 332), much more expensive to install than overhead lines, but in crowded cities the former are preferable if the undertaking can stand the cost. In this country, distribution circuits in towns are cabled with few exceptions, but overhead work is sometimes used to begin with, and cable substituted later on when the demand can be gauged accurately. Feeders or lines which do not require to be tapped *en route* (except long transmission lines) should as far as possible be placed underground; distribution lines, on the other hand, are more conveniently run overhead, as the cost of service lines is much less. This is an important point with a new undertaking; where houses are far apart, as in rural districts and colonial cities, the number of services per mile is abnormally low, so the cost has to be kept down if any profit is to be made. For long-distance transmission, aerial lines are universal.

Some idea of the relative cost of underground and overhead transmission lines is to be obtained from the following figures (pre-war; for pre-war and post-war prices *see* §§ 195, 564), but these may only be taken as a general guide, since

		200	500	1 250	10 000 to 15 000	30 000
Kilowatts . . .		200	500	1 250	10 000 to 15 000	30 000
Voltage		6 to 10 kV	6 to 10 kV	10 to 12 kV	50 to 100 kV	100 kV
Capital cost per kW per ml.	Overhead .	35s.-20s.	20s.-10s.	12s.-6s.	3s.-1s. 6d.	1s.
	Underground	75s.-50s.	40s.-25s.	22s.-15s.	3s. 6d.-2s.	1s. 6d.

conditions differ enormously in individual cases, and even 1d. per kW per mile means £12 500 when the transmission of 30 000 kW, a distance of 100 mls., is in question. A.C. can hardly be transmitted underground at pressures exceeding 33 000 V, owing to the magnitude of capacity currents (§§ 288, 311) (*see also* Table 50, § 332).

In comparing the costs of transmission by 3-phase A.C. and by the Thury D.C. series system (§ 317), J. S. Highfield gives various estimates, from which the figures in the table below are deduced.

Cost per kW per ml. of line or cable (erected) for transmitting		(*a*) 10 000 kW	(*b*) 30 000 kW
		s. d.	s. d.
Overhead—	(1) 60 kV, 3-phase	3 4	2 0
	(2) 60 kV, D.C.	2 8	1 5
	(3) 100 kV, 3-phase	2 6	1 1
	(4) 100 kV, D.C.	2 2	0 11
Underground—	(5) 20 kV, 3-phase	7 6	5 6
	(6) 50 kV, D.C.	3 6	-
	(7) 100 kV, D.C.	3 0	1 6

The assumptions on which these (pre-war) figures are based are :—

Overhead.—6 wires for A.C., 4 for D.C. Line 100 mls. long; P.F. 0·85; full-load pressure drop, 10 %; lattice steel towers 150 yds. apart.

Underground.—Cables in stoneware ducts. Copper £62 per ton ; lead £13 9s. per ton. D.C. system, two wires equally insulated; sectional area—case 6 (*a*), 0·25 sq. in.; 7 (*a*) 0·125 sq. in.; 7 (*b*), 0·35 sq. in. A.C. system—case 5 (*a*), two 3-core cables 0·175 sq. in. area; case 5 (*b*), two 3-core cables 0·35 sq. in. area. Current density in cables 850 A per sq. in. Cost of trenching, laying, and two- or three-way conduit—cases 5 (*a*), 6, and 7, £834 per ml.; case 5 (*b*), £1 100 per ml. Further information relating to the cost of transmission is given §§ 332, 333.

At pressures for which they are applicable (§ 288) underground cables have the advantage of not being ordinarily exposed to lightning,* and of being out of the reach of most other extraneous causes of break-down. The security of supply is therefore greater with cables (where these are applicable) but when a break-down does occur it is more difficult and costly to locate and repair than is the corresponding break-down on an overhead line. Deterioration in cables can generally be detected before break-down occurs, but the nature of faults on overhead lines (breakage, short-circuit, etc.) is such that the occurrence is sudden. From the point of

* The possibility of a lightning discharge being carried to a buried cable by an outcrop of a conducting strata or water-filled fissure, should be taken into consideration. Instructive notes on this and associated matters are to be found in *Elektrotechnik und Maschinenbau*, Vol. 56, p. 105.

view of public safety and the safety of workmen cables have the advantage. The inductive drop is much greater in overhead lines than in cables (§ 310), but, on the other hand, the charging current is generally much greater in cables than in overhead lines (§§ 304, 311).

335. Telephones.—In every electric supply undertaking, and especially where there is transmission of power over a distance, telephone communication is necessary between the different sub-stations and the power-house. For this service overhead lines are almost invariably used. It is preferable to carry these circuits on a different alignment to the power wires, because when there is a fault in the transmission service interference is likely to result between it and the telephone circuits, and it is at such times that clear speech is most important. In any case a double metallic circuit should be used, and not a single line with an earth return. The wires should be systematically transposed at frequent intervals, so as to neutralise the effects of induction due to variations in the current in the power line and also to the normal cyclic variation in an alternating current line; each 3-phase power circuit should also have two points, approximately dividing the total length evenly, at which the wires are altered in position 120°, so as to give one complete transposition in its length. In long lines several complete rotations or transpositions are allowed. It is necessary to safeguard the line against accidental contacts with the power circuit, whether due to breakage or to trees, and also to safeguard the operators against shocks from the line becoming charged inductively. In some cases abroad it has been necessary, in order to prevent theft of wire, deliberately to charge the line to high pressure at night.

Although in very long lines the size of the telephone conductor becomes important, it is not so within the limits of transmission of power. Copper, phosphor bronze, mangan bronze, and silicon bronze wires are mostly used, and a wire of 100 lbs. per ml. (say No. 14 S.W.G.) is large enough electrically; a smaller size would be too liable to mechanical damage. For long spans copper wire is unsuitable, and these special bronzes have much greater tensile strength; but as the alloy and the strength are increased the conductance is decreased in a much greater proportion (*see* Table 49, § 331). The weight of a telephone wire may be taken without serious error from Table 40, § 280, according to its gauge or sectional area, whether it is copper or bronze. The cost of mangan bronze was normally about 1s 3d. to 1s 6d. per lb. pre-war, but varies with that of copper; phosphor bronze and silicon bronze are about 20 °/。 dearer.

A useful paper on telephone troubles in the tropics was read before the Institution of Electrical Engineers by W. L. Preece (*Jour. I.E.E.*, Vol. 53, p. 545). Amongst other points specially worthy of notice in India are the following: It is not uncommon for insects to find their way into a subscriber's instrument through the switch-hook; this should therefore carry a brass plate which keeps the slot in which the arm works entirely covered. There should be no terminals above the instrument, but the conductors should be taken through holes into the case and sealed up. Internal wires should be separated as much as possible. Lightning protectors should be fixed where the wires enter the building, and not by the instrument; otherwise a fire may easily result. For the overhead line the use of glass insulators of the oil-filled type is suggested tentatively, as a protection against insects. As a protection from lightning troubles on the line, causing break-downs at the pole box, the use of the vacuum type of protector is recommended, in which two carbon blocks are inserted in an exhausted glass tube, the opposite surfaces being serrated and fixed about $\frac{1}{16}$ in. apart. A fuse in the circuit in addition is always essential. The use of an additional earthed iron wire, on the top of the poles, is also recommended (*see also* § 347). *Mutatis mutandis*, these same precautions are advisable in power circuit accessories, such as relays; mice cause many breakdowns every year.

336. Bibliography (*see* explanatory note, § 58).

OFFICIAL REGULATIONS.

Regulations prescribed by the Electricity Commissioners under No. A. 13 of the regulations for securing the safety of the public, made by the Board of Trade under the Electric Lighting Acts, 1882 to 1909. [There are two sets of these regulations, for pressures not exceeding and exceeding medium pressure D.C. and low pressure A.C.]

Indian Electricity Rules (1937) prescribed by the Central Government; reprinted in *The Law relating to Electrical Energy in India and Burma* (Thacker & Co.).

STANDARDISATION REPORTS, ETC.

B.S. Specifications.

No. 65. Salt-Glazed Ware Pipes.

No. 125. Hard-drawn Copper Solid and Stranded Circular Conductor for Overhead Power Transmission Purposes.

No. 128. Bare Annealed Copper Wire for Electrical Machinery and Apparatus.

No. 134. Iron or Steel Tubular Poles for Telegraph and Telephone Lines.

No. 137. Porcelain Insulators for Overhead Power Lines (3 000 V and Upwards).

No. 139. Red Fir Wood Poles for Telegraph and Telephone Lines.

No. 144. Creosote for the Preservation of Timber.

Nos. 174 to 181. Overhead Line Wire Material (non-ferrous) for Telegraph and Telephone Purposes.

Nos. 182 to 184. Galvanised Iron and Steel Wire for Telegraph and Telephone Purposes.

No. 215. Hard-Drawn Aluminium and Steel-cored Conductors for Overhead Power Transmission.

No. 223. Electrical Performance of High-Voltage Bushing Insulators.

No. 446. Braided Cables with Copper Conductors for Overhead Transmission Lines.

No. 513. European Larch Poles for Transmission Lines.

No. 607. Reinforced Concrete Poles for Electrical Transmission and Traction Supports.

No. 672. Hard-Drawn Cadmium-Copper, Solid and Stranded Circular Conductors for Overhead Power Transmission Purposes.

Books.

First Principles of the Electrical Transmission of Energy. W. M. Thornton (Pitman).

The Principles of Electric Power Transmission by Alternating Currents. By H. Waddicor (Chapman & Hall).

Overhead Power Lines. By W. Morecombe (Chapman & Hall).

Theory of Electric Cables and Networks. A. Russell (Constable).

Electrical Design of Power Transmission Lines. W. T. Taylor and R. E. Neale (Chapman & Hall).

Overhead Transmission Lines and Distributing Circuits. F. Kappre (Constable).

Three-Phase Transmission. W. Brew (Crosby Lockwood).

Constant Voltage Transmission. H. B. Dwight (Wiley).

Overhead Electric Power Transmission. A. Still (McGraw-Hill).

Transmission Line Construction. R. A. Lundquist (McGraw-Hill).

Electrical Transmission and Distribution. J. R. Beard (Pitman).

Electric Power Systems. W. T. Taylor (Pitman).

Central Station Electricity Supply. A. Gay and C. H. Yeaman (Pitman)

Electric Mains and Distributing Systems. J. R. Dick and F. Fernie (Benn Bros.).

Standard Polyphase Apparatus and Systems. M. Oudin (Low).

I.E.E. Papers.

British Practice in the Construction of H.T. Overhead Transmission Lines, B. Welbourn. Vol. 52, p. 177.

Design of High-Pressure Distribution Systems, J. R. Beard. Vol. 54, p. 125.

The Distribution of Electricity, W. B. Woodhouse. Vol. 59, p. 85.

Economic Aspects of Extra-High-Tension Distribution by Underground Cable, R. O. Kapp. Vol. 59, p. 94.

The Possibility of Transmission by Underground Cables at 100 000/150 000 Volts, A. M. Taylor. Vol. 61, p. 220.
Report on Tests of Hard-Drawn Copper Wires and Cables for Overhead Transmission Lines (B.E.R.A.). Vol. 61, p. 997.
Report on Tests of Hard-Drawn Aluminium Wires and Cables (B.E.R.A.). Vol. 61, p. 1 013.
Report on Tests of Galvanised Steel Wires and Cables (B.E.R.A.). Vol. 61, p. 1 026.
The Rating of Cables for Intermittent or Fluctuating Loads, *ibid.* Vol. 61, p. 363.
Single-Core Sheathed Cables for Alternating Current, W. Cramb and N. I. Calderwood. Vol. 61, p. 477.
Permissible Current Loading of British Standard Impregnated Paper-Insulated Cables (B.E.R.A.). Vol. 61, p. 517.
Electric Line Calculations; their Practical Application to Transmission and Distribution Problems, W. T. Atkins. Vol. 61, p. 1 044.
A Vector Treatment of Long Transmission Lines, S. Holmes. Vol. 62, p. 471.
The Current-Carrying Capacity of Solid Bare Copper and Aluminium Conductors, J. W. Melsom and H. G. Booth. Vol. 62, p. 909.
Low-Tension Cables on Single-Phase Circuits, S. W. Melsom and W. E. Bear. Vol. 63, p. 190.
Single-Core Armoured Cables for Alternating Current, G. M. Harvey. Vol. 63, p. 368; and Prof. Cramb, Vol. 63, p. 379.
Dielectric Problems in High-Voltage Cables, P. Dunsheath. Vol. 64, p. 97.
Permissible Current Loading of British Standard Impregnated Paper-Insulated Cables (B.E.R.A. 66, see earlier paper above). Vol. 64, p. 161.
Circuit Constants in Transmission Line Calculations, A. C. A. Caldwell, Vol. 64, p. 243.
The Design of City Distribution Systems and the Problem of Standardisation, J. R. Beard and T. G. N. Haldane. Vol. 65, p. 97.
Transmission and Distribution, J. R. Beard. Vol. 65, p. 338.
33 000 Volt Cables with Metal-Sheathed Cores, P. Dunsheath. Vol. 65, p. 468.
Conflicting Cable-Sheath Loss Formulæ, L. C. Hutchinson. Vol. 65, p. 903.
Irregularities in Continuously Loaded Cables, A. Rosen. Vol. 65, p. 989.
Sheath Losses in Single-Core Cables for 3-phase Transmission, T. N. Riley. Vol. 65, p. 1 006.
The Physical Properties of Lead Cable-Sheaths, P. Dunsheath and H. A. Tunstall. Vol. 66, p. 280.
Galvanised Steel Conductors for Overhead Transmission Lines, E. C. Walton. Vol. 66, p. 1 065.
Overhead Transmission Lines in High Winds, E. H. Lamb. Vol. 66, p. 1 079.
Pressure Testing of High-Voltage Cables, E. A. Bevis. Vol. 66, p. 1 086.
Sheath Losses in Single-Conductor Lead-Covered Cables, A. H. M. Arnold. Vol. 67, p. 69; and Prof. Cramb, Vol. 69, p. 335.
Overhead Electric Lines, W. B. Woodhouse. Vol. 67, p. 217.

Three-phase Systems of Unarmoured Single-Conductor Cables (B.E.R.A.) Vol. 67, p. 359.

Construction of the 'Grid' System in Great Britain, G. B. J. Wright and C. W. Marshall. Vol. 67, p. 685.

The Prevention of Ionisation in Impregnated Paper Dielectrics, S. G. Brown and P. A. Sporing. Vol. 67, p. 968.

The Impedance and Power Losses of 3-phase Overhead Lines, P. D. Morgan and S. Whitehead. Vol. 68, p. 367.

Water-Penetration Effects in Lead-Sheathed Power Cables, E. A. Bevis. Vol. 68, p. 434.

Standardisation of Distribution Voltage, Council of I.E.E. Vol. 68, p. 516.

Surges and Over-Voltage Phenomena in Transmission Lines due to Lightning, Dr. H. Norrinder. Vol. 68, p. 525.

Surge Investigations on Overhead Lines and Cable Systems, S. W. Melsom and others. Vol. 68, p. 1 476.

Transmission and Distribution, J. R. Beard and J. Hacking. Vol. 69, p. 730.

Suspended Insulated Conductor Vibration, P. J. Ryle. Vol. 69, p. 805.

Interference between Power and Communication Circuits (B.E.R.A.). Vol. 68, p. 587.

Two Transmission Line Problems; Suspension Insulators; Conductor Vibration. P J. Ryle. Vol. 69, p. 805.

The Design of a Distribution System in a Rural Area. E. W. Dickenson and H. W. Grimmett. Vol. 70, p. 189.

The Lower-Voltage Sections of the British Grid System. C. W. Marshall. Vol. 74, p. 105.

Some Aspects of the Electrical Transmission of Power by Means of Direct Current at Very High Voltages. H. Rissik. Vol. 75, p. 1.

Some Measurements on the Electrical Characteristics of Insulator Strings. W. G. Standring. Vol. 75, p. 111.

Variation in Distribution of Wind Pressure on Overhead Lines (E.R.A. Report). Vol. 76, p. 677.

Voltage Variation at Consumers' Terminals (E.R.A. Report). E. B. Wedmore and W. S. Flight. Vol. 76, p. 685.

Tests on the Electric and Magnetic Properties of Aluminium-Steel Cored Cable. J. A. Clegg. Vol. 77, p. 59.

Vibration in Overhead Conductors. T. Varney. Vol. 77, p. 407.

Transmission-Line Insulators under Deposit Conditions. W. J. John and F. M. Sayers. Vol. 77, p. 629.

Loss of Revenue on Heating and Lighting Loads, due to Poor Voltage Regulation. F. S. Naylor. Vol. 79, p. 33.

Routine Over-Voltage Testing of High-Voltage Cables. C. Kibblewhite. Vol. 79, p. 82.

Suspension Insulators for E.H.T. Transmission Lines. I. S. Scott-Maxwell. Vol. 79, p. 246.

The Electrical Characteristics of 132-kV Line Insulators under Various Weather Conditions. J. S. Forrest. Vol. 79, p. 401.

The Jointing and Terminating of High-Voltage Cables. W. Holttum. Vol. 80, p. 517.

The Gas-Impregnated Cable. A. N. Arman. Vol. 81, p. 625.

CHAPTER 15.

PROTECTION OF CIRCUITS AND APPARATUS.

337. Conditions against which Protection is Required.—The two main functions of the systems and devices used to protect electrical circuits and apparatus are: (1) The prevention of damage wherever possible, and in other cases the restriction of damage, as regards extent and degree; (2) the maintenance of supply and operation in all parts of the system with the exception of the section directly affected by the fault. The principal irregularities which may cause damage to circuits or apparatus, and against which protection is therefore required, are: (*a*) Excessive current, due to overload or short circuit (*see* §§ 338-344): (*b*) Excessive pressure, due to switching surges, resonance or lightning (*see* §§ 345-351): (*c*) Failure of insulation, resulting in leakage to earth or between wires (*see* §§ 352-354): (*d*) Low voltage; or complete failure of supply, by loss of voltage at the generator, transformer, etc., feeding the circuit, or by interruption of the circuit (*see* § 355): (*e*) Reversal of current or power flow (*see* § 358): (*f*) Fire risk (§ 356): (*g*) risk from salt-storms and from birds and, in the tropics, flying foxes, flying into the lines. The causes and effects of these irregularities, and methods of protection, are discussed in the paragraphs stated. The need for protection has risen with the voltages and powers concerned in electricity supply systems and, though the total cost of protective gear is high, it is small in comparison with the value of the equipment protected and with the cost of the damage which might otherwise be occasioned.

338. Cause and Effect of Excessive Current; Short Circuit.—The power or 'load' in any electrical circuit is measured in watts or kilowatts (§§ 48-56) and is proportional to the product of pressure by current. The term 'overload' is, however, generally applied only to excessive current, partly because the standard system of transmission and distribution is the 'constant voltage system' (Chapter 20 *passim*), and partly because an increase in voltage does not increase the heating of conductors (§ 49) but simply increases the stress upon the insulation. The value of the current flowing in any circuit is determined by Ohm's Law (§§ 17, 44) provided that allowance be made for any back E.M.F. in the circuit (*e.g.* that of a motor or secondary cell), and that the impedance of the circuit (instead of its ohmic resistance) be considered in the case of alternating current. Thus, excessive current may result from the resistance between the supply mains being too low as, for example, when a low resistance motor is switched straight on to the mains, or when an excessive number of lamps or other current-consuming devices are connected in parallel between the mains. If the mains themselves or two parts of a winding, etc., at different potentials come into metallic contact or are bridged by a conductor (such as a spanner) of negligible resistance, the current becomes abnormally high (§ 339) and there is said to be a 'short circuit' between the points concerned. Short circuit is thus the extreme case of excessive current or overloading. In circuits where a back E.M.F. is normally operative, the reduction of this back E.M.F. is equivalent to a reduction in resistance or impedance and results in an increase of current. Thus, increasing the mechanical load on a motor results in a reduction of back E.M.F. (Chapter 28), hence the current flowing from the mains increases, and if the load on the motor be excessive, the current will also become excessive.

The principal dangers arising from excessive current are (i) overheating of the conductors; and (ii) the mechanical forces to which the latter are subjected.

Heating Effect.—The heat developed in a current-carrying conductor varies with I^2R (§ 49) and thus increases with the square of the current. The safe temperature limits for insulating materials have been discussed in § 80; the permissible currents in insulated wires for stated temperature are tabulated in § 280; and the heating of cables and overhead lines is discussed in §§ 291, 328. From these paragraphs there may be seen the effects of excessive current as regards temperature rise in ordinary circuit-conductors. In coiled windings the heating produced, particularly at the inner layers, is generally more serious owing to the low thermal conductivity and relatively small sectional area of the paths available for the dissipation of heat.

Mechanical Effect.—Every current-carrying conductor establishes round itself a magnetic field (§ 32) which, reacting with the magnetic field round a neighbouring current-carrying conductor produces a mechanical force between the two—of attraction or repulsion, according to the directions of current flow. The left-hand diagram in Fig. 55 *a* represents the individual fields round two parallel conductors (viewed in cross-section) which carry current in the same direction. It will be seen that these fields are opposed in the space between the conductors and cancel out more or less completely. The resultant lines of force are as indicated in the right-hand diagram (Fig. 55 *a*), and tend to draw the conductors together. On the other hand, if the currents in the

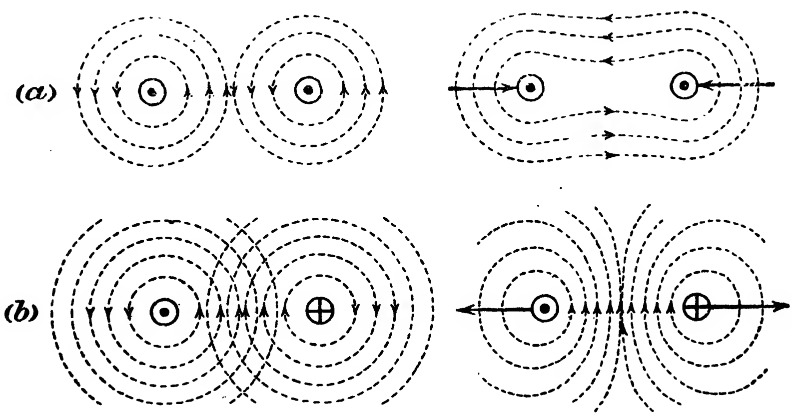


FIG. 55.—Attraction and repulsion between current-carrying conductors.

conductors are in opposite directions, as in Fig. 55 *b*, the resultant field between the conductors is more intense than elsewhere, and there is a crowding of the magnetic 'lines' which tends to force the conductors apart. The case represented in Fig. 55 *b* may be that of the lead and return of the same circuit, and it will be seen that the force between the conductors tends to open out the circuit so that it encloses maximum area (*see also* § 368, and a case in point at the end of § 327).

The mechanical force of attraction (or repulsion) between two straight parallel conductors carrying a direct current of I amps. is given approximately by: $F = 0{\cdot}45I^2 \times 10^{-7} / a$; where F = force, in lbs. per in. run; and a = distance between centres of conductors, in inches. If the conductors carry alternating current the maximum value of the current, for the same effective value I, is $\sqrt{2}\,I$ (§ 30), hence the maximum value of the force between the conductors is: $F_{max.} = 0{\cdot}9I^2 \times 10^{-7} / a$ lb. per in. run. Also the force oscillates between this maximum value and zero with twice the frequency of the A.C. supply, and is therefore much more likely to produce mechanical damage than is the sustained (and lower) force between two conductors carrying D.C. of the same effective value. According to L. B. W. Jolley (*Electrn.*, Vol. 85, p. 677), the *average* force between 3-phase bus bars mounted in one plane is given by: $F = 0{\cdot}338\ I^2 \times 10^{-7} / a$ lb. per in. run where I = R.M.S. amps.; and a = distance between centres of bars, in inches.

Examples (1) The steady force between two conductors, 3 ins. apart, carrying 2 000 A direct current, is : $F = 0{\cdot}45\ I^2 \times 10^{-7} / a = 0{\cdot}45 \times (2\ 000)^2 \times 10^{-7} / 3 =$ 0·06 lb. / in. = about $\frac{3}{4}$ lb. per ft. run.

(2) The maximum value of the fluctuating force on two bus bars 6 ins. apart carrying 25 000 A alternating current (as at the first moment of a short circuit) is: $F = 0{\cdot}9 \times (25\ 000)^2 \times 10^{-7} / 6 = 9{\cdot}37$ lbs. / in., or 112 lbs. / ft. run.

Under short-circuit conditions the force between current-carrying bus bars, generator-connecting cables, accumulator-connecting strips, etc., may be sufficient to cause deformation of the conductors and, possibly, breakage of insulators. The initial value of the short-circuit current is much greater than that of the steady or sustained short-circuit current (*see also* §§ 339, 370) and the instantaneous peak value of the current depends upon the point in the E.M.F. wave at which the short circuit occurs (§ 339). This instantaneous value of the current determines the maximum instantaneous force operative under short-circuit conditions; the formulæ in the preceding paragraphs apply only to steady D.C. or A.C. as the case may be.

Isolating switches (§ 362) may be opened by the force to which the blade is subjected under short-circuit conditions. Jolley (*loc. cit.*) gives formulæ for calculating the magnitude of this force under stated conditions; in the case of a switch 12 ins. between contacts the torque tending to open the switch when carrying 20 000 A ranges from 28 lb.-ft. with a blade 1 in. wide to $40\frac{1}{2}$ lb.-ft. with a blade $\frac{1}{4}$ in. wide. The total force distributed along the blade of a 300 A isolating switch, 10 ins. long, is about 100 lbs. when the current is 20 000 A, and 600 lbs. at 50 000 A. A bolt or latch is generally provided to prevent the switch from being opened by these forces.

In all the above cases it is assumed that the conductors are not near iron; if they be, the magnetic field produced by given current is greatly increased (§ 41) and the mechanical forces are correspondingly greater. There is no simple method of determining the reluctance of the path followed by the leakage flux in such cases, but the experienced designer can estimate the probable forces on the end connections of generator windings, on transformer coils, etc., with sufficient accuracy to enable adequate mechanical support to be provided.* The forces developed in such cases under short-circuit conditions are of the order of several tons, hence very substantial clamps are required to prevent movement of the windings which would abrade the insulation, or deformation which would break the insulation or cause stationary and rotating parts to foul.

Where D.C. generators or rotary converters are concerned the liability to flashing over on overload (*i.e.* excessive sparking, developing into flashing between commutator bars and possibly between brushes) may impose a lower limit upon the permissible load than do considerations of heating or mechanical stress.

339. **Calculation of Short-circuit Current.**—Theoretically it is a simple matter to calculate the current flowing in any case of short circuit by applying Ohm's Law (§§ 17, 44), but, in practice, the factors concerned are variable and more or less indeterminate. In the simple case of, say, a 'dead short' (*i.e.* a direct connection of no appreciable resistance) between the conductors of a feeder at a point 1 ml. from a generator which is connected directly to the feeder, the current flowing is limited only by the impedance of the generator and that of the 2 mls. (lead and return) of cable. If the pressure drop in the generator and cable with normal full-load current I amps. be: $p = (IZ / E) \times 100$ °/ₒ, where E = generator voltage, and Z = impedance of generator and cable in ohms, we have: $Z = pE / 100\,I$, and if this be the only impedance in circuit (*i.e.* feeder short circuited at the far end), the short-circuit current $= E / Z = 100I / p$ or $(100 / p) \times$ full-load current. Thus if a circuit be 'shorted' at a point between which and the generator there is 5 °/ₒ pressure drop on full load, the short-circuit current will theoretically be $100 / 5 = 20$ times the full-load value.

* *See also Theory and Calculation of Electric Circuits*, La Cour and Bragstad (Longmans); and *Principles of Transformer Design*, Still (Wiley).

There are, however, several factors to be considered. In the first place, the current so calculated may be greater than the short-circuit output of the generator (§ 1 020, Vol. 3) which is naturally the heaviest current that can flow even with a short circuit at the generator terminals. Again, no heavier current can persist than corresponds to the maximum output of the prime mover (allowing for losses in the generator), though the stored energy of the moving parts will momentarily increase the output greatly. So far, it has been assumed that the generator voltage is fully maintained on short circuit, but this is far from being the case, even though automatic voltage regulators (§ 147) endeavour to maintain constant voltage. Further, it has been assumed that the reactance is known and constant, but, actually, it is very difficult to determine the exact value of reactance in a short-circuited system because this varies with the position of the fault, with the resistance of the fault itself, and with the saturation of all iron-cored windings in the circuit.

In the early days of A.C. engineering it was common to specify low internal reactance in alternators for the sake of close voltage regulation (§ 147), but it is now usual to provide greater reactance in order to limit the short-circuit current, dependance being placed upon automatic voltage regulators in order to maintain constant voltage under normal variations of load. Even with the higher internal reactance now employed, the short-circuit current may be 15 or 20 times the normal full-load current, but it quickly falls to, say, 2, 3 or 4 times full-load current owing to the generator voltage being greatly reduced by the reaction of the armature when carrying heavy current. Under short-circuit conditions the action of automatic voltage regulators obviously tends to increase the short-circuit current; to overcome this objection it can be arranged that the regulators automatically *reduce* the generator voltage when the main current exceeds a predetermined value.

It is the maximum instantaneous value of the short-circuit current which determines the maximum mechanical stress imposed upon windings, etc. (§ 338), and it says much for the construction of modern turbo-alternators that they will withstand dead short-circuit at full field excitation without mechanical injury. If the short-circuit current wave is initially asymmetrical (as it may be under the most unfavourable conditions) its amplitude may be about 1·8 times that of the initial short-circuit current under symmetrical conditions. An approximate formula for the maximum instantaneous value of the short-circuit current per phase under the most unfavourable (asymmetric) conditions is—

$$I_{max.} = 1{\cdot}8 \times E \times \sqrt{2} / Z = 2{\cdot}55\, E / Z;$$

where E = phase voltage; and Z = impedance per phase, in ohms. The duration of this severe current rush is very brief, and after a few cycles the current settles to its steady short-circuit value of 2-4 times full-load current. The actual value of the initial surge is a maximum if the short-circuit occurs when the E.M.F. wave is at its maximum; if the 'short' occurs at some lower instantaneous value of E.M.F., the short-circuit current increases with the E.M.F. and prevents the latter from attaining its normal maximum value. The inductance of the path followed by the short-circuit current retards the increase of current from the normal to the short-circuit value and allows time for the E.M.F. to decrease somewhat. The thermal capacity of the conductors in the circuit allows them to carry the initial current rush without dangerous rise of temperature provided that the circuit be interrupted in a fraction of a second; even this brief delay permits the current to decrease (owing to the reduced E.M.F.), and greatly reduces the duty imposed upon the circuit breaker (§ 370).

340. Limitation of Current; Protective Reactances.—The short-circuit current in any circuit may be reduced by increasing the reactance of the circuit, and this may be accomplished by connecting in series with the latter an inductive coil of wire (generally called a 'reactance coil'). The only loss of energy in this coil is the I^2R loss (§ 49) due to its ohmic resistance, plus the losses in its iron magnetic circuit (if any). The inductance of the coil reduces the power factor of the circuit (§§ 44, 45, 154), but does not involve dissipation of energy. As explained in the preceding paragraph, if the reactance causes p °/₀ voltage drop when carrying the normal full-load current of the circuit, the short-circuit current through the reactance—when the latter is connected directly to the full supply voltage—is $(100 / p)$ times full-load current. If it is desired to limit the maximum current of an alternator to 5 times full-load value, the total reactance (measured in terms of the percentage voltage drop which it produces with full-load current) must be $p = 100 / 5 = 20$ %, and if the alternator has 8 % reactance (as above defined), the external reactance required is 12 %.

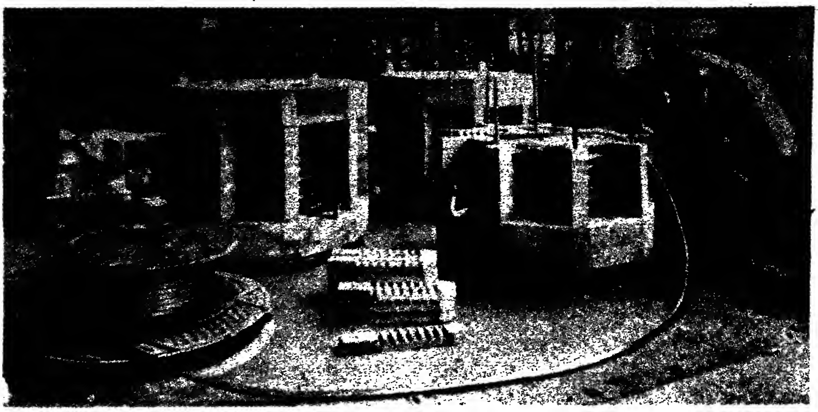
Reactances generally consist of large-section strip copper (or insulated cable) the ohmic resistance of which is so low as to cause negligible loss of energy. In air-core reactances the turns are separated and supported by porcelain, bricks, or concrete to secure insulation and to prevent deformation by mechanical forces on short circuit (§ 338). Iron-clad oil-immersed reactances (with iron magnetic circuits) are much smaller than air-core reactances for equal inductance, and they have the further advantage of being free from stray fields (which may affect instruments or induce eddy currents in steelwork near air-core reactances).

Iron-cored reactors must be so designed that saturation does not occur with the maximum possible short-circuit current, in order that the ohmic value of the reactance may be sensibly constant in all conditions. The oil-immersed type is superseding the older concrete clad pattern, and in a certain large power station, for example, there are banks of reactors giving 12 % reactance on 50 000 kVA.

Generator reactances of from 10-20 % (on the voltage drop rating defined above) are commonly used in series with alternators to limit the magnitude of the short-circuit current. *Bus-bar reactances*, of from 25-50 %, are connected between the sections of sub-divided bus bars so that, in the event of a 'short' on one length of bus bar the current which can flow to the fault from the other sections is limited; these reactances are traversed only by current flowing from bar to bar and not by the current delivered by one or several generators to a set of bars and flowing thence to feeders. *Feeder reactances*, connected in series with individual feeders, are of about 5 % (limiting the maximum current to 20 times full-load current), this relatively low reactance being adopted in order to reduce the voltage drop and the lowering of power factor.

Reactances cannot be used to reduce the maximum current to a non-injurious value; they simply reduce the peak value of the current thus reducing mechanical stresses (§ 338) and the power to be interrupted (§ 370). The actual interruption of the circuit pending the removal of the fault is effected by fuses (§ 342) or circuit breakers (§ 343).

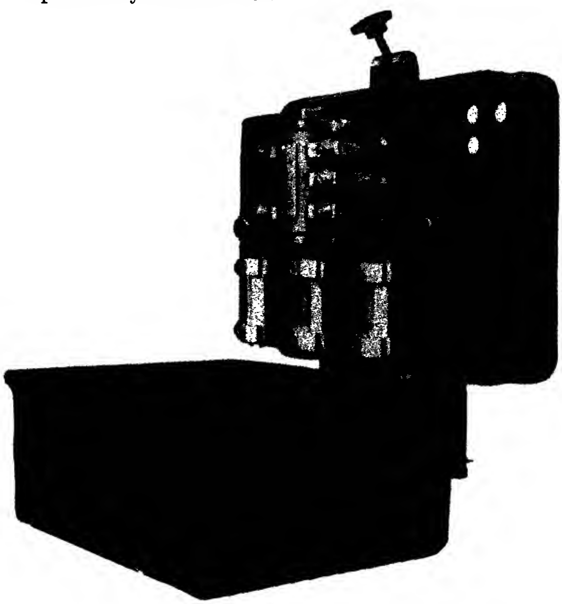
The reactance $2\pi fL$ of a coil (§ 44) varies with the product of frequency by inductance; the considerable reactance required in current-limiting reactances involves high inductance L, the



General Electric Co., Ltd. (London).

PROTECTIVE REACTANCE COILS UNDER CONSTRUCTION.

These coils are designed to give 5 % reactance on a 11 000 V, 1 000 A, feeder circuit. The simplicity and strength of the construction are shown clearly. The stranded copper conductor is laid in the grooves of the moulded concrete arms, and the completed coil is practically indestructible.

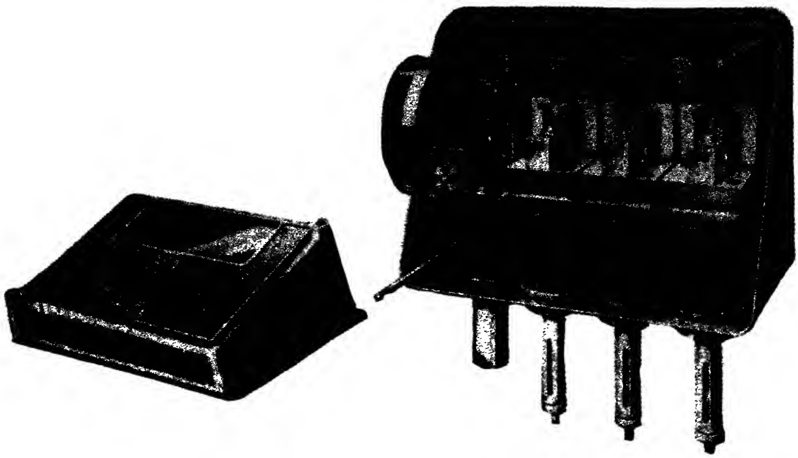


British Thomson-Houston Co., Ltd.

TRIPLE-POLE INSTANTANEOUS RELAY.

This type of relay can be used for overload and for leakage protection. A moving contact carried on a spring-actuated drum is normally held 'off' by a catch, which is tripped by the plungers being pulled up by the solenoids on a predetermined current being exceeded. The moving contact bridges fixed spring contacts in its 'on' and 'off' positions and may thus be used to break or make circuit, or for both purposes. It can be made to control two independent circuits. Current adjustment is by raising or lowering the plungers, and the movement of the drum is independent of the pull on the plungers. Delayed action can be obtained by shunting the trip coils with time-limit fuses.

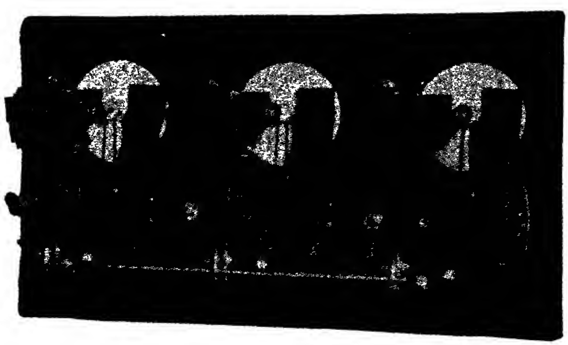
[*To face p.* 608.



British Thomson-Houston Co., Ltd.

DEFINITE TIME-LIMIT RELAY.

The equipment comprises three overload coils, and a time-element device, circuit-closing mechanism, and operating trip coil. When any one of the overload coils operates, the time-element trip coil is energised, and the circuit closing mechanism commences to overcome the retarding effect of the time element. After a predetermined time, which is adjustable within wide limits, the secondary tripping circuit is closed. If required, one of the overload coils can be replaced by a sensitive coil, and the relay arranged to operate instantaneously on a small leakage fault whilst retaining the time limit characteristic for overloads.



Everett, Edgcumbe & Co., Ltd.

TRIPLE-POLE INDUCTION-TYPE OVERLOAD RELAY WITH INVERSE TIME LAG.

The movements are similar to those of the induction ammeter (Plate p. 144). The current and time settings are independently adjustable—the current by the position of the weight on the horizontal graduated beam, and the time by regulating the travel of that beam over a vertical scale. The contacts are of carbon and are seen at the bottom of the instrument. The time-current curves of all these relays are identical so that perfect discriminative protection is obtained.

[*To face p.* 609.

frequency f of commercial supply being low. On the other hand, a very small inductance has a reactance high enough to obstruct the flow of high-frequency surges due to lightning, etc. (§§ 45, 346).

341. Interruption of Excessive Current.—The effects of excessive current may be utilised to obtain protection by making part of the circuit more sensitive than the rest to these effects, and arranging that the effects open the circuit (*i.e.* interrupt the current) at the selected point. Thus the heating effect of the current may melt a 'fuse' when the current exceeds a predetermined value; or the electromagnetic force developed by a solenoid may operate a mechanism which opens a switch in the circuit, either 'instantaneously' (as quickly as the mechanism can operate) or in accordance with a predetermined time element (§ 344).

342. Fusible Cut-outs; Fuses.—Fusible cut-outs, in which a fine and easily fusible wire or 'fuse' is connected in series with the circuit wires, are used in all domestic branch circuits and house services (§ 514, *et seq.*, Vol. 2). They are also used in industrial circuits, particularly for pressures up to 600 V and for (normal) currents up to 600 A; the cost of renewing heavy current fuses is a consideration and the rating of fuses (*i.e.* the current at which they melt) is less definite than that of switch-type circuit-breakers, hence the latter are generally employed in important circuits where an attendant is available to re-close the switch.

Tin or an alloy of low melting-point is generally used for fuses up to, say, 200 A normal current. The specific resistance of such metals is relatively high, hence the cross-sectional area required is much larger than that of copper fuses of the same rating. Copper fuses, for all but the heaviest currents, are inconveniently fine; they are easily damaged mechanically and by corrosion, with the result that they melt at less than the intended current. Whereas tin and similar fuses are not corroded seriously because their melting-point is low, copper fuses may often be at or near red-heat for considerable periods, with the result that they are gradually oxidised.

The so-called 'Bimetal' fuse wire has important advantages. This consists of a copper wire, which would be fused at once by the current in the circuit it is designed to protect, sheathed with lead; the lead greatly increases the radiating surface, thus assisting in the rapid dissipation of the heat developed, and, having a greater cross-section than the copper, also carries some proportion of the current, despite its low conductance. Should the current rise above normal the lead first melts off, and the fine copper wire (having to carry the whole current) then necessarily follows suit and breaks the circuit instantly. A fuse of this nature can carry some 80 °/₀ of its fusing current without danger of melting, whereas a copper fuse, under the like conditions, would be red-hot. The smallest size of bimetal fuse wire at present available carries about 6 A, so that for the smallest circuits a single strand of very fine copper or tin wire is generally used.

TABLE 51.—*Fusing Current of Wires.*

Fusing Current. Amps.	Copper.		Tin.		Lead-tin (2 : 1) Alloy.	
	Diameter. In.	Approx. S.W.G.	Diameter. In.	Approx. S.W.G.	Diameter. In.	Approx. S.W.G.
1	0·002 1	47	0·007 2	36	0·008 3	35
3	0·004 4	41	0·014 9	28	0·017 3	26
5	0·006 2	38	0·021 0	25	0·024 3	23
10	0·009 8	33	0·033 4	21	0·038 6	19
15	0·012 9	30	0·043 7	19	0·050 6	18
20	0·015 6	28	0·052 9	17	0·061 3	16
25	0·018 1	26	0·061 4	16	0·071 1	15
30	0·020 5	25	0·069 4	15	0·080 3	14
50	0·028 8	22	0·097 5	13	0·112 9	11
70	0·036 0	20	0·122 0	11	0·141 3	9
100	0·045 7	18	0·154 7	8	0·179 3	7
150	0·059 8	17	0·202 9	6	0·234 8	4
200	0·072 5	15	0·245 8	3	0·284 5	2
250	0·084 1	14	0·285 1	2	0·330 1	0
300	0·095 0	13	0·322 0	0	0·372 8	3/0

Table 51 shows the approximate fusing current of various sizes of copper, tin, and lead-tin (2Pb : 1Sn) alloy wires, the values given being calculated from Preece's formula : $I = a\sqrt{d^3}$; where I = fusing current, in amperes ; d = diameter of wire, in inches ; and a = 10 244 for copper ; 1 642 for tin ; and 1 318 for the lead-tin alloy. These figures are only approximations, as the length of the fuse, its direction (vertical or horizontal), the nature of the terminals holding it, the method of carrying it—whether in free air, on a porcelain bridge, or enclosed in a tube or cartridge—all affect the result. Enclosure in a tube filled with powder or submersion in oil (§ 375) naturally affect the rating of the fuse very materially by changing the facilities for the removal of heat. Table 51 is, however, a useful guide to suitable dimensions for well-ventilated fuses in air; if the fuse be mounted in a small asbestos tube, it may melt at half the current stated in the table. The resistance of a fuse causes a loss of pressure of from 0·1-0·5 V or more.

Table 51A, from the I.E.E. wiring regulations (tenth edition)

TABLE 51A.—*Approximate Current Rating of Fuse-Links Composed of Tinned Copper Wire or Standard Alloy * Wire in British Standard Cut-Outs.*

Current Rating, Amps.	Tinned Copper Wire.		Standard Alloy* Wire.	
	Diameter (in.).	S.W.G.	Diameter (in.).	S.W.G.
1·8	—	—	0·016 4	27
3·0	0·006	38	0·024	23
5·0	0·008 4	35	0·032	21
8·5	0·012 4	30	—	—
10·0	0·013 6	29	—	—
15·0	0·020	25	—	—
17	0·022	24	—	—
20	0·024	23	—	—
24	0·028	22	—	—
30	0·032	21	—	—
37	0·040	19	—	—
46	0·048	18	—	—
53	0·048	18	—	—
60	0·056	17	—	—
64	0·056	17	—	—
83	0·072	15	—	—
100	0·080	14	—	—

* The term 'Standard alloy' refers to the tin-lead alloy (63 °/。 tin, 37 °/。 lead) specified in B.S.S. No. 88.

The current ratings in Table 51A refer to the normal maximum current of the circuit and do not refer to the overload at which the cut-out will operate. The values of the currents given are approximately those necessary to comply with B.S.S. No. 88. Where cut-outs are known to conform to this Specification the size stated by the manufacturer on the case of the cut-out should be adhered to in preference to that given in Table 51A, if the cut-out is loaded to its full capacity.

gives the safe current rating, *not* the fusing current, of both copper and standard tin-lead alloy fuse wires.

No matter how carefully an installation is fitted with fuses at first, there is always a danger that the occupier, after a fuse has melted or 'blown,' will replace it by a larger one in order to save trouble. By the use of standard non-interchangeable cartridge or screw-plug fuses, or by marking each fuse carrier with the current it is intended to carry and putting spare fuses alongside, something can be done to prevent this: but it is not unusual to find a piece of comparatively heavy iron or copper wire inserted where tin wire had been used originally. The protective value of the fuse is then illusory.

A certain amount of heat is required to raise a fuse wire to the melting-point, the amount being greater the heavier the fuse, the higher its specific heat, and the higher the melting-point. The rate at which heat is developed in the wire varies with I^2R, hence twice the current will bring the fuse to the melting-point in (roughly) one-quarter the time; in other words, fuses have an inverse time element (§ 344), but owing to the uncertainty regarding the condition of the wire and its cooling facilities, it is not possible to determine and apply this time element with the same accuracy as in circuit breakers.

In circuits where the normal current does not exceed 10 A the fuses should interrupt the circuit before or when the current is three times the normal value; for working currents exceeding 10 A, the fuses should blow at or below twice the working current. Fuses for high voltage circuits are mentioned in § 375.

A possibility that must be guarded against in 3-phase circuits is the blowing of the fuse in one-phase (due to its own deterioration or to an unbalanced fault) leaving the fuses intact in the other two phases. This would leave the circuit alive beyond the fuses, and 3-phase apparatus might continue in operation on the two sound phases, the current in which might be high enough to damage the windings, but not high enough to blow the fuses. Switch fuses are available with automatic releases so arranged that, when one fuse blows, all phases are opened mechanically.

Constructional details of fuses are described in § 375; and the installation of fuses is discussed in § 514, *et seq.*, Vol. 2.

343. **Circuit-breakers.**—Any type of switch which is capable of interrupting safely (without sustained arcing or undue damage

to contacts) the short-circuit current of a circuit may be termed a 'circuit-breaker' (§§ 365, 367). Such a switch is always arranged so that it can be operated by hand (either directly or by remote control, § 372) at the volition of the attendant, but it is also arranged so that it can be opened automatically by the action of a relay (§ 124) and trip coil. The switch is closed (by hand, electromagnetically, or otherwise) against the action of a powerful spring which tends to open the switch and is only prevented from doing so by a latch or trigger. This latch, when released by the movement of the plunger or core of a 'trip coil,' allows the switch to open instantaneously. The excitation of the trip coil solenoid may be effected by the main current, the coil then being connected in series with the switch, or it may be effected by current, drawn from a storage battery or auxiliary D.C. bus bars in a local circuit which is closed by a relay. If the circuit-breaker is fitted with a series-connected trip coil it can be arranged that the tripping plunger is raised at any desired value of the current, thus providing the circuit-breaker with automatic overload protection. Alternatively, if the trip coil be connected in shunt, across the supply leads, it can be arranged that so long as the supply voltage exceeds, say, 50 °/ₒ of the normal value the latch of the switch remains closed, but directly the voltage falls below the predetermined minimum the latch is released (by the action of the trip coil) and the switch is opened; the switch has then automatic protection against low voltage, or a 'no-volt release.'

There would be obvious mechanical difficulties in arranging several trip coils (excited by different electrical connections) to operate a single release latch, but the same end can easily be attained electrically, by the use of relays. A relay consists essentially of an electromagnet the armature of which, when attracted to or released by the core of the magnet, closes an auxiliary electric circuit. Just as an electric bell can be rung by pressing any one of a number of 'pushes,' so can the trip coil circuit of a circuit-breaker be excited by the action of any one of a number of relays (*see* Fig. 59). If the respective relays be arranged to operate on overload, low-voltage, reverse power, etc., a single circuit-breaker protects the circuit against all the contingencies covered by the relays. The relays are the controlling elements of the protection, and the protection which they afford is the automatic opening of the main circuit in the event of predetermined conditions arising.

Circuit-breakers can interrupt much greater power than fuses (§ 371), and they isolate the circuit completely, the switches in both poles or all the phases of the supply being coupled mechanically and opened simultaneously. Whereas a fuse provides only overload protection, a circuit-breaker and its relays can afford protection against all contingencies. Also, the setting of the various relays can be adjusted easily and accurately over a wide range.

The constructional features of circuit-breakers, trip coils, and tripping mechanism are discussed in §§ 368, 372. Various types of relays are described in §§ 344, 355, 358, 359.

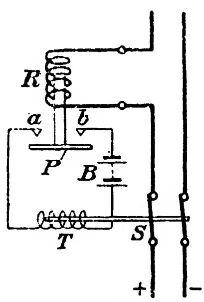


FIG. 56.—Diagrammatic representation of instantaneous overload relay and trip coil.

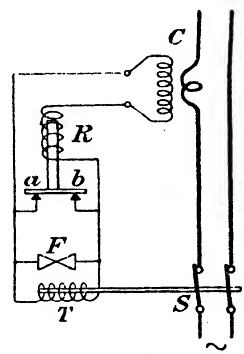


FIG. 57.—Overload relay with current transformer, and trip coil with fuse time element.

344. Overload Relays; Time Element.—The principle of the simplest type of overload relay is illustrated diagrammatically in Fig. 56. The relay coil *R* is in series with the circuit to be protected and, when the current therein exceeds a predetermined value, the plunger *P* is raised, short-circuiting the contacts *ab* and closing the local circuit containing a battery *B* and trip coil *T*. The coil *T* being excited, its core trips the switch *S* and opens the main circuit. The coil *R* in the main circuit could be used as the actual tripping coil and is often so used in low or medium voltage, moderate current circuits where neither the size of the conductor nor the insulation required makes it difficult to wind a suitable coil. For heavier current and/or higher voltage, the coil *R* is supplied from a current transformer (§ 108), as in Fig. 57, and the advantage of having a separate trip coil is that the relay can be delicate and sensitive whilst considerable power can be used to operate the trip coil; also, the latter can be actuated by any one of several relays (Fig. 59).

The overload relay on D.C. motor starters operates on the principle illustrated in Fig. 56, except that the contacts *a*, *b* are generally connected in parallel with the 'no-volt' or 'hold-on' coil instead of to a special tripping coil; then, when *a*, *b* are short-circuited by *P*, the hold-on coil loses its excitation and the starter handle is pulled to the 'off' position by a powerful spring.

In D.C. or single-phase A.C. circuits a single overload relay controlling a double-pole circuit breaker is sufficient, but in 3-phase A.C. circuits overload coils must be provided in two phases if the neutral is insulated and in all three phases if the neutral is earthed (§ 354); the circuit will then be opened no matter in which phase the excessive current flows.

The setting of overload relays can be varied so that the relay operates at any desired current between, say, normal full-load current and three times the latter.

The relay illustrated in Fig. 56 would cause the switch *S* to be opened *directly* the current exceeded a predetermined value and might thus involve unnecessary interruptions of working, for in many cases a momentary surge of current, far exceeding the permissible steady current, would not injure the circuit or apparatus. To allow for this, the relay may be furnished with a 'time element' which prevents the main switch from being tripped until the excessive current has been maintained for a predetermined time.

The time element may introduce a definite delay (say from 1-3 secs.) in the tripping, or the delay may be varied inversely with the main current ('inverse time element').

Instantaneous Relays are used in various protective systems (§ 359) to cause the main circuit to be opened directly some critical condition arises (*e.g.* lack of balance) which is a definite indication of a fault on the circuit protected.

Definite Time-limit Relays are used in a graded series on successive circuit breakers to prevent the whole length of a feeder being shut down simultaneously. Thus, Fig. 58 represents a series of circuit breakers with overload relays *R* used on a feeder between a generating station *G* and substations

S. If the relays R_1 be given a definite time element of 1 sec.; R_2, 2 secs.; and R_3, 3 secs., the relays will operate progressively from the far end of the feeder towards the station until the fault or overload is thus switched out. The object is to maintain supply in those sections which are nearer the generating station than the faulty section. To allow for the fact that a fault at *X* (which would be heavier than a corresponding fault in the more remote sections, § 339) is protected only by a relay with long time

FIG. 58.—Overload relays with graded definite time limits.

element, the relays may be arranged to operate with fixed time element up to a certain overload, and instantaneously at heavier overloads.

One method of arranging for a definite time element is indicated in Fig. 59. The trip coil *A* is connected, in series with a battery *B*, to bus bars *C* across which are connected the various relays, any one of which may bring about the opening of the main switch. Thus, at *a* there is an instantaneous or inverse time

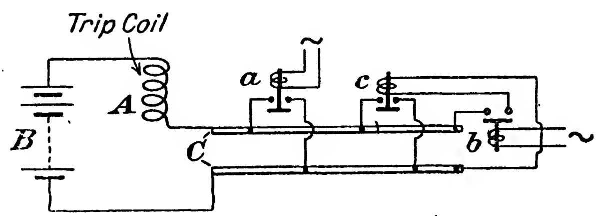


FIG. 59.—Various types of relays applied to trip coil.

element relay; and at *b*, *c* there is a definite time element combination, the instantaneous relay *b* (excited from the A.C. circuit to be protected) closing the circuit of the tripping relay *c*; until *c* closes, the current flowing through A is insufficient to operate the tripping mechanism. The definite delay in operation of the latter is determined by a pendulum and clockwork device, by the flow of mercury through a small orifice, or by other equivalent means.

Inverse Time Element Relays.—One method of securing a delay in action which decreases with the magnitude of the overload is to fit the plunger of an instantaneous relay (Fig. 56) with a dashpot; the timing of oil dashpots is, however, affected appreciably by temperature changes, which alter the viscosity of the oil.

The most accurate inverse time characteristic is given by induction relays. An induction relay consists of an induction ammeter movement (§ 102) the moving element of which is fitted with contacts which the angular travel of the disc close the trip circuit due to contacts. The movement of the disc is damped by a permanent magnet. For a given current the time lag can be varied by adjusting the travel of the disc required to close the trip contacts. For a given setting of this travel, the time required to execute it decreases as the current increases. This time, however, does not decrease indefinitely but attains a limiting minimum value as the operating current increases without limit. This minimum time of operation is known as the 'short-circuit time lag'. In this respect the induction relay differs from all other devices, such as fuses, for obtaining time lags, and if two or more such relays ars connected in series, the one with the smaller time setting will always operate first, however large the current may be. The current setting induction relays is varied, either by adjusting the mechanical force controlling the movement, or by variation of the number of turns of the winding through which the current passes.

Yet another method is illustrated in Fig. 57. In this case the relay *R* opens the contacts *ab* directly the main current exceeds a predetermined value. Current then flows through the fuse *F* and the trip coil *T* in parallel; mostly through *F* because of its lower resistance. After a time, which is shorter the heavier the current, the fuse *F* melts, and the whole current then passes through *T* and trips the switch. The weakness of this method is that the fuse *F* gradually deteriorates (§ 342) and may then cause the main switch to be opened unnecessarily.

Fixed or inverse time element relays are re-set automatically if the overload is removed before tripping occurs.

The setting of any type of relay is expressed as a percentage of the full-load conditions in the main circuit protected; if the relay is used with current or voltage transformers, the stated setting refers to the main circuit current or voltage.

(For reverse-power relays, *see* § 358.)

345. Cause and Effect of Excessive Pressure.—The whole or a part of an electric circuit may be subjected to abnormally high pressure (i) by a direct flash of lightning or by electrostatic induction from charged clouds (§ 346); (ii) by the sudden interruption of a highly inductive part of the circuit (§ 349); (iii) by sudden direct application of the normal voltage (§ 349); (iv) by resonance (§ 350); or (v) by the peculiar and unstable characteristics of arcs and sparks, particularly 'arcing grounds' (§ 351). Whatever its cause, the possible effects of excessive pressure are break-down of insulation and consequent danger to life and material (§ 352). Abnormal pressure would invariably lead to break-down were it not for the following facts: (*a*) The insulation of all properly designed circuits and apparatus is capable of withstanding a pressure much higher than the normal pressure (Chapter 40), and in the case of extra high voltage systems the insulation is capable of withstanding indefinitely many of the pressure surges occurring in service. (*b*) A definite and considerable amount of energy is required to break down insulation so that if an abnormal pressure can be removed quickly enough the insulation will remain uninjured, though it would be broken down if the pressure were applied for a longer period (§ 72). (*c*) In many instances the abnormal voltage has a very high frequency of oscillation and will therefore take a path of high ohmic resistance (*e.g.* an air gap) in preference to the normal circuit which offers enormous impedance to the high-frequency current (§ 135 (1)).

If the cause of abnormal voltage cannot be avoided, the circuit must be safeguarded either by providing a suitable path of discharge for the excessive pressure, or by reinforcing the insulation of the circuit at the danger points, or by a combination of these methods.

346. Lightning Arresters and Surge Absorbers.—A direct stroke of lightning will almost inevitably flash over the insulators and probably destroy the line at that point. Induced surges caused by lightning may, however, keep to the line, and affect apparatus in the power station or substation, or spark across an insulator and put the line to earth. Such surges, and some due to causes within the circuit itself, are of variable but always very high frequency, and will therefore take the least inductive, but not necessarily the best conducting, path to earth. Lightning arresters are designed to take advantage of this fact, and frequently consist of a spark gap, in one form or another, which the ordinary line voltage cannot break down, together with a carbon or other resistance in series. Should a high-pressure discharge cause an arc to strike across the gap, the line current will follow, but the series resistance limits the current and the arc dies down or is automatically extinguished, magnetically or otherwise. In order to ensure the discharge taking its allotted path, an inductive coil or 'kicking coil' (§ 45) is generally connected in series with the line itself on the station side of the arrester; the oscillating discharge is thereby forced to follow the alternative path. In some places in South Africa, where thunderstorms are

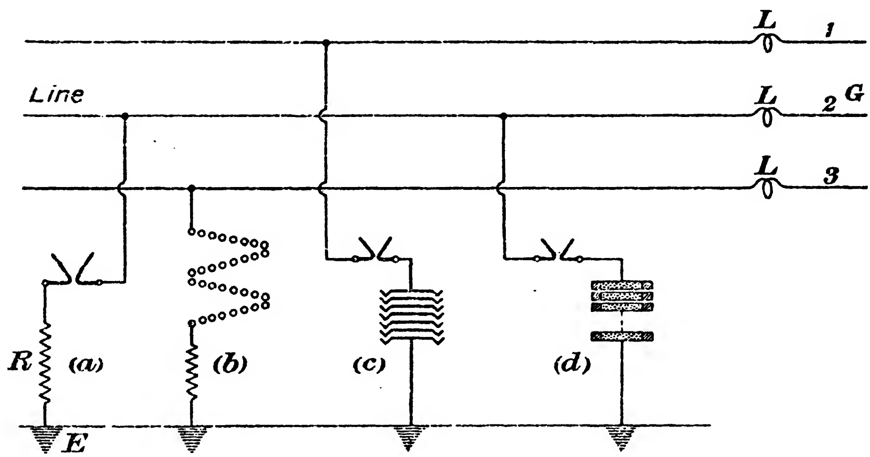


FIG. 60.—Various types of lightning arresters.

(Actually there would be only one arrester per phase, and the arresters on the three phases would be of the same type.)

both frequent and violent, iron inductance coils have been used instead of the more usual copper coils, and have been found more effective.

Comb Arresters.—One end of a non-inductive resistance is connected to the line to be protected and the other end is connected to a 'comb' or serrated strip of metal, the teeth of which are set a short distance from those of a second comb. The latter is connected to earth. Lightning or other voltage surge breaks down the air gap between the combs, but a 'power discharge' (*i.e.* continued flow of current at the normal line voltage) is prevented by the high resistance in series with the gap. This type of arrester is suitable for line pressures up to 100 V direct current or 400 V alternating current.

Horn Arresters.—The general arrangement of a horn-type arrester is shown at (*a*) Fig. 60. The horns may be of copper or galvanised iron about ½ in. diam., and they are connected between line and earth in series with a high non-inductive resistance. High-frequency surges find it easier to break down the air gap and flow through the resistance R than to pass through the impedance of inductive apparatus in the generating station G. In order to oppose such an impedance to the high-frequency discharge outside the station coils L (of low reactance to low frequency current) are connected in the line on the station side of the arrester.

When the gap between the horns is broken down by lightning the line current tends to establish an arc, but the magnitude of the line current is limited by the series resistance, and the arc runs up the horns until it breaks from extreme length. A useful setting is stated to be 1 mm. per 1000 V *plus* 1 mm. to prevent constant discharge.

The resistance R may be that of a water column in an insulating tube through the closed top of which is brought the connection from the horn arrester. When a discharge occurs some of the water is converted to steam and the remainder is driven down the tube into a surrounding tank. An arc is struck between the top electrode and the column of water, but as the latter continues to descend the discharge is soon interrupted. The steam then condenses and the arrester is re-set by the return of water from the outer tank.

The horn gap arrester is capable of dealing with heavy surges, but it can only operate on over-voltage and is useless on a low-voltage, high-frequency surge; if the gap be set to protect the line against high frequency surges at a pressure only slightly exceeding the line voltage, dust, steam, insects, etc., may cause unnecessary break-downs. Horn-type arresters are used for line pressures up to 15 000 V (D.C. or A.C.), and for the protection of trolley wires (at 400-650 V, D.C.) two horn gaps may be used in series, one being provided with a magnetic blow-out coil (§ 365) connected across a non-inductive resistance which is shunted across the second arrester; the magnetic blow-out comes into action in the event of sustained flow of D.C. across the gaps.

Impulse Protective Gaps.—In order to obtain protection against pressure surges of steep wave front (§ 349) without adopting an unduly small air gap (which would introduce risk of break-down at normal voltage), the ordinary horn-gap arrester may be provided with an intermediate electrode between which and the two horns there are connected impedances of different characteristics. It is arranged that, at line frequency, the impedances are proportional to the break-down voltages of the parts of the total gap across which they are shunted. At high frequency, however, the impedance of one of these shunts is much greater than that of the other; most of the high-frequency voltage is therefore imposed between the auxiliary electrode and one of the horns, with the result that this gap breaks down; the whole of the high-frequency voltage then comes upon the other gap which also breaks down. In effect there are two gaps in series, their total length being available as insulation against the line voltage, whereas practically the whole of a high-frequency voltage is placed immediately across a fraction of the total gap.

Multiple Gap Arresters consist of a series of cylinders, or truncated cones, with a short gap between each pair, the terminal elements connected to line and earth respectively (Fig. 60 *b*); sometimes the cylinders are connected in series with a high resistance, and in other cases some of the gaps are shunted by a resistance. The arc is broken either by the cooling effect of the metal or by the use of certain non-arcing metals—zinc, antimony, and bismuth. The number of gaps is generally about $E / 800$, where E = normal voltage between line and earth.

Water-jet Arrester.—In the jet arrester the line is connected straight to earth through a fine jet of water, the resistance of which is so high that the normal leakage is very small; the jet arrester provides a permanent leak to earth for high-frequency surges, irrespective of voltage; it is particularly useful for dispelling slowly accumulating static charges. In the case of low-tension D.C. installations a tank is substituted, and conducting plates within it are adjusted to allow a small continuous leakage from pole to pole, through the water, whenever there is a likelihood of lightning troubles. This type of arrester can only be used where there is a constant supply of water and no danger of freezing. Electrode-type electrically heated steam boilers (Chapter 26) afford excellent protection against over-voltage, the lines being earthed through the relatively low resistance of the water in the boiler.

Electrolytic Lightning Arrester.—Sheet aluminium trays of V‾V-section (Fig. 60 *c*) are mounted one above the other with porcelain insulators between the rims of consecutive trays. The trough of each tray is filled with electrolyte similar to that used in electrolytic rectifiers, and the whole stack is placed in a steel tank which is then filled with insulating oil. The bottom tray is connected to earth and the top tray is connected to line. A film of aluminium hydroxide is formed upon the trays by electrolytic action, and the number of trays used is such that the total resistance of the films is sufficient to withstand, say, 50 °/₀ higher than line voltage. Excess voltage (above about 350 V per cell) breaks down the films of hydroxide, but the latter re-form directly the excess voltage has been dissipated and thus prevent the maintenance of a power discharge.

The stack of trays constitutes a condenser and—in order that there may not be a continual capacity current, and in order to prevent disintegration from continual leakage—it is necessary to use a horn gap in series with the arrester. Since the film on the trays gradually dissolves in the electrolyte it is necessary to re-charge the cell by short-circuiting the horn gap (through a suitable resistance) for a few seconds once a day; this is an inconvenience.

Oxide Film Arrester.—This arrester depends upon the fact that lead peroxide is a relatively good conductor, whereas litharge (into which the peroxide is converted by heat) is an insulator. Capsules about 7 ins. dia. × ½ in. deep, consisting of metal discs fixed to a porcelain insulating and spacing ring, are filled with lead peroxide and stacked one above the other, the stack being connected in series with a horn gap arrester as in Fig. 60 *d*. The inside of the metal discs of the capsules is coated with insulating varnish, but when the voltage per capsule exceeds, say, 400 V the varnish is punctured and a discharge flows to earth. The heat developed by I^2R loss in the lead peroxide between the points of puncture converts the peroxide to litharge and thus seals the puncture and re-sets the arrester.

Thyrite Arrester.—Thyrite is a ceramic material, the electrical resistance of which decreases (and hence the discharge current increases) about 12½ times each time the voltage is doubled. Discs of the material are assembled with built-in series gaps. These arresters are intended chiefly for primary transmission systems, and act without appreciable time-lag.

On 3-phase lines it is necessary to remember that if the arresters on all phases are connected to a common earth, and if there is insufficient damping resistance in circuit with each, the lines may be practically short-circuited. With horn arresters this is not an uncommon mistake.

Moscicki condensers * are sometimes used to absorb high-frequency surges of any voltage; they will take care of rapid surges, have no permanent leak to earth, and can be installed where water is not available for jets. They are generally used in combination with Giles valves. Mechanically, they are rather fragile. They have been installed in various stations in Rhodesia and are fully considered in a paper by Wragg (*Trans. S. African I.E.E.* June, 1915). The use of condensers may increase the dangers arising from arcing grounds (§ 351).

Whereas a choking coil or inductance retards the growth of current and causes the applied E.M.F. to "pile up" on the end turns of the inductance to which it is applied (§ 349), a condenser has the opposite effect and tends to flatten the wave-front of the applied E.M.F. A system of protection which utilises these two phenomena and is applicable to English conditions consists in connecting a choke coil and a length of lead-sheathed cable in series between an overhead line and the generator or other apparatus in the power station or sub-station. The sheathing of the cable is connected to earth and so is the neutral point of the generator or other apparatus to be protected. The leading-in cable from each line may thus be regarded as a condenser connected in parallel with the corresponding phase of the generator, etc. The choking coil delays the increase of the current set up by the lightning or surge E.M.F. and this current charges the condenser (*i.e.* the cable) to a moderate voltage, much lower than that of the surge. The choking coil is sometimes omitted, reliance then being placed entirely upon the protective condenser-action of the cable. In either case the abnormal voltage on the line is dissipated partly by the ohmic loss experienced in surging to and fro on the line, and partly by flowing to earth through the cable-condenser.

* In these condensers a glass tube closed at one end is coated inside with silver (deposited chemically); the outer coating may be a similar layer of silver or the tube may be immersed in a conducting solution of glycerine and water contained in an outer vessel. By the use of a suitable thickness of glass and by avoiding sharp corners therein the condensers can be made to withstand high voltages. A Moscicki condenser described by W. M. Mordey (*Jour. I.E.E.*, Vol. 43, p. 621) consisted of eight tubes each 2 ins. dia. × 2 ft. 9 ins. long (3 ft. 2 ins. with connections); the condenser was intended for A.C. working at 10 000 V. and had a total capacity of 0·03 μF.

The nature and purpose of protective cables and surge absorbers are concisely defined in a paper by H. W. Clothier, B. H. Leeson and H. Leyburn,* with examples from practice. A *protective cable* is a cable a few hundred yards long connected between an overhead line and station apparatus; and a *surge absorber* is usually an inductance coil of high capacitance to earth connected in series with the line. Lightning arresters and arc gaps are shunt devices, but protective cables and surge absorbers are series connected, and their primary action is therefore to reduce not the amplitude of an impulse wave or surge but the steepness of its front. This reduction in steepness, may, however, prevent the wave from reaching its full amplitude, particularly if it is short. The length of cable required for effective protection depends on the extent to which the insulation of the line is higher than that of the station apparatus. Often the cable used near stations in thickly populated districts is long enough to give satisfactory protection against surges.

347. Earth Wires.—A continuous steel earth-wire (often barbed) is generally run along the top of the poles of a transmission line, and serves to protect the conductors to some extent from lightning, by maintaining a zone at earth potential and by acting as a lightning conductor (§ 348). If underground cables are used to carry aerial lines across a street, as is sometimes the case, the overhead earth-wire should be brought down also, and wound on to the cable sheathing; and earth plates should be provided at each side of the crossing. The wire should in any case be earthed at every second or third pole if possible. Where no good natural earth can be found in which to bury the coil of earth-wire, an iron pipe is driven into the ground and either coke or salt filled in; it should be placed where rain will run in. The earth connection for all types of protective devices should be as short as possible to be effective, and especially for condensers. On a wood-pole line the use of an earth wire increases the risk of short-circuiting by birds. (See § 324, Electricity Commissioners' Regulations on earth-wires.)

The difficulty met with in finding a reliable low-resistance earth, in rural districts especially, has led to the adoption on the Continent of the system of protective switching in conjunction

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* *Jour. I.E.E.*, Vol. 82, p. 445. See also E. T. Norris, Paper No. 302, C.I.G.R.E., Paris, 1937, and *El. Ind.*, Oct. 1937, p. 1245; also "Lightning Protection," *Power Engineer*, Dec. 1930, p. 458.

with an 'artificial earth'; this is described in § 358*a*. The unreliability of earthing resistances generally was well brought out by an investigation at the N.P.L.*

348. Lightning Conductors.—In order to secure absolute protection of buildings from lightning † a complete network of wires, connected with earth at many points, would be made to cover the whole structure; this is indeed practically done in the case of magazines. Ordinarily one or more lightning conductors are used, according to the size of the building, and the nearer the arrangement corresponds to a complete screen the better will the protection be. Iron or steel wire or stranded rope is considered to be more effective than copper, and is also less liable to be cut away and sold, but is more susceptible to corrosions.

A conductor should run as directly as possible from its highest point to earth, not following the contour of the building but bridging over all projections. It should be so supported that there is no risk of its fracture by subsidence of the structure. As far as possible it should be run where it will not be within striking distance of metals on the inside of the walls, such as gas or water pipes or electric wiring, as there is always a danger of a discharge flashing over; insulators should not, however, be used as supports. It is good practice to connect together all the separate conductors on a building by horizontal ring conductors both on the roof and near the ground, and also to connect them electrically to any outside metal work, such as rain pipes, iron or lead roofing, ventilating pipes, and the like. There cannot be too many multiple vertical points or aigrettes; apart from the main vertical rods, short ones should be joined to the upper horizontal conductor at frequent intervals, and especially at all points above the general level. Lightning conductors sometimes terminate in a large corkscrew-like aigrette, of several spirals, apparently to improve their appearance; this acts as a powerful choking coil, and is probably worse than having no conductor at all, as a high-frequency discharge will almost certainly choose another path.

Joints in the conductor should be made both mechanically and by soldering, and the conductors should preferably be painted, even if already galvanised. For iron or steel conductors the best earth plate is a perforated pipe of the same metal, containing the end of the conductor packed round with granulated carbon, and placed where rain off the roof will keep it moist. Modern copper earth plates are often made of No. 16 gauge sheet metal with a number of triangular tongues or projections stamped out from the solid to form points from which the discharge may take place

* 'An Investigation of Earthing Resistances,' J. P. Higgs, *Jour. I.E.E.*, Vol. 68, p. 736.

† A very instructive address on this subject, by A. Hands, is reported in *Electricity*, Vol. 30, pp. 126, 185, 191.

more readily. It is convenient to have disconnecting links arranged so that the resistance from one earth plate to another can be readily measured through the intervening ground. This varies enormously in different localities, but a comparatively high resistance is immaterial in a place where a really good natural earth can nowhere be found. Owing to electrolytic action between the earth plates and moist ground, D.C. tests of earth-plate resistance are somewhat inaccurate, though, by reversing direction after each test, results near enough are obtained; there are, however, methods of and apparatus for testing, using interrupted or alternating currents. The customary method of ascertaining the resistance x of an earth is by means of two other auxiliary or independent earths y and z. By means of the Wheatstone bridge (§ 120), readings (both direct and reversed) are taken of each pair in turn, deducting the resistance of the leads and recording the average value of each pair in ohms. Then if $(x + y) = p$; $(x + z) = q$; and $(y + z) = r$, it follows that $x = (p + q - r)/2$.

349. **Switching Surges.**—Abnormal stress may be placed upon the insulation of a circuit either when 'switching on' or when 'switching off.' On switching a transformer into circuit the voltage may rise to about twice its normal value unless it happens that the switch is closed at the instant when the voltage is a maximum and the magnetising current (lagging 90°) is therefore zero for the moment. If the switch be closed very slowly a flash-over will ultimately occur at the moment of maximum voltage; this avoids the voltage surge otherwise set up but it damages the switch contacts. In this and other cases the pressure surge on switching-in may be reduced by closing the circuit through a high resistance which is connected between charging contacts (§ 368) and the main switch contacts.

Apart from the possibly excessive value of the pressure surge when switching-in, there is a temporary concentration of stress on the end turns of inductive windings. At the moment of switching-on practically the whole applied pressure is concentrated on the end turns, the building-up of the current being delayed by capacity effects. The steeper the wave-front of the applied pressure the more severe is this concentration of stress. Protective measures include reinforcement of the insulation on the turns concerned, or the use of a suitably insulated reactance in series with the winding. "Co-ordinated" transformers have special arrangements of windings to secure equal capacity distribution.

On switching off or otherwise interrupting the circuit of an inductive winding (*e.g.* a motor field winding by returning the starter to 'off') there is a sudden collapse of the magnetic field which, in collapsing, induces an E.M.F. in the winding. This E.M.F. is higher, the greater the initial magnitude of the field and the more rapid its collapse. To protect the switchgear from the vicious arcing, and the insulation from the severe strain which otherwise arises, the inductive winding should be switched in parallel with a non-inductive resistance a moment before it is disconnected from the main circuit; there is thus provided a circuit in which the energy stored in the magnetic field (§ 57) may be dissipated harmlessly.

The violent fluctuations of load in electric arc furnaces, including frequent interruptions of circuit during the early stages of melting, impose severe stresses on the end turns of the transformers supplying the furnaces.

350. **Resonance.**—As explained in § 47 a circuit containing inductance and capacity in series may be in resonance, in which case the voltage across the inductance and across the capacity may be indefinitely high, however low the applied voltage. The resonant voltage is only limited by the ohmic resistance of the circuit, and may easily be high enough to break down the insulation of the circuit. The relation between inductance and capacity required to establish resonance varies with the frequency of the current (§ 47) and there is therefore especial danger of resonance: (i) If an excited alternator be run up to speed (or a motor or converter be allowed to slow down) whilst connected to a circuit, because the current then passes through all values of frequency below the normal value. (ii) If the pressure wave be not a pure sine wave, because resonance may then occur at the frequency of some of its harmonics. (iii) If the circuit be subjected to an arcing ground (§ 351), because the irregular currents then flowing contain many harmonics.

Since the amplitude of resonance decreases as the ohmic resistance increases, the temporary addition of resistance is a useful precaution where there is risk of resonance. The useful employment of resonance in half-wave and quarter-wave transmission is referred to in § 318.

351. Arcing Grounds: Intermittent Earths.—In a transmission system, the neutral point of which is earthed directly or through a resistance (§ 354), the current flowing through an earth fault on one phase to the earth connection of the neutral will be sufficient, ultimately if not at once, to operate the overload protection devices (§§ 342, 343) or the leakage or balance selective protective devices (§§ 357 *et seq.*). If, however, the system be operated with isolated (non-earthed) neutral the only effect of an earth fault on one phase of a 3-phase star-connected system will be to raise the potential of the sound phases to $\sqrt{3}\ E$ volts above earth, where E is the normal voltage between line and neutral. Such, at any rate, is the theory of the isolated-neutral system and if the earth connection on the faulty phase be a definite one, the new distribution of potential will be effected without much surging and will then remain steady; provided that the insulation of the sound phases can withstand the higher voltage to which it is subjected the system can remain in service until there is an opportunity to locate and remedy the fault. If, in the meantime, an earth fault occurs on one of the other phases as well there will be a short circuit between the two faulty phases.

One of the chief dangers of the isolated neutral system arises from the fact that an earth fault on one of the lines is rarely in the form of a definite connection to earth. It is almost invariably in the form of an arc which, being shunted by the capacity of the line to earth, is unstable. After the first extinction of the arc there is left on the line a relatively steady high-voltage charge which, added to the normal line voltage, causes the arc to be struck again. This action may be repeated indefinitely, exceedingly high voltages being built up by cumulative charging of the line, and surges being established which vary in frequency and amplitude according to the electrical constants (R, L, and C) of the circuit and the position of the 'arcing ground' in the system. Apart from the possibility of their establishing resonance (§ 350), arcing grounds subject the insulation of the line to abnormal voltages.

One method of suppressing arcing grounds consists in providing each line with an *arc suppressor*, *i.e.* an automatic device which, in the event of a break-down to earth, at once connects the line affected definitely to earth near the station. The line thus being rendered 'dead' the arc is extinguished, but the definite earth connection involves considerable shock to the system, and by raising the voltage of the sound phases (as explained above) introduces a risk of break-down at some other point. It is generally arranged that the definite connection to earth is temporary, in the first instance, so that normal service may be resumed if the earth fault is cleared; if the fault persists the suppressor is locked 'in' the next time it closes.

An alternative method of protecting systems against arcing grounds consists in using the *Petersen earth coil* which is designed to neutralise the capacity effect of the line and, by removing the residual charge on the latter, to prevent the arc from being re-struck. The action of the coil may be explained as follows * :—

Referring, for simplicity, to a single-phase network, the phases 1, 2 (Fig. 61) have capacities C_1, C_2 with regard to earth; and the 'earthing coil' L is con-

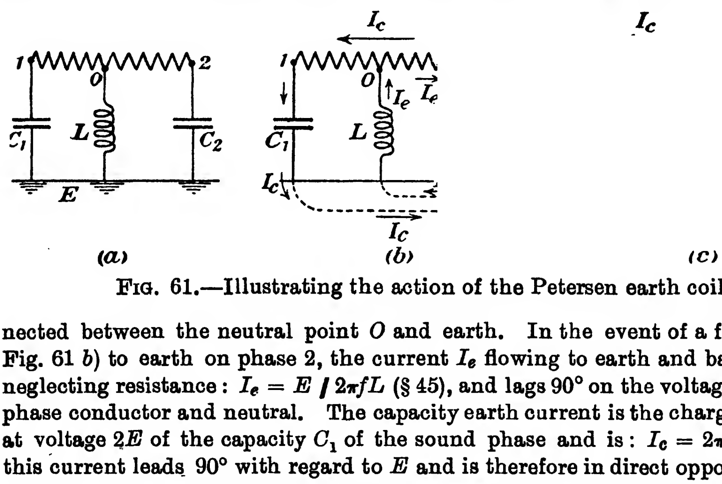

FIG. 61.—Illustrating the action of the Petersen earth coil.

nected between the neutral point O and earth. In the event of a fault ($2 - X$, Fig. 61 *b*) to earth on phase 2, the current I_e flowing to earth and back *via* L is, neglecting resistance: $I_e = E / 2\pi fL$ (§ 45), and lags 90° on the voltage E between phase conductor and neutral. The capacity earth current is the charging current, at voltage $2E$ of the capacity C_1 of the sound phase and is: $I_c = 2\pi fEC$ (§ 46); this current leads 90° with regard to E and is therefore in direct opposition to the current I_e. The paths of the currents I_e, I_c are shown by the arrows in Fig. 61. In order that I_e may equal I_c: $2\pi fL = 1 / (2\pi fC)$, *i.e.* the inductive reactance of the earth coil must equal the capacity reactance of the network capacities against earth. If this condition be fulfilled the currents I_e, I_c will cancel out in the fault $2 - X$, *i.e.* the earth fault current will be zero and the arc will be suppressed; without the coil L the capacity current of the sound phase would flow through the earth fault and cause intermittent arcing.

Actually the currents I_e, I_c have each a power component (due to the resistances, etc., of the circuits); these components do not cancel, but add together to form the resultant current I_r through the fault (Fig. 61 *c*). It is claimed that

* *See also Elekt. Zeits.*, Vol. 40, p. 5; Vol. 42, p. 695; and *Science Abstracts*, Vol. 22, B, No. 830; Vol. 25, B, No. 113.

the residual earth current is very small (from 4-15 °/₀ of I_c), and that it is incapable of maintaining the arc; also, that effective protection is provided even when the inductive and capacity reactances are not balanced accurately, so that there is ± 30 °/₀ difference between I_e and I_c.

It is claimed that the Petersen coil is far more effective than a simple resistance or gap discharger between neutral and earth, in dispersing the dangerous charge on the faulty line, but opinions differ as to the kVA capacity of lines to which the system can safely be applied, and as to the possibility of dangerous pressures being established by resonance between the capacity of the lines and the inductance of the earthing coil. It has been proposed to make the earthing coil a 'dissonance coil,' *i.e.* of such inductance that it is not in resonance with the capacity of the system, but this seems to remove the essential feature of the Petersen system whilst still leaving the possibility of resonance at harmonic frequencies.

From tests and practical experience with a 'neutral grounding reactor' (Petersen coil) in an American installation, W. W. Lewis (*Jour. Amer. I.E.E.*, Vol. 42, p. 467) concludes that the system with reactor is more like an isolated-neutral system than a grounded-neutral system from the standpoint of voltage stresses, except that excessive voltage rises due to arcing grounds are eliminated. The system with reactor has an advantage over the grounded-neutral system in that arcs are eliminated without short-circuit. The reactor will probably be limited to comparatively low voltage and short systems owing to the cost of installing it on high voltage, long systems, and the difficulty of obtaining a current balance at the arc; also, its use will probably be limited to isolated-neutral systems, the operation of which is not satisfactory but on which, for some reason, it is not desired to connect the neutral straight to earth.

The value of earthing the neutral through a resistance as a protection against arcing grounds and other causes of voltage rises has been discussed by K. Edgcumbe who reaches the following conclusions:—

1. Three-phase systems with insulated neutrals are dangerous owing to their liability to transient voltage rises due to intermittent earths.

2. The connection of the neutral point of a 3-phase system direct to earth is inadvisable owing to the unlimited current which may flow in the event of an earth fault.

3. Earthing the neutral point through a resistance affords complete protection against voltage rises due to intermittent earths. It is valuable in suppressing rises due to all other causes, limits the current in the event of an earth fault, and enables advantage to be taken of leakage tripping.

4. The earthing choker is valueless on complicated systems, always involves a serious risk of resonance, offers no advantages over the earthing resistance as a means of suppressing intermittent earths, and is useless as a protection against voltage rises due to any other causes (*El. Rev.*, Vol. 90, p. 399).

352. Failure of Insulation; Leakage Protection.—The causes of failure in the insulation of any part of a circuit may be: (i) deterioration of the insulation by overheating (§§ 72, 80) caused by overload or otherwise; or (ii) stressing of the insulation by voltage higher than it will withstand even in its normal condition, such excessive voltage being due to any of the causes discussed in §§ 345-351. The effect of the failure is to introduce danger to life from shock; possible failure of insulation in other circuits by the admission to or near them of pressure higher than that for which they are insulated; and possible flow of leakage current which may cause damage by electrolysis, char surrounding insulation, woodwork, etc., by its heating effect and thus introduce risk of fire, or be of such magnitude as to constitute a short circuit with all its serious consequences (§ 338). To prevent failure of insulation it is necessary to avoid the causes of failure specified above.

Once insulation has failed, the only safe course is to isolate the affected portion of the circuit and repair the insulation. Theoretically a single failure in the insulation between a conductor and earth should not matter if the insulation be intact throughout the remainder of the circuit. Actually, however, the failure subjects the insulation of the other line or lines to the full voltage of the system (§§ 351, 354) and the danger of shocks is also increased. If the neutral be earthed, an earth fault on any line will result in short-circuit through the resistance of the fault and of the neutral earth connection.

Theoretically, several faults may exist simultaneously without disturbing operation, so long as they are *all* on the same pole or phase, but actually there may be a pressure difference of 10 or 15 V between two points in a wiring system (much more in other cases) and this is sufficient to cause considerable leakage under favourable conditions (*cf.* rail return in traction systems, § 901, *et seq.*, Vol. 3).

The leakage current between a nominally insulated conductor and earth may be measured by a milliammeter connected between the conductor and earth, and when the total leakage current exceeds 1 / 1 000 of the maximum current supplied steps should be taken to locate the leakage and improve the insulation of the system.

Long before the leakage from a faulty system becomes sufficient to operate overload-protection devices (§§ 342, 343) the leakage current is dangerous, and it is desirable that the faulty section should be isolated automatically by a *leakage-protection device.* This may consist of a relay which is actuated by the leakage current itself, or it may utilise the fact that when there is leakage the algebraic sum of the currents in the three conductors of a 3-phase system is no longer zero.

In the Howard leakage detector a current transformer is connected in the earthing wire of, say, a switchboard frame, and the secondary of the current transformer is connected to a tripping relay (§ 344). Then if there is leakage to earth from the bus bars (in the example chosen) the current transformer carries the earth current and the relay trips the circuit breaker and isolates the defective bars.

In the Ferranti-Field leakage-protection system for cables, a coil connected to the trip-relay is wound on an iron core which surrounds the 3-phase cable to be protected. In the event of leakage from any one of the cable cores, the algebraic sum of the currents in the latter is no longer zero; a resultant flux therefore traverses the iron core and induces an E.M.F. in its winding which operates the relay (*see also* § 359 (i)).

Other selective or discriminative systems of protection which also isolate the defective section in the event of leakage, are described in § 359.

353. **Earthing.**—Regulation 21 of the Electricity Regulations (Factory and Workshop Acts) runs as follows:—

Where necessary to prevent danger, adequate precautions shall be taken either by earthing or by other suitable means to prevent any metal other than the conductor from becoming electrically charged.

This regulation applies at all pressures exceeding 125 V alternating or 250 V direct. The term 'earthed' as defined in the Regulations means connected to the general mass of earth in such manner as will ensure at all times an immediate discharge of electrical energy without 'danger.' This is defined as danger to health or to life or limb from shock, burn or other injury or from fire or explosion.

Methods to be adopted and precautions to be observed in earthing specified parts of electrical systems are discussed very fully in the *Memorandum on the Electricity Regulations,** which should be consulted; also, the full text of the I.E.E. Wiring Regulations. For notes on Earthing in Mines see § 821 Vol. 3. It must here suffice to say that all bare metal—such as, machine or switchboard frames, transformer tanks, cable sheaths

* H.M. Stationery Office, 4d. net.

(metallic), etc.—which may be rendered 'live' by leakage or by direct contact with charged conductors must be 'earthed' by connection to a suitable 'earth plate' (§ 348 and § 821, Vol. 3). In some instances the bare metal which must be earthed is used to prevent access to live parts, as in the case of metal screens enclosing switchgear; in other cases, *e.g.* motor frames, transformer tanks, etc., it is a constructional part of the apparatus. Where, as in portable apparatus, a permanent earth connection cannot be made to the frame, it is usual to provide a special earthing conductor in the cable supplying the apparatus in question, this conductor leading back to some point at which a permanent earth connection is established.

If an operator must necessarily work on or near live metal he should be provided with rubber gloves and an insulating mat or stand; and he should be prevented, by an insulating screen, from touching earthed metal. It should be remembered that it may be dangerous to touch even the insulation of conductors at high or extra-high pressure. Working on live overhead conductors is extremely dangerous and demands the utmost vigilance. It is possible to receive a fatal shock when working on a nominally dead line which runs parallel to live conductors, owing to the high-pressure charge induced by the latter (*see Science Abstracts*, Vol. 25, B, No. 1039).

354. Earthing the Neutral.—During normal operation the 'neutral point' of any electric circuit is at earth potential, and by connecting it to earth it is kept at this potential whatever the irregularities on the system. It is usual to make the connection between neutral and earth through a resistance which limits the current flowing in the event of a 'dead (low-resistance) earth' on one line. Iron grid resistances, water resistances, and carbon resistances are used for this purpose; carbon resistances have several advantages one of which is that the negative temperature coefficient of resistance of this material allows the current to increase gradually until the circuit breakers operate. If the neutral points of two or more paralleled machines or stations be earthed, precautions must be taken to prevent the circulation of current in the parallel earth connections.

With an earthed neutral, an earth fault on any line at once operates the circuit breakers or selective protection gear; the only disadvantage is that a shut-down may be occasioned by a transitory break-down from line to earth. Theoretically a system with insulated neutral can be kept in service with an earth fault on one phase but there are serious practical disadvantages in such a system (§ 351).

The general import of the various British regulations on this subject is that, where the pressure of supply between the conductors of a system of mains exceeds 125 V the neutral point at the generating station, sub-station, or transformer supplying the circuit must be earthed and the insulation of the mains must be maintained efficiently at all other points; if the current passing through the connection to earth exceeds 1/1000 of the maximum supply current of the circuit, the insulation of the latter must be improved. The neutral point of the star winding of each 3-phase circuit used for extra high pressure (over 3000 V) may be connected with earth (at one point only, *viz.* the station, sub-station, or transformer) or it may be insulated. If connected to earth through a resistance the latter must be low enough to ensure that the main fuse or circuit breaker acts in the event of an earth fault. If the neutral point is not earthed a separate electrostatic voltmeter must be connected between each distinct circuit and earth, and if the indications of the voltmeters show the insulation of any of the circuits to be faulty the insulation must be restored.

354*a*. Earth Leakage Trips.—If the exposed metal work of apparatus supplied from a system with an earthed pole be connected to a low-resistance earth, a breakdown of the insulation will cause the passage of sufficient current to melt the fuses or to operate the controlling circuit breaker and thus isolate the faulty apparatus. Sometimes, however, it is impossible to obtain an earth connection of low enough resistance to pass sufficient current to operate overload protective devices; and in such circumstances a breakdown of insulation results in exposed metal work being charged to a high potential. To avoid this source of danger the method of automatic protection by leakage trips is extensively used on the Continent, and is now commercially developed in this country.*

The principle of a leakage trip is that of isolating a faulty circuit when the exposed metal sheathing of any cables or apparatus comprised within it becomes charged to a stipulated potential with respect to earth. The tripping mechanism for the automatically operated circuit breaker must be sensitive so that a very small value of the operating voltage is required. The resistance of the actual connection between metal work and earth is then immaterial. The essence of a leakage trip is that it responds to the potential of the

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* From 1935, Messrs. Nalder Bros. & Thompson have taken up the manufacture of these protective devices, under licence from the Continental patentees.

exposed metal and not to over-current as does a fuse or overload circuit breaker. This method of protection has been fully developed by T. C. Gilbert.*

In a consumer's installation each appliance should preferably be separately protected, the metal work (not belonging to the circuit) being connected to a protective wire which passes through the leakage trip-coil and thence to the artificial earth. The leakage current operating the trip opens the circuit breaker on *all* poles,

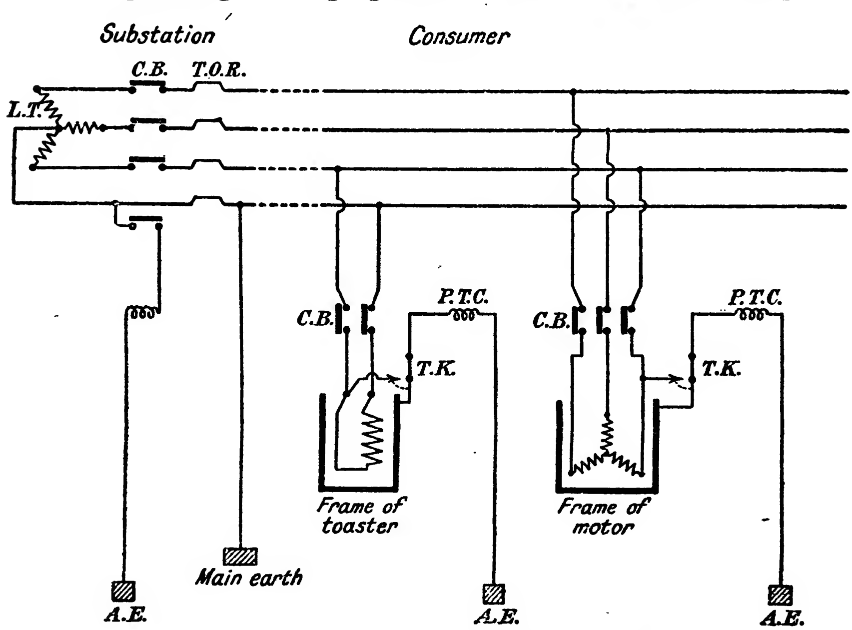


FIG. 61A.—Diagram of protective switching.

C.B. = circuit breaker. A.E. = artificial earth. T.K. = test key.
T.O.R. = thermal overload release, operating circuit breaker.
P.T.C. = potential trip-coil, operating circuit breaker.

and the switch incorporating the device is used in place of, and not in addition to, the ordinary switch. The main earth wire is diverted through the trip-coil instead of going direct to the earth connection. A high resistance earth is now immaterial; with 200 ohms the trip will operate at 20-24 V and with 500 ohms at less than the human danger-point of 42 V. Even with 1 000 ohms this generally occurs.

Fig. 61A illustrates the system diagrammatically. The low-

* *Artificial Earthing for Electrical Installations* (Benn).

tension lines from a sub-station are shown, together with part of a consumer's installation, *viz.* a toaster and a 3-phase motor. The distribution generally is protected by a leakage device and artificial earth at the sub-station; and (as shown in the diagram) the tripping device breaks the circuit not only on all three poles but also on the connection of the neutral to the trip-coil. Ordinarily there would also be an overload release operating the same circuit breaker, and actuated by a coil and a bimetal thermal trip, but no fuses; the thermal device acts where there is a prolonged overload of amount insufficient to actuate the breakers, but in case of short-circuit the coil acts first. For sub-station work, a time lag is used to prevent a shut-down from transient faults. On the consumer's side, the two appliances are shown as individually protected, though one device could be used for the whole at some sacrifice of the efficiency due to segregation of trouble. A toaster is chosen because its metal case does not protect the operator from contact with the live wires, so that earthing it in the ordinary way through a 3-pin socket would be risky. Leakage to the frame of the apparatus shown, from the live wires, would immediately open the circuit on all poles.

Mr. Gilbert summarises the disadvantages of 'solid earthing' and the corresponding advantages of 'artificial earthing' under six heads, which are here abbreviated:—

(1) With solid earthing, heavy currents must flow outside the normal conducting parts of a circuit before isolation, by blowing the fuse on one pole only, can be effected, with consequent risk of high potentials, fire and damaged apparatus. With artificial earthing only a few mA are needed to effect isolation, which occurs on *all* poles within 1½-2 periods of the supply. The small current can be safely passed through a human body.

(2) With solid earthing, it is doubtful whether the lead sheathing of light lead-covered cables or the metal of conduit systems can deal with these heavy fault currents safely; whereas the small currents of the artificial earth system can certainly be carried by these and do their work.

(3) Solid earthing *must* have very low-resistance earths, which can often neither be obtained nor maintained; whereas several hundred ohms are permissible with artificial earthing. This is the most important point of all.

(4) Circuit fuses must be correctly adjusted, with solid earthing, if isolation is to be effected, and even so it is a slow process; whereas, with the artificial earth system the protection is both rapid and completely independent of the circuit fuses, whether correctly rated or meddled with. If the leakage persists, the switch can neither be closed nor tied in against it; otherwise, when the leakage has been removed, the circuit can be restored at the switch without the fuses having been burnt out. In fact, the system could be extended to the elimination of fuses.

(5) Solid earth connections cannot readily be tested with the heavy currents they are called upon to carry; and the usual form of test with small currents does not ensure that the large current can be carried at all; whereas a test key is an essential part of the protective switches, and in some cases acts automatically.

(6) The connection to a solid earth of any apparatus (such as a toaster or an electric fire), of which the outer case does not form a complete and effective earth shield over the live elements, introduces the risk of shock that would be absent if the casing were not earthed; with protective switching there is no possibility of high potentials appearing upon the surface of any protected part, and the casing of apparatus with exposed elements is safe under all conditions, as the trip will operate under a safe pressure of from 8 to 24 V.

In the matter of wiring, this system renders unnecessary the use of a large earth conductor (half the conductivity of the largest wire to be protected, under the I.E.E. rules), and it appears proven that the cheaper wiring systems, properly installed, may be rendered quite as satisfactory as the heavy screwed conduits so generally used in Great Britain. For farm and rural work most engineers will agree with Mr. Gilbert (as do the Authors) that tough rubber insulation systems are the safest.

It has long been a matter of discussion whether the cases of service cut-outs and meters should be earthed; generally it is not done because of the danger of internal arcing. There is no doubt whatever that the cases of prepayment meters, which are handled by consumers, should be protected; but with solid earthing there is no certain protection. With the system here described it becomes perfectly safe, as the leakage current is limited to the safe value of about 25 mA.

355. **Low-voltage and Interruption of Supply.**—The inconvenience and financial loss (to supplier and consumer) occasioned by interruption of supply must be avoided as far as possible by securing safety and reliability in all parts of the supply system and by isolating faulty sections before the damage has time to spread (§ 357). Abnormally low voltage of supply is naturally associated with some radical defect in the supply equipment or its conditions of operation; also, supply at low voltage cannot be utilised efficiently* or, in some cases, with safety.† For

* Even 5 % less than rated voltage involves 15-20 % reduction in the candle power of tungsten filament lamps.

† At reduced supply voltage motors require a heavier current to drive a given load; overheating then occurs. If the drop in voltage is sufficient to cause the motor to stop, the machine then short-circuits the mains.

both of these reasons it is necessary to interrupt the supply if the voltage becomes abnormally low (say 50 °/₀ of normal). The interruption is generally effected at the main switch of the circuit concerned so that when the voltage again becomes normal, or when supply is resumed after interruption from any other cause, full voltage may not inadvertently be applied abruptly to apparatus which was in service when the supply failed.

The 'no-volt' or 'low-voltage' release for a circuit breaker consists of a pressure-wound (*i.e.* shunt) solenoid which holds open a switch in the trip circuit as long as the supply voltage exceeds, say, 50 % of normal. Directly the voltage drops below the predetermined limit, the solenoid releases the tripping switch and the circuit breaker is opened. In the case of motors used in conjunction with starters (Chapter 29) the low-voltage device is arranged to hold the starter 'on' until the voltage becomes dangerously low, and then to allow the starter to be returned to the 'off' position by a spring so that the motor has to be re-started in the regular manner when supply is resumed.

A definite air gap is needed in the magnetic circuit of low-voltage releases to ensure that residual magnetism does not hold the device 'on' after the voltage has fallen below the prescribed limit. It is common to specify that a low-voltage device shall not hold, when switching in, if the voltage is lower than 80 % of normal and that it shall release, in service, if the voltage falls to 50 % of normal. In variable-speed motors where the field current varies within wide limits the low-voltage release may have to be connected across the mains (instead of in series with the field windings) in order that it may not open at the lower values of field current.

If the supply pressure exceeds 600 V, the low-voltage solenoid is generally supplied through a potential transformer.

Interlocks of various descriptions are used to prevent switches from being closed whilst workmen have access to parts which would then become live (§ 373).

356. Fire Risk.—The fire risk from the wiring, switchgear, and accessories of a domestic lighting, heating, or power installation is negligible provided that the whole of the equipment is by reputable makers and is installed in accordance with the Wiring Regulations of the I.E.E. (London), or the corresponding rules of similar bodies in other countries. Similarly, the Home Office Regulations for the use of electricity in factories, workshops, mines, etc., take into consideration the special conditions of these services, and compliance with these Regulations eliminates practically every risk. Fire arising from a wiring installation or its accessories can only be due to overheating, leakage, or open arcing or sparking; against all of these contingencies suitable provision is laid down by the rules and regulations mentioned. Even a 'dead short' between the conductors of a multicore cable in an explosive atmosphere is unlikely to cause fire or explosion if the circuit is provided with proper protective devices, because the latter isolate the faulty section before the arc can penetrate the outer insulation of the cable.

The main fire risk in a modern electrical installation is probably in the oil switches and generators. In the past a number of disastrous switchboard fires have been started by oil switches being unable to interrupt safely the enormous amount of power flowing through them under short-circuit conditions. This danger has been reduced by increasing the 'breaking capacity' (§ 371) of oil switches: and the risk of any general conflagration is further reduced by the provision of vent pipes which carry oil vapour away to the open air; by the use of 'explosion proof' switch tanks; and by the use sometimes (§ 378) of a switchboard construction in which each switch is in a separate fireproof compartment, the latter having a drain for the removal of oil, should any escape. A common provision in major switch houses is to fill with carbon dioxide any switch or transformer compartment in which fire may break out.

In the event of arcing within the windings of a generator due to break-down of insulation, there is a great danger of the fire being fanned and spread by the blast of air blown through the machine for ventilation (§ 146). This danger may be reduced by the provision, in the outgoing air ducts, of fusible links which release dampers cutting off the air *supply* if the temperature of the outgoing air becomes so high as to indicate fire; or by arranging that the electrical protective gear, which cuts the generator out of circuit in the event of break-down, also cuts off the air supply. It is now usual for generators to be ventilated by air which is circulated in a closed circuit. This avoids carrying dust into the windings. Adequate provision must be made for cooling the circulating air and the air may be charged with nitrogen to such an extent that it will not support combustion.

To eliminate the risk of overheating and fire which would result from failure in the supply of cooling air (or water or oil) to a machine, etc., dependent upon forced cooling, automatic devices should be used to give an alarm and shut down the plant in that event.

357. Selective Protection.—In distribution networks where large amounts of power are transmitted through interconnected cables it is imperative that a faulty machine or circuit should be isolated promptly from the remainder of the system in order that sound parts of the system may not be affected by currents flowing to the fault. The greater the degree of subdivision of the system, the smaller is the area affected by isolation of a faulty part. On the other hand, the greater the extent to which the feeders are interconnected (so as to form a network with alternative lines of supply to practically every point), the more difficult it becomes to isolate a faulty section promptly and with absolute discrimination. Overload relays with graded time elements (§ 344) offer one means of opening first the switch nearest to the fault, but if the fault can also be fed through another cable connected to the first beyond the point of break-down it is obviously necessary to isolate the fault by opening switches on both sides of it. This can be accomplished by directional relays (§ 358). Alternatively, each section of the network can be protected by one or other of the special systems of selective protection described in § 359; these systems all operate on the general principle of comparing the conditions at the two ends of the portion of the circuit which they protect; in this way, it is possible to discriminate between a fault in the section protected and abnormalities due to load fluctuations or to a fault elsewhere in the network which will be cleared by other protective gear.

Another method of selective protection which has been used extensively of late years is that in which the time lags of the relays are automatically graded according to their distance from the fault. This system, known as distance-protection, is explained in § 359.

358. Reverse Current and A.C. Directional Relays.—The simplest type of reverse-current switch is the reverse-current 'cut-out' sometimes inserted in battery-charging circuits the latter should the direction of current be opposite to that which is required for charging. A reverse-current switch or relay for a D.C. circuit requires only a current coil for its operation and it will act directly the current reverses. In an A.C. circuit, however, the alternating current has no definite direction of its own; the actual direction of the current reverses in each 'cycle,' and 'reversal' of an alternating current in the sense here considered can only be defined in terms of the relation between the current and voltage waves. An alternating current is said to be reversed when the relative directions of current and voltage are reversed. To determine when this is the case it is necessary to employ a device operated by both current and voltage, *i.e.* one which discriminates between forward and reverse *power*. An A.C. relay responsive to direction of power flow is generally called a directional relay.

It is obvious that either a dynamometer-type or induction-type wattmeter (§ 109) can be used as a directional relay, the movement of the instrument being fitted with a contact maker in the trip circuit, instead of with a pointer. The connections are such that so long as the power is 'forward' the relay contacts are held open, but when the power reverses they are closed. The induction-type relay may operate the trip contacts through a cord wound round the spindle of the induction-disc; this provides a time element (§ 344) and prevents the main circuit from being opened by momentary reversal of power.

Reverse-power relays are used to prevent alternators or transformers from being fed by the bus bars or circuits to which they should supply power; also, to prevent a feeder-fault from being supplied through a feeder connected in parallel with the defective one. These relays cannot be used on interconnector cables which may, in normal service, have to carry power in either direction between two stations. If the main voltage becomes very low, as it may do on heavy faults, there is a risk that the reverse-power relay will not operate; and, in the past, some reverse-power relays have operated on forward power at very low power factor. Modern wattmeter-type reverse-power relays can be relied upon not to operate on forward power under any circumstances, and to operate on reverse power at pressures down to 10 % of normal voltage. For complete protection two relays are needed in a 3-phase system with insulated neutral, and three relays if the neutral be earthed.

359. Selective Protection Systems.—The principal systems of selective protection for feeders, generators, and transformers are described below and their general characteristics are indicated. The automatic protection of electrical networks and apparatus is a specialised branch of engineering with an extensive literature of its own, but it is desirable that every electrical engineer should be familiar with the main principles of the subject.

The 'pilot' wires used in some protective systems have only to carry weak, low-voltage current for the operation of relays; they are therefore of small cross-section and have relatively light insulation. The pilot circuit in the Merz-Price balanced voltage system of protection as applied to a 3-phase feeder generally consists of a three-core 7 / ·029 low pressure cable; provided that the pilot cable is connected to current transformers at each end of the feeder, as in Fig. 62, it need not be laid along the same route

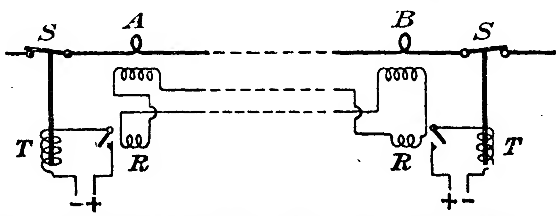


Fig. 62.—Merz-Price balanced voltage system for feeder protection. (Connections for one phase only.)

as the feeder. 'Sheathed' pilot cables are virtually three-core concentric cables, each pilot wire being provided, outside its main insulation, with a thin metallic sheath for reasons explained at (*c*) below; the sheaths are insulated from each other by a light external covering.

The construction of split-conductor cables, in which each of the halves of the main conductor acts as pilot wire to the other half, is illustrated in Figs. 66, 67 (Sec. (*d*) below). The insulation required between the two 'splits' of each phase is only that needed to withstand the P.D. existing between the splits under fault conditions. Normally, the halves of a split-conductor carry equal currents and there is no P.D. between them at any cross-section of the cable.

(*a*) *Merz-Price Balanced Voltage System.*—This system is used for the protection of feeders and depends upon the balancing of E.M.F.'s induced in current transformers placed at each end of the feeder and connected by 'pilot' wires. Fig. 62 shows the connections for one phase only, for simplicity. The secondaries of the current transformers *AB* are connected in opposition so that, normally, no current flows through the relays *RR*. On the occurrence of any fault in the feeder, the main current at *B* no longer equals that at *A*, hence current flows in the relay circuit and the switches *SS* are tripped by *TT*, completely isolating the defective feeder. The direction of the main current is immaterial, hence the system is applicable to ring mains. It is essential that the transformers *AB* should balance at all loads as long as the feeder is sound and, in order that the current-voltage characteristic may be linear the transformers have air gaps in their magnetic circuits. Owing to the electrostatic capacity of the pilot wires and the high P.D. between them when the feeder current is heavy, there is then a considerable capacity (condenser) current flowing through the pilot wires. This may operate the relays unnecessarily unless their setting is relatively insensitive. The difficulty is overcome by the use of sheathed pilot wires (*see* (*c*) below).

(*b*) "*Translay*" *System.*—The Translay system of automatic protection developed by the Metropolitan Vickers Electrical Co. Ltd. is a modification of the balanced voltage system just described. At each end of the protected feeder there

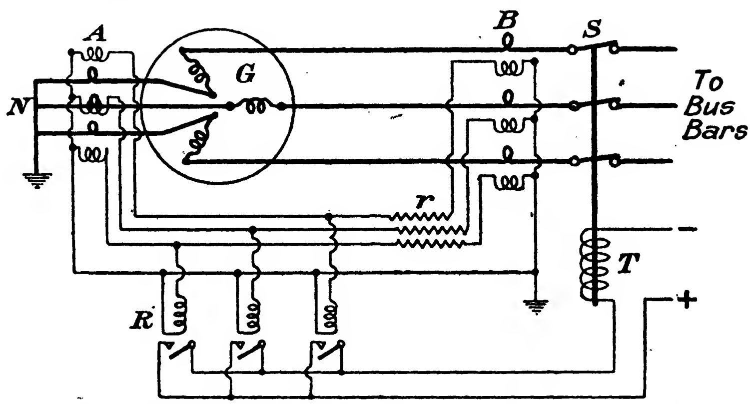


FIG. 63.—Merz-Price balanced current system for generator protection.

is an induction relay having an ammeter movement of the transformer type described in § 102. The action of this ammeter movement depends upon the secondary circuit being closed; if no current can flow in this circuit, no operating torque will be produced. The secondary circuits of the two Translay relays at the end of the protected feeder are interconnected by pilots in such a way that, with equal current flowing in the same direction through the relays, the secondary voltages are opposed. In this condition no current can flow in the secondary circuit of either relay and both of them are inoperative. When due to a fault the equality of the relay currents is disturbed, the secondary voltages no longer balance, and a current circulates in the pilot-wires and relay windings which gives rise to an operating torque, so that both breakers controlled by the relays are opened. As the maximum voltage on the pilots is under 100 V, very little trouble due to capacitance currents is experienced, and any tendency to improper operation due to this cause can be prevented by internal compensation of the relay.

(*c*) *Merz-Price Circulating Current System.*—This system, which is used for the protection of alternators and transformers, is shown in Fig. 63 as applied to a 3-phase alternator *G*. Current transformers are placed at *A* between the alternator phases and the neutral point *N*, and at *B* between the alternator and the main switch *S*. The current transformer secondaries are connected in series with compensating resistances *r*. During normal operation a current of about 5 *A* circulates through the secondaries of the current transformers and the pilot wires, but there is no current through the relay coils connected between the pilot wires and the neutral. On the occurrence of a fault the current balance in the pilot wires is disturbed, the relays *R* are operated, and the trip coil *T* opens the main switch *S*.

Ordinary instrument transformers are used, without air gap in the magnetic circuit. If the system be applied to the protection of, say, a 6 600 / 440 V delta / star transformer, with a 10 : 1 star-connected instrument transformer on the high-voltage side, the low-voltage instrument transformer would be delta-connected, and its ratio would be $(10/1) \times (6\,600/440) \times \sqrt{3} = 260:1$.

This system of protection is more sensitive and stable than the balanced-voltage system, but it is inapplicable to feeders because the resistance of the pilot wires would then be prohibitively high. The current in the pilot wires is proportional to the main current, hence fuses in the former provide overload protection.

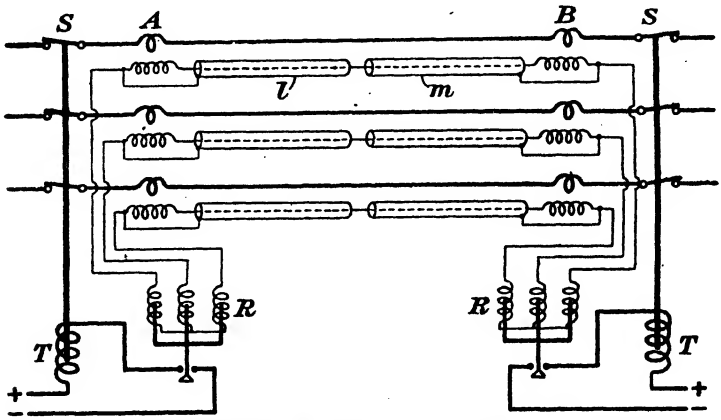


FIG. 64.—Beard-Hunter sheathed-pilot system for feeder protection.

(*d*) *Beard-Hunter Sheathed-pilot System.*—This system is identical with the Merz-Price balanced voltage system (Fig. 62) except that the capacity current trouble mentioned at (*a*) above is eliminated by providing each pilot wire with a sheath *l*, *m* (Fig. 64). The sheaths are interrupted at the centre as shown, and from a study of the connections in Fig. 64 it will be seen that the capacity currents no longer pass through the relay windings, hence the relays may be set more sensitively than in the Merz-Price system.

(*e*) *Merz-Hunter Split-conductor System.*—Referring to Fig. 65, there are used, in each phase of the line, two conductors of equal electrical resistance connected in parallel at each end of the length to be protected, but otherwise insulated from each other. Under normal conditions the total current in each phase is divided equally between the pair of conductors, but when a fault occurs this balance is disturbed. The two conductors of each phase are wound in opposite directions on current transformers at *A*, and so also at *B*. Under normal conditions, no current flows through the trip relays *R*, but directly the current balance in the 'split conductors' is disturbed, the relays *R* operate at both ends of the section and the trip coils *T* open the switches S. No pilot wires are required, but the main cables must be specially constructed on the split-conductor principle. A cable with six electrically identical cores (Fig. 66) may be used with two cores in parallel for each phase, or each phase may be served by two concentric cores (Fig. 67)* in which case the inner and outer must be transposed at intervals to maintain equal impedance in both halves of the split conductor.

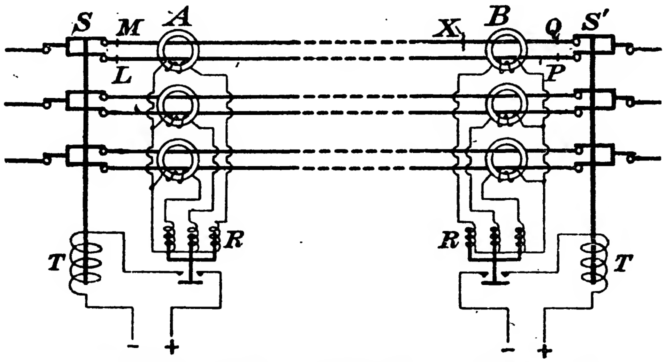


FIG. 65.—Merz-Hunter split-conductor system for feeder protection.

This protective system can be set for very low fault currents without risking disconnection of sound feeders. It will be seen that the 'split' is continued through the switches S at each end; this is to ensure that when one set of switches S' is opened, the other set also opens. If the splits were joined at LM and PQ, a fault at X (near the end of the cable) would cause the switch S' to open, but the

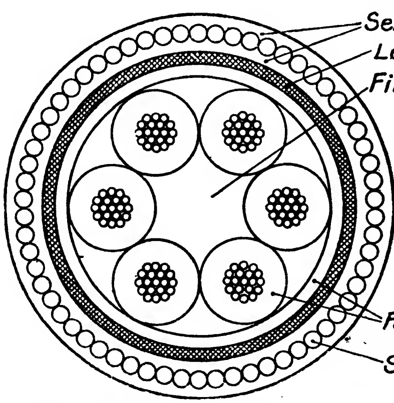


FIG. 66.—Six-core cable for 3-phase split-conductor system.

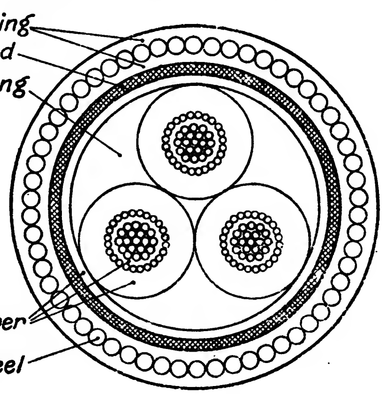


FIG. 67.—Three-core concentric split-conductor cable.

impedance of the paths $LPQX$ and MX would be so nearly equal that the switch S would probably remain closed. With the split continued through the switches, current can only flow along MX after S' has opened, hence A is unbalanced and S also opens.

* The overall diameter may be reduced by using concentric elliptical cores.

The split-conductor system is hardly suitable for pressures exceeding 20 000 V because the size of the individual cores is small (for the amount of power which it is desirable to transmit by a single feeder) and the stress on the insulation is therefore severe (§ 288).

(*f*) *Hunter Four-core Pilotless System.*—This system is a combination of the Merz-Price balanced voltage and the split-conductor systems. One phase (II in Fig. 68) is protected on the split-conductor system whilst the other phases are protected on the Merz-Price system, using the splits of phase II instead of pilot wires. Any fault on phase II causes the transformers *C*, *D* to be excited and the

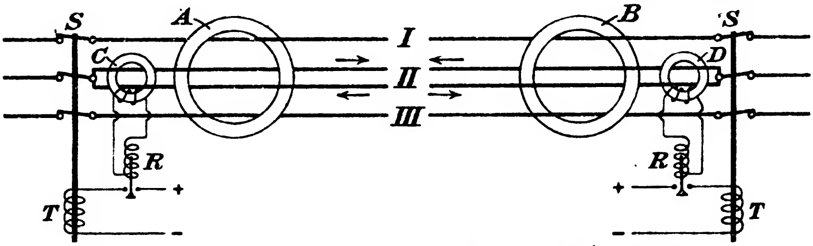


FIG. 68.—Hunter 4-core pilotless system for feeder protection.

switches *S* to be tripped. On the balancing transformers *A*, *B* the phases I and III are in opposition to the splits of phase II, and are also in opposition to each other. Normally, *A* and *B* produce equal and opposite E.M.F.'s in the splits as shown by the arrows, but in the event of any fault on I or III, this balance is disturbed, a circulating current flows round the splits of phase II, and the transformers *C*, *D* cause the switches *S* to be tripped.

(*g*) *Beard Self-balance System.*—The application of this system to alternator protection is shown in Fig. 69. The line and neutral connections of each phase winding are taken through a transformer which is connected to the tripping relay. In the event of a fault to earth or between phases the incoming and outgoing currents are no longer equal, the transformer *T* is excited, and the relay is operated. If the neutral leads be carried to the switchboard (the neutral connection and the transformers *T* being then at the switchboard), this system protects against faults in the cables between generator and switchboard, as well as in the generator itself.

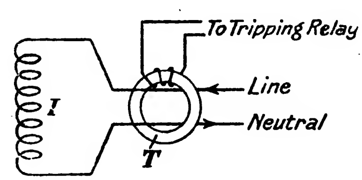


FIG. 69.—Beard self-balance system. (Connections for one phase only.)

(*h*) *McColl Biased-Relay System.*—Referring to Fig. 70, current transformers *CT* are installed at each end of the feeder, and each transformer is connected to two circuits in parallel, one of these being dotted in Fig. 70 for the sake of clearness. The pilot wires form one branch from the secondary of each transformer, and the other branch (dotted in the figure) is formed by the operating coil *O* of a differential relay and a resistance *r*, which is adjusted so that this circuit is of the same resistance as one of the pilot wires. The restraining coils *R* of the relays are connected one in series with each pilot wire. The fulcrums of the beams carrying the relay plungers are nearer the operating coils than the restraining coils, hence the latter exert the greater moment (with equal currents in *O* and *R*) and the relay has a bias to hold open the trip contracts *T*.

So long as the feeder is sound, the current transformers at each end deliver equal currents, and the currents in the operating and restraining coils of each relay are equal, hence the beam is held down by *R* and the trip contacts remain open. If a fault occurs in the feeder, the secondary current delivered by the transformer *CT* – 1 is greater than that delivered by *CT* — 2, the difference between these currents dividing between the duplicate circuit (dotted) at the left-hand station, and the duplicate circuit at the right-hand station. Since the latter circuit is, with regard to *CT* – 1, in series with both pilot wires, the total resistance of this path is three times that of the duplicate circuit at the left-hand station. As a consequence, 75 $^{\circ}/_{\circ}$ of the excess current flows through the operating coil of the relay in the supply station, and the trip contacts *T* are closed if the additional pull now obtained at *O* is sufficient to overcome the initial bias of the relay. The action of the relay depends entirely upon the relative magnitude of the currents in its two windings regardless of the actual value of the main current. Directly the trip contacts *T* are closed, the oil switch *S* is opened in the usual way; the trip circuits themselves are not shown in Fig. 70.

During normal operation, current circulates continuously through the pilot wires. If the latter be broken accidentally, the whole output of each current transformer is diverted through the operating coil of its relay and the trip circuit

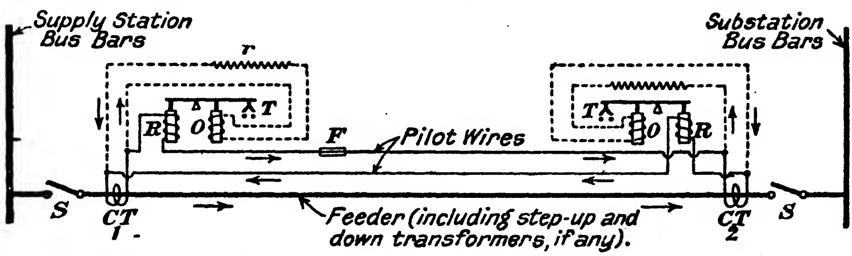


FIG. 70.—McColl biased-relay system applied to a feeder. (Connections for one phase only.)

is closed. If a fuse *F* be inserted in the pilot circuit, this melts in event of sustained overload, and by opening the pilot circuit causes the relays to operate. The equipment then gives protection against overload as well as against faults in the feeder.

(i) British Thomson-Houston Biased Transformer System.—In this system use is made of a special transformer, which is illustrated diagrammatically in Fig. 71. The 'operating' coil *AA* produces a flux as shown by the solid lines and this induces an E.M.F. in the secondary winding *CC* which is connected to the trip relay (not shown). The 'restraining' or 'biasing' winding *BB* produces a flux as shown by the dotted line; this has no direct effect upon the winding *CC*, but by increasing the flux density in the iron which it traverses, the biasing flux affects the ratio of transformation between the windings *A* and *C*.

Fig. 72 represents the application of the system to the protection of a single-phase feeder. The general principle of the protection is the same as in the Merz-Price balanced voltage system (Fig. 62), except that the trip relay is served by the transformer *AC* instead of being connected directly in the pilot circuit. The distinctive feature of the system here described is the addition of the biasing coils *BB*, which are connected across the secondary terminals of the current transformers *TT*, and therefore carry a current the magnitude of which varies with the main current. As already explained, the ratio of the transformer *AC* depends upon the value of the current in the biasing coil *B*, hence the sensitivity of the combination is greater the lower the load on the feeder. The amount of restraint is negligible up to full load on the feeder but, under overload conditions, the biassing transformer prevents the relay from being operated by: (i) Capacity currents in the pilot wires of a sound feeder; or (ii) currents in the pilot wires due to imperfect balancing of the transformers *TT*.

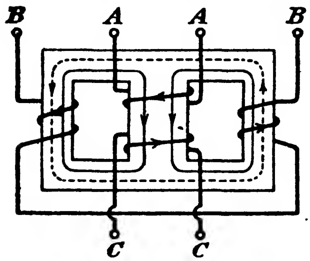


FIG. 71. — Illustrating the principle of the biased transformer.

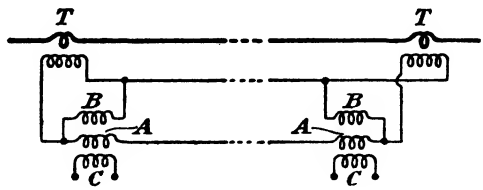


FIG. 72.—B.T.H. biassed transformer system applied to a single-phase feeder.

In a 3-phase system this method of protection can be used in conjunction with separate 'earth relays' and 'line-fault relays'; and the former can be set for maximum sensitivity because they are not affected by the heavy currents which flow through the line-fault relays when a sound feeder is carrying short-circuit currents to a fault beyond. For further information *see El. Rev.*, Vol. 90, p. 928.

(*j*) *Ferranti-Hawkins Core-balanced System.* — This may be described as a combination of the Merz-Price and the Ferranti-Field (§ 352) systems. Selective protection is obtained, but against earth faults only (which, in practice, always

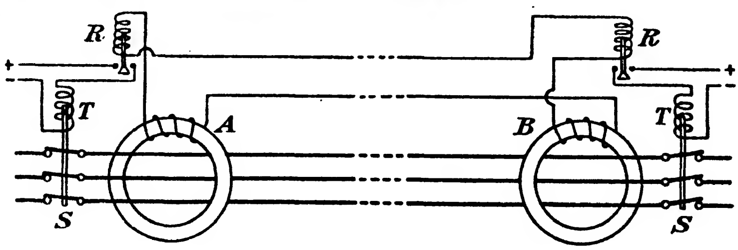


FIG. 73.—Ferranti-Hawkins core-balance system of protection against earth faults.

accompany faults between phases on feeders). A ring-type transformer surrounds the 3-phase cable at each end (*AB*, Fig. 73) and, as long as the cable is sound, the currents in the 3-phases (whether balanced or not) produce no field in the transformer cores. Directly an earth fault occurs, the vector sum of the currents in the cable is no longer zero, the relays *R* are excited and the main switches are tripped.

(*k*) *Bowden-Thompson Sheathed Cable System.*—The main cables used in this system are provided with thin metallic sheaths between and insulated from the cores, and between the cores and the lead sheath. Thus, in Fig. 74, *L* represents the sheath between cores, and *M* that between the cores and the lead sheathing.

Any fault between the cores necessarily reaches the sheath L before the main cores are affected; the current which then flows through the transformer B to earth excites the relay R and causes T to trip the main switch S. An incipient earth fault reaches the sheath M and trips the main switch in the same way before the fault reaches the lead sheath. If the cable be damaged from outside, the sheath M is earthed before the main core and, since M is maintained at a potential different from that of earth (by the transformer C), a current now flows through B and the switch is tripped as before.

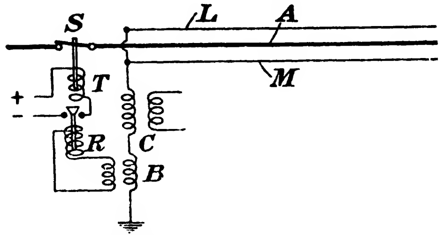


FIG. 74.—Bowden-Thompson sheathed cable system.

(*l*) *Distance Protection.*—This system is in some ways similar to the graded time lag system described in § 344, but special relays, known as impedance relays, are used. These relays have the characteristic property that their time lag of operation is proportional to their distance from the fault, to the current of which they respond. Impedance relays can be controlled by associated directional relays, § 358, so that operation can only take place when the direction of power flow is into the section protected, and the special automatic time characteristic ensures that the relays nearest to the fault, *i.e.* those controlling the faulty section, operate before all the others. Impedance relays are of many types, but the simplest consists of an induction relay element, § 344, in which the travel of the movement required to close the trip contacts is made proportional to the voltage by means of a special pressure control magnet. The voltage is least on the relays nearest the fault, hence these operate first. Distance protection by impedance relays is only suitable for transmission networks embodying considerable lengths of line, as the time discrimination required for selective protection is dependent upon the impedance of the sections between the various circuit breakers controlled by the relays.

Other systems have been devised for the automatic selective protection of A.C. circuits and apparatus, and there are many modifications of the systems described above, but the notes here given cover the main principles of the art. The relative merits of the various systems of protection is a subject beyond the scope of this work; some of the factors involved are: The capital cost of the protective equipment (including pilot wires and special cables, if any); the possible sensitivity of setting, consistent with stability; the type of transformers required in the protective circuits, and the extent to which the characteristics of transformers must be balanced to prevent unwarranted shut-down; and the extent to which the protective gear is unaffected by normal fluctuations in load, and by faults in zones for the protection of which it is not responsible.

360. Bibliography (*see* explanatory notes, § 58).

REGULATIONS.

As in § 151; also various regulations by the Electricity Commissioners.

B.S. SPECIFICATIONS.

No. 88. Low-pressure Electric Cut-outs, Type O.

No. 94. Watertight Glands for Electric Cables.

No. 142. Electrical Protective Relays.

No. 196. Reversible protected-type Two-pin Plugs and Sockets with Earthing Connections.

No. 646. Ordinary-Duty 250 Volt Cartridge Fuses.

BOOKS.

Artificial Earthing for Electrical Installations. T. C. Gilbert (Benn).

Rural Electrification. A. and V. Ekstroem (Authors).

Theory and Calculation of Transient Electric Phenomena and Oscillations, C. P. Steinmetz (McGraw, Hill).

Automatic Protection of A.C. Circuits. G. W. Stubbings (Chapman and Hall).

A.C. Protective Systems and Gear. J. Henderson and C. W. Marshall (Pitman). *See also* § 386.

I.E.E. PAPERS.

Merz-Price Protective Gear and other Discriminative Apparatus for Alternating Current Circuits, K. Faye-Hansen and G. Harlow. Vol. 46, p. 671.

Earthed *Versus* Unearthed Neutrals on Alternating-Current Systems, J. S. Peck. Vol. 50, p. 150.

Pressure Rises, W. Duddell. Vol. 52, p. 1.

Current-limiting Reactances on Large Power Systems, K. M. Faye-Hansen and J. S. Peck. Vol. 52, p. 511.

Automatic Protective Switchgear for Alternating-current Systems, E. B. Wedmore. Vol. 53, p. 157.

Control of Large Amounts of Power, E. B. Wedmore. Vol. 56, p. 269.

Some Transient Phenomena in Electrical Supply Systems, E. W. Marchant, Vol. 56, p. 445.

Protection of Alternating Current Systems without the Use of Special Conductors, Major K. Edgcumbe. Vol. 58, p. 391.

Automatic Protective Devices for Alternating-current Systems, A. E. McColl. Vol. 58, p. 525.

Earthing: Report of the Earthing Sub-Committee of the Wiring Rules Committee. Vol. 58, p. 468.

Protection of Alternating-current Circuits and Apparatus, E. T. Norris. Vol. 58, p. 750.

Aluminium Electrolytic Arrester with an Introduction on Electrical Disturbances, A. G. Ramsey. Vol. 57, Supp., Part 2, p. 306.

Protective Apparatus for Turbo-Generators, J. A. Kuyser. Vol. 60, p. 176.

Mechanical and Electrical Effects of Large Currents on High-tension Switchgear, C. C. Garrard. Vol. 60, p. 887.

An Investigation of Earthing Resistances, J. P. Higgs. Vol. 68, p. 736.

The Design of Apparatus for the Protection of Alternating Current Circuits, A. S. FitzGerald. Vol. 62, p. 561.

The Design of Electrical Plant, Control Gear and Connections for Portection against Shock, Fire and Faults, H. W. Clothier. Vol. 63, p. 425.

Rupturing Capacity of an Oil Circuit-Breaker, E. B. Wedmore and others. Vol. 65, p. 913.

Reverse-Power Relays for 3-Phase Generator and Feeder Protection, G. E. Taylor. Vol. 66, p. 1 148.

Introduction to Researches on Circuit-Breaking (B.E.R.A.). Vol. 67, p. 557.

Protection of 3-Phase Transmission Lines and Feeders, T. W. Ross and H. G. Bell. Vol. 68, p. 801.

Some Recent Advances in the Design of Relays for the Protection of A.C. Systems, C. L. Lipman. Vol. 70, p. 545.

The Resistance of Earth Electrodes (E.R.A. Report), P. D. Morgan and H. G. Taylor. Vol. 72, p. 515.

Statistical Survey of the Performance of Automatic Protective Systems (E.R.A. Report Ref. F/T94). Vol. 79, p. 541.

Lightning, B. L. Godlet. Vol. 81, p. 1.

The Use of Protective Multiple Earthing and Earth-Leakage Circuit Breakers in Rural Areas (E.R.A. Report Ref. F/T112), H. G. Taylor. Vol. 81, p. 761.

Line Protection by Petersen Coils, with special reference to Conditions prevailing in Great Britain, H. Willott Taylor and P. F. Stritzl. Vol. 82, p. 387.

Safeguards against Interruptions of Supply, H. W. Clothier, B. H. Leeson and H. Leyburn. Vol. 82, p. 445.

Surge Protection of Power Transformers, Miller and Thomson, 1938.

MISCELLANEOUS.

Some Protective Relays for A.C. Circuits, Kenelm Edgcumbe. *El. Rev.*, Vol. 69, pp. 126, 163, 233.

Protective Devices against Earth. *Electrn.*, May 25, 1923, p. 565.

CHAPTER 16.

SWITCHGEAR AND SWITCHBOARDS.

361. Functions of Switchgear and Switchboards.—The general purpose of 'switchgear' is to make and break circuits, thus controlling the operation of electrical apparatus; and the term 'switchboard' is generally applied to the group of switches, measuring instruments, and indicating devices which are used for the control of a particular circuit or an extensive network as the case may be. When the circuit is 'made,' the switchgear must be capable of carrying safely the current which flows, but as regards breaking the circuit, it is necessary to discriminate between: (*a*) 'isolating switches' (§ 362) which are suitable only for isolating a circuit *after* the current flow has been interrupted by other means; (*b*) non-automatic 'switches' (§§ 363-367, 374), which are suitable for breaking a load current; and (*c*) automatic 'circuit breakers' (§§ 365, 367), which are capable of interrupting abnormally heavy currents such as those flowing to a short circuit (§§ 339, 370). (*Note.*—Switching in lighting and other domestic installations is discussed in Chapters 21, 22, Vol. 2; and motor control is dealt with in Vol. 3, Chapter 29.)

362. Isolating Switches.—These switches, which are not suitable for breaking a load current, are used to isolate high-tension apparatus from the rest of the circuit and to sectionalise high-tension circuits. For example, an isolating switch is generally provided between an oil switch and the bus bars, and on the other side of the oil switch as well if the latter controls ring mains.* By opening the isolating switch (or switches) the oil switch can be made completely 'dead' and therefore safe for access to all its parts. The isolating switch consists of one or several copper blades which engage with spring contact clips

* Sometimes an isolating switch is provided between the generator and the main oil-circuit breaker but this is unusual, for it is generally expected that the circuit breaker can be attended to when the generator is shut down.

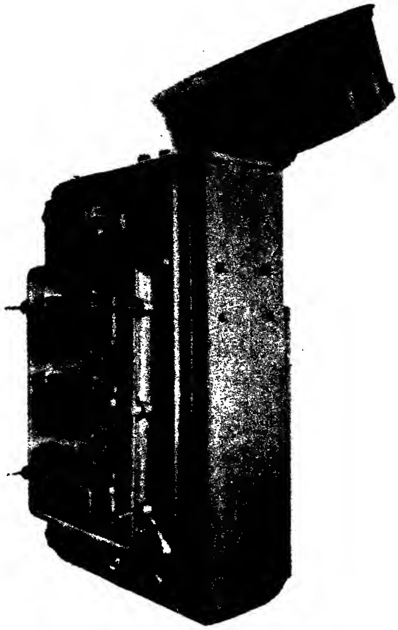
mounted on insulators. The circuit leads are connected to the two contact clips and the isolating blade or link is withdrawn when the circuit is to be opened. The switch blade may be pivoted in one of the contact pieces or at an independent fulcrum, and it is operated either by an insulated handle on the blade or by an insulated pole with a hook which engages in a ring on the switch blade. The conductors to and from an isolating switch should be as nearly as possible in line with the switch blade in order to reduce the mechanical force which tends to open the switch under short-circuit conditions (§ 338). If the power operative on short circuit exceeds 15 000-20 000 kVA the isolating switch blade should be held by a latch or bolt which must be released before the switch can be opened. Wherever possible an air-break isolating switch should be interlocked with an oil switch so that the former can only be opened or closed when the oil switch is in the 'off' position.

Isolating switches of modified design can be used, when neither making nor breaking a load current, as 'selector' switches to prepare for the closing of the circuit (by a switch or circuit breaker) on any one of two or more alternative paths. An oil-immersed isolating switch can be used to interrupt a moderate flow of power, as when sectionalising bus bars, when the duty of the switch is rather to transfer load from one part of the system to the other than to interrupt the flow completely; for the latter purpose a load-current switch or circuit breaker must be used.

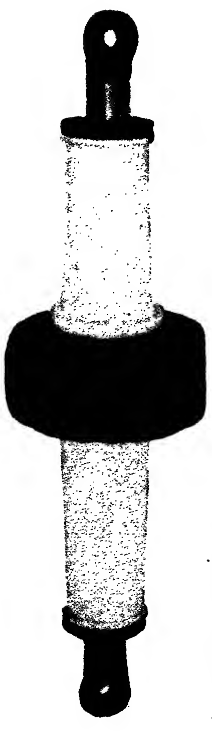
363. **Knife Switches.**—The B.S. Specification, No. 109, defines a knife switch as one in which the moving element takes the form of a current-carrying hinged blade, moving in its own plane, and entering or embracing the circuit contacts. So far as high-tension circuits are concerned such a switch is simply an isolating switch and is not suitable for opening a circuit when carrying load current. For low-tension circuits the knife switch may be used to interrupt a load current, but in order to reduce the damage caused by arcing at the contacts when the blade is withdrawn, it is usual to provide a 'quick-break' device. This generally consists of an auxiliary blade pivoted on the inner edge of the main blade; when the latter is withdrawn the auxiliary blade is held for a time by the contact clips, and the pull on a spring between the main and auxiliary blades increases as the main blade is moved away. At a certain stage in the movement, the pull on the auxiliary blade

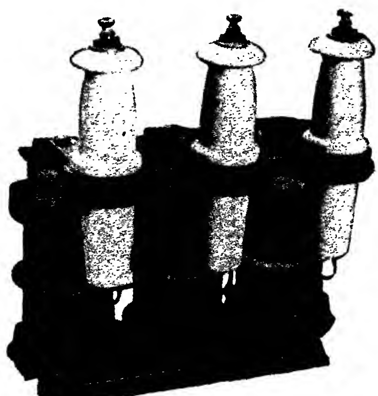
McColl Biassed Relays.

The relays shown form part of the protective gear in a large British power house and are connected to a 15-mile, 33 000 V feeder. The biassed relay operates when the fault bears a definite relation to the load on the circuit.



General Electric Co., Ltd. (London).





Everett, Edgcumbe & Co., Ltd.

Current and Potential Transformers.

The current transformer (left) is suitable for use on a 12 000 V system. The straight-through primary prevents breakdown due to surges; and the ring-type core, without joints, secures constant ratio and absence of phase displacement between primary and secondary currents. The three-phase potential transformer (right) is for a 6 600 V system. The primary is sectionalised to reduce the voltage between layers, and the whole transformer is impregnated with insulating compound to exclude dust and moisture. For higher pressures potential transformers are generally oil-insulated.

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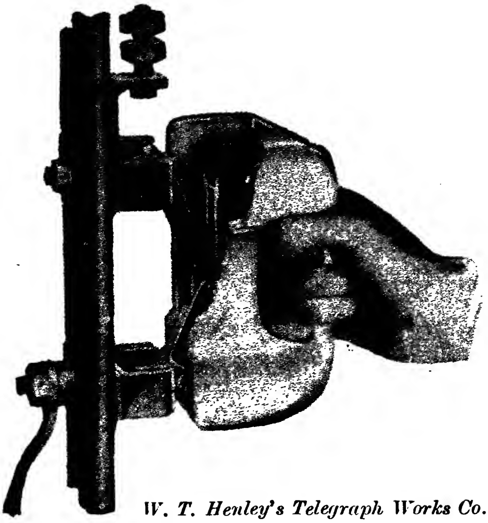
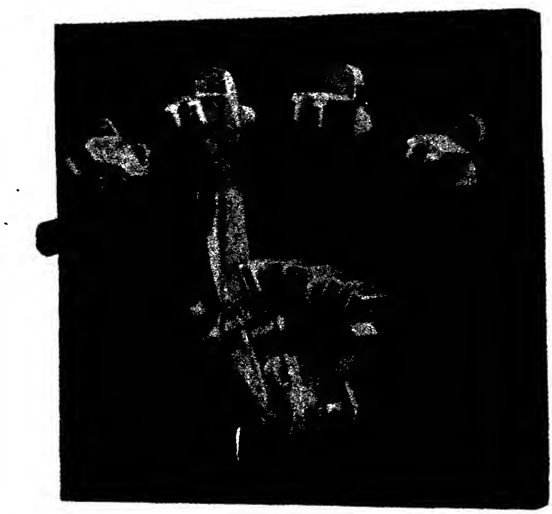


W. T. Henley's Telegraph Works Co., Ltd.

PORCELAIN HANDLE WITH QUICK-BREAK ISOLATING LINKS.

This equipment is interchangeable with a porcelain-grip fuse carrier, and can be used to disconnect a circuit whilst carrying load. It serves the dual function of isolating link and knife switch, and can be used in distribution pillars or other applications where there is not room for an ordinary knife switch. The main copper link has an auxiliary 'flicker blade' for each contact, and the tension on the springs of the flicker blades is limited by a stop.



Dorman & Smith, Ltd.

SINGLE-POLE MULTIWAY SWITCH WITH QUICK-BREAK ACTION.

This switch is made for currents from 50 to 300 A, 250 V, and with 2, 3, 4, or 5 'ways.' Contact jaws are provided for both ends of the multiple copper blades so that the swivelling hinge portion is not relied upon to carry current. When the T-handle is drawn fully 'off' the switch can be turned to left or right for closing on the desired 'way,' without touching other jaws in passing. A spring poppet registers the blade into alignment.

[*To face p.* 653.

becomes so great that this blade leaves the contacts; it is at this moment that the circuit is broken, and as the auxiliary blade leaves the contacts at high speed (whatever the speed of the main blade), there is very little destructive arcing.

The inner contact may be at the hinge of the blade, but by using a separate pivot block (in line with two contacts which are used only as contacts) it becomes unnecessary to pass current through the hinge, and the further advantage of a double-break (§ 368) is obtained. For very heavy currents (up to 15 000 A) a number of switch blades are mounted on a common spindle and fitted with a common handle; the blades are interleaved with upstanding plates at the hinge, and when the switch is closed the blades penetrate between similar plates forming the fixed contact; in switches of this type for 3 000 A or heavier current, clamping bolts are used to hold the blades in close contact with the contact plates. In the blade itself the current density may be 800-1 000 A per sq. in., but at the contacts it should not exceed 80-100 A per sq. in. of contact surface with spring clips. If the contact surfaces be clamped by a bolt, the current density is usually the same as for rubbing contacts save for the slight increase occasioned by the slot which is necessary in order that the bolt may be inserted into the contact.

Multipole knife switches consist of two or three blades insulated from each other, but coupled mechanically by a bridge piece, or mounted on a square shaft, so that they can simultaneously be moved into or out of the circuit contacts of a 2- or 3-wire circuit. This is generally the most convenient way of ensuring that a circuit is completely isolated from the supply; opening a switch in one wire of a 2-wire circuit, or two wires of a 3-wire circuit, interrupts the flow of current, but the circuit remains 'live' through the switch in the other line.

The contact blocks of knife switches may be provided with lugs for the 'front connection' of the circuit wires or they may have stems which go through the base or panel on which the switch is mounted so that the leads may be attached by 'back connection.' The latter arrangement is safer and is generally employed. In knife switches with multi-blade contacts it is usual for the plates to pass through the panel and form the rear connection as well as the contact connection. This avoids joints in the fixed contacts and enables good contact to be obtained between the strap conductors at the rear and the terminal of the knife switch. The use of screwed studs and nuts is to be deprecated for very heavy currents and the strap type of contact is generally used for circuits of 1000 A and upwards.

A 'throw-over' knife switch is provided with two sets of circuit contacts on opposite sides of the blade hinge. If the hinge block forms one of the circuit terminals, the switch can only be used as a two-way switch, for the purpose of connecting the circuit at the hinges to either of the two circuits which terminate at the other contacts. If, however, each blade has an independent pair of circuit contacts on each side of the hinge (the latter not carrying current), the switch can be used to complete either one of two circuits which may be electrically independent. The 'throw-over' knife switch is often useful in that it allows either, but not both, of two connections to be effected and thus, for example, prevents alternative sources of supply from being connected simultaneously to a circuit. In its 'off' position a throw-over knife switch stands perpendicular to the base on which the contact blocks are mounted.

The common 'tumbler' switch (§§ 500, 507, Vol. 2) as used in house-lighting branch circuits is a quick-break knife switch, but for mechanical reasons the details of construction differ from those of the knife switches used for heavier currents. A spring-actuated quick-make mechanism is sometimes embodied in tumbler and knife switches (in addition to the quick break), to eliminate the sparking and overheating which would occur if the switch were closed very slowly.

364. **Horn-Break Air Switches.**—An ordinary air-break knife switch is not suitable for use in high-voltage circuits, and is generally limited to pressures not exceeding 660 V; but if such a switch be used in conjunction with a horn gap it is applicable to switching on high-tension overhead lines. One terminal of the horn gap carries one of the circuit contacts of the knife switch, and the blade of the latter is carried by an insulator attached to the operating mechanism. The switch blade carries the other horn and it is arranged that the main contacts open before the circuit is broken; the break occurs on the arcing connections, some distance away from the main contacts, and the arc is then extinguished automatically (§ 346). The switch is operated from ground level by means of any convenient linkwork. Prior to the introduction of oil switches, horn-break air switches were

used on high-tension circuits in stations, but they are now used only for outdoor service.

365. Air-Break Circuit-Breakers.—Every switch breaks a circuit when it is opened, but the term 'circuit-breaker' is reserved for mechanical devices which break (automatically unless otherwise specified) a circuit under abnormal conditions. These conditions may be low voltage, reverse power, overload or a combination of these, but a circuit-breaker must be capable of interrupting excessive current without injury, whatever the other conditions of the circuit. It is therefore necessary to make arrangements for reducing arcing to a minimum, both in degree and duration, and for preventing the main contacts from being damaged by such arcing as does occur.

In this type of switch the circuit contacts are generally heavy blocks of copper mounted on a slate or marble base from which they are insulated by mica. The contact-making element is a laminated bridge piece built up from springy strips of phosphor-bronze or copper with a steel backing strip outside. The ends of this arched bridge piece are cut at such an angle that, when the switch is closed, the strips make end-on contact with the fixed contact blocks. The angle between the plane of the strips and the face of the contact blocks is about 45°,* so that as the laminated 'brush' is pressed on to the contacts, usually under considerable mechanical pressure exerted by a toggle mechanism, there is a wiping and bedding action at the ends of the strips. The main contacts are thus 'self-cleaning' and the resilience of the laminated brush makes it possible to obtain good contact over a large area, as is necessary for heavy currents. In order that there may be no deterioration of the main contact surfaces by arcing, the moving system carries auxiliary copper contacts (electrically in parallel with the main contact brush) which make contact before, and break contact after, the main brush. The moving system also carries light fingers which terminate in renewable carbon blocks; the latter make contact with similar carbon blocks on the fixed contacts *before*, and break contact *after*, the auxiliary copper fingers. Thus, referring to (*a*) in Fig. 75, when the circuit breaker opens, the

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* This result is sometimes obtained by using a brush built up of flat strips, cut away at about 45° at each end, and bedding on contacts with inclined faces (*cf.* the faces of a mitred joint in a picture frame).

main contacts, *A*, open first, without sparking since the current is simply transferred to the auxiliary copper fingers; the auxiliary copper contacts, *B*, carry the load only for a small fraction of a second, and before they have time to become dangerously overheated, they leave the fixed contacts, thus transferring the load to the carbon arcing tips, *C*. The actual breaking of the circuit occurs as the moving carbon contacts leave the stationary ones. By this time the whole moving system of the circuit breaker has acquired considerable speed, hence there is a 'quick-break' between the carbon tips. Also, as explained in § 66, carbon is almost a non-arcing material compared with metals, and is much less damaged than copper tips would be; when necessary, the carbon tips can be easily and cheaply renewed. The carbon tips are at the top of the switch so that the rising arc can damage no other part.

Circuit breakers of the above type can be built to carry 10 000 A or even heavier currents, and are used extensively in D.C. and A.C. systems, usually for pressures not exceeding 660 V. Circuit breakers for moderate currents (up to 250 A or so) may have simply the main contacts and carbon arcing tips, and the moving contact may be in the form of a wedge-shaped bar which engages between springy, tapered circuit contacts.

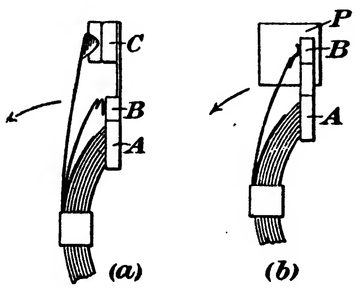
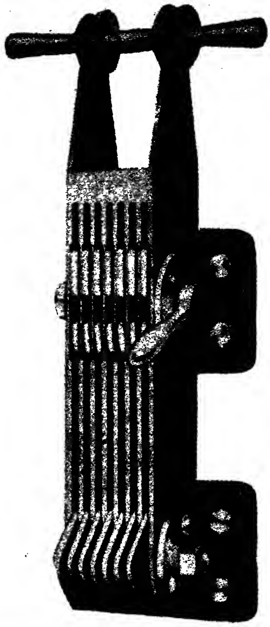


FIG. 75.—Main and auxiliary contacts in air-break switches with laminated brushes (diagrammatic).

In some cases (*e.g.*, § 372 (3)) a *magnetic blow-out* is added to assist in extinguishing the arc. This consists of a powerful electromagnet,* *P*, Fig. 75 (*b*), which establishes a magnetic field at right angles to the length of the arc between the fixed and moving contacts at *B*. In this case the switch has only the main laminated contact at *A* and the renewable copper sparking tip at *B*; it is not usual to employ carbon arcing tips as well as a magnetic blow-out.

* Connected between the circuit contact and the line so that it carries the current which is to be broken. If the current is alternating, the blow-out field reverses with the current and the blow-out action is unidirectional. Though theoretically applicable to A.C. switches, the magnetic blow-out is generally used on D.C. switches only. The reactance drop in the magnet coil (which must be in series with the main circuit) is objectionable where A.C. is concerned.



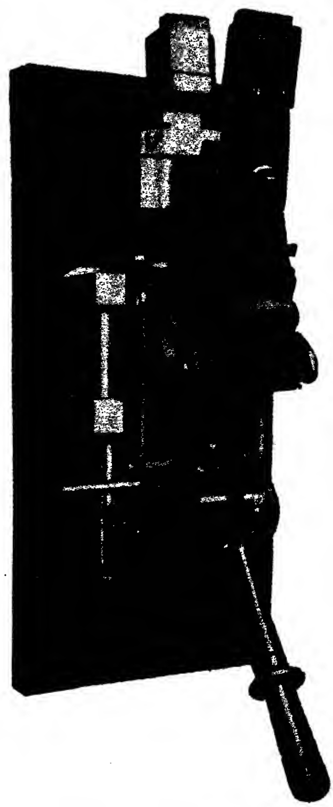
Ferguson, Pailin, Ltd.

Multiblade Knife Switch for Heavy Currents.

This type of switch has been standardised in sizes from 300 A to 10 000 A carrying capacity. The strips forming the contact jaws pass straight through the panel and form the terminals for connections at the back. This decreases the number of joints and reduces the voltage drop; also, the fixing bolts are independent of parts carrying current. The hinge and contact jaws on the sizes from 4 000 A upwards are provided with clamping bolts, and with a permanent handle which eliminates the use of spanners.

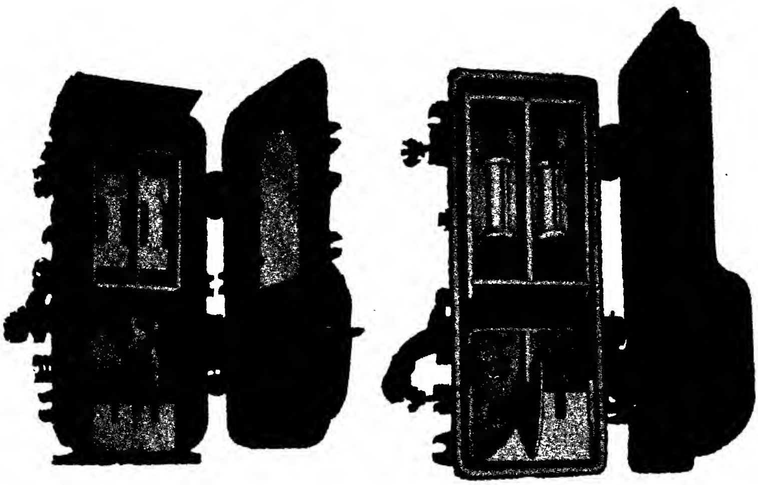
Air-Break D.C. Circuit Breaker.

The breaker illustrated is rated at 2 000 A and is suitable for use on D.C. circuits up to 660 V. The laminated main contact brushes are protected by two sets of copper-to-copper auxiliary contacts and by carbon arcing-contacts. The mechanism is of the 'free-handle' type, and a quick break is obtained without the use of auxiliary springs, the breaker tripping free of the mechanism. The closing mechanism is of the toggle type, and the tripping plunger (gravity controlled) rises freely before striking the trip lever.



British Thomson-Houston Co., Ltd.

[*To face p.* 656.



General Electric Co., Ltd. (London).

INDUSTRIAL AND FLAMEPROOF IRONCLAD SWITCHES.

These photographs afford an interesting comparison between an ironclad switch (on the left) designed for general factory service and one (on the right) designed for use in mines or other places where the atmosphere may be explosive. In both instances the switch is interlocked with the case so that the latter cannot be opened while the switch is closed, neither can the switch be closed while the case is open. An insulating fireproof arc shield and barrier over the contacts eliminates the risk of short-circuiting on overload. The case of the flameproof switch is particularly robust, and the wide machined flanges of the joint cool the gases expelled in the event of an internal explosion, thus preventing the ignition of an explosive atmosphere outside.

[*To face p.* 657.

The sense of the field is such that the arc, which is a current-carrying conductor, is driven upwards (§ 35) on arcing horns (§ 364) and, being thus lengthened, it is quickly extinguished. If there is any difficulty in providing a large clear air space for the dissipation of the arc, the surroundings (particularly any metal with which the arc might come in contact) must be protected by fireproof, insulating shields.

Small enclosed circuit breakers for ratings of 0·5 to 25 A are now available for the protection of domestic and small power installations. The automatic trip is operated either by a thermal device for small overloads or by an electromagnetic device for short circuits. The thermal trip give an inverse time characteristic whilst short circuits or leakage (§ 354*a*) are interrupted instantaneously. Circuit breakers for domestic installations offer the advantages that the dangers due to careless fuse replacements are avoided; also the supply can be restored immediately after interruption if no permanent fault exists.

366. Ironclad and Flame-proof Air-break Switches.—The distinction between ironclad and flame-proof switchgear is mainly one of degree. A 'flame-proof' switch is enclosed by a case which will withstand without injury the explosion within it of a maximum-explosive mixture of methane and air (or an equivalent explosive mixture); also, it will not transmit ignition from the internal explosion to a surrounding atmosphere of explosive composition under any conditions of service within its rating. These two requirements are fulfilled by making the containing case of great mechanical strength and by providing it and its cover with wide machined joints which permit the escape of gases produced by an internal explosion, but cool them well below the ignition point of the outer explosive atmosphere before the latter is reached. The term 'ironclad,' on the other hand, is generally applied to switches which are not flame-proof, but which are enclosed by an iron casing sufficient to protect the switch against mechanical damage, tampering or accidental contact, and drippings of water, etc.* These distinctions are of a mechanical nature, and the same

* Hitherto the term 'ironclad' has been used loosely to describe switches which differed greatly in the degree of their protection against mechanical injury, weather, etc. It is obviously preferable to distinguish between mere mechanical protection (by expanded metal, etc.), total enclosure, drip-proof, and weather-proof protection, as in the case of electric motors.

electrical considerations apply whether the switch be enclosed by light sheet metal or by a flame-proof, mining-type casing. The metal casing and the operating handle (if of metal) must be efficiently earthed. There must be adequate clearance and insulation resistance between all live parts of the switch and the metal enclosure; an insulating barrier, acting as an earth shield, should be provided between the poles; and an insulating lining should be fitted to prevent any arc which may arise in service from reaching the casing. The switch itself, which should be capable of interrupting safely at least 50 °/₀ higher than its rated current differs only from the corresponding open type air-break switch in mechanical details to suit its enclosure. An interlock (§ 373) is necessary between switch and cover so that the security afforded by the latter cannot be lost by the switch being used with the cover open.

Ironclad switchgear is commonly provided with a hemp or asbestos packing in the cover joint, but if any such packing be used in the joints of flame-proof switchgear a flame-proof vent must be provided in the casing for the relief of internal pressure. Cables are taken into the casing through suitable weather-proof or flame-proof fittings, as the case may be, and the connections to the switch are on the face of the slate or marble panel which carries the switch.

Ironclad and flame-proof switches (single, double, or triple pole) are generally limited to currents not exceeding 500 A and pressures not exceeding 660 V. D.C. or A.C. Oil-break ironclad switches are ordinary oil-break switches (§ 367) in tanks of special mechanical strength. Oil-immersion eliminates the risks associated with open sparking and sometimes makes possible a smaller casing than is required by an air-break switch.

367. Oil Switches and Circuit Breakers—General. — The terms 'oil switch' and 'oil-immersed circuit breaker' have been used indiscriminately in the past, but it is now recognised that the term oil switch should be applied only to non-automatic mechanical devices for breaking currents up to the rated capacity of the switch (§ 371); whereas an oil-immersed circuit breaker is a mechanical device (automatic unless otherwise specified) for breaking the circuit under abnormal conditions such as those of short circuit. The constructional features of both types are described in § 368.

The main advantage of oil immersion is the assistance obtained in quenching the arc which forms when the contacts are separated. The size of the arc is reduced by the cooling effect of the oil and by the hydrostatic pressure which the oil exerts upon the vapour column; also, the head of oil above the contacts forces the insulating liquid between them at the earliest possible moment after their separation. In the case of alternating current the arc is momentarily extinguished as the current passes through zero, and the combined cooling, mechanical, and insulating effect of the oil is generally sufficient to prevent the arc from being struck again. Where direct current is concerned no assistance is obtained from the form of the current itself (there is no natural recurrent zero in a direct current), hence the arc endures longer than where alternating current is employed. Tests have shown, however, that oil switches and circuit breakers are capable of interrupting direct current under load or short-circuit conditions comparable with those for alternating current. The oil is soon blackened by carbonisation, but the actual amount of carbon formed is only a small fraction of 1 °/₀ of the oil after the switch has operated thousands of times, and the properties of the oil, so far as extinguishing the arc is concerned, appear to be quite unaffected. There is not much inducement to use oil switches in D.C. circuits up to 660 V,* the air-break circuit breaker being quite satisfactory for such pressures, whether direct or alternating; and for D.C. traction circuits operating at 1 500 or 3 000 V there are high-speed circuit breakers, applications of which are discussed in § 372 (3). Though air-break switchgear in explosion-proof and flame-proof casings (§ 366) is quite safe for use in explosive atmospheres, it is sometimes more convenient to use oil-immersed switches and, in such services, there is a field for D.C. and A.C. oil switches at all pressures. Probably the principal objection to the use of oil switches in D.C. circuits lies in the high voltage which may be induced when breaking a highly inductive circuit (§ 349). In an air-break switch, even with magnetic blow-out, the circuit is broken less rapidly than in an oil switch, and the inductive 'kick' is therefore lower. The importance of providing shunt discharge paths for the voltage induced in any highly inductive circuit (*e.g.* shunt motor field coils,

* This has hitherto been about the highest pressure used in D.C. circuits, excepting circuits on the Thury system (§ 317). In the latter, the main (series) circuit is never opened; apparatus is switched 'out' by short circuiting its terminals; the load current is constant and is never broken.

brake magnet windings, etc.) has already been mentioned (§ 349), and is especially great where oil switches are used.

368. Constructional Features of Oil-immersed Switches and Circuit-Breakers.—The main components of any oil-immersed switch are the oil tank; the insulators used to insulate the fixed contacts from the tank; the moving contact or bridge-piece; and the mechanism used to operate the latter (*see also* §§ 343, 372, 373).

Useful information regarding containing tanks will be found on p. 677 of *Switchgear Stages* (see § 386). For rectangular tanks the empirical formula

$$p = 4ft^2(a^2 + b^2) / a^2b^2$$

gives good results, where p = max. safe applied pressure, lbs. / sq. in.; f = max. safe stress, lbs. / sq. in.; a and b = lengths of sides of tank-end, inches; and t = thickness of tank-end, inches. The value of f is taken as 34 000 lbs. / sq. in. for steel.

The insulators carrying the fixed contacts are generally mounted on the cover of the tank, and for extra high voltage circuits (say over 33 kV) they are usually of the condenser type.* The terminal stems, connected to the conductors of the external circuit, are led through these insulators and terminate in the circuit contacts of the switch. The moving contact is in the form of a bridge piece which connects the circuit contacts when it is made to bear upon them. Generally the bridge piece is a solid bar or laminated brush of such cross-section that it will carry the heaviest currents which have to pass through the switch without dangerous overheating. Sometimes, however, the bridge piece is of insulating material with a contact piece at each end to engage with the circuit contacts when the switch is closed; the moving contacts are then connected by a fuse or through a series trip coil either of which opens the circuit in event of overload (§§ 342-344, 375). The plane of the circuit contacts is horizontal (except in oil-immersed drum controllers and other special switches) and the bridge piece is raised or lowered, to make or break circuit by means of a rod

* *i.e.* built up by alternate concentric layers of dielectric and metal foil, so as to form a number of condensers in series; by suitably adjusting the capacity of each condenser the voltage distribution across the series can be made uniform (§ 289). The pressure gradient in a 'bulk' terminal insulator, consisting of a relatively thick mass of porcelain, moulded composition, etc., is far from uniform and the utilisation of the insulating material is correspondingly inefficient. Condenser bushings are coming into general use for all oil-circuit breakers of large rupturing capacity for pressures of 11 000 V and upwards.

passing through the cover of the tank. The operating rod is insulated from the bridge piece by micarta, bakelite, or other suitable material. If a bridge piece, *C*, Fig. 76 (*a*), is used in conjunction with two circuit contacts *AB*, there are then two breaks, *XX*, in series when the switch opens, and if the rod, *R*, moves downwards at 5 ft./sec. the total speed of breaking at the contacts

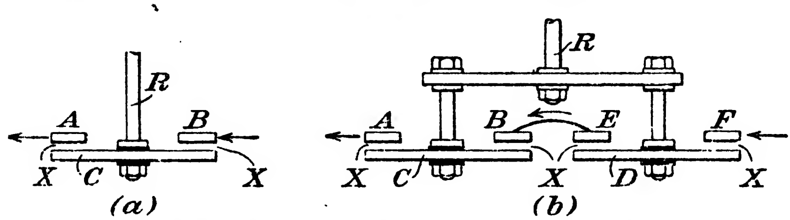


FIG. 76.—Diagrammatic representation of double and quadruple breaks.

is 2 × 5 = 10 ft./sec. Similarly, if two bridge pieces *CD*, and four stationary contacts, *A*, *B*, *E*, *F*, be used as shown (diagrammatically) in Fig. 76 (*b*); and *R* moves downwards at 5 ft./sec. the four breaks in series open at a total speed of 20 ft./sec. The modern tendency, however, is to use not more than two breaks, and single-break designs are being developed on all hands.

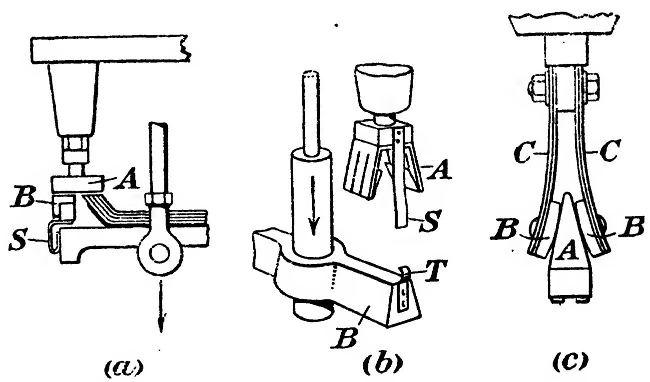


FIG. 77.—Main and auxiliary contacts in oil switches (diagrammatic).

The circuit contacts are massive blocks if the moving contact is of the laminated brush type (§ 365), or springy clips if the moving element has Vee-shaped knife contacts. In the construction shown diagrammatically in Fig. 77 (*a*), the main, laminated brush contact opens first at *A*, and the arc is struck on the solid copper piece, *B*, which is spring-supported at *S*, makes butt contact with the stationary contact block, and is easily renewable when required. Carbon arcing tips are not suitable for use in oil. In Fig. 77 (*b*) the wedge-shaped block, *B*, and the springy fingers, *A*, constitute the main contacts; the auxiliary arcing contacts, *ST*, separate after the main contacts; and by that time the piece, *B*, is moving so rapidly that a 'quick break' is obtained. In Fig. 77 (*c*), the moving contact, *A*, is of narrow triangular section, and is forced between two solid contact blocks, *BB*, which are carried by laminated springy fingers, *C*; arcing contacts (not shown) are fitted as in Fig. 77 (*b*).

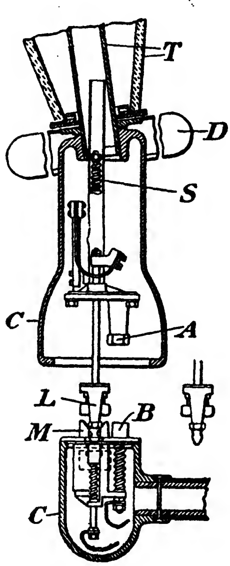
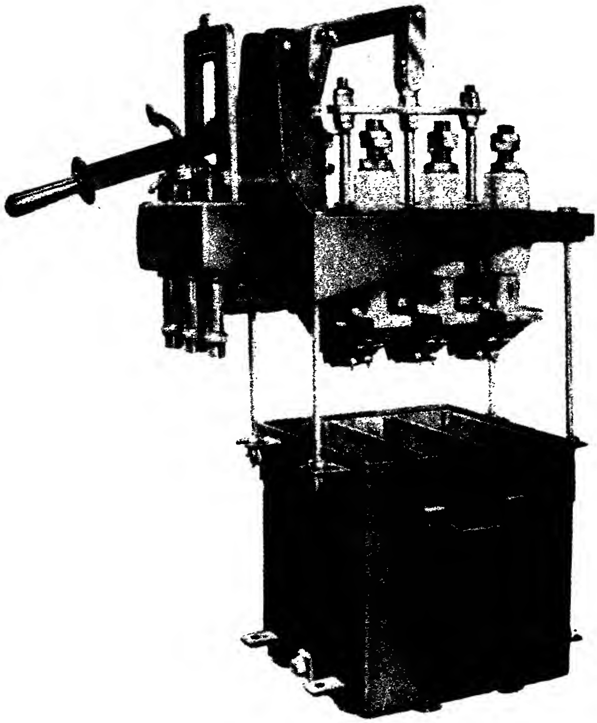


Fig. 78.—Main and auxiliary contacts of Metropolitan Vickers oil-immersed circuit-breaker.

An ingenious method of increasing the speed of breaking is illustrated in Fig. 78; in the position shown the main butt contacts, *AB*, have separated, but the auxiliary contact, *L*, which is formed as a latch, is drawn down in engagement with the clips, *M*, thus maintaining the circuit through the switch. Meanwhile the spring, *S*, is being compressed by the downward movement of *L*, and when the main contacts are 6 or 7 ins. apart, and moving at high speed, the spring withdraws *L* from the clips, and pulls it upwards rapidly. The speed of separation of *L* and *M* is the sum of the upward speed of *L* and the downward speed of *M*. The same figure also shows the shield, *D*, fitted to the lower end of the condenser terminal, *T*, to screen it from the arc; and the smooth-profile corona shields, *C*, which prevent corona discharge from the sharp edges of the contacts.

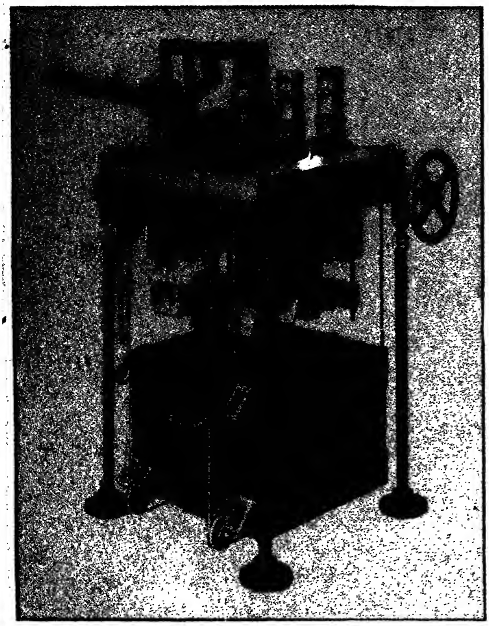
Clothier (*op. cit.* p. 680) notes that whereas the Continent tends to use oilless circuit-breakers, American design favours adding boxed contacts to the oil-immersed type as one means of improving operation and reducing the physical dimensions corresponding to existing standard ratings. This influences British design to some extent, but it has been established that a satisfactory margin of safety has been secured by adequate strength of enclosure for voltages up to 20 000 V with plain contacts in oil. Beyond this range, the lower current values make the use of boxed contacts a reasonable economy. One particular construction, known as the 'turbulator,' follows the design of the 'baffle-contact' explored by the B.E.R.A. Tests have shown remarkable results in reduction of stress in a circuit-breaker enclosure, because the device takes up the stress within its smaller volume and also reduces the stress by shortening the arc



General Electric Co., Ltd. (London).

MEDIUM VOLTAGE, HEAVY-CURRENT OIL SWITCH.

The illustration shows the G.E.C. Type IIIA switch (Table 52, § 371) with its tank lowered and the contacts closed. The normal capacity of this switch is 1 000 A at 660 V. A specially long break is provided, and the clearances are on a liberal basis, actually exceeding the requirements of the B.E.S.A. specification. The tank is lined with 5-ply birch which is divided into compartments so that the phases of the switch are separated.



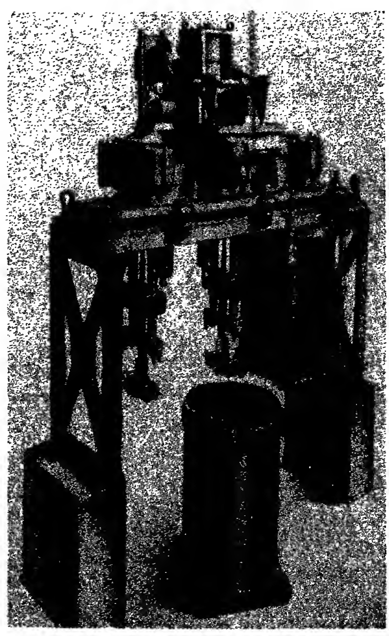
Johnson & Phillips, Ltd.

MEDIUM VOLTAGE, HEAVY CURRENT OIL SWITCH.

This switch is built for rated carrying capacities of 1 500 A and 2 500 A at 650 V. The fixed contacts are of the laminated brush type insulated by a slate base which is supported by the iron framework. An arcing tip is provided on each fixed contact. The tank-lowering gear is operated by the hand-wheel shown. The switch is closed by lifting the handle, engaging the switch mechanism, and pushing the handle downwards. Opening by hand is effected by pressing the tripping lever on the handle. The switch can neither be closed under fault conditions, nor opened slowly at any time. The trip coils are fitted on the front of the board, below the operating handle.

E.H.T. HIGH-POWER OIL CIRCUIT BREAKER FOR REMOTE ELECTRICAL OPERATION.

This circuit breaker is suitable for use on systems up to 35 000 V where an arc-rupturing capacity of over 1 000 000 kVA is required. The fixed contact studs are built on the condenser terminal principle (§ 368) and are strongly braced together at the lower end. The moving contacts are of special design to ensure that good contact is maintained even when heavy fault-current is flowing. Wedge-type renewable arcing tips are employed. The oil tanks are attached to the common cast steel frame by suspension bolts; four small retaining bolts are also fitted to facilitate the removal of the tanks by a combined carriage and lowering device. When the breaker opens on short circuit, clean air is drawn into the air chambers as the oil gases are discharged from the vents. The breaker is normally operated by solenoids but can be tripped by hand if necessary. The closing mechanism is a parallel-motion linkwork fitted on each side of the flexible hinge to balance the closing forces. No live metal is accessible when the breaker is in service, hence no side barriers or protective doors are required on the circuit breaker side of the structure when this unit is used with stonework cubicles. The lead-in connections are in compound-filled boxes and pass through the rear wall to the isolating switch and terminal cells.



Metropolitan-Vickers Electrical Co., Ltd.

[To face p. 663.

duration. The gas passages are designed to increase the turbulence of the discharge, hence the name.

An important factor in the design of switch contacts is their behaviour under the mechanical forces developed by short-circuit currents. As explained in § 338, the mechanical force due to the field round the conductors of a closed circuit tends to increase the area enclosed by the circuit, hence a laminated brush contact of the type shown in Fig. 79 is subjected to forces, *FF*, which tend to reduce the mechanical pressure at the contacts, and may cause the contacts to become overheated and welded together. With two inverted brushes, as in Fig. 80, bearing on an intermediate contact block, *C*, the forces *FF* (tending to enlarge the circuit) now press the brushes more firmly into contact. The converse

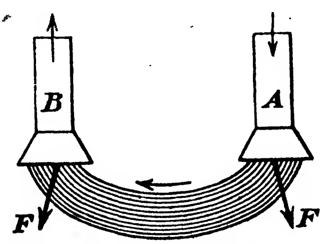


Fig. 79.—The electromagnetic forces, F, tend to open the contacts.

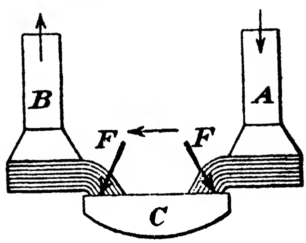


Fig. 80.—The electromagnetic forces, F, improve the contact between the brushes and the block, C.

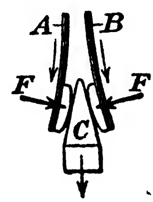


Fig. 81.—Electromagnetic attraction between A and B increases the contact pressure on C.

action, *i.e.* attraction between conductors carrying current in the same direction (§ 338), causes the fingers *A*, *B* (Fig. 81) to bear more heavily upon the intermediate contact *C*. Contacts which are self-closing under electromagnetic forces are naturally to be preferred.*

In all the cases illustrated by Figs. 77, 78 the circuit contacts are carried by the cover of the switch tank, and the switch is opened by the moving contact or bridge piece travelling downwards from the fixed contacts. This is the usual arrangement, and has the advantage that when the oil tank is lowered the whole of the switch is accessible for inspection or repair; it must, however,

* The three examples cited are reproduced from 'Mechanical and Electrical Effects of Large Currents on H.T. Switchgear,' C. C. Garrard. *Jour. I.E.E.*, Vol. 60, p. 887.

be isolated by an isolating switch (§ 362) before it is touched. Sometimes the circuit connections are made through insulators in the bottom of the tank and the moving element travels upwards to open the circuit; this arrangement has the advantage that the tank is shallower (for a given head of oil over the break) than if the moving contact travels downwards. Also, the moving contact and its operating mechanism can be inspected whilst the live circuit contacts remain submerged; on the other hand, the tank must be emptied before the circuit contacts can be reached and even then they are not easily accessible.

The formation of dangerous switching surges (§ 349) may be prevented by placing 'buffer resistances' in circuit temporarily before the main contacts of the switch close and after they open. This precaution—which renders less sudden the growth or decay of the magnetising current of machines or transformers, or the charging current of cables—may be effected by the use of auxiliary 'charging contacts' on the main switch. Like the auxiliary arcing contacts, the charging contacts make contact before (and open contact after) the main contacts, but the same auxiliary contacts cannot be used both as arcing and charging contacts; for whereas the arcing contacts have to carry the full main current temporarily, the charging contacts are in series with a high non-inductive resistance which acts as a 'buffer' when switching on or off.

If desired, auxiliary switches can be fitted to oil switches so that they open or close relay, signalling or other auxiliary circuits synchronously with the operation of the main switch.

Notes on the operating, tripping, and interlocking mechanism of switches are given in §§ 372, 373, and further information on constructional factors which influence the breaking capacity of oil switches are given in § 371. For high-speed circuit-breakers see § 372 (3) below and §§ 869, 914 in Vol. 3. The treatment and testing of switch and transformer oils is dealt with in § 403, Vol. 2, and § 1 034, Vol. 3.

368a. Circuit-Breakers of Low Oil Capacity: Expansion-Type and Air- or Gas-Blast Circuit-Breakers.—Owing to the fire risks attendant upon the use of large quantities of oil in assemblies of oil circuit-breakers for heavy duty, many attempts have been made to develop breakers suitable for high voltages in which these risks are avoided by greatly reducing or eliminating the use of oil.

The 'orthojector' circuit-breaker,* as built for a breaking capacity of 5 000 000 kVA at 500 kV, represents an advanced application of the principle of restricting the amount of oil to that required for satisfactory interruption of the circuit, ceramic material being used instead of oil for the general insulation of live parts. Four circuit-breaker units, electrically in series and mechanically interconnected, are mounted on stacks or columns of insulators. When the breaker contacts open, an arc is 'drawn' between them in the oil inside a perforated insulating sheath, the vapour escaping freely until the contacts are far enough apart to ensure that the arc will not be re-struck after it has been extinguished. This degree of separation having been reached, the moving contact continues to travel upwards and its lower end now enters a chamber which is so shaped that vapour generated from the oil therein is expelled from the bottom of the chamber along the axis of the arc. At the same time a fixed piston, inside the upward-moving tubular contact, forces a jet of oil through a nozzle at the lower end of the contact. The combined effect of the mechanically produced oil jet and the thermally-generated blast of oil vapour, both directed along the axis of the arc, is to ensure that the arc is extinguished at the first passage of the current through zero, after the separation of the contacts has reached a certain minimum distance, depending on the voltage for which the breaker is designed.

In the 'expansion type' circuit-breaker the basic principle is that of the extinction of the arc by the expansive force of vapour from a liquid in which the arc is initiated. For pressures up to 30 kV water can be used as the expansive liquid, but it suffers from the disadvantage of a relatively high freezing point. For higher voltages a special oil of low freezing point (– 60° C.) is used. The amount of liquid required in breakers of this type is quite small, and the function of the liquid is not to provide electrical insulation but only to generate the vapour for arc extinction. It is possible to generate a blast of gas for extinguishing the arc from suitable solids † mounted so that they are heated by the arc. For

* Shown by the Ateliers de Constructions Electriques de Delle at the International Exhibition, Paris, 1937; see *El Rev.*, Vol. 122, p. 51.

† *E.g.* certain synthetic resins; see *E.T.Z.*, Vol. 59, p. 165, for notes on these and other 'oilless' circuit-breakers.

further particulars of the expansion breaker an article by J. Mosebach may be consulted.*

Another type of H.T. breaker is that in which the arc is extinguished by a jet of compressed gas. Air can be used for this purpose, but some advantage is gained by employing such a gas as carbon dioxide, which possesses superior cooling properties. The gas for arc extinction is delivered to the breaker at a pressure of 115 to 185 lbs. per sq. in. and adequate storage capacity can be continuously maintained by an automatically controlled compressor.†

369. Air and Oil-Switch Ratings; Current Densities.—The rated capacity of air-break switches and circuit-breakers ‡ is the largest current (at rated frequency in the case of A.C.) which they will carry continuously under the required conditions of service without exceeding 30° C. temperature rise (40° C. rise in the case of switches rated above 2 000 A and 20° C. rise in the case of switches rated below 100 A), the temperature of the surrounding air being not higher than 40° C. When determining this temperature rise the connections should be such that the temperature rise in them is not less than 80 °/₀ or more than 100 °/₀ of the rise permitted in the switch. The object of this clause is to eliminate abnormal heating or cooling of the switch by thermal conduction from or to the connecting leads. The permissible temperature rise (measured by thermometer) in tripping, closing, and blow-out coils under service conditions is 60° C. for cotton, silk, paper, etc., impregnated; 70° C. for enamelled wire; and 90° C. for micanite, asbestos, and bare coils.

The rated normal current of an oil switch or oil circuit-breaker is defined as that which the apparatus can carry continuously with a temperature rise not exceeding 30° C. for switches and circuit-breakers rated at 200 A or less; 40° C. for 260-800 A, and 50° C. above 800 A rating. The 'standard reference ambient tempera-

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* *Electrical Times*, 22 Oct., 1936, p. 531.

† Development of Compressed Air High Speed Switches, *Bull. Associatus Suisse Elect.*, Vol. 26, p. 590.

‡ The notes in this paragraph are based upon B.S. Specifications Nos. 109, 110 (Air-break Knife Switches, Isolating Switches, and Circuit Breakers, for not higher than 660 V; excluding totally enclosed and flame-proof types) and B.S.S. No. 116, Oil Circuit Breakers, Switches and Isolating Switches, but the actual specifications should, of course, be consulted when the precise terms and conditions are of importance.

ture' has a peak value of 40° C. and an average value of 35° C. over 24-hour periods.

A complete statement of the rating of an oil switch or oil-circuit-breaker includes the number of poles, service voltage, normal current, frequency, breaking capacity, working capacity, short-time current (1 sec. and 5 sec.) and operating duty. Standard definitions of these and other terms are given in § 371.

The current rating may be increased as the frequency decreases, and must be decreased as the frequency increases, by an amount which depends upon the design of the switch; in a particular case, a switch rated at 600 A, 50 cycles was rated at 800 A, 25 cycles. The highest standard voltage rating at present contemplated in this country for oil switches is 220 000 V, but switches can be built for higher voltages if required.

The maximum permissible current densities in the various parts of a switch or circuit-breaker are those which are consistent with the temperature rises specified above, and which permit the switch to operate indefinitely without undue deterioration of the contacts. Many factors bear on these points, hence it is impossible to give definite figures for the current density; but as a general guide it may be taken that 600-1 000 A / sq. in. of section is permissible in connections, switch blades, and bridge pieces, the lower value being used for currents of 3 000 A or over; whereas 75-100 A / sq. in. of contact surface is a reasonable allowance where spring clips and blades are concerned, rising to 400 or 600 A / sq. in. of contact surface in the case of contacts subjected to high mechanical pressure (by bolting or by toggle mechanism, etc.). All contact surfaces should be formed on relatively heavy masses of metal in order that the contacts may have considerable capacity for heat; this greatly affects the breaking capacity of the switch (§ 371).

370. Breaking Capacity Required in Circuit Breakers.—The breaking (or rupturing) capacity of an oil switch or circuit breaker is the maximum kVA which it will interrupt at rated voltage. It is given numerically by the product $nEI/1\,000$; where E = rated voltage; I = the actual current *at the moment of separation of the contacts;* and $n = 1$ for single-phase, 2 for 2-phase, and 1·732 for 3-phase systems respectively. The most severe conditions under which a circuit-breaker can be required to act are those of short circuit. As explained in § 339 it is not easy to calculate accurately the current flowing under short-circuit conditions, and in the case of circuit-breakers, the problem is further complicated by the fact that the current to be determined is that which is flowing at the moment of separation of the contacts. If the contacts opened instantaneously on the occurrence of a short circuit they might be called upon to break 10 or even 20 times the total rated kVA of the generators connected to the system (§ 339); if, however, the contacts open $\frac{1}{5}$ sec. after the incidence of the short circuit they will not be required to interrupt more than, say, 6 times the total rated kVA capacity of the generators feeding the fault (assuming the generator reactance to be 10 °/₀; *see* § 340); whilst if the opening of the contacts be delayed for, say, $1\frac{1}{2}$ secs. by an artificial time lag, the current to be broken will probably be that corresponding to about 3 times the rated kVA capacity of the generators, *i.e.* it will be the steady short-circuit current of the system.

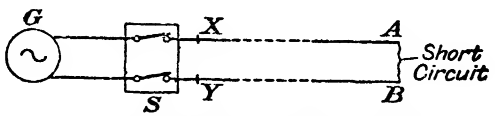


FIG. 82.—Short circuit at the far end of a feeder connected to a single generator.

The current flowing at the circuit breaker S (Fig. 82) is limited by the reactances and resistances in the complete circuit, $GABG$, between the generator and the short circuit, including the reactance of the generator itself. In the case of a circuit-breaker at a power station, maximum current flows when the short circuit is at XY (Fig. 82) immediately beyond the switch. The reactance in circuit is then only that of the generator plus that of any protective reactance (§ 340) or transformer which is connected between the generator and the circuit breaker.

Suppose that the rated capacity of the generator is 10 000 kVA, that the generator reactance is 10 °/₀ (*i.e.* reactance drop at full load = 10 °/₀ of normal voltage, *see* § 340), and that the external reactance is 4 °/₀; then: (*a*) The initial kVA at the moment of short circuit = $10\,000 / (\frac{10}{100} + \frac{4}{100}) = 71\,430$ kVA. (*b*) The kVA to be interrupted by the circuit-breaker, assuming the current to have fallen to 0·6 of its initial value by the time the contacts open, is: $0{\cdot}6 \times 71\,430 = 42\,860$ kVA.

Even in such a simple case as that considered in the preceding example there is considerable latitude for error in estimating because it is necessary to assume the extent to which the current will have decreased at the moment of opening the contacts, *i.e.* the extent to which the voltage is lowered as a result of the short circuit. For example, if there be high external reactance, which delays the demagnetising of the alternator field, the short-circuit current may still be 75 °/ₒ of its initial value after $\frac{1}{8}$ sec. and the circuit breaker (in the example chosen) must then interrupt 0·75 × 71 430 = 53 500 kVA. A considerable factor of safety is essential to allow for this uncertainty, and for the effects of abnormal pressure surges, resonance, etc.

In practice it is often difficult to determine the effective reactance of a short-circuited system (upon which depends the initial value of the short-circuit kVA). The general method of procedure may be illustrated by considering a short-circuit at *XY* (Fig. 83)

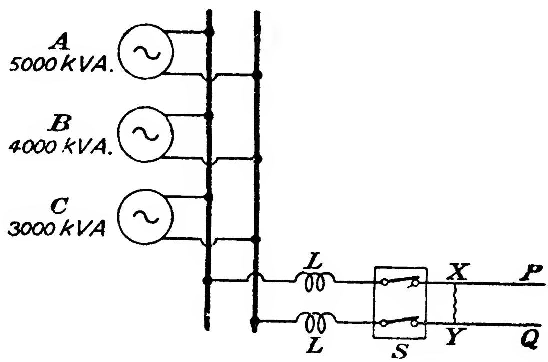


FIG. 83.—Short circuit on a feeder connected through reactance coils to several generators in parallel.

immediately beyond a circuit-breaker, *S*, which is connected through reactances, *L*, to bus bars on which three generators, *A*, *B*, *C*, are connected in parallel. These generators are assumed to be, respectively, of 5 000, 4 000, and 3 000 kVA rated capacity; total 12 000 kVA. The total current flowing at *XY* (and hence the kVA at rated voltage) could be calculated by considering the bus bar voltage to be applied to a total reactance of $(a + b)$ ohms where a = total reactance of the two coils *L*; and b = equivalent reactance of the three generators in parallel. Since, however, the reactances of generators, reactance coils, feeders, etc., are generally expressed as percentages (*see* § 340) it is simpler to work on this basis, but it must be remembered that the 'percentage reactance' of any machine or circuit is referred to *its own rated full load;*

if the actual load is greater, the percentage reactance must be increased in the ratio of the actual load to the rated load. The following example will make this clear * :—

The total kVA capacity on the bus bars in Fig. 83 is 12 000 kVA, and if the reactance of generator *A* is 10 % (based on its own rating of 5 000 kVA) it is (12 000 / 5 000) × 10 % = 24 % with reference to the bus bar kVA. Similarly, if the reactance of *B* be 8 %, and of *C* be 12 %, their reactances referred to 12 000 kVA are (12 000 / 4 000) × 8 % = 24 %, and (12 000 / 3 000) × 12 % = 48 % respectively. Adding the reciprocals of these reactances we have $\frac{1}{24} + \frac{1}{24} + \frac{1}{48} = \frac{5}{48}$ which is, itself, the reciprocal of the equivalent reactance of the three generators in parallel. Thus, referred to the bus bar capacity of 12 000 kVA, the effective reactance of the three generators is $\frac{48}{5} = 9{\cdot}6$ %. Again, if the total reactance of the two coils, *L*, be 5 % on a 5 000 kVA rating, it is (12 000 / 5 000) × 5 % = 12 % with reference to 12 000 kVA. Under these conditions the initial kVA at the short-circuit = 12 000 × 100 / (9·6 + 12) = 55 000 kVA. As the total reactance in circuit is rather high (21·6 %) it may be assumed that the kVA to be interrupted when the contacts open in $\frac{1}{5}$ sec. is 0·7 × 55 000 = 38 500 kVA.

For a switch at position *S* (Fig. 83), there is always a possibility of a short circuit at *XY*, close to the switch, hence this condition should be assumed when calculating the breaking capacity required, but for a switch at the far end of the lines *PQ*, the reactance and resistance of the latter must necessarily be between the switch and the power station and should therefore be included in the calculation, the percentage reactance of the line with reference to its own rated capacity being increased to correspond to the bus bar kVA as in the preceding paragraph. The calculation of the actual reactances of cables and overhead lines (from which the ‘percentage reactance’ at once follows) is discussed in §§ 299 *et seq.* and 310.

In the case of a short circuit at the far end of a line, the impedance of which is high compared with that of the generators, the kVA to be interrupted is determined almost entirely by the impedance of the line, and it may then be assumed that the bus bar voltage remains constant, so that the kVA to be interrupted is equal to the initial kVA and is given by (Rated kVA of line × 100 / Percentage impedance of line). If, however, the line impedance be low compared with that of the generators it is necessary to allow for the impedance of both; and in this case the kVA to be interrupted is, say, 75 % of the initial kVA owing to the fall in voltage caused by demagnetisation of the generator field.

* For many other examples of short-circuit calculations in more or less complicated networks, the reader may be referred to an excellent paper by W. A. Coates in the *Metropolitan Vickers Gazette*, June, 1921.

For example, suppose that a feeder rated at 1 000 kVA has 3 % reactance and 4 % resistance (referred to its own rating in both cases) and suppose that this feeder is connected to a 3 000 kVA station in which the generator reactance is 10 %. On the basis of 3 000 kVA, the feeder reactance is (3 000 / 1 000) × 3 % = 9 %, and its resistance is (3 000 / 1 000) × 4 % = 12 %. The total reactance is thus (9 + 10) = 19 % and the resistance (neglecting that of the generator) is 12 %. The percentage impedance is therefore $\sqrt{[(12)^2 + (19)^2]}$ = 22·5 % and the kVA to be interrupted is 0·75 × (3 000 × 100 / 22·5) = 10 000 kVA.

In the absence of definite information it is usually safe to assume that the 'short-circuit reactance' of a modern alternator is 10 % and that of a transformer about 4 %, reckoned on the rated capacity of the generator or transformer as the case may be. The 'short-circuit reactance' may be less than the reactance under conditions of normal magnetic flux density and is equal to (100 / x) %, where x = Current on dead short circuit at rated voltage / Rated full-load current (§ 340).

Though the methods explained above provide a convenient means of estimating the kVA to be interrupted, the duty actually required from the switch varies widely according to the point in the voltage wave at which the short circuit is established, and according to the point in the current wave at which the contacts are separated.

B.S.S. No. 116 contains valuable sections on the selection of oil circuit-breaker ratings for load conditions and for short-circuit conditions.

371. Factors Determining Breaking Capacity of Oil Switches.—It is not possible to give any single value as the breaking capacity of an oil circuit-breaker or switch under all circumstances. The breaking capacity in kVA or MVA (million volt-amperes) depends materially upon the circuit conditions and the methods of testing. B.S.S. No. 116 (1937) is in two parts, dealing respectively with: (1) 3-phase oil circuit-breakers with up to 500 MVA breaking capacity and 1-phase oil circuit-breakers, switches and isolating switches; (2) 3-phase oil circuit-breakers of more than 500 MVA breaking capacity. The full text of this Specification must be consulted where its application is concerned, but the following notes indicate the bases adopted, and explain some of the more important factors involved:

An *oil circuit-breaker* is a device capable of making and breaking the circuit in oil under normal and abnormal conditions, such as that of short circuit.

An *oil switch* is a device suitable for making and breaking in oil current not greatly in excess of the rated normal current.

An *oil isolating switch* is an oil switch suitable for disconnecting the circuit only when carrying no load current.

The *number of poles* is said to be one, two, three or more, according to whether one, two, three or more conductors or lines are to be broken.

The *break* is the sum of the gaps introduced in one pole between contacts, or arcing contacts (if any), when the switch or circuit-breaker is in the fully-opened position.

The *travel* is the distance through which the moving contacts pass between the closed and open positions.

Opening-time (until separation of the arcing-contacts). The opening-time of a circuit-breaker is measured from the instant of application of the tripping power to the circuit-breaker when in the closed position to the instant of separation of the arcing contacts, any time-delay device being adjusted to its minimum setting, or, if possible, cut out entirely.

A *loop* is the part of an alternating wave that extends from any zero to the next.

The *arc-duration* or *arcing-time* of a circuit-breaker is the time interval between the instant of separation of the arcing contacts and the instant of arc-extinction. For the purpose of indicating the number of current zeros after the instant of separation of the arcing-contacts up to the instant of arc-extinction, arc-duration or arcing-time may be referred to as including a stated number of loops.

Total-break-time (until final arc-extinction). The total-break-time of a circuit-breaker, from the closed position, is the sum of the opening time and the arc duration as defined above. (Note—The total-break-time must not be taken as the total duration of mechanical operation, which is measured up to the instant when the moving contact reaches the end of its stroke.)

The *make-time* of a circuit-breaker is the interval of time between the initiation of the closing operation and the instant when the arcing contacts touch, and includes the operating time of an auxiliary equipment used to close it.

The *rating* of a switch or circuit-breaker is the set of values assigned by the maker to define the working conditions for which it is built.

An *operating duty* is a defined sequence of making and / or breaking operations carried out without any deliberate alteration of the main circuit in which the switch or circuit-breaker is placed.

The *service voltage* is the R.M.S. working-voltage of the system at the point where a switch or circuit-breaker may be installed.

The *recovery voltage* is the normal-frequency R.M.S. voltage that reappears between the poles of a circuit-breaker after final arc-extinction.

The *active recovery-voltage* is the R.M.S. voltage at the instant of arc-extinction. It is a measure of the severity of the test-circuit as controlled by normal-frequency voltage.

The *active voltage-factor* is one by which the recovery voltage is multiplied to determine the active recovery-voltage for a given short-circuit power-factor and D.C. component.

The *re-striking voltage* is the high-frequency transient voltage that exists at, or in close proximity to, each zero current pause during the arcing-time; the important attributes being the amplitude and rate-of-rise (expressed in volts per micro-second) at the time of final arc-extinction.

The *normal current* of a switch or circuit-breaker is the R.M.S. current that it is capable of carrying continuously under prescribed conditions.

The *short-time (1 second or 5 seconds) current* of a switch or circuit-breaker is the R.M.S. current that it is capable of carrying in the fully closed position for the stated time under prescribed conditions.

The *breaking-current* is the current broken by a pole of a circuit-breaker at the instant of contact separation: (i) The *symmetrical breaking-current* is the R.M.S. value of the A.C. component of the breaking-current. (ii) The *asymmetrical breaking-current* is the R.M.S. value of the total breaking-current which includes both the A.C. and the D.C. components of the breaking-current.

The *breaking capacity* of a circuit-breaker is expressed by two quantities: (i) The *symmetrical breaking capacity* is the R.M.S. value of the A.C. component of current that can be broken at a stated voltage simultaneously in all poles of a circuit-breaker. (ii) The *asymmetrical breaking capacity* is the R.M.S. value of the combined A.C. and D.C. components of current that can be broken at a stated voltage by any one pole of a circuit-breaker.

The *making-current* of a circuit-breaker is the peak value of the maximum current-wave (including the D.C. component) in the first cycle of the short-circuit current after the circuit is closed by the circuit-breaker.

The *making-capacity* of a switch or circuit-breaker is the making-current that it is capable of making and carrying instantaneously at rated service-voltage under prescribed conditions.

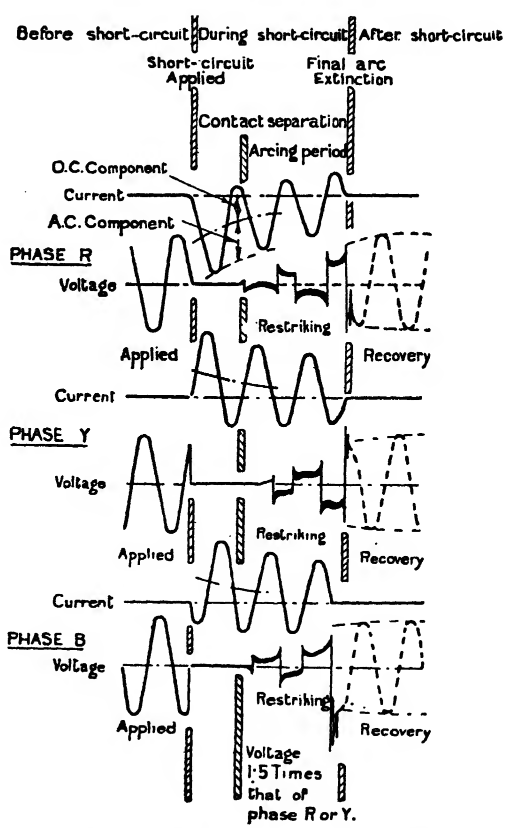


FIG. 83A.—Typical Oscillogram of three-phase short-circuit.

Basis of Rating and Tests.—Values of short-circuit current (such as making-current at a specified service-voltage, breaking-current at a specified recovery-voltage, and short-time current during a specified time) are used to express the rating of a circuit-breaker and the results obtained during type-tests. A typical oscillogram showing the varying values of currents and voltages as functions of time obtained with a three-phase circuit-breaker is given in Fig. 83A.*

* Reproduced by permission from B.S.S. 116—1937.

MVA Rating.—The fundamental symmetrical breaking capacity rating in amperes assigned to a circuit-breaker is converted into an MVA rating by multiplying it by the rated service-voltage, the phase-factor, and 10^{-6}.

Criteria of Severity.—Generally accepted criteria of severity for tests and ratings are given in B.S.S. 116, but no standard values can yet (1938) be given for the rate of rise of re-striking voltage, which also affects the severity of the service demanded from a circuit-breaker. The rate of rise of restriking voltage depends on: (1) Recovery voltage, p.f. and d.c. component, each of which influences the amplitude of the re-striking voltage transient; (2) natural frequencies, which control the time taken by the re-striking voltage transient to reach its maximum amplitude.

Statement of Duty.—A standard requirement is that an oil circuit-breaker shall be capable of operating at any currents up to its rated making-capacity and rated breaking capacity in accordance with the following duty:—

$$B - 3' - MB - 3' - MB.$$

In this and similar expressions, B denotes a breaking and M a making operation; MB denotes making, followed by breaking without any intentional delay; and the numeral (here in minutes) denotes the interval of time between the successive operations.

Constructional factors which influence the actual breaking capabilities of oil switches and circuit-breakers include: (i) The form and mass of the contacts, and the mechanical strength of the switch components. (ii) The speed of breaking contact, the number of breaks in series per phase, and the total length of break per phase. (iii) The clearance between phases and between live metal and earthed metal (the tank) below oil and in air. (iv) The volume of oil in the tank and the head of oil over the contacts at the moment of opening; and the suitability of the oil employed. (v) The amount of air space above the oil and the efficacy of the vents for the discharge of oil vapour. (vi) The mechanical strength of the tank and its supports. The relative importance of these factors varies widely with the design of the switch. The basic requirement is that the arc be extinguished as quickly as possible, and that conditions in the gap then prevent re-striking of the arc.

The contacts should not be forced apart by electromagnetic forces (§ 369) and no conductor in the switch should be capable of deformation by the mechanical forces developed under short-circuit conditions (§ 338).

A quick break reduces the heating of the contacts at the moment of separation, thus reducing the stability of the arc; and extinguishes the arc more rapidly, thus reducing the volume of vapour produced. Other factors being equal the arcs at a multiple gap are less stable than the corresponding arc at a single gap; and the greater the total length of break, the less chance there is of the arc persisting. The disposition of the conductors in some oil switches is such that there is a magnetic blow-out effect (§ 365).

The clearance from phase to phase, and between phases and earthed metal (*vide* B.S. Specification No. 116 of 1937) is always of importance as regards insulation under normal conditions; and it is of special importance when the contacts open under excessive load, because the arc may produce a short circuit between phases or to earth if the clearances be not ample. Barriers of insulating material between phases and insulating linings in the tank reduce this risk; the barriers may be of 3- or 5-ply non-resinous wood (birch or maple); resinous wood is apt to cause the contacts to become foul and possibly cause sticking. For pressures above 6 600 V (or at lower pressures if the current be heavy, say, 1 000 A or over) the circuit-breaker for each phase is often placed in a separate tank; the single-tank construction is sometimes used, mainly on the Continent, for 33 000 V switches of small rupturing capacity.

Tables 52 and 52A give the B.S. Clearances for indoor and outdoor types respectively of circuit-breakers of ratings up to 500 MVA; the clearances for apparatus of higher breaking capacity are slightly different (*see* B.S.S. 116, Pt. 2).

TABLE 52.—*British Standard Class A and Class B Clearances for Indoor Type Circuit-Breakers, up to 500 MVA Rated Breaking Capacity.*

NOTE.—The length of insulator given is the direct length regardless of the shape, *i.e.* the length along the centre line.

1	2		3		4		5		6		7	
Rated Voltage.	Minimum Length of Insulator in Air.				Minimum Clearance to Earth in Air.				Minimum Clearance between Poles or between Terminals on One Pole in Air.			
	Class A.		Class B.		Class A.		Class B.		Class A.		Class B.	
kV.	in.	mm.	in.	mm.	in.	mm.	in.	mm.	in.	mm.	in.	mm.
3·3	2	51	3½	89	2	51	2½	63	2	51	3½	89
6·6	3½	89	5	127	2½	63	3	76	3½	89	5	127
11	5	127	7	178	3	76	4½	114	5	127	7	178
22	8	203	—	—	5½	140	—	—	9½	241	—	—
33	12	305	—	—	8¾	222	—	—	14	356	—	—

NOTES.—(i) Class A clearances are to be regarded as minimum values that may be used in any circumstances.

(ii) Class B clearances are recommended for oil switches and oil circuit-breakers used in the more important positions or under more onerous conditions, where failure may be occasioned by:—

pressure between the closed contacts. It is necessary to provide not only for suitable pressure between the contacts (which pressure must be high where laminated brushes are used) but also for the compression of springs which are powerful enough to open the switch rapidly; in the case of blade and spring clip contacts the operating springs must be powerful enough to overcome the friction between the contacts and still leave a net force sufficiently great to accelerate the moving parts rapidly. Any switch which is required to open automatically, in the event of predetermined abnormal conditions, used to be provided with some form of latch, the opening of which left the moving system free to be displaced by the compressed operating spring, but modern high-speed D.C. circuit-breakers

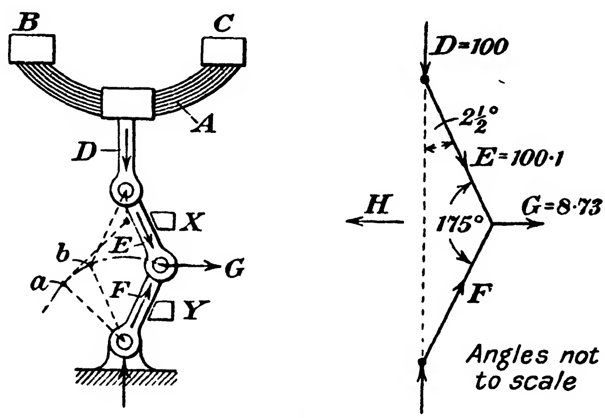


FIG. 84.—Diagrammatic representation of toggle mechanism.

avoid any latchwork; on this fact their high-speed properties depend (*see below*, 'High-speed breakers,' § 372 (3)); also, the operating handle must be "free" in the sense that the switch cannot be held closed if the circuit conditions are such that the trip mechanism operates. The force required to close the switch and the force stored in the compressed spring ready to open it are of considerable magnitude, especially in heavy current switches with laminated brushes; and, while it is necessary that the closing force should normally exceed the opening force, it must be arranged that a relatively small tripping force will release the mechanism. In this connection the toggle mechanism is particularly useful.

Referring to Fig. 84, the laminated brush, A, is pressed on to the contacts, BC, by the linkwork, DEF, which is so designed that when it is moved to the right from the dotted position *a*, *b*, the rod, D, is moved vertically upwards. The pressure between A and BC is a maximum when the links, EF, are in line with D, but this position is unstable, so the mechanism is pushed over until the links, EF, rest against stops, XY. The pressure between the contacts is still considerable, but the resultant force at G is relatively small hence application of a relatively small force opposed to G will bring the links first to the vertical position and then to the left of it, thus 'breaking' the toggle and allowing a compression spring (not shown) on the spindle, D, to open the contacts rapidly.

If A bears upon each contact, B, C, with a force of 50 lbs. the total thrust in D (see enlarged diagram of forces, Fig. 84) is 100 lbs. The thrust in E $= 100 / \cos 2\frac{1}{2}°$ $= 100 / 0{\cdot}999 = 100{\cdot}1$ lbs. = thrust in F. The resultant of the thrusts in E and F $= 2 \times 100{\cdot}1 \times \sin 2\frac{1}{2}° = 8{\cdot}73$ or, say, $8\frac{3}{4}$ lbs. If a pull, H, greater than $8\frac{3}{4}$ lbs., be applied as shown, the apex of the toggle will move to the left and the toggle will be 'broken.' So long as the links, EF, are to the right of the vertical, against the stops, the mechanism is stable.

The valuable property of this mechanism is that a small lateral (closing) force is sufficient to produce a high pressure (lbs. / sq. in.) between the contacts, whilst an equally small (tripping) force is sufficient to release the mechanism.

Modern practice, at least in large plants, has gone almost exclusively over to remote electrical control, usually coupled with automatic indication at the control station of the results of any operation and its sequence of operations; it also assists in providing for electrical interlocking, in place of mechanical interlocking by means of Castell keys, etc.

Manual operation is simple and convenient in the case of small and medium sized switches, the whole switchboard occupying comparatively small space and the connecting linkwork between the operating handle and the switch being light and easily manipulated. Where high power, high voltage switches are concerned, however, it may be necessary to place the switches some distance away from the control board in order that the switches may be housed safely and conveniently, and in order that the control board for the whole of a large plant may be reduced to conveniently small dimensions. Switches may be operated by hand from a considerable distance through a series of rods (or steel tubing) connected by bell cranks where required, but this system of remote control does little to reduce the dimensions of the control board; moreover, it demands increased physical effort on the part of the operator. In such cases electrical remote control offers obvious advantages; * the switch is closed by aid

* An extreme example of the possibilities of electrical remote control of switches is to be found in the 'Handyell' system of remote switching on supply station networks without the use of pilot wires or special cables. Each of the switches to be controlled is provided with a device consisting of a magnet coil and a condenser

is no difficulty in applying also reverse power, leakage, and various selective systems of protection (*see* § 357 *et seq.*).

The time elapsing between the incidence of a short circuit or other fault and the opening of the main circuit-breaker is an important consideration.* As explained in § 344 a definite or an inverse time lag may be introduced deliberately in the action of the relay, but in the case of an ordinary oil-immersed circuit-breaker intended to open 'instantaneously' on short circuit, the relay closes and the trip coil is fully energised within (say) 0·1 sec., and the main contacts are separated within (say) 0·2 sec. from the incidence of the short circuit. (*But see below* (3) High-speed Circuit-Breakers.) The arc is generally extinguished in less than 1 cycle (*i.e.* less than 0·02 sec. in the case of 50-cycle A.C.) after the arcing tips separate and in no case should it persist for more than a few cycles. The moving parts of the switch are accelerated, moved to the end of their stroke, and brought to rest in less than 1 sec., and in order that there may be no violent mechanical shock at the end of the stroke, the moving parts are generally brought smoothly to rest by arranging that the tubular guides act as dashpots, or by equivalent means.

(3) *High-speed Circuit-Breakers.*—D.C. generators and rotary converters, particularly those supplying high voltage direct current (*e.g.* 1 500 V or 3 000 V for traction), are liable to flash-over on the commutator in the event of a short circuit on the D.C. system (§ 869, Vol. 3). It has been found that such flashing-over can be prevented to some extent if the generator or converter is protected by a circuit-breaker capable of operating and reducing the current below the flashing value in less time than is required for a commutator bar to pass from one brush arm to the next. A standard air-break circuit-breaker may operate in about 0·1 sec. but by eliminating mechanical trip gear and reducing the inertia of the moving parts all electric high-speed circuit-breakers have been developed which operate in 0·005-0·01 sec. These circuit-breakers are effective in preventing flash-over on dynamo or converter commutators, but such rapid operation is undesirable in A.C. circuit-breakers because it would increase the shock to the system and increase the breaking capacity required in the circuit-breaker

* Reference should be made to B.S.S. No. 116 of 1937 on Oil Circuit-Breakers, etc., for A.C. Circuits.

without effecting any useful purpose. Their use is practically confined to D.C. traction.

While these reasons accounted for the *original* installation of high-speed circuit-breakers, they have been *retained* for quite different reasons. Practical experience, reinforced by oscillograph tests, showed that with old types of traction rotary-converters there was no great difficulty in momentarily interrupting both a flash-over and the external short-circuit current before they could effect serious damage; but the flash-over was apt to re-establish itself within a fraction of a second of the breaker opening. As the flash-over is a direct path from brush arm to brush arm, no switching operation could then interrupt it. The modern theory, practically proven, is that the arcing caused by a heavy short circuit produces ionised air in quantity, which gives the flash-over a conducting path. The breaking of the external circuit allows the terminal voltage of the generator, which was reduced almost to zero by the short circuit, to build up again rapidly, with the consequent re-establishment of the flash-over viâ the ionised air round the commutator. Precautions against this danger have now been incorporated in the design of rotary converters (§ 869, Vol. 3). A further and very important use of the apparatus is for the protection of overhead lines in countries where thunderstorms are a constant menace.

In construction and operation the polarised type circuit-breaker differs from the ordinary type in that it is held closed magnetically, and that tripping is effected by direct reduction of the magnetic flux in the holding circuit by means of the main current, instead of through the instrumentality of a trigger or similar mechanism described above in (2) of this paragraph. The elimination of all such mechanism, which has itself to operate before the breaker can begin to open the circuit, greatly increases the speed of operation; tests show that the contacts can generally be relied on to separate within 0·01 sec. or even 0·005 sec. of the establishment of a short circuit. The highest speed of operation is obtained by arranging the breaker to operate *on the rate of increase of current,* either alone or, more commonly, in conjunction with the ordinary excess current gear. The rate of rise of current under severe short-circuit conditions on a large traction system may be of the order of 1 000 000 A per second. If that part of the breaker main circuit which provides for the excess-current tripping is shunted by means of a shunt made deliberately inductive, by surrounding it with iron laminations, the division of current between the trip circuit and the inductive circuit will be upset when the current is varying very rapidly, and most of it will tend to take the non-inductive path through the trip circuit; thereby initiating the tripping *immediately* on the establishment of a fault, without even waiting for the current to exceed the maximum allowable in the circuit. Alternatively the breaker can be operated by a relay energised by a current transformer in the main D.C. circuit.

The remarks made in (2) of this paragraph concerning design and operation of ordinary types apply generally to high-speed breakers, the principal differences being such as would be expected in view of their mechanism and the severity of the conditions under which they are called upon to operate. Arc chutes, blow-out details and contacts receive special attention. As regards contacts, some designs utilise laminated main brushes and auxiliary arcing contacts, but at least one successful type has a single solid butt contact only, with no auxiliary contacts at all; this arrangement has the advantage of robustness, as light arcing contacts are apt to be rapidly burnt and consequently to lose their proper 'lead' to ensure their closing before and opening after the main contacts.

The high-speed circuit-breaker operating mechanism is particularly adaptable to automatic or remote control. The holding coil can be operated from a separate constant-potential source such as a battery or, through suitable resistances, direct from the main power supply. It should be borne in mind that any temporary decrease in the operating voltage for the holding coil will for the time being affect the calibration of the breaker. An important matter in design is to protect the control wiring as far as possible from the danger of being damaged by any arcing which may in the most unfavourable circumstances originate in the power circuit.

Constructional details differ according to the manufacturer, and can be found in the leaflets and catalogues issued by various firms; being highly specialised, descriptions and diagrams would be out of place here. Manual as well as automatic operation is, of course, essential. The arc is extinguished by a powerful blow-out magnet forcing it upwards; and in some designs for high-pressure circuits there are two such, and the arc is divided. In the best apparatus a 'trip-free' mechanism is incorporated, which will protect the circuit if short-circuit conditions exist at the moment of attempting to re-close the breaker.

(4) *The High-speed Limiter.*—A new device, known as a high-speed limiter, may partly supersede the high-speed circuit-breaker on railway traction circuits as well as in conjunction with mercury-vapour rectifiers. It is said to act in about half the time required by a high-speed breaker, and it limits the short-circuit current by the insertion of resistance, instead of breaking it; *viz.* to about half the peak value, which will no doubt be improved upon. The moving parts do not carry the main current, so can be of light weight, and their movement is determined by the rate of increase of the current under short-circuit, as mentioned in the previous sub-paragraph (3) for breakers.

372a. **De-ionising Devices.**—As explained above, de-ionisation of the gap is of prime importance in accelerating the extinction of an arc, and improved means of de-ionisation are chiefly responsible for the increased breaking capacity of modern switchgear. The efficacy of such devices as explosion pots, the turbulator and other means of producing blasts of gas and oil across the gap in oil switches (§ 368), and the practicability of expansion-type and air- or gas-blast switches, (§ 368*a*) depend largely on the mechanical displacement of ionised gas or vapour from the danger zone. Another application of the same principle is in preventing flash-over at the commutators of rotary converters (§ 869, Vol. 3).

The *de-ion circuit-breaker,* designed to provide maximum opportunity for de-ionisation of the arc-path, embodies a stack of thin metal plates separated by thin spacing pieces of insulating material. The arc is blown by a magnetic field on to this stack of plates and is thus cut into a number of short arcs in series. The net effect of the magnetic, mechanical and thermal displacement, dismemberment and cooling of the arc is to de-ionise the gap almost instantly when the current passes through zero.* In other words, the dielectric strength of the gap is built up more rapidly than voltage is restored, and the arc is therefore not re-established.

* For further information on the theory and applications of De-ion circuit-breakers, see *Jour. Amer. I.E.E.*, Vol. 48, pp. 93, 96, 101; *El. Journal*, Vol. 26, p. 97; *El. Times*, Vol. 76, p. 551; *Engineering*, Vol. 129, p. 152; *Trans. Amer. I.E.E.*, Vol. 52, p. 568.

373. Interlocks and Indicating Devices.—Mechanical and electrical 'interlocks' are of vital importance in the safe manipulation of electrical switchgear, and they are used in an endless variety of forms. Whilst the details may be modified to suit any requirements, the principles involved are few and simple. As an example of mechanical interlocking, a switch handle may be provided with an extension piece or coupled to a rod which acts as a bolt, making it impossible to open the cover or enclosure of the switch until the switch handle is 'off'; and equally impossible to put the switch handle into the 'on' position until the cover or enclosure is closed. Again, interlocking devices similar to those used in a railway signalling-frame may be employed to ensure that certain switches are not closed simultaneously, or that switches are closed only in a predetermined sequence. The latter function is easily performed by electrical interlocking, it being then arranged that switch A closes a circuit which must be closed before switch B is unlocked or operated automatically (by a solenoid), as the case may be. In draw-out type switchboards (§ 380) it is made mechanically impossible for any parts to be 'live' whilst they are accessible.

It is generally evident by inspection whether an open-type, manually operated switch is 'off' or 'on,' but wherever the switch is concealed or enclosed it is necessary to have a definite indication of its position. This may be provided by attaching 'on' and 'off' labels to the operating handle in such a way that only the appropriate legend is visible through an aperture provided for the purpose. Red and green lamps (or preferably plain lamps behind red and green lenses) are used extensively to indicate the setting of a switch, auxiliary circuits being arranged so that the red light is shown when the switch is 'on' and the green light when it is 'off.' It is becoming increasingly common to provide switchboards with key diagrams made on translucent glass and provided with lamps interlocked electrically with the main switchgear so that the actual circuits completed are illuminated from the back of the diagram.

A complete system of automatic indicators and alarms is very necessary where the switchgear is remote-controlled.* Audible alarms (bells or hooters) may be given automatically in the event

* A valuable treatment of the subject of remote control is given in Part 4 of the paper by H. W. Clothier, *Jour. I.E.E.*, Vol. 71, p. 285.

of circuit-breakers opening, lightning arresters operating, overheating in bearings, or interruption or other irregularity in the supply of ventilating air, circulating water, etc. One alarm may be common to all these causes, discrimination being effected by an annunciator similar to that used in ordinary bell-circuits.

A red lamp and audible alarm are desirable to indicate failure in a potential circuit (voltmeter or wattmeter pressure circuit) due to blown fuses or broken leads.

374. **Special Switches.**—An important type of switch not hitherto mentioned is the 'faceplate' type, as exemplified in the majority of motor starters (§ 736, Vol. 3). In this type of switch, which is also much used for selecting instrument circuits, a series of circuit-contacts are mounted on an insulating baseplate and a moving contact (generally of the laminated brush type) is moved parallel to the baseplate (either on the arc of a circle or along a guide rod) so as to touch the appropriate contact stud or studs. There is considerable friction between the moving and fixed contacts if the dimensions and bearing pressure are sufficient to permit heavy currents to be carried safely. Except for weak current circuits this type of switch is not suitable for interrupting current as a 'quick break' in the accepted sense of the term is not possible. To eliminate arcing on the contacts of a faceplate motor starter it is often arranged that the current is always interrupted at a 'contactor' in the circuit. The term 'contactor' is applied to switches (air break or oil-immersed) which are capable of breaking a load current and which are operated electromagnetically—especially in connection with the control of motors. For currents up to 500 or 600 A, the moving contact is generally solid and arranged to give a rolling motion on the fixed contact as the contactor closes or opens. In heavy-current contactors, or medium-current contactors which have to carry full load for long periods, the moving contact is of the laminated-brush type (§ 365) and may be moved on a straight line perpendicular to the plane of the fixed contacts by the action of a solenoid, or it may be moved on the arc of a circle by means of a bell-crank mechanism. Air-break contactors are used largely for the control of traction motors, and for motors in heavy industrial service, generally for pressures not exceeding 660 V but sometimes for pressures up to 3 300 V, three-phase. There is no basic distinction between contactors and circuit-breakers (air-break or oil-immersed, as the case may be).

Switches differing indefinitely in details of mechanical construction and electrical connection are used for 'multi-way' switching. A few typical methods are illustrated diagrammatically in Figs. 85-90; some special switches used in the control of lighting circuits are described in Chapter 21; and various types of motor starters are described in Chapter 29.

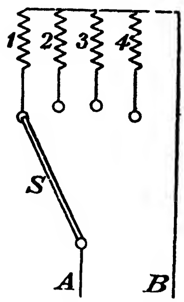


FIG. 85.—Single-pole multiway switch selecting one of several loads.

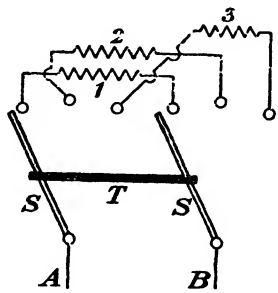


FIG. 86. — Double-pole switch selecting one of several loads.

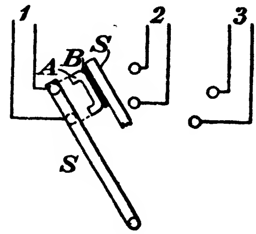


FIG. 87.—Switch closing one of several independent circuits (*cf.* Fig. 90).

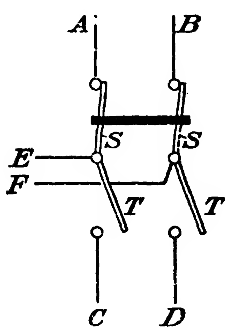


FIG. 88.—Double-pole change-over switch.

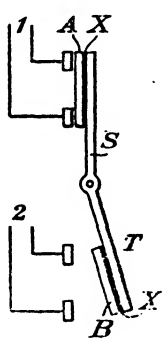


FIG. 89. — Change-over switch closing either of two independent circuits.

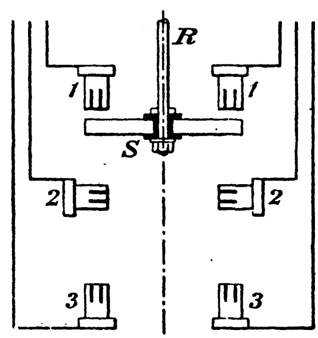


FIG. 90.—Switch closing one of three circuits (*cf.* Fig. 87).

In Fig. 85, the pivoted switch arm, S, connects A to one terminal of any one of four loads 1, 2, 3, 4; the other terminals of the latter being permanently connected to B. For purposes of isolation there must be a double-pole switch between AB and the supply.

In Fig. 86 the two switch arms, S, coupled mechanically by the insulating piece, T, connect the supply leads, AB, to any one of the loads 1, 2, 3. In this case the load circuits are electrically independent and if SS has an 'off' position it can serve as the double-pole switch between the mains and the load circuits.

The switch arm, S, in Fig. 87, is a purely mechanical device. It carries the contact-bridge, A (from which it is insulated at B), and this bridge closes any one of three circuits 1, 2, 3 which are electrically independent and may have different sources of supply.

The double-pole switch, SS, Fig. 88, has extension blades, TT (at say 135° with SS) so that the leads, EF, can be connected either to AB or to CD, according to whether the switch is closed in the up or the down position. In some cases a single pair of blades, SS, is swung through 180° to effect the alternative connection. By either method only one of the two connections can be made at once.

In Fig. 89 the arm, ST, carries insulated contact-bridges, AB, which close *either* circuit 1 *or* circuit 2 (*cf.* Fig. 87). Similarly, in Fig. 90, the switch blade, S, is moved by the rod, R, along the dotted axis to close any one of three circuits (possibly electrically independent) which are connected to the contacts 1, 1; 2, 2; and 3, 3.

The 'drum controller' (*see also* Chapter 29) is a development of the principle illustrated in Figs. 87, 89, and 90, a spindle carrying contact-segments being rotated about an axis parallel with a row of contact-fingers between which the segments effect any desired sequence of connections.

Typical of switches which are 'special' in the method by which they are operated, rather than in the switching which they perform, are current-limiter switches which open-circuit or produce a flicker when the demand of a circuit exceeds a predetermined value (§ 272), and time switches, operated by a clock.

375. Fuses.—The protective action and rating of fuses has already been discussed in § 342. The simplest mounting for a fuse is between two terminals (on an insulating base) to which are connected the circuit wires on each side of the fuse. Such an 'open' fuse wire is, however, very dangerous; when the fuse 'blows' molten metal may injure a bystander or start a fire. The fuse should be so cased in and arranged that its melting causes no damage to the surroundings. Small fuses for house-lighting circuits * are commonly mounted between brass terminal plates which are carried by a porcelain block and separated by a porcelain partition round or through which the fuse wire is threaded; the whole is enclosed by a screw-on porcelain cover. Before renewing such a fuse, the switch controlling the circuit must be opened, otherwise, if the fault be still present, the new fuse will blow directly it completes the circuit and may seriously injure the operator. This risk is eliminated by mounting the fuse in a porcelain tube which is provided with a terminal block

* Seldom used now, as all fuses are concentrated in the distribution boards, see §§ 511, 515, Vol. 2; but still found in old installations.

at each end; these blocks make contact with spring clips on an insulating base, the clips being connected to the circuit wires. The porcelain tube is shaped externally as a hand-grip or handle and, to renew the fuse, the porcelain carrier must be withdrawn completely from the live terminals; even if the fuse blows directly the carrier is replaced in the clips, the porcelain tube protects the operator from injury. The carrier can be formed with a hood at each end to cover the live clips and make it impossible for the operator to touch the latter when removing or replacing the carrier.

The totally enclosed or cartridge fuse is similar to the porcelain tube type in general construction, but the tube is of fibre or card-board and is filled with incombustible powder which helps to prevent arcing when the fuse blows. In the porcelain-grip fuse the same end may be attained by threading the fuse wire through a tortuous channel. It is generally impossible to fit a new wire to a cartridge fuse, and, by using cases of different dimensions, it can be ensured that only fuses of the intended rating are inserted between a particular pair of terminals. This advantage is shared by the screw plug type of fuse which is essentially a short cartridge fuse arranged to screw into a socket and make contact between two terminals on the same principle as the screw-cap lampholder.

For industrial service porcelain grip fuses are commonly mounted inside a cast-iron case together with switches which are interlocked (§ 373) with the cover of the case so that the cover cannot be opened until the switch is open; neither can the switch be closed whilst the cover is open. The fuses being on the load side of the switch the fuse clips are dead whilst the cover is open and there can be no 'open sparking.' For use in explosive atmospheres the case and its cover are stronger and have wide machined joints to render them 'flame-proof' (§ 366). House-service fuses are of the porcelain grip type mounted, generally without switches, in a small iron case which is sealed to prevent tampering. If the fuses for each pole are in separate cases, the latter should be mounted side by side so as both to open inwards, the distance between the cases being insufficient to allow both cases to be open at once. The fuses for both poles may be mounted in a single casing if provision be made to prevent accidental short-circuiting. The cover is often lined with asbestos, and asbestos-covered fuse wire is often employed. Cut-outs of this type are suitable for pressures up to 600 V. Combined switch and fuse units for industrial service can be built for any desired pressure.

An alternative to the explosion-proof air-break switch and fuse for mining service is the combined oil switch and fuse shown diagrammatically in Fig. 91. The fuse wire, *F*, forms the connecting link between the moving contacts, *A*, *B*, and is always submerged in oil, except when the tank is lowered to allow the fuse to be replaced. The rating of the fuse is, of course, much higher in oil than in air.

Oil-immersed fuses carried by a porcelain cover with hand grip were formerly used on switchboards for high power and high voltage, but it was found that the blowing of the fuse on short circuit was of explosive violence, the fuse tank being often shattered and the oil causing a dangerous fire. Oil-immersed switches with overload trip-gear are therefore now used almost invariably for all high-power circuits and for most circuits above 600 V.

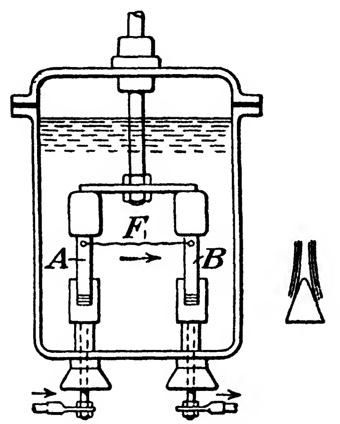


Fig. 91.—Oil-immersed switch and fuse.

A most successful type of high tension fuse consists of a short fuse wire held in tension by a spiral spring, the whole being enclosed in a long glass tube which is filled with carbon tetrachloride or other liquid of similar type. When the fuse blows, the spring contracts and a specially-shaped piston piece attached to it forces the liquid (which is non-inflammable and an insulator) on to the arc. This type of fuse is available for full load currents up to 100 A and all pressures up to 132 kV, and there seems to be no reason why its range cannot be extended to any requirements.

An ingenious and effective means of combining fuse-protection and breaking capacity over a wide range of rated currents in circuits for working voltages up to about 200 kV consists in winding several fine fuse wires in parallel as helices on a ceramic carrier, the whole being enclosed in an insulating tube filled with specially selected sand. When the fuses blow, the heat and the metal vapour form sintered helices of sand, constituting a high resistance which momentarily carries, but quickly interrupts, the short-circuit current. Fuses of similar construction, but for rated currents up to 120 A, are used successfully in rail cars operating on 17·3 kV, 16 $\frac{2}{3}$-cycle, single-phase supply.* Various combinations of fuses have been devised † to combine satisfactory protection against short-circuit and sustained overload with ability to carry temporary overloads, the general principle being to make the heating characteristic of the fuse correspond more or less closely to that of the apparatus protected.

B.S. Specification No. 88 (1937) standardises fuses for up to 800 A and 250 V to earth in four categories of duty corresponding to maximum prospective currents of 1 000, 4 000, 16 500 and 33 000 A in the test circuit. Standard sizes of fuses (maximum current ratings, in amperes) for the four categories range respectively from 5 to 60 A, 5 to 600 A, 30 to 800 A and 30 to 800 A.

376. Types of Switchboards.—The main types of switchboard to be considered are: (1) The panel type (§ 377), in which the switchgear and instruments for a particular machine, feeder, etc., are mounted on a panel and in an undivided enclosure behind the latter. (2) The cellular type (§ 378), in which each of the main elements of the switchgear for the machine, feeder, etc., is enclosed in a separate compartment behind, or away from, the panel on which the control levers and indicating instruments are mounted. (3) The ironclad and mining types (§ 379), in which ironclad or flameproof switch-gear is assembled on structural steelwork supports, the bus bars, instruments and connections being enclosed like the switchgear; or the whole may be arranged as an ironclad pillar. (4) Draw-out type boards (§ 380) which may be of the ironclad pillar pattern or the panel pattern, the characteristic feature in either case being the disconnection of the gear from the bus bars by the act of drawing it forward on runways. (5) Outdoor assemblies of weather-proof switchgear (§ 381).

377. Panel-Type Switchboards.—There are still in use many low-tension switchboards with the contacts of the switches mounted on the front of slate or marble panels; the stems of the contacts lead through the panel, and nuts at the back hold the contacts to

* For further information, see *E.T.Z.*, Vol. 59, p. 222.

† A combination of two fuses in series, connected in parallel with a third, has useful characteristics; see *E.T.Z.*, Vol. 59, p. 264.

the panel and clamp cable lugs, etc. to the contact stems. On the front of the panels are open-type knife switches, field-regulating rheostats, etc. ; also, the measuring instruments and, at the top of the panels (so that the arcs have a clear path upwards), the air-break circuit-breakers. Even where none but skilled attendance is provided such open-type panels are dangerous for any higher pressure than 250 / 500 V, 3-wire, D.C., and the trend of modern design is to place nothing but the control handles and indicating instruments on the fronts of panels, all the live parts being protected from accidental contact.

Early high-voltage switchboards were often of the open type with both switches and connections on the front of the panels, the risk of accidental contact, short-circuit, and flash-over being reduced by placing barriers of slate between the components at right angles to the panels. The modern cellular switchboard (§ 378) is a development of this principle.

There is little advantage in using slate or marble panels for any but low-voltage boards. Apparatus for pressures exceeding 650 V is usually insulated by porcelain and carried by steel or cast-iron supports on a rolled steel framework. A typical panel-type board for high-voltage circuits comprises a framework of channel and angle irons with sheet-steel front panels. An enclosure is made behind each panel by sheet steel or expanded metal partitions and a door at the back gives access to each cubicle from a gangway between the 'board' and the wall. The control levers project through the front panel, and the latter carries the indicating instruments. When the doors are closed all the live parts are completely inaccessible, and the doors may be interlocked with isolating switches so that the gear in the cubicle cannot be live whilst the door is open (unless it is deliberately made live for purposes of testing). The whole of the metal framework, panelling, etc., is bonded together and connected permanently to earth.

378. Cellular Type Switchboards.—In these boards, metal or insulating sheets, or brickwork or concrete partitions, are placed between panels and, to a greater or less degree, between the component parts of the equipment on each panel. The aim is to establish mechanical barriers (insulating or of earthed metal) between phases and, as far as possible, between individual pieces of apparatus. These are usually concrete walls and partitions in conjunction with a structural steel framework. The latter is arranged so that there is a minimum of earthed metal in the cubicles of the board and so that doors and other fittings can be mounted by the maker of the board without demanding special accuracy in the erection of the concrete or moulded stone slabs at the site. Concrete or moulded stone is more convenient to use and more compact than brickwork, and it withstands arcing or explosions better than steel or thin sheets of insulating composition; also it can be moulded with holes, seatings, etc., for attachments. Thoroughfare insulators are used to carry connections through the concrete partitions in the cubicle structure.

A concrete or similar partition gives the same operating safety as a much greater air gap between live parts and this favours compact construction. On the other hand, the minimum permissible clearance to earth must be allowed between partitions and the gear enclosed, and every partition must be at least 2 ins. thick; also, for practical reasons, the cells must be rectangular and of uniform depth, so that too much space is occupied if the cellular principle be carried too far. More compact construction is possible if doors can be provided in both the back and the front of the board. The bus bars may be mounted in concrete troughs along the top of the board or, where duplicate bus bars are used, at the back and front of the top compartment in the board. The isolating links occupy a cell immediately below the bus bars. The oil switch stands on the floor, and behind it (in separate cells, if access can be had to the back as well as the front of the board) may be the instrument transformers and the protective transformer. There are many other possible arrangements. The vent pipe from the oil switch discharges outside the cubicle.

Switchgear in this type of board is generally 'remote-controlled'—either mechanically or electrically from a control desk on which also are mounted all the indicating, recording, and synchronising instruments, etc. The construction is costly if the subdivision be thorough and of substantial construction, and if the individual cells be large enough for convenience in access. On the other hand, the strong walls and partitions are valuable from the mechanical standpoint in that they afford substantial supports for the gear; and the barriers undoubtedly reduce the risk of accidental short-circuiting by tools, etc., and prevent the spreading of damage by fire or flash-over. Of recent years the armourclad

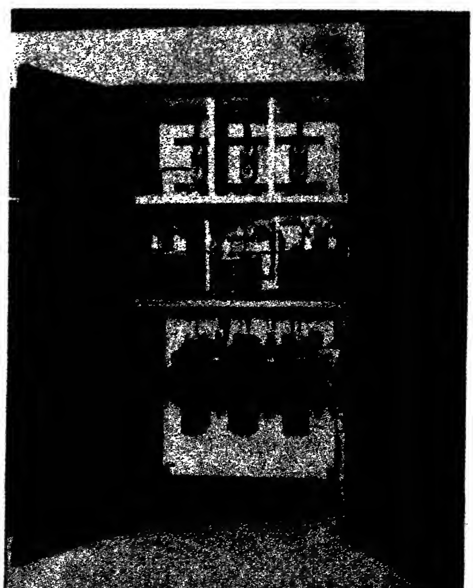
Ferguson, Pailin, Ltd.

CONTROL BOARD AND E.H.T. CELLS WITH MECHANICAL REMOTE-CONTROL.

The cells are of moulded stone having steel doors provided with reinforced glass windows. The oil-immersed circuit breakers have a rated rupturing capacity of 250 000 kVA. A separate welded-steel elliptical tank is provided for each pole and is fitted with a treated wood lining. The generator breakers are provided with a half-cock synchronising position. Remote control is effected by a special system of levers with pipe drive.

STONEWORK CUBICLE-TYPE SWITCHBOARD.

The cubicle is built up of moulded stone slabs cemented into a wrought-iron framework; the latter takes all shocks and stresses of operation. The illustration shows the oil circuit breaker with its closing contactor, the oil-immersed potential transformers with primary fuses, and the isolating switches for one set of bus bars. Similar cubicles, on the other side of the central wall, accommodate the isolators for the second set of bus bars, the current transformers, and (for ring mains) the isolators on the feeder side of the oil circuit breaker. The bus bars are in moulded stone troughs along the top of the cubicle, and the steel doors for the isolator compartments are separate from the main doors. The circuit breaker vent pipes are not in position in the illustration, and the phase barriers between the potential transformers have been removed to make way for a special transformer but the grooves for them can be seen.



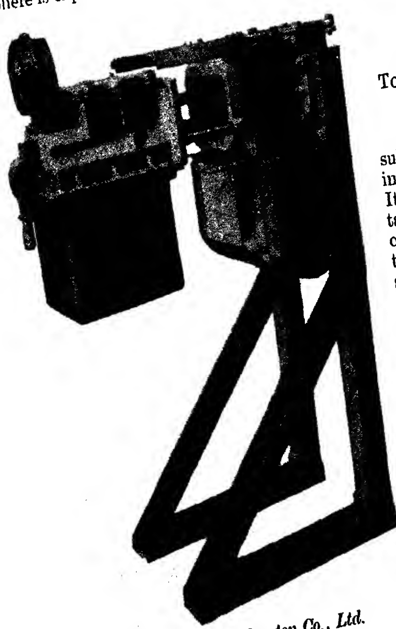
Metropolitan-Vickers Electrical Co., Ltd.

[*To face p.* **694.**

Mavor & Coulson, Ltd.

IRONCLAD SWITCHBOARD BUILT ON THE UNIT PRINCIPLE.

The board illustrated includes all the switchgear necessary for the control of two pairs of 3-wire generators and fourteen feeders (*see also* Fig. 92). It is built in four sections for easy handling and shipping. Similar assemblies, with flameproof gear throughout, are supplied for use in fiery mines or other situations where the atmosphere is explosive.



TOTALLY-ENCLOSED SWITCHGEAR OF UNIT CONSTRUCTION.

This type of switchgear is equally suitable for mining service or for industrial service indoors or outdoors. It can be mounted on wall or pedestal, and can be used with draw-out or non-drawout circuit breaker. In the draw-out pattern illustrated, the shrouded sockets render accidental contact impossible, and the safety interlocks eliminate all risk of 'open sparking.' Cable boxes or conduit fittings can be attached to the top, bottom, or back of the connection chamber (behind the socket chamber), and the bus bar chambers (below the sockets) can be bolted together to form a continuous chamber for a complete switchboard.

British Thomson-Houston Co., Ltd.

[*To face p.* 695.

compound filled type of gear has tended to supersede the cellular type for switchgear equipments in large power stations.

379. **Ironclad and Flameproof Switchboards.**—The switchboards described under this heading are particularly useful for general industrial service. They are compact and simple, and all the components are protected against mechanical injury and against accidental contact with live parts. For low and medium voltage circuits, in situations where the atmosphere is not explosive, the board may be built up from ironclad air-break switches, ironclad fuses, and ironclad instruments mounted on a supporting framework of angle irons or steel tubing. Connections between the iron-

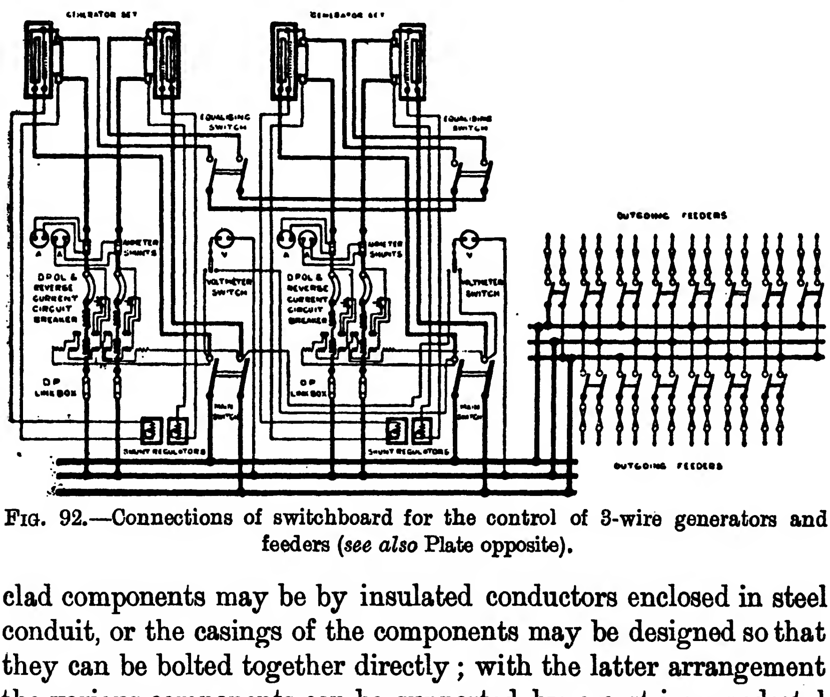


FIG. 92.—Connections of switchboard for the control of 3-wire generators and feeders (*see also* Plate opposite).

clad components may be by insulated conductors enclosed in steel conduit, or the casings of the components may be designed so that they can be bolted together directly; with the latter arrangement the various components can be supported by a cast-iron pedestal or pillar instead of a framework of tubing or rolled sections. Whichever of these arrangements be employed, the casings and the supporting structure—in fact all exposed metal—is permanently earthed.

The unit method of construction of ironclad switchboards is by no means limited to simple distributing boards. Thus Fig. 92 shows the connections of the board illustrated opposite for the control of two pairs of 400 / 200 V, 3-wire, D.C. generators, ten 400 V feeders, and four 200 V feeders. Each pair of generators is controlled by a double-pole overload and reverse-current circuit-breaker and a double-pole switch. Double-pole equalising switches are also provided for equalising the series windings of the generators. Each generator has its own moving coil ammeter, and a voltmeter with voltmeter switch is provided for each pair of generators. Four shunt regulators, one for each generator, are mounted at the bottom of the generator panels. Each of the outgoing feeder panels consists of a double-pole ironclad switch with double-pole fuse box. The 400 V feeders are connected between the two outer bus bars, and the 200 V feeders are connected between outer bar and inner, and balanced. The cable fittings for the feeder panels are all suitable for two-core, wire-armoured cable, those for the generator connections being arranged for V.I.R. cable. Each pair of generators is driven by an A.C. motor mounted between them, the switchgear for the motors being separate from the D.C. switchboard.

For mining service the switchgear must be flameproof (§ 366) and there is a tendency to employ standard 'mining-type' switchboards for other industrial services where the atmosphere may be more or less explosive or where rough usage, moisture, etc., may be expected. In such cases, and for any pressure higher than 600 V (whether the atmosphere be explosive or not), it is usual to employ oil switches.

Whether the gear be flameproof or simply 'ironclad,' and whether air-break or oil-immersed switches be used, the general arrangement is the same. The casings of the components, together with the conduit (if any) between components, form an earthed metallic enclosure for the live parts and connections. The covers are interlocked so that no live parts can be inadvertently exposed. Cables are led in through watertight glands, conduit fittings, or sealing boxes filled with insulating compound, as the case may be. In the case of assemblies representing several 'panels,' the components of each panel and the panels themselves are built together on the unit principle. The bus bars which run through the group of 'panels' are encased like the rest of the gear; they may be bare and mounted on porcelain insulators, or micarta-sheathed and carried by insulating bushings, or bare rods supported by bridge-pieces may be 'run solid' with insulating compound. Any measuring instruments required may be mounted beneath cast-iron covers with reinforced-glass windows; automatic releases are similarly protected. There is no limit to the number and variety of components which can be assembled to provide a switchboard for any desired purpose.

380. Draw-out Switchboards.—The draw-out type of switchboard originated by the firm of Reyrolle is now made in a number of patterns, the essential feature being that the whole of the switchgear is mounted on some form of carriage and is entirely isolated (*i.e.* 'dead') when the carriage is drawn out on its runway. This is accomplished by plug or knife contacts on the removable portion of the gear which engage with fixed bus bar and feeder contacts only when the carriage is in its service position, all the live parts being then inaccessible to the operator, and the various covers of the gear and the oil-switch tank being incapable of removal. If it is desired to inspect or adjust any of the live parts, or to open a cover or lower the oil tank, the switch must first be put into the 'off' position. The carriage can then be drawn out by a handle or racking gear provided for the purpose. Directly the contact plugs on the moving portion leave the fixed contact sockets (which they do before either becomes accessible to the operator) shutters fall automatically in front of the fixed contacts. When the carriage is withdrawn to the limit of its travel, all the components which it carries are completely accessible and entirely disconnected from the circuit contacts; at the same time, the circuit contacts are covered by shutters. The plug and socket contacts act as isolating switches on both sides of the gear on the carriage; they are separated automatically by the act of drawing out the carriage and, in order to ensure that these contacts are not used even inadvertently to make or break a current (§ 362), it is arranged that the carriage can be neither withdrawn nor returned unless its main switch is 'off.' The carriage runs on a machined track in order that the plug contacts may keep in alignment with their sockets.

'Armoured' draw-out switchboards resemble the mining-type boards described in § 379 as regards the mechanical nature of their 'ironclad' protection, but in the draw-out boards of this type a fixed panel contains the incoming and outgoing leads (*e.g.* bus bars and feeders) and the contact sockets of each, whilst the oil switch, automatic trip gear, ammeter, voltmeter, etc., are mounted on a carriage. The carriage runs on substantial knee-brackets fixed to each side of the back panel. As many panels as may be required can be assembled side by side on the unit principle. Armoured panels of this type are used in all sizes from those suitable for individual motors in mining service to those capable of acting as circuit-breaker panels in large central stations. As the whole of the gear is totally enclosed, and proof against weather and vermin, it can be used out of doors.

'Truck-type' or 'panel-type' draw-out switchboards resemble ordinary panel-type high-voltage boards (§ 377). The incoming and outgoing bars and cables with appropriate contact sockets are mounted at the back of the enclosure behind an earthed metal screen with automatic shutters for the apertures through which the contact plugs normally pass. The whole of the rest of the gear and the front panel itself are carried by a framework, which has rollers and runs on an accurately machined track. No gangway is needed behind the enclosure or between panels for access; the whole of the gear can be wheeled clear of the board for inspection or overhaul and a spare panel can be run into the empty cubicle to maintain service if necessary.* This type of draw-out board is lighter in construction than the armoured type described above and it is not weatherproof but it is entirely satisfactory for indoor applications, with currents up to, say, 500 A per panel at 11 000 V. The armoured gear is built with 3-phase circuit-breakers capable of carrying, say, 400 A at 44 000 V or 1500 A at 22 000 V, and of 500 000 kVA breaking capacity (§ 371); with single-phase circuit-breakers (*i.e.* three coupled circuit-breakers in separate tanks for a 3-phase circuit) much higher breaking capacities can be obtained.

381. Outdoor Switchgear.—Outdoor substations, comprising transformers and switchgear [§ 921 (2), Vol. 3], have been used for many years past and there is no doubt that this practice will extend as extra high-voltage transmission becomes more common. The obvious advantage is the great saving on cost of buildings, simple concrete foundations and light structural steel-work supports being used instead of a masonry structure and its heavier foundations. The obvious difficulty is the exposure to weather. As stated in § 380 armoured draw-out switchgear is completely weatherproof and ordinary high-voltage circuit-breakers are quite reliable for outdoor service if fitted with suitable terminal bushings and if the closing and trip gear be protected by a weather-proof casing. Similar remarks apply to high-voltage static transformers. The switchgear and transformers are, in fact, at least as reliable as the transmission lines so far as atmospheric conditions are concerned; if severe cold is experienced the oil can be kept at any desired temperature by aid of thermostats and electric heating coils.

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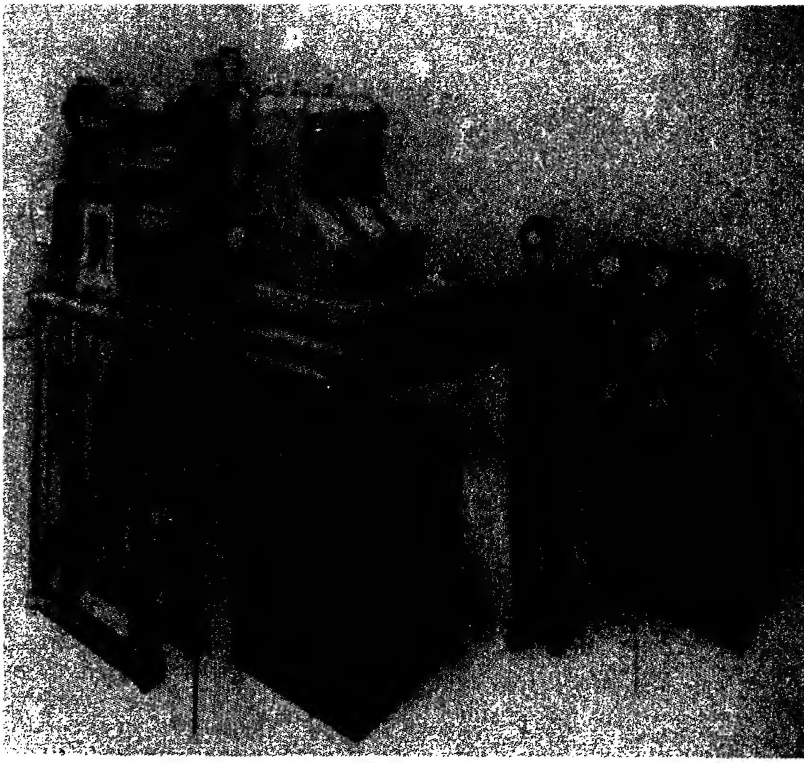
* This advantage, which is enjoyed also by 'armoured' draw-out gear, is attained only in draw-out boards and is of great practical importance.

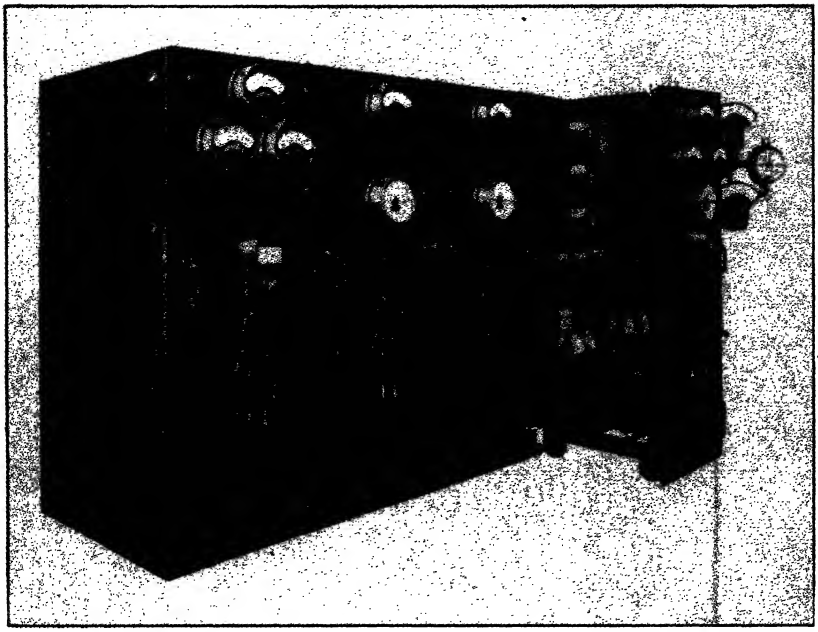


A. Reyrolle & Co., Ltd.

ARMOURED DRAW-OUT SWITCH FOR 12 000 V, 3-PHASE, 750 A.

This switch is suitable for controlling generating plant in a station having an aggregate capacity of 50 000 kW. The equipment comprises two sets of 3-phase bus bars, a 3-phase oil-break switch, three current transformers, 3-phase potential transformers (mounted on a carriage behind the switch), and cable dividing boxes. Every conductor is 'ironclad;' and the bus bars, current transformers, etc., are immersed in insulating compound. When the switch carriage is withdrawn (as shown) for access to the working parts, the live portions are screened by shutters which fall across the socket openings. (Note the yard rule against the standard in the foreground.)

[*To face p.* 698.



Johnson & Phillips, Ltd.

DRAW-OUT TRUCK TYPE SWITCHBOARD.

The stationary portion of each cubicle is bolted to the floor and contains the bus bars, fixed contacts, cable box, or cable sealing end. The truck carries the oil switch, current, and potential transformers, and the instruments which are mounted on the front plate. When the truck is withdrawn for inspection all the parts upon it are automatically rendered 'dead' and, at the same time, the fixed contacts, which remain 'live,' are automatically screened.

[*To face p.* 699.

The large air gaps between lines and the long terminal bushings required at extra high pressures, together with the large dimensions of e.h.t. switchgear and transformers, combine to make masonry switch houses large and costly. With outdoor gear the clearances must be increased to allow for swinging of conductors and the possibility of birds perching on or flying between live parts. At pressures below 25 000 V outdoor switchgear is probably more costly than indoor gear (including the structural work in both cases), but at 50 000 V there is a saving of 25-30 °/₀ in the total cost of an outdoor equipment,* and the saving is still greater at higher pressures.

382. General Arrangement and Construction of Switchboards.—Much information on this subject is embodied in the preceding paragraphs, to which the following references and summaries may be added.

The I.E.E. Wiring Regulations contain clauses dealing with the position, construction, and arrangement of switch and distribution boards.

Some of the factors to which attention is called in connection with mines (§ 822, Vol. 3) are of general application; and the following points, from a Memorandum (1916) of the British Home Office, may also be noted:—

It is undesirable that main fuses should be placed behind the panels of low or medium pressure switchboards. The blowing of a fuse, particularly under heavy short-circuit conditions, on a station switchboard, might readily lead to a further short circuit. If fuses for instruments, etc., are placed behind switchboards they should be guarded so that an arc cannot spread, and placed so as to be accessible. In the case of large switchboards there should be access to the back from both ends, to obviate an attendant being trapped in case of accident. For screening off high-tension boards expanded metal is recommended. On polyphase boards there should be divisions or barriers between phases at all places where an arc is liable to be accidentally started, *e.g.* at isolating switches, etc. On high-pressure boards, isolating switches should be placed on both sides of oil-switches on feeder circuits where the feeders are capable of being made live from the distant end.

Other points, many of which are embodied in the preceding paragraphs of this chapter, are as follows:—

Separate panels for each machine, transformer, feeder, etc., make for safety and simplicity in operation and maintenance. In many existing stations the high-voltage and low-voltage panels are on different floors. It is generally most convenient to place the main oil switches and transformers on the ground floor or in

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* According to an article by J. B. Rudkin, *El. Rev.*, Vol. 90, p. 567, describing outdoor switchgear at Goesgen (Switzerland) for 135 000 V.

the basement; with remote electrical control the control gear can be placed where-ever convenient; remote mechanical control is less flexible in this respect. Remote electrical control, placing all the main switches of the station under the direction of one man, is almost standard practice in large new stations; where there are inter-connected stations a 'load dispatcher' may control the men on the master switchboards of the individual stations by telephone.

On boards for direct manual operation fuses should be enclosed and away from face level. Air-break circuit-breakers and lightning arresters should always have a clear path upwards for arcing. Instruments should always be where they can be read easily and without parallax from the operator's station; also, they should be away from rheostats or other sources of heat. On control desks for remote electrical control ammeters, voltmeters, and synchroscopes should be in full view at the back of the desk; switch levers or buttons, rheostats, and synchronising plugs should be easily accessible; relays, integrating watt-hour meters, and other equipment to which only occasional reference is required may be at the bottom of the panel.

All main current-carrying conductors should have good facilities for cooling and be free to expand and contract without serious restraint. Iron should not be placed where it would be subject to stray fields. All parts in which eddy currents may be induced should be non-magnetic and of high electrical resistance (natural or produced by saw cuts or other device).

Conductors, fuses, contacts, and other current-carrying parts should be inaccessible whilst they are 'live,' and all exposed metal work should be earthed. Provision should be made to prevent unauthorised operation of switchgear or access to live parts, and means should be provided for the definite locking of switches 'off' in case of need. Interlocking to ensure correct sequence of switching and to prevent access to live parts should be employed wherever practicable. The general design and arrangement of switchgear should facilitate cleaning and supervision, and it should be possible to get complete and easy access to all parts for repair (subject to the parts being first rendered 'dead').

383. Bus Bars and Switchboard Connections.—In all but small installations the bus bars are in duplicate and provision is made for sectionalising them. The bar for each pole or phase may be (electrically) in the form of a closed loop or 'ring main' with isolating switches at intervals so that any desired section can be isolated for cleaning or repair. Alternatively two sets of bars may be used with isolating switches in each and with cross-connecting switches, so that any desired section of one set of bars can be isolated and replaced by a section of the other set. The insertion of reactance coils between the sections of bus bars fed by different generators limits the power flowing to a short circuit (§§ 340, 370).

Bus bars generally consist of a number of relatively thin strips of copper or aluminium. The width of the strips may be, say, 8-12 times their thickness, and the strips are mounted on porcelain or other insulators with their width in a vertical plane, thus securing maximum stiffness against deflection by their own weight.

The strips composing each bar are electrically in parallel, but should be held definitely apart by spacing pieces. The object of the laminated construction is to reduce eddy currents and increase the radiating surface.* Extra strips can be added at any time if the carrying capacity of the bars has to be increased. The strips for each bar are side by side in a horizontal plane, but the bars themselves may be in either a vertical or a horizontal plane. Placing the bars in a horizontal plane reduces the overall height of the board, but it must be possible to get at the bars from above for cleaning. Bars in a vertical plane are more easily accessible as a rule, and their maximum stiffness is then opposed to the mechanical forces developed between the bars on short circuit.

Aluminium offers important advantages as a material for bus bars. The larger cross-section required for the same electrical conductivity makes aluminium compare unfavourably with copper where insulated cables are concerned, but in the case of bus bars the difference in dimensions between copper and aluminium is of no appreciable importance as regards the cost of the insulating supports. On the other hand, the larger radiating surface of the aluminium bars, and the fact that their weight is roughly half that of the equivalent copper bars, are important advantages. Adhering to commercial sizes of bar or rod it will be found that aluminium bars of the same width, but 50 °/$_o$ thicker than the copper bars which would be used, or aluminium rod $1\frac{1}{4}$ times the diameter of copper rod, gives sufficiently nearly equal conductivity. The exact value of the resistance of bus bars is unimportant, since it is always very low. On the other hand, care is required to avoid high local resistance at joints.

The best method of connecting consecutive lengths of aluminium bar is by overlapping the bars for a distance equal to 10 or 12 times their thickness and bolting them together. The contact surfaces should be coated with vaseline and then rough filed, the file cuts being at right angles on the two surfaces; the surfaces are then clamped together *without removing the dirty*

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* It is the radiating surface which determines the permissible current density for given temperature rise. A 2-in. × 1-in. copper bar carrying 2 000 A has 0·036 sq. in. of radiating surface per ft. run per amp., compared with 0·018 sq. in. in the case of a 4-in. × 2-in. bar carrying 8 000 A. If the larger bar be divided into eight strips each 4 ins. × $\frac{1}{4}$ in., spaced well apart, the radiating surface is increased to 0·102 sq. in. per ft. run per amp.

*vaseline.** Joints made in the same way between copper bars have as low resistance as soldered joints. Permanent connections between copper or brass parts are often tinned and 'sweated,' but any sweated joint should be supplemented by a grub screw, bolt, or other mechanical device. The advantage of tinning the surfaces of copper joints which are to be clamped lies in the fact that the soft tin spreads and gives contact over a greater area; also, the flow of the metal during the final stages of clamping exposes clean surfaces at the contact. The use of tinfoil in clamped joints does not reduce, but generally increases, the contact resistance.

Aluminium bus bars are practically immune from corrosion (even in battery rooms), but joints between aluminium and other metals should be painted to exclude moisture; otherwise electrolytic corrosion will occur. Similarly, where aluminium rests upon plain slate, or other material capable of carrying a leakage current when damp, the aluminium should be painted or a piece of mica should be placed between the surfaces.

Most of the high voltage connections on modern switchboards consist of bare copper strip or rod, thus reducing the amount of inflammable material in the construction. Rod can be bent equally easily in any plane, but rectangular strip is difficult to bend in the plane of its width. All connections must be so supported that they cannot be deformed to any dangerous degree under short-circuit conditions (§ 338); at the same time, bus bars and all strip or rod connections must have lateral freedom or sufficient flexibility at bends to allow for thermal expansion and contraction. Varnished cambric offers advantages as an insulating material for switchboard cables (§ 287).

Low voltage connections in instrument and relay circuits, etc., are commonly made by V.I.R. wires (preferably with fire-resisting braiding), supported on porcelain cleats. It is convenient to have the circuits arranged so that standard instruments can be connected quickly for calibration tests.

384. Instrument Transformers.—The function and general characteristics of current and potential transformers are discussed

* Any attempt to remove the dirty vaseline exposes the clean filed metal to oxidation; the whole object of the method of preparation described is to protect the clean metal from even momentary exposure to the air. Joints made as described do not deteriorate during a period of years (*vide El. Times*, July 27, 1911, p. 77; and *Jour. I.E.E.*, Vol. 60, p. 889).

in § 108 (*see also* B.S. Specification No. 81, 1936). Ring-type current transformers threaded on the terminal leads inside the oil-switch casing are convenient for the operation of ammeters, overload trips, or other devices unaffected by phase error in the transformer (*see* § 108), but they should not be used for any device operating on the wattmeter principle or demanding special accuracy and uniformity of calibration. In transformers provided with a primary winding the carrying capacity of the latter should be equal to that of the main in which the transformer is connected.

It is important that the resistance in the secondary circuit of current transformers should be as low as possible; an ammeter and a trip coil can be operated in series in this circuit if the trip gear is sensitive (*i.e.* does not require much power for its operation), but the current element of any wattmeter type device should not be in series with a trip coil because the phase error caused by the latter would lead to serious inaccuracy. The same current transformer can generally be used to serve an ammeter, wattmeter, and core-balance protective gear, but the maker's advice should always be taken in regard to the loading of instrument transformers. In mining or armoured switchgear (§§ 379, 380) the use of current transformers can often be avoided by mounting the ammeter inside the switch case and connecting it in the h.t. circuit (with its case at line potential); suitable clearance is provided between the instrument and the earthed case of the switch, and the instrument is read through a window.

Voltage transformers for pressures up to 6 600 V are generally air-cooled, those for higher pressures being oil-immersed or enclosed in a casing filled with insulating wax or compound; cases filled with wax or compound should be mounted so that the filling cannot escape if it softens or melts in service. Any number of instruments, etc., can be connected in parallel to one potential transformer provided that the rated burden of the latter is not exceeded (§ 108). Voltmeters, low-voltage releases, and synchroscopes in a 3-phase system can be used in conjunction with a voltage transformer on one phase only, but voltage transformers are required on at least two phases for wattmeters and reverse-power relays (§ 110).

Instrument transformers for use in automatic selective protection systems have generally to fulfil special conditions in regard to their characteristics (§ 359).

385. Equipment of Typical Switchboards.—The functions and conditions of service of switchboards differ so widely that no useful purpose would here be served by detailed description of individual boards; for this the reader must be referred to the technical press and the proceedings of professional institutions. The following notes on the usual equipment of various types of panels (according to whether the supply is A.C. or D.C.) may, however, be useful:—

Generator Panel.—The generator leads are connected (through isolating switches if required) to circuit-breakers whence connection is made (through isolating switches in the case of high-voltage machines) to the bus bars of the station. Voltmeter, frequency meter, and synchroscope connections are always made on the generator side of the main switch or circuit-breaker, and generally the ammeter (or ammeters in the case of a polyphase machine) is also connected on the generator side of the main switch.* It is desirable that watt-hour meters be provided on each generator panel. A field-regulating rheostat and ammeter are required, in addition to a field switch with auxiliary contacts which close a shunt circuit for the safe discharge of the energy stored in the field. Over-load and reverse-power or other protective relays are required, and a power factor indicator is desirable. Synchroscopes may be placed on a bracket projecting from one end of a switchboard or machine and bus bar voltmeters together with the synchronising gear may be located on a special synchronising panel.

Balancer Panel.—There are many systems of balancing 3-wire D.C. systems, each of which requires appropriate switchgear. With the simplest balancing equipment (two auxiliary machines in series between the 'outers') the equipment required on the control panel is three single-pole switches, two starters, two field rheostats, and an ammeter in each machine circuit.

Summation Panel.—This panel (for measurements only) has a watt-hour meter recording the total output of a number of generators, and possibly a frequency meter and a power factor indicator.

Control Panel.—The equipment comprises master switches and pilot lamps in the low-voltage D.C. circuits of the coils or servo-motors operating remote-controlled switchgear; also, the measuring instruments of the main circuits thus controlled, these instruments being served by instrument transformers on the main panels.

Battery Panel.—There are many possible arrangements of storage batteries and their auxiliaries to suit various applications and different methods of allowing for the change in voltage per cell during charge and discharge (§ 432, Vol. 2).

Where end-cells are used for regulation the battery panel carries a double regulating switch so that the number of cells across the bus bars and across the generator can be varied independently. There are also an ammeter and double-pole fuses between the battery and the bus bars. The same or an adjoining panel carries the generator switch (with minimum cut-out) fuses, ammeter, field regulator, and a change-over switch by means of which the generator can be connected to the

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* It is usual to connect all the instruments, on the generator panel, on the generator side of the main circuit-breaker. This ensures that all the instruments are dead when the breaker is open and the generator is stationary. Instrument transformers are always placed on the generator side of the circuit-breaker.

battery or to the bus bars as desired. By means of a 3-way switch a single voltmeter can be used to measure the generator, bus bar, and battery voltages.

If a reversible booster set be used to add to the voltage of the main generator during charging, or to that of the battery during discharging, no 'end cells' are needed for regulation. The battery circuit includes an ammeter and fuses, and a double-pole change-over switch by means of which the cells can be connected straight to the bus bars or in series with the booster. The motor driving the booster requires an ammeter, double-pole switch, fuse and starter; whilst the booster requires a field reversing and regulating switch and a circuit breaker which opens if the fuse blows in the booster-motor circuit. Two voltmeters with multi-way switches provide for measuring the generator, bus bar, booster, and battery voltages.

Station Panel.—The equipment on this panel provides for the control of the station lighting and auxiliary power circuits. Change-over switches are required if (as is desirable) there are alternative sources of supply. Main switches, starters, rheostats, measuring instruments, etc., are provided for the individual circuits supplied, according to requirements. (See also *Distribution and Motor Panels.*)

Feeder Panel.—On station feeder panels connections are taken from the bus bars through an air-break or oil-immersed circuit breaker to the outgoing cable. A voltmeter on the bus bar side of the circuit breaker shows the bus bar voltage, and an ammeter between the circuit breaker and the feeder shows the load on the latter. If desired an integrating watt-hour meter may be fitted to measure the energy supplied; a recording ammeter or wattmeter is sometimes useful. Overload and split conductor or other protective relays (§ 359) are required on each feeder panel. One frequency meter may serve a number of feeder panels.

Distribution Panel.—The incoming mains are connected through a switch or circuit breaker, as the conditions may demand, to the distribution bus bars. To the latter the load circuits are connected through knife switches or oil switches with fuses in either case, or through circuit breakers if required. Small distribution boards as used for house-lighting circuits are described in §§ 511, 517, 521, Vol. 2. The consumer's panel in an industrial installation taking energy at high voltage requires an oil-immersed circuit breaker with isolating switches on the line side, and instrument transformers if the energy be metered on the line side of the step-down transformer. The low-voltage terminals of the main transformer are connected to a distribution panel which has a voltmeter and main ammeter and, if desired, ammeters and energy meters for the individual circuits supplied from the distribution bus bars. Where the supply tariff takes account of power factor, it is advisable to provide a power factor indicator or recorder for the installation as a whole or, if practicable, for each of the main circuits.

Motor Panel.—The incoming mains are taken to a main switch (double- or three-pole) of the type appropriate to the electrical and service conditions. Thence leads are connected through fuses to the starter (Chapter 29). The provision of an ammeter on each motor panel contributes greatly to safety in operation and efficiency in maintenance. It is useful to arrange for the easy connection of a recording wattmeter in the motor circuit at any time for the purpose of a power test.

General.—Isolating switches should be provided on all high-voltage panels so that the whole of the gear can be disconnected from the incoming and outgoing leads; with draw-out gear no special isolating switches are required. Instrument transformers are generally required on heavy current and / or high-voltage A.C. panels (§§ 108, 384).

Where automatic protective gear is used the appropriate transformers, relays, etc., are mounted on the switchboard (§ 359). If fuses are used they are inserted in each pole or phase of the circuit, but overload relays need be connected only in one side of each possible lead and return path, *i.e.* one relay for a D.C. or single-phase 2-wire circuit; two relays for a D.C. 3-wire, two-phase 4-wire, or three-phase 3-wire circuit; and three relays for a three-phase 4-wire circuit. Where reverse power relays are used they should be fitted to each generator and to each one of a group of feeders working in parallel.

Voltmeters and ammeters should be used in each phase of a polyphase system if the load may be unbalanced. Recording instruments are provided wherever a permanent, continuous record is required. Where attention is paid to power factor correction, power factor indicators should be fitted on generator, converter, and feeder panels. Air- or oil-temperature indicators, water- or oil-flow indicators, and other special devices may be mounted on the appropriate main panel, or on the control panel if remote control is practised. Remote electrical control can be provided on any panel. Lightning arresters are desirable on any panel which is connected to overhead lines.

386. Bibliography (*see* explanatory note, § 58).

REGULATIONS.

H.O. Electricity Regulations for Factories and Workshops.

H.O. Regulations as to the Installation and Use of Electricity in Mines.

I.E.E. Wiring Rules.

STANDARDISATION REPORTS, ETC.

(1) *I.E.C. Publications.*

No. 47. I.E.C. Definitions and Rules for Switchgear (Preliminary).

(2) *B.S. Specifications.*

No. 81. Instrument Transformers.

No. 109. Air-Break Knife Switches and Laminated Brush Switches for Voltages not Exceeding 660 V.

No. 110. Air-Break Circuit Breakers for Voltages not Exceeding 660 V.

No. 116. Oil-Immersed Switches and Circuit Breakers for Alternating Current Circuits.

No. 124. Totally Enclosed Air-Break Switches for Voltages not Exceeding 660 V.

No. 126. Flameproof Air-Break Switches with or without Fuses for A.C. and D.C. Voltages not Exceeding 660 V.

No. 127. Flameproof Air-Break Circuit Breakers for A.C. and D.C. Voltages not Exceeding 660 V.

No. 130. Totally Enclosed Air-Break Circuit Breakers for Voltages not Exceeding 660 V.

No. 158. Standard Marking and Arrangement for Switchgear, Bus Bars, Main Connections and Auxiliary Wiring.

No. 159. Bus-Bars and Connections constructed of Bare Copper or Aluminium.

No. 160. Slate and Marble Insulating Slabs for Electric Power Switchgear up to and including 660 V. A.C and D.C.

No. 162. Electric Power Switchboards for Indoor Installations up to and including, 33 000 V.

No. 194. Switchgear Equipment for D.C. Circuits when the Voltage does not exceed 660 V.

No. 195. Switchgear Equipment for 3-ph. A.C. Circuits when the Voltage does not exceed 33 000 V.

No. 214. Distribution Boards.

No. 229. Flame-proof Enclosures for Electrical Apparatus and Tests for Flameproof Enclosures.

No. 268. Switchgear Cells and Cubicles constructed of Concrete or Moulded Stone.

No. 764. Automatic Change-Over Switches and Contactors for Emergency Lighting Systems.

(*See also* B.S. Specifications on Motor Starters and Controllers, Chapter 29, Bibliography).

(3) B.E.A.M.A. Standardisation Rules for Electrical Machinery.

BOOKS.

Electric Switch and Controlling Gear. C. C. Garrard (Benn Bros.).

High-Tension Switchgear. H. E. Poole (Pitman).

High-Tension Switchboards. H. E. Poole (Pitman).

Switchgear Practice. H. E. Poole (Chapman & Hall).

Switchgear Stages. H. W. Clothier (Laybourne).

I.E.E. PAPERS.

Switchgear Standardisation. C. C. Garrard. Vol. 56, p. 213.

A General Survey of the High-Tension Switchgear Field. S. Ferguson. Vol. 64, p. 49.

The Breaking Performance of High-Power Switchgear; and a New Form of Quenched Arc Switch. L. C. Grant. Vol. 68, p. 1089.

The Distribution of Energy Liberated in an Oil Circuit-Breaker. (B.E.R.A.) Vol. 69, p. 557.

Metal-Clad Switchgear, Automatic Protection, and Remote Control, with particular reference to Developments during the Last Seven Years. H. W. Clothier. Vol. 71, p. 285.

Some Notes on Oil Circuit-Breaker Design and Performance. H. Pearce and T. T. Evans. Vol. 71, p. 703.

Modern Practice in Germany and the European Continent with regard to Supervisory Control Systems as applied to Large Interconnected Supply Areas. M. Schleicher. Vol. 75, p. 710.

Some Notes on Rates of Rise of Restriking Voltage Subsequent to Interruption of Alternating-Current Power Circuits. C. H. Flurscheim. Vol. 76, p. 323.

Remote Control of Power Networks. G. A. Burns and T. R. Rayner. Vol. 79, p. 95.

The Development of the Single-Break Oil Circuit-Breaker for Metal-clad Switchgear. D. R. Davies and C. H. Flurscheim. Vol. 79, p. 129.

Restriking Voltage, and its Import in Circuit-Breaker Operation. H. Trencham and K. J. R. Wilkinson. Vol. 80, p. 460.

Apparatus used for High-Power Switchgear Testing. J. S. Cliff. Vol. 80, p. 593.

Control Rooms and Control Equipment of the Grid System. J. D. Peattie. Vol. 81, p. 607.

Safeguards against Interruption of Supply. H. W. Clothier, B. H. Leeson and H. Leyburn. Vol. 82, p. 445.

Note.—Much information on switches and switchgear is contained in papers which deal primarily with other subjects.

MISCELLANEOUS.

Important articles appear frequently in the technical press. *See also* the Bibliographies of Chapter 15 (§ 360) and Chapter 29 (Vol. 2).

ELECTRICAL ENGINEERING PRACTICE

CONTENTS OF VOLUME II.

PART IV.

TRANSFORMATION, CONVERSION, AND STORAGE.

CHAP.
17 THE TRANSFORMATION OF ENERGY.
18 SECONDARY CELLS.

PART V.

DISTRIBUTION AND CONTROL IN BRANCH CIRCUITS.

19 ELECTRIC CIRCUITS AND CONNECTIONS.
20 SYSTEMS OF SUPPLY.
21 BRANCH SWITCHES, SWITCHING, AND ACCESSORIES.
22 CONTROL AND WIRING OF BRANCH CIRCUITS.
23 WIRING SYSTEMS.
24 THE COST OF AN ELECTRIC INSTALLATION.

PART VI.

APPLICATIONS OF ELECTRICAL ENERGY.

25 ELECTRIC LIGHTING.
26 HEATING.
27 CUTTING AND WELDING.

CONTENTS OF VOLUME III.

PART VI (*continued*).

28 ELECTRIC MOTORS.
29 MOTOR CONTROL.
30 ELECTRIC DRIVING.
31 ELECTRIC HOISTING.
32 ELECTRICITY IN MINING.
33 ELECTRICITY IN AGRICULTURE.
34, 35 TRACTION.
36 ELECTRIC ROAD VEHICLES.
37 ELECTRIC PROPULSION OF SHIPS.
38 INDUSTRIAL PROCESSES; CHEMICAL AND METALLURGICAL.

PART VII.

SPECIFICATIONS: TESTING: RULES AND REGULATIONS.

39 SPECIFICATIONS, DEPRECIATION AND MAINTENANCE.
40 TESTING.
41 RULES AND REGULATIONS, ETC.

COMBINED INDEX TO VOLUMES I, II AND III.

Entries relating to the present Volume I are in roman type; those to Volumes II and III in *italic*, some of them referring to the fifth edition of Volume II.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669-1060.

ABBREVIATIONS and symbols, 6.
Abrasives, production of, 981.
wheels, high-speed, 775.
Absolute temperature, 166, *591A.*
units, 2.
Absorption of heat, 619.
ratio, light, 580.
ACCELERATION—
automatic, 741.
energy demand for, 883.
in lifts, 794.
— traction, 879.
negative, 899.
— in lifts, 796.
on local lines, 865.
power required for, 882.
station output due to, 883.
Accelerator for heating, 627.
Accessories, fittings, etc., Vol. II, Chaps. 21-3.
for conduit wiring, 542.
on ships, 678, 964.
Accidents in mines, 812.
from failure to earth metal, 533.
Accumulators (Chap. 18), see "Secondary cells."
as phase advancer, 160.
steam, 177.
Accuracy of instruments, 92 *et seq.*
in time measurement, 428B.
Acetylene, 973.
Acheson process for abrasives, etc., 981, 982.
Acid loss in batteries, 432.
Acid-proof paints, 76.
Acre-foot, 202.
Activated aluminium, 647A.
carbon, 647A.
Active component, 12A.
"Active recovery voltage" defined, 371.
— voltage-factor" defined, 371.
Acyclic generator, 134, 137.
Aczol, 68.
Adapters, 496.
cost, 571.
Addition of loads of various P.F., 157.
Adhesion; adhesive force, 871, 890.
Adhesive tape, 74.
cost (Table 74), 571.
Administration of the Electricity Acts, 1046.
Adsorbers in dehumidification, 647A.
Advance alloy, 67 (Table 6).
for thermopile, 646A.
Advantages of electricity in agriculture, 844.
mining, 812.
ship propulsion, 957.
A.E.G. rectifier, 423.
Aerial lines, Chap. 14, Vol. 1.
specification for, 1007 (see "*Overhead lines*").
"Aerodynamo" wind set, 165.
Ageing, *electrical, 634.*
magnets, 83.
ovens, 642.
"Agrico" wind set, 165.
AGRICULTURE, ELECTRICITY IN (Chap. 33)—
advantages of, 844.
bee-keeping, 856.
cost of cables and overhead lines for, 846.
credits and finance in, 859.
dairy work, 855.
distribution for, 847.
drainage, 853.
Electricity Commissioners' Memorandum on, 846.
electro-culture, 857.
energy and power data, 845 et seq., *858.*
ensilage, 852.
farms and farm buildings, 847.
fodder treatment, 852.
haulage, 854.
industrial power for, 849.
irrigation, 853.
lighting and domestic power, 848.
overhead lines for, 846.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

AGRICULTURE, ELECTRICITY IN (*cont.*)—
plant for, 845.
ploughing, 851.
poles for rural lines, 846.
poultry farming, 856.
power, domestic in, 848.
— *and energy data, 845* et seq., *858.*
— *required by machines, 850.*
— *supply for, 845.*
pumping, 853.
ring mains for, 846.
rural lines for, 845 et seq. (*see* "Rural lines").
shafting v. *portable motors, 850.*
statistics, 844.
transformer and consumer data, rural lines 845 (Table 179).
transmission by rural lines, 846.
AIR—
and oil immersion, 400.
-blast cooling, 400.
— *motors, 670.*
— switches, 372-4.
— *transformer, 400.*
-break switches, 364 *et seq.*
— — — B.S.S. for, 365.
capacity for taking up heat, 647A.
clearing by precipitation, 996.
compressors, 766 (Tables 144-7).
conditioning, 615, 616, 647A.
-cooled generators, 146.
— *jacketing of walls, 647A.*
— *mercury vapour lamp, 589.*
core high-frequency furnace, 647.
data for fans, 764, 765.
dielectric, 73 (Table 7), 78, 79, 287.
filtering methods, 647A.
-gaps, 43, 45.
— *in magnetic clutches, 808.*
— in solenoid, 355.
gas (producer), 178.
heating by compression, 176.
— by chemical process, 176.
— *electrically, constants, 619.*
-ports, lighting, 613.
-pump, condenser, 175.
resistance in traction, 879.
supply to generators, 356.
temperature and cables, 291.
— *in tests, 1024.*
— *standard in rating transformers, 402.*
Ajax-Northrup furnace, 639, 978.
Ajax-Wyatt furnace, 639, 647.
Albedo, 600.
Albertol, 74.
Alcohol fuel, 178, 179.
engine, 180.
Alkali, electrolytic, 635, 984.
production, 984.
Alkaline cells, 434 (see "*Secondary batteries*").
Alklum cells, 434.
All-electric house, 576.
"*All-electric*" *remote control, 741.*
Allis engine, 172.
All or part switching, 501, 576, 628.
Alloy steel furnaces, 646, 979.
Alloys, resistance of, 67 (Table 6).
for superheater tubes, 170.
"*All-storage*" *cooker, 628.*
"*All-watt*" *induction motor, 688.*
Almelec, 63.
ALTERNATING CURRENT GENERALLY (*see also sub-headings below,* "Single-phase," "Three-phase")—
and continuous, 10, 294.
— — *distribution, 475-8.*
— — — *in welding, 656.*
arc lamps, 591, 592.
boosters, 142.
— *synchronous, 411.*
converters, 409 et seq.
elementary, 10 *et seq.*
frequencies, coupling different, 388.
— *harmonics and transients, 394, 407.*
high frequency, 144.
locomotives, 919.
motor-generators, 388.
motors (see "*Motors (A.C.)*").
potentiometer, 95 (2).
railway construction, 919.
rectified, 13.
rectifying, 415 et seq.
regenerative braking, 900.
return circuit, 905.
supply meters, 113 *et seq.*
transmission, 294 *et seq.* (*see* "Transmission").
wattmeters, 110
Single-phase—
— *and 3-phase compared, 476.*
— — *transformers, 394, 399.*
— elementary, 11.
— transmission, 297-300, 304, 305.
Two-phase, 16.
Three-phase—
alternators, 134, 141, 143.
auto-transformer, 396.
cables, 311.
elementary, 15.
kVA, 110A.
kVAR (reactive KVA), 110A, 116A, 117.
lines, 306, 313.
power, 110.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

ALTERNATING CURRENT GENERALLY (*cont.*)—
Three-phase (cont.)—
power factor meters, 110A.
sequence, 150.
supply, 463-7.
to 1-phase or 2-phase transformer, 394.
traction motors (see "*Motors, traction*").
transformers and converters, 387, 391, et seq.
— transients in, 394, 407.
transmission, 294 et seq. *Chap. 11.*
v. *D.C. in mines, 814.*
— — for ship propulsion, 958.
— — — traction, 867, 868.
voltmeter, 100.
wattmeters, 110.
ALTERNATORS—
asynchronous, 144.
back-to-back test of, 1021.
delta and star connections, 143.
drying by embedded heaters, 963.
elementary, 132, 133.
excitation of, 140.
hydraulic drive, 254.
impedance, 137.
parallel running, 149, 150.
power to drive, 164.
pressure regulation, 147.
rating, 136.
reactance, 147.
short-circuit tests of, 1020.
specification of, 1001.
speed of driving, 145, 254.
star and delta connection, 143.
synchronising, 149, 321.
synchronous, 143.
testing (*Chap. 40*), *1017-26.*
turbine driven, 145, 146.
voltage regulation, 147.
water-wheel driven, 254.
Altitude and temperature of transformers, 402.
effect on power, 179.
transformer rating, B.S.I., 402.
ALUMINIUM—
activated, 647A.
alloy conductor material, 63.
and thermal storage, 627.
arresters, 346.
bromide cycle, 166.
bronze, 67 (Table 6).
bus-bars, 383.
by electrolysis, 635, 975.
cables, 290.
conductors, 324, 331.
constants, 63, 66, 308.
energy for melting, 647 (*Table 101*).
hydrate in Drumm battery, 873.
ALUMINIUM (*cont.*)—
in quasi-arc welding, 653.
overhead wires, 328.
production, 975.
properties, 63, 66, 308, *645* (*Table 98*).
rectifier, 417.
reflecting surfaces, 599, 646A.
regulations as to, 324.
shaft cables, 819.
steel-cored cables, 917.
Aluminium-bronze, 67 (Table 6).
Alundum and aloxite, 85, *981.*
cement, 636.
Ambient temperature in tests, 1023-5.
— — standard, in oil switches, etc., 369.
American battleships compared, 961.
frequencies, 135.
plants and modern practice, 191, 196.
terms for motors, 670.
Ammeters, 97, 100, 135, 385.
Ammonia as refrigerant, 647A.
production, 973.
— in refrigeration (*q.v.*), *773.*
Ammonium sulphate, 169, *973.*
Amorphous carbon, 66.
electrodes, 641.
Amortisseur windings, 679.
AMPERE (*see also* "Current")—
balance, 101.
definition, 2, 3.
effective or virtual (R.M.S.), 29.
elementary, 25
-hours, 28 (*see below*).
— meters, 97, 113, 114.
international, 2, 3.
maximum, A.C., 31.
meters (*see* "Ammeters").
-second, 2, 28.
-turns, 42.
— on instruments, 98.
— — magnet, 81.
virtual (R.M.S.), 29.
Ampere-hour capacity of traction cells, 940 (see also "*Secondary batteries*").
efficiency of cells, 431, 432, 434.
Ampere's rule, 33.
Amplifying, 418A, 420, 421.
Amplitude of curve, 56.
Analysis of coal, 168.
— — working costs, 194, 269.
Andhra Valley plant, 242.
Angle insulators, 330.
stays, 326.
Angold arc lamps, 594.
Ångstrom unit, 589, 591A.
Anion and cation, 970.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Annealed and hard-drawn copper, 295.
Annealing, electrical, 646.
Annual flow off catchment, 204.
Annuities for loan repayment, 1014.
Anode and cathode, 127, *970.*
Anthraquinone, 986.
Antimony, 66, 127, 346, *991.*
Aperiodic instrument, 90.
A-posts, 323.
Apparatus, protection of, Chap. 15.
Apparent power, 56, 110, 153.
  resistance, 44 (*see* "Impedance").
Applications of arc welding, 649.
APPLICATIONS OF ELECTRICITY (see also *Vol. II, Chaps. 25 to 27*)—
  in agriculture (*Chap. 33*), see "*Agriculture.*"
  — *arc welding, 649.*
  — *cutting and welding* (*Chap. 27*).
  — *driving* (*Chap. 30*), *747* (*2*).
  — *heating* (*Chap. 26*).
  — *hoisting* (*Chap. 31*).
  — *industrial processes* (*Chap. 38*), see "*Processes.*"
  — *lighting* (*Chap. 25*).
  — *mining* (*Chap. 32*), *823* et seq., see also "*Mining.*"
  — *road vehicles* (*Chap. 36*), see also "*Road vehicles.*"
  — *ship propulsion* (*Chap. 37*), see "*Ship propulsion.*"
  — *traction* (*Chaps. 34, 35*), see "*Electric traction*"; "*Railways*"; "*Road vehicles*"; "*Tramways.*"
Approval of systems of supply, 1047.
ARC—
  cutting, 656-9.
  -duration defined, 371.
  extinction by gas, in circuit-breakers, 368A.
  furnaces, 640, 971.
  -incandescent "pointolite," 597.
  industrial processes, 635.
  lamps and frequency, 135.
  — — *gas compared, 609.*
  — *efficiency, 583, 594, 595.*
  — *enclosed, 593.*
  — *flame, 594.*
  — *general, 592A.*
  — *magazine, 594.*
  — *negative resistance of, 591A, 592A.*
  — *open, 592B, 599.*
  — power factor, 156.
  — *principle of, 592A.*
  — *Sperry, 613.*
  — *titanium and tungsten, 597.*
  lighting dynamo, 138.
  radiation furnaces, 640.
ARC (*cont.*)—
  resistance furnaces 640.
  suppression coil, Parsons-Reyrolle, 407.
  suppressor, 351; Chap. 16 *passim.*
  welding, automatic, 654.
  — *carbon, 651.*
  — *characteristics of arc, 657.*
  — *general, 650.*
  — *generators for, 656.*
  — high frequency for, 144.
  — *in gases, 655.*
  — *quasi-arc, 653.*
  — *various uses for, 649.*
  — *with metal electrodes, 652.*
Architects and illumination, 598, 601, 602.
Arcing grounds, 351.
  time defined, 371.
  tips, 365.
Arcwall coal-cutters, 834.
Area and volume required for plant, 196.
Argentan, 67 (Table 6).
Argon in lamps, 588B, 589.
Armature, 132, 133.
  control of shunt motors, 717.
  — *of motor, 671.*
  -volts, 138.
Armco iron, 83.
ARMOURED—
  cables, 283, 290.
  conductors, I.E.E., rule, 557.
  draw-out switchboard, 380.
Armouring, conductivity of, 821.
Arno meter, 274.
Aron meter, 115.
Arrangement of switchboards, 382.
Arresters, lightning, 346.
Artificial daylight, 578.
  earth and leakage, 354A, *471, 472, 482, 632* (see "*Earth leakage*").
  silk, 74.
  sunlight, 588, 592, 595A, 597.
Asbestos, 73 (Table 7), 74, 80, 85.
Ash disposal, 196.
  precipitation, 996.
  removal as slag, 171.
  separation, magnetic, 809.
Asphalt, 75.
"Association" cable, 281, 284 (*see* "Cable").
Asynchronous alternator, 144.
  motor generator, 388.
Atmos boiler, 170.
Atmospheric condenser, 175.
Atomic hydrogen in arc welding, 655.
Attraction between conductors, 338.
Austin constant-current system, 678.
  — — *for winches, etc., 791.*

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Autoclave, 630.
Auto-compensated induction motor, 688.
AUTOMATIC—
acceleration, 741.
— railway, 921.
arc welding, 654.
brakes on lifts, 797.
control gear, 738.
— of heating in rooms, 620.
devices for switchgear, 373.
hydro-electric stations, 187, 217.
landing gear on lifts, 797.
motor control, 742.
regulation of 3-wire system, 388.
stations and sub-stations, 187.
sub-stations, 428, 869.
switches, 365 *et seq.*
Auto-transformer, 396, *479.*
for arcs, 595.
— motors, 724.
starter, B.S.I. definition, 736.
starters, 738.
three-phase, 396.
Auto-vapour system, distillation and evaporation, 626.
Auxiliaries on ships, 678, 964.
Auxiliary transformer connection, 394, 395.
Average value of sine wave, 30.
Axle-driven railway lighting plant, 929 et seq.

BABCOCK & Wilcox boilers, 170.
Back E.M.F., 28.
Backfiring in mercury-vapour rectifier, 423.
Backward cells, 432.
Baffle-contact in circuit-breaker, 368.
Baily furnace, 636.
Bakelite, 73 (Table 7), 74, 75.
Baking by infra-red rays, 646A.
— enamel, 643.
— ovens, bread, 644.
Balanced and unbalanced circuits, 110.
voltage protection, 359.
Balancer, field rheostat, 736.
panels, 385.
Balancers, 388, 461.
and 3-wire generators, 141.
static, 141.
Balancing reservoirs, 240.
3-wire system, 461, 463.
Balbach-Thum process, silver, 989.
Baling presses, cotton, 776.
Ballistic galvanometer, 96.
Band and belt conveyors, 835.
saws, 775.
Banki turbine, 133.
Bar coal cutters, 834.
Bare conductors, 4 (*see also* "Bus bars," "Overhead lines," etc.).
— in buildings, 561.
Barges, electrical, 965.
Barlow's method for finding run-off, 204.
Barn line-shafting and portable motors, 850.
Barometric condenser, 175.
Barreter tubes, 64, 583.
Basalt, 74.
Bastian boiler, 625.
meter, 114.
Bathrooms, heating in, 632.
Batten lampholders, 485.
BATTERY-(IES), Secondary (see "*Primary-cells,*" "*Secondary batteries;*" see also *Vol. II, Chap. 18*)—
charging sets, cost (Table 76), 573.
cut-outs, 358.
elementary, 127, 128.
floating, 142.
"*Keepalite,*" *430.*
lamps, Krypton, 585.
meters, 114.
panels, 385.
Battleships, steam consumption of, 961.
Bauer-Wach system of exhaust turbines, 963.
Bauxite, 85, *975.*
Bayonet lampholders, 485, 487.
Bazin's formula, 210, 211.
BB alloy, 67 (Table 6).
Beacon metal, 67 (Table 6).
B.E.A.M.A. ("British & Allied Electrical Manufacturers' Association"), 152, *1059.*
Beard-Hunter sheathed pilot system, 359.
Beard self-balance protective system, 359.
Bearer wires, earthing, 533.
Bearings, motor, 671.
Beaver's test for tinning, 282.
Beck searchlight, 613.
Bedford rural area, cost of overhead lines, 332 (Table 50).
Bedplates built up and welded, 649.
Bed-warmers, 631.
Bee-keeping, electricity in, 856.
Bells, electric, in mines, 839.
Belt driving, 164.
and band conveyors, 835.
Bending machines for conduit, 538.
— rolls, 775.
Benson boiler, 170.
Benzine, 73 (Table 7).
Benzol, 169.
B.E.R.A. ("British Electrical Research Association"), 368.
B.E.R.A. circuit-breakers, 368.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Berlin Diesels, 180.
Berry system, transformers, 395, 402, and Fig. 109.
Beryllium, 591A.
hydrate in Drumm battery, 873.
B.E.S.A., now B.S.I. (*see* "British Standards Institution").
Betts process, lead, 992.
Biassed relay and transformer protection, 359.
BIBLIOGRAPHIES, 58, 87, 125, 152, 163, 184, 199, 258, 267, 276, 293, 336, 360, 386, *429, 435, 457, 483, 509, 532, 563, 577, 614, 648, 668, 712, 745, 782, 810, 843, 861, 934, 955, 967, 998, 1016, 1038, 1060.*
Bichromate cell, 127.
Bi-fluid plants, 166.
Bimetal fuse wire, 342.
Binary converter, 413A.
fluid (vapour) cycles, 166.
Bipolar electrodes, 970.
Bird-guards, 324, 330.
Birds and overhead wires, 915.
Birkeland-Eyde process, 974.
Bismuth, 65, 67 (Table 6), 121, 127, 346, *961.*
Bisulphide of carbon manufacture, 635.
Bitumen, 73 (Table 7), 74.
cables, 283, 287.
— *in mines, 819.*
dielectric, 287.
"*Black body,*" *583, 589, 591A.*
Black-bulb-thermometer, 647A.
"*Black Light,*" *591B.*
Blast-furnace gas, 167, 178, 181.
— — *in collieries, 810.*
— *power for, 778.*
Bleach, electrolytic, 894.
Bleeding steam, 176.
Block signalling, 933.
Blooming mills, 778.
Blowers and exhausters, 766.
Board of Education illumination, 604.
Board of Trade, 324 (*see* "Electricity Commissioners," "Home Office," "Ministry of Transport," "Regulations and Rules").
— — unit (*see* "Unit").
Boiler plant in G.B. statistics, 170.
BOILERS, *domestic, 615, 621* et seq., *627.*
— *cost, 574.*
— *wash, 624.*
mercury, 166.
BOILERS, STEAM (*see also above*, "Boilers")—
Atmos, 170.
Babcock, Benson, Bonecourt, Stirling, 170.
Bastian, 625.
electrically-heated, 625.
BOILERS, STEAM (*cont.*)—
flash, 170.
general, 166 *et seq.*
grate area, 170.
heating surface, 170.
-house efficiency, 171.
— percentage cost of, 196.
— volume and capacity, 196.
La Mont, 170.
Loeffler, 170.
losses, 171.
space occupied by, 196.
specification of, 1009.
spinning, 170.
Sulzer, 170.
Velox, 170.
welded, series, 191.
Boiling, hot-plates for, 630.
rings, cost (Table 77), 574.
Bolts replaced by electric welds, 649.
Bombay, Baroda & Central India Railway, 868, 915.
Bonding rails, 904.
and welding rails, 903.
cost of, 925.
steel catenary to contact wire, 917.
Bone, Prof., gas v. *electricity, 622, 628.*
Bonecourt boiler, 170.
Boosters, 142.
for batteries, 432.
synchronous, 411.
Boosting and bucking, 389, 395.
traction, 906.
transformer, 395, 406.
vehicle batteries, 949.
Booth furnace, 640.
Bootmakers' machinery, 775 (Table 153).
Boring machines and mills, 775.
Boron steel, 979.
Boucherot motors, 684.
Bougie decimale, 579.
Boulder crates, 236.
Bow collectors, railway, 913.
— *tramway, 912.*
Bowden-Thomson sheathed-cable system, 359.
Bowl fires, 620.
fittings, 572, 603, 605, 606.
— *cost of, 572.*
Bracket holders, 485.
Brackets, cost of, 572.
tramway, 910.
Brakes; braking, 899.
on "electrics," 945.
— *lifts 797.*
— *motors, 715.*
regenerative, 900, 945.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

BRANCH circuits, control, switches and wiring (see *Chap. 22*).
distribution board, 511, 521.
switches (*see* "Switches").
Brass, 65, 67 (Table 6).
and thermal storage, 627.
arc welding, 649.
Baily furnace for, 636.
conduit, 540.
energy for melting, 647 (Table 101).
melting, 639, 647.
plating, 994.
properties of, 65, 67 (Table 6), *645 (Table 98).*
Brazing, electric, 660.
Bread ovens, 644.
Breakage of overhead wires, 324.
Breakdown voltage, 70, 72.
— of air, 78, 79.
Breakfast cookers, cost (Table 77), 574.
"Break" in circuit-breakers defined, 371.
Breaking capacity of switches, 369-71.
current defined, 371.
BREAKING STRESS—
aluminium, 308.
bronze, 331.
copper, 295, 307, 324.
dip and, 328, 329.
insulators, 330.
of wires, 324
overhead construction, 324 *et seq.*, 328 *et seq.*
poles, 324, 325.
stay wires, 326.
steel wires, 309.
Breathing valves, 589.
Bridge, Wheatstone's, 120.
megger for cable tests, 120, *1032.*
Bridges and overhead lines, 914.
strengthening by arc welding, 649.
Brightness defined, 580.
intrinsic, 597, 599.
Brighton line electrification, 921 (2).
Brine pipes for cooling, 646A.
BRITISH and Allied Electrical Manufacturers Association (B.E.A.M.A.), 152, *1059.*
BRITISH Electrical Research Association (B.E.R.A.), 368.
BRITISH Standards Institution (B.S.I., formerly B.E.S.A.) Reports, 5, 6, 7, 12, 23, 58, 67, 87, 92, 108, 125, 136, 152, 173, 184, 279, 293, 311, 324, 336, 360, 363, 369, 371, 372, 375, *1055.*
cables and wires, 279 *et seq.*
definition of fractional horse-power, 710.
— — starters, etc., 736.
— — terms in connection with circuit-breakers. *See under the various heads.*
BRITISH Standards Institution (*cont.*)—
specification for transformers, 402.
standard specification (B.S.S.)—
— conductors, 279.
— fuses, 375.
— motors, 670.
— — rivers, 209.
— rating, 136.
— switchgear, 365, 369, 371, 372.
— trolley wire, 909.
groove for trolley wheel, 912.
plugs and sockets, 952.
pressure and frequency, 1047.
rails, 901.
trackwork, 901.
traction motors, 895.
tramway poles, 910.
BRITISH Thomson-Houston—
— auto arc welder, 654.
— frequency meter, 112.
— protective system, 359.
BRITISH—
thermal unit (B.Th.U.), 48, 50, 52, 53.
— — conducted through walls, roofs, etc., 647A.
— — from coke, gas, and electricity for water heating, 622.
— — required to heat air, 619.
— — — — — materials, 618.
Bronze—
energy for melting, 647 (Table 101).
phosphor-, 66, 331, 335.
properties of, 65, 67 (Table 6), 331, 335 *645 (Table 98).*
silicon, 67, 329, 331, 335.
Brown-Boveri rectifier, 423.
— speed control, 716.
Brown coal, 168.
Brush Co.'s starter for converters, 413.
tapping switch, Fig. 108.
Brush discharge, 316.
volts, 138.
Brushes, 66, 133.
B.S.I. (*see above*, "British Standards Institution").
B.Th.U. (*see* "British Thermal Units").
B.T.U. (Board of Trade), (*see* "Units").
Bucking and boosting, 389.
transformer, 142.
Buckley's pocket-book, 204.
Buffer battery, 430.
— resistance, 368.
Building research station's work on heating, 620.
Building up field, 138.
Buildings for power-house, 196.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Bulbs for valves, 419.
Bulkhead fittings, 572.
Bunching conductors, 4, 280 (Tables), *543, 544 (37).*
in casing, 536 (27), 537.
Burden of instrument transformer, 108.
Burma mines, 991.
BUS BAR(s)—
— attraction between, 338.
— connections, 383.
— excitation, 148.
— reactance, 340.
Butt welding, 660, 661, 665, 666.
By-product power, 230, 230A, *776.*
cost of, 188.
By-products from fuel, 169.

CABLES (*see also* "Conductors," "Transmission," "Wires")—
and cords, flexible, distinguished, 525.
— lightning, 334 *note.*
— overhead lines, 334.
— wires, Chap. 13.
armoured, 283, 290.
"Association" grade, 281, 284.
bitumen insulated, 283, 287.
British Standard, 279 *et seq.*
cab-tyre sheathed, 74, 283.
capacity and charging current, 307, 311.
class of, 283.
construction and jointing, 290.
couplings for, cost (Table 74), 571.
drop of pressure in, 24, 286.
extra high pressure, 288, 289.
fault localisation in, 1032.
fireproof, 283.
flexible (q.v.), 284, 285.
gas-filled, 289, 290A.
grade of, 281.
graded, 289.
heating of, 291, 312, 338.
I.E.E. rules, 280, 285, *513.*
impedance, 310.
inductance, reactance, impedance, 310.
in mines, 819, 820.
insulated, 310 *et seq.*
insulation of, 525.
— resistance of, 1029.
intersheath, 289, 311, 319.
laying and jointing, 290.
localising open circuits in, 1032.
magnesia, 556.
Makers' Association (C.M.A.), 281, 284, *566.*
mining (see *Vol. III, Chap. 32*).
"*Nonazo*" (*Table 63*), *566.*
CABLES (*cont.*)—
oil-filled, 289.
on shipboard, 959, 964.
paper insulated, 311.
power factor of, 1030.
pressure drop, 24, 286.
"protective," 346.
"*Pyrotenax,*" *566.*
rating of, 280 (Tables, 40 A to 40 K).
reactance, 310.
resistance (*see* "Resistance").
screened, type E.H.T., 289.
specification for, 1006.
— of small, 534 (5), (6).
steel-cored aluminium, 917.
sub-main, 511, 520.
submarine, 292.
testing, 1027 et seq.
tests, loop, 1032.
tropical, 281.
underground, Chap. 11.
vulcanised india-rubber, 283, 287.
— — — *cost, 566.*
Cab-tyre sheathing cables (C.T.S.), 74, 283, *551.*
— — *cost of, 565.*
— — *for mines, 820.*
CADMIUM—
-copper alloy, 65, 331.
in copper trolley wires, 909.
in lamps, 592A.
properties, 67 (Table 6), 127.
standard cell, 128.
Calcium by electrolysis, 635.
carbide, 635, 973.
nitrate, 974.
production, 980
Calculations of power for traction, 884-6.
of short-circuit current, 339.
Calico looms, 776.
printing, 777.
Calido alloy, 67 (Table 6).
Californian Edison Co., 315.
Calorie and great calorie, 48, 52.
Calorific values, 168, 170, 171, 178, 191.
Calvete tele-switch, 505.
Cambric insulator, 73 (Table 7), 74, 287.
Cambridge Scientific Instrument Co.'s potentiometer, 95 (2).
Campbell's potentiometer, 95 (2).
Canal falls, developing, 216, 218.
Canals and forebays, 231.
CANDLE—
lamps, 586.
— cost (Table 74), 571.
power, 579, 580.
— horizontal and spherical, 581.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

CANDLE (*cont.*)—
power of arc lamps, 591, 594, 597, 599.
— per watt, 582, 583.
— polar curves, 581.
standard, 579.
Cap insulators, 330.
Capacitance method of tapping grid, 427.
CAPACITY (*see also* next entry)—
for absorbing heat, by air, 647A.
of lifting magnets, 806.
— secondary cells, 430 et seq.
— traction cells, 940, 941.
requirements of lifts, 799.
CAPACITY, ELECTROSTATIC—
cables, 307, 311.
concentric cables, 311.
condensance and, 46.
currents (*see* "Charging currents"), *1030.*
elementary, 2, 46.
frequency and, 135.
of insulator, 330.
overhead lines, S.P., 305.
— three-phase, 306.
power factor and, 156.
reactance, 46, 135, 304.
resonance and, 350.
tables of, 307.
Capital cost and charges, plant, 194, 195.
— electric traction, 925 et seq.
Capstans and winches, 790, 791.
Carbide of calcium, 635, 973.
CARBON (*see also below,* "Carbons")—
bisulphide and tetra-chloride, manufacture, 635, 983.
breaks, 365.
electrodes, 66, *641.*
filament lamps, 584, 599.
lamps, 646A.
— cost, 571.
— efficiency, 583.
— for heating, 620.
properties, 66 (Table 6), *645* (*Table 98*).
resistors for furnaces, 617, 635 (*Table 96*).
rod resistors, 636.
steel, 66 (Table 6).
— electrodes, 653.
temperature coefficient of, 583.
tetrachloride, 77, 375, *404, 983.*
CARBONS (*see also* "Carbon," "Graphite")—
activated, 647A.
arc, 591, 599.
— welding, 651.
dioxide, 404.
for furnace heating, 636.
Carborundum, 67, 85, *635, 981.*
resistors, 636.
Carcel, 579.
Card-room machinery, 776.
Car-engine heaters, cost (*Table 77*), *574.*
Care of accumulators, 432.
Cargo vessels, electric drive for, 962.
Carpet sweepers, 573.
Carriage and water-power, 217.
Carriages, cars (see "*Coaches,*" "*Road vehicles*").
Carry-over storage of water, 244.
Carry-over storage of water (*see* "Water storage and power"), 244.
Car-switch lift control, 797.
Cartridge fuses, 375.
CASCADE—
connection in ship propulsion, 958.
converter, 413.
— Brush Co.'s starting method, 413.
coupling, 898.
induction motor sets, 694.
multivibrators in, 428B.
speed control for induction motors, 727 (*Table 135*).
Casing, cost of, 569.
wiring, 535-7.
Castings, arc welding, 650.
replaced by welded plates, 649.
Cast iron, 64, 67 (Table 6), 82.
— energy for melting, 647 (*Table 101*).
— welding, 652.
steel, 82.
Castner process, 980, 984.
Castor oil, 73 (Table 7).
Cast steel, 82.
Catchment areas, 202, 203.
Catenary construction, 914, 917, 918.
Cathode and anode, 127.
(Kathode) and anode; catholite and anolite; cation and anion; 127, *970.*
ray oscillograph, 118.
Caustic alkali production by electrolysis, 635, 984.
— — in Koenemann process, 176.
Cavitation, 214.
C.C. (*see* "Continuous current").
Cedes wheel in road traction, 944.
Ceiling fans, 758.
— tests of, 1036.
roses, 490, 491, 534 (*17*).
— cost, 571.
CELLS (*see also* "Primary cells," "Secondary cells")—
elementary, 127.
for caustic alkali, 984.
— road traction (see "*Secondary batteries*").
photo-electric, 420A.
standard, Clark & Weston, 95, 128.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Cellular type switchboards, 376, 378.
Celluloid, 73 (Table 7).
Cellulose silk, 74.
Cement as insulator, 75.
mills, 779.
Census of production, 780.
Central Electricity Board, 185, 194, *1041.*
Central refrigeration, 773.
Central stations, 185 *et seq.*
— *and welding load, 667.*
output statistics, 197.
Centralisation of plant, 185 *et seq.*
— and national security, 191.
— peak loads, 186, 191.
Centre-pole construction, 909, 910.
CENTRIFUGAL—
fans, 764.
force opposing steam pressure, 170.
pumps, 768, 770.
separation of water-borne material, 238.
CERAMIC(S)—
and air-conditioning, 647A.
insulator tests, 1033.
Ceylon, water-power, 243.
C.G.S. (centimetre-gramme-second) system of units, 2.
Chain coal cutters, 834.
conveyors, 835.
mortisers, 775.
welding, 661.
"Change-circuit" system, 264.
change-over switch controller, 736.
— *-speed motors, 670.*
Changing form of A.C., 477.
D.C., 478.
Channels, water, 211, 212, 237.
CHARACTERISTIC CURVE, 134, 138.
motor, 672.
of industrial loads, 780.
— *Mather & Platt train-lighting dynamo, 931.*
— *shunt motor, 675.*
— *traction motor, 886.*
series, shunt and compound, 753.
typical, of A.C. and D.C. motors, 670 (*Table 113*).
Characteristics of rectified current, 416 (*Table 58*).
Charcoal iron, 82.
Charge indicator, 104.
Charges for electric supply (*see* "Tariffs").
cutting off supply for non-payment of, 512.
for rural energy, 860.
— *traction* (*tramway and trackless*), *925.*
standing (fixed) and working, 194, 269.
CHARGING—
accumulators, 432, 433.
— *for vehicles, 948.*
— *Drumm type, 873.*
contacts, 368.
electrolytic arresters, 346.
CHARGING (OR CAPACITY) CURRENT—
and power factor in cables, 1030.
cables, 307, 311, 351, 359.
earths and, 351.
elementary, 46.
frequency and, 135.
overhead lines, 135, 305, 306.
power factor and, 156.
protective systems and, 359.
Chatterton's compound, 74.
cost (*Table 74*), *571.*
CHEMICAL—
air heating, 176.
and electro-chemical equivalents, 970 (*Table 213*).
— *metallurgical industrial processes, Vol. III, Chap. 38.*
— *processes* (*Chap. 38*), see "*Processes.*"
corrosion, of lead, 553.
Chester plant, 223.
Chicago, Milwaukee and St. Paul Railway, 863.
Chichester street lighting, 612.
Chick-rearing, 856.
Chlorate of soda and potash by electrolysis, 635, 984.
Chlorine production, 984.
Chocolate and air-conditioning, 647A.
Choking coils, 45, 348.
— *for arcs, 595.*
— *in welder, 657.*
Chrome steel, 979.
for steam tubes, 170.
Chromite, 85.
CHROMIUM—
alloys, 83.
electrodes, 597.
in titanium arc, 597.
plating, 994.
Chronic alloy, 67 (Table 6).
Chucks, magnetic, 807.
Church heating, 619, 620.
Cigar lighters, 631.
CINEMATOGRAPH—
air-conditioning in, 647A.
heating, 620.
lamps for, 586.
motors, 705.
regulations for, 562.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

CIRCUIT(S) (*see also* "Circuit-breakers" below, and *Vol. II*)—
and connections, Chap. 19.
closed, 9.
elementary, 9, *436*, *437*.
magnetic, 41.
open, 9.
protection of, Chap. 15.
short (*see* "Short-circuit").
Wiring and control of, Vol. II, Chap. 22.
CIRCUIT-BREAKERS—
B.S.S. for, 365, 369-372.
expansion-type, 368A.
general, 342 *et seq.*, 361, 365 *et seq.*, 368A.
high-speed, 372 (3).
— *in traction, 869, 914.*
I.E.E. rule as to, 508.
of low oil capacity, 368A.
"orthojector," 368A.
with extinction, 368A.
CIRCULAR—
flexibles, 484.
mill, 292 (footnote), 309 (Table 45).
saws, 775.
Circulating current protection, 359.
water, 175.
Clark cell, 128.
CLASSIFICATION—
instruments, 89 *et seq.*
insulators, 73.
materials, 59, 60.
switchgear, 361.
traction, 864.
water-power, 203.
Class of cables, 283.
— dielectrics, 70 *et seq.*
Claude process, ammonia, 973.
Clearance on overhead railway construction, 914.
Clearances in oil-switches, 371.
Cleat(s), cost of, 569.
current rating of cables on, 280 (Tables 40 D, E and H).
system of wiring, 546-8.
— — — *cost, 565.*
Climax alloy, 67 (Table 6).
Clocks, A.C. mains, cost (Table 76), 573.
electric and quartz, 428B.
Clock-type meter testing, 1035.
Closed circuit, 438.
or pressure type water-heater, 622A.
Clothes-washers, electric, 755.
Clothing, heating electrically, 631.
Clutches, electro-magnetic, 751, 808.
for starting induction motor, 724.
Clutches for synchronous motor, 722.
friction, 751.
hydraulic, 230A, *963*.
C.M.A. standard cables, 281, 284, *566*.
COACHES, RAILWAY—
heating and ventilation in, 928.
lighting, 927.
power generation in, 929-32.
COAL—
and electricity compared, 576, 622, 628.
cleaning, magnetic, 809.
coke and, 168.
consumption, 191 to 194.
cutters, 834.
gas, 178.
grate area and, 170.
mines (see "*Mines*").
sampling and analysis, 168.
sorting by U.V. rays, 587.
storage, 196.
washing and screening, 837.
Cobalt, 67 (Table 6), 81, 127.
alloys, 83.
-steel magnets for motors, 673.
Cobra process, timber, 86.
Coefficients, hydraulic, 206, 207, 210, 212, 247.
of reflection, 580.
Coercive force, 81-3.
COIL—
armature, 132, 133.
choke, 45, 348.
dissonance, 351.
pressure reducing (volt-box), 95, 107.
reactance, 45, 348.
"*Coiled-coil*" *lamps, 585.*
— *cost (Table 74), 571.*
Coils and cores of transformer, 398.
Coke, 168.
as resister, 636.
-fired boilers, 168, *622*.
ovens and by-products, 169.
— *power for, 778.*
— gas, 167, 181.
— — *in collieries, 816.*
COLD—
light, 578 note.
saws, 775.
storage machines, 647A, 773 (*see* "Refrigeration").
Collection of current, railways, 913.
— — *tramways, 912.*
Collector ring, 133.
Collectors for third-rail, 920.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Collieries (see also " *Mines* "), *818.*
power for, 779.
use of gas in, 816.
Colliers, electrically-driven, 957.
COLOUR(S)—
for cables, phases, poles, 150, 280.
in fluorescent lamps, 591A.
-matching light, 578.
signals, railway, 921.
Comb arrester, 346.
Combined sets, cost, 189.
Combustion, internal and external, 166.
Comet alloy, 67 (Table 6).
Commercial measurements, 97.
Commissioners, Electricity (*see* " Regulations and Rules ").
Commutating poles (*see* " Interpoles ").
Commutation, sparkless, 139.
COMMUTATOR—
and brushes, 671.
explained, 133, *671.*
motor and frequency, 135.
motors, A.C., 699 et seq.
rectifiers, 416.
single-phase motor control, 734.
three-phase motor control, 735.
— *for power-factor correction, 687.*
Companies and local authorities, generating plant of, 195.
COMPARISON OF—
A.C. and D.C., 475-8.
— — — *motors, 753.*
electricity and compressed air, 833.
— — *gas lighting, 609.*
induction motors, 684 (Table 121).
methods of conversion and transformation, 425.
— — *cooking, 576, 622, 628.*
— — *speed control, 726 (Table 134).*
single-phase motors, 690 (Table 122).
steam and electric traction, 894.
various road vehicles, 954 (Table 205).
Compensating windings, 671.
Compensation, power-factor, 687.
Compensator, B.S.I., definition of, 736.
for starting induction motors, 724.
Composition of alloys, 67 (Table 6).
— — fuels, 168.
Compound engines, 172.
— *motors, 677, 753.*
— — *starting and control of, 720.*
— — *for lifts, 796.*
-wound generators, 134, 138, 148.
Compounding mercury vapour rectifier, 422.
Compounds, insulating, 74.
Compressed air as dielectric, 78.
-air locomotives for mines, 832.
— v. *electricity in mines, 833.*
Compressors, air, 766 (Tables 144-7).
for air heating, 176, *847A.*
— *ice-making, 773.*
— *mines, 833.*
CONCENTRIC—
cables, capacity, 311.
lampholders, 486.
wall sockets, 495.
wiring, 559, 560.
CONCRETE—
and thermal storage, 627.
as insulator, 74.
-mixer, power for, 779.
poles, 323.
Condensance, 46, 304.
Condensation, avoidance of in plant, 963.
-cracking of water-vapour, 214.
in conduits, 540.
CONDENSER (ELECTRIC)—
cable as, 304.
electrostatic, for lighting, 480.
elementary, 46, 57.
in air-core induction furnace, 639.
in spark welding, 665.
Moscicki, 346.
power factor and, 156, 160.
type insulators, 368.
-type motors, 689, 690.
— voltmeters with, 107.
Condenser for mercury-vapour plant, 166.
Condensers, steam, 175, 191.
Condensing engines, 172.
Condensite, 74.
Conditioner units, air, 647A.
Conditioning water for boilers, 191.
Conditions in agriculture, 844.
of Contract, General, I.E.E. model, 534 note, 999, 1000.
Conductance, 18.
Conductivity of armouring, 821.
— *carbon electrodes, 641.*
— metals, 62 *et seq.*
thermal, of materials, 627, 647A.
CONDUCTOR RAILS, *901.*
railway, 920.
resistance of, 901, 902.
steels for, 64.
CONDUCTORS (*see also* " Cables," " Conductor rails," " Wires," and under various metals)—
aluminium, 63.
attraction and repulsion of, 338.
bare, 4, *561.*

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Conductors (*cont.*)—
bare, in buildings, 561.
bronze, 65, 66, 331.
copper, 279 *et seq.*, 370.
colours for distinguishing, 280.
current density, 27.
definition, 4, 59.
dimensions, weight, resistance (Tables), 280.
drop of volts in, 286.
earthed, 4, 353.
economic section of, 333.
formulæ for line, 324 *et seq.*
hard-drawn copper, 307.
I.E.E. rule as to, 513.
in series, 445.
in specification, 534 (5).
insulation of (*see* Chap. 13), *525.*
insulators and, 59.
Kelvin's law, 333.
lightning, 348.
regulations as to, 324, 336.
resistance, weight, etc. (Tables), 280.
Conduit—
bending machine, 538.
cost of, 568.
wiring, 538-45.
— cost of, 565.
— in specification, 544.
Connecting charge, 574.
Connections and Circuits (see also *Vol. II,* "*Circuits and Connections*"), *Chap. 19.*
and joints, 488, 489.
between generating stations, 186.
bus bars and, 383.
for heat control, 618.
in mines, 820.
of transformer, 394, 397.
phase, 150.
to supply, 185.
Connectors, plug, 489, 497.
cost of, 571.
Constantan alloy, 67 (Table 6).
Constant—
-current, *see next entry.*
pressure battery charging, 948.
temperature in furnace, 636.
time, 44, *402.*
voltage feeding points, 473.
Constant Current—
battery charging, 948.
D.C. motors, 678.
dynamo, 138.
lighting, 446.
system (Thury), 289, 294, 317, *419.*
— in mines, 815.
Constant Current (*cont.*)—
transformer, 405.
transmission, 289, 294, 317, 318.
"*Constants*" *in meter testing, 1035.*
Constants of—
aluminium, 308, 331.
bronze, 331.
cadmium-copper, 331.
conductors, 67 (Table 6), 331.
copper trolley wire, 909.
hard-drawn copper, 307.
insulators, 73 (Table 7).
steel wire, 309, 331.
water-power, 202.
Constant pressure dynamo, 138.
Construction of—
cables, 290.
oil switches, 368.
switchboards, 382.
trolley line, 909.
Consumer(s)—
and average load-factors, 780 (*Table 167*).
data for rural lines, 846.
failure to earth metal, 533.
pressure, 23.
wires and cut-out, 514.
Consumption of carbon electrodes, 641.
Consumption of Energy (*see also* "Energy"; "Power required")—
and maximum demand, 576.
in private lighting, 606, 607.
— public lighting, 612.
— refrigeration, 773.
Contactors, 374.
Contactor-type starters, 736, 738.
Contents, Table of, ix, x.
Continuity tests, 120A.
Continuous Current (D.C.), (*see also* "Direct current").
and short-time rating, 136.
compared with A.C., 10, 294 *et seq.*
conversion of, 409 et seq.
direction of, 33 to 35.
elementary, 10, 14.
furnaces, 636.
generator (*see* "Dynamo").
mills, steel, 778.
motor (*see* "Motor, D.C.").
rating of motors, 670.
rectification of, 415 et seq.
transmission, 294, 297, 317, *419.*
wave generator, 420.
Contract charges for agriculture, 860.
"*Model, General Conditions of, I.E.E.,*" *534 note, 999, 1000.*

CONTROL—
and damping, 90.
automatic, of motors, 742.
for installation, 534 (12), 570.
-gear, construction of, 738.
— flame-proof, 740.
— for motors, cost of, 711.
in branch circuits (see *Vol. 2, Chap. 22*).
instruments and cables on ships, 959.
of A.C. motors, general, 721.
of traction motors, 873, 898.
— — heating, 618.
— D.C. motors, general, 716.
— — traction motors, 873, 897.
— — tramway motors, 895.
— efficiency with electric drive, 747 (3).
— lifts, 797.
— — speed, 796.
— motors, 713 et seq., *873.*
— polyphase induction motors, 723.
— street lights, etc., at peak, 608, 615, 622.
— tramway motors, 895.
of wiring circuits (see *Vol. 2, Chap. 22*).
on G.I.P. Railway, 916.
panels, 385.
power and water in water-heaters, 622.
power factor correction and, 161.
push-button, on lifts, 797.
remote, 359, 372, 373, 378, *741.*
thermostatic, 615.
transmission and, Part III.
units, cooker, cost (*Table 77*), *574.*
"*Controlenses,*" *591A.*
CONTROLLER—
definition of, 713.
— and rating, B.S.I., 736, 737.
for cranes and hoists, 788.
— winding, 827.
liquid, 739.
motor, in mines, 822.
Convected heat, 616.
Convection and radiation losses, 620.
Convectors, 574, 620.
Conventional signs and symbols, 7.
CONVERSION—
and transformation of energy (*Chap. 17*), *387* et seq.
— — of D.C. voltages, 385.
methods compared, 425.
CONVERTERS, 142 (see *Vol. II, Chap. 17*).
binary, 413 (*a*).
cascade, 413.
for traction, 142, *869*
in mines, 814.
metadyne, 389A.
CONVERTERS (*cont.*)—
rotary, 408 et seq.
welding, 667.
Conveying, hoisting, etc., Chap. 31.
Conveyors, coal, 196.
and loaders, 196, *835.*
— (*non-mining*), *803.*
Cookers, breakfast, cost (*Table 77*), *574.*
COOKING, ELECTRIC—
and heating, wiring for, 530.
apparatus, cost of, 574.
by induced current, 629.
comparison of methods and costs, 576, 622.
general, 628.
I.E.E. rule as to, 633.
on vehicles, 928.
safety in, 632.
"*Cool light,*" *578, 591A.*
COOLING—
air in tests, temperature of, 1024.
and heating air, 647A.
— — curves, 1025.
— — electric, on shipboard, 963.
by hydrogen, 80A, 191, *671.*
of transformers, 400.
— — (*B.S.I.*), *Table 55, 402.*
towers, water, 175.
Copal, 74.
Copenhagen diesels, 180.
COPPER—
and thermal storage, 627.
annealed, 62, 66, 279.
arc welding, 649.
area of, conductors, 279.
breaking stress, 62, 66.
British standards for, 279.
bus bars, 383.
by electrolysis, 635.
cadmium, 909.
-cadmium wire, 331
conductivity, 62.
conductors, 62, 66, 279.
— formulæ for, 295.
— regulations for, 324, 336.
-constantan couple, 122.
density, 62, 66.
dip and stress of, 327 *et seq.*
elasticity, 62, 66.
energy for melting, 647 (*Table 101*).
expansion coefficient, 66.
extraction and refining of, 987.
for transmission, 328.
fuses, 342.
general formulæ, 295.
hard-drawn, 66, 295, 307.
in electro-chemical series, 127.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

COPPER (*cont.*)—
line feeders, 923.
melting, 639, 746.
-nickel-plating, 994.
-oxide rectifier, 417.
-plating, 994.
price fluctuations of, 332.
properties of, 645 (Table 98).
resistance, 62, 66.
sheathed cables, 359 (*see also* "Inter-sheaths").
standard, I.E.C., 62.
temperature coefficient, 62, 66.
trolley wire, constants of, 909.
weight, 62.
wires, standard, 279.
Cord grip, 485.
Cords, flexible, 285.
Cordite drying, 619.
Core-balanced protection, 359.
Cores, material of, 82.
— *and coils of transformers, 398.*
Cornice and bowl lighting, 602, 603, 605, 606.
Cornish boilers, 170.
Corona discharge, 316.
Correction of power factor, 159-162.
Corrosion, electrolytic, 324, *907.*
of lead, 553.
Corundum, 85, *981.*
"*Cosmos*" *hot-plate, 630.*
COSTS (*see also* "Cost of" *below*)—
capital and working, 194, 269.
— comparative analysis of working, in G.B., 194, and Tables 25, 26.
determination of, with electric drive, 747 (3).
pre-war and post-war (prices), 530 h, 564.
running, of "electrics," 947.
tariffs and (Chap. 12).
transmission and distribution (G.B.), 269.
unit below selling price, 622.
with electric cooking, comparative, 578, 622, 628.
working and fixed, 194.
COST OF (*see also* "Costs" *above*)—
adhesive and rubber tape (Table 74), 571.
battery-charging sets (Table 76), 573.
boilers, domestic (Table 77), 574.
boiling rings (Table 77), 574.
brackets (Table 75), 572.
breakfast cookers (Table 77), 574.
cable, V.I.R. (Tables 68, 69), 566.
— *couplings (Table 74), 571.*
cab-tyre wiring, 566.
carbon lamps (Table 74), 571.
car engine heaters (Table 77), 574.
casing (Table 72), 569.
COST OF (*cont.*)—
ceiling fans (Table 76), 573.
— *roses (Table 74), 571.*
central station plant, 195.
centrifugal pumps (Table 76), 573.
Chatterton's compound (Table 74), 571.
cleats, 569.
clocks, A.C. mains (Table 76), 573.
combined steam sets, 189.
conduit (Table 71), 568.
connecting installation, 575.
connectors (Table 74), 571.
convectors (Table 77), 574.
cooker-control units (Table 77), 574.
cooking apparatus (Table 77), 574.
counterweight pendants (Table 75), 574.
distribution boards (Table 74), 570.
— *lines, 575.*
domestic fans (Table 76), 573.
— *motors (Table 76), 573.*
electric installations (Chap. 24).
— *ploughing, 851.*
— *railways, 919A, 926.*
— supply, 269.
— *traction, 925* et seq.
extra fuel for extra units, less than average, 265.
— *high-tension cable mains, 846.*
fittings, lighting (Table 75), 572.
flat irons (Table 77), 574.
flexible cord (Table 70), 567.
flood-lighting projectors (Table 75), 572.
fluorescent lighting (Table 74), 571, 591A.
fodder treatment, 852.
frequency standardisation, 135.
fuse wire (Table 73), 570.
geysers (Table 77), 574.
"grid," 195.
hair-dryers (Table 76), 573.
heating and cooking apparatus (Table 77), 574.
hot-plates (Table 77), 574.
hydro-electric plants, 216, 218.
immersion heaters (Table 77), 574.
installations, Chap. 24.
irons (Table 77), 574.
kettles (Table 77), 574.
lampholders (Table 74), 571.
lamps, candle; coiled-coil; dual-purpose; infra-red; mercury-vapour; therapeutic; tubular; ultra-violet; violet-ray; etc. (Table 74), 571.
— *hand (Table 75), 572.*
"*Lavalect,*" *622A.*
lead-sheathed cables (Tables 68, 69), 566.
lighting fittings (Table 75), 572.
main wires and control, 570.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

COST OF (*cont.*)—
motors and control gear, 711 (Tables 128 to 130).
— domestic (Table 76), 573.
Neon lamps (Table 74), 571.
" Nonazo " cables (Table 68), 566.
ovens (Table 77), 574.
overhead lines, 332, 334.
panel heaters (Table 77), 574.
pendants (Table 75), 572.
percentage, for parts of steam plant, 196.
percolators (Table 77), 574.
power-factor corrections, 162.
pre-war and post-war (prices), 530 h, 564.
pumps (Table 76), 573.
radiators (Table 77), 574.
reflectors (Table 75), 572.
refrigerators (Table 76), 573.
rural lines, 846.
screw-eyes, insulating (Table 74), 571.
service lines, 575.
Severn barrage, 230.
shades (Table 75), 572.
soldering irons (Table 77), 574.
steam and electric traction, 894.
— sets, 189.
steel conduits (Table 71), 568.
sterilizers (Table 77), 574.
street lighting, example, 612.
sub-station losses, 426.
switches (Table 73), 570.
table lamps (Table 75), 572.
testing sets (Table 74), 571.
time-switches (Table 74), 571.
toasters (Table 77), 574.
tramways, buses, and rail-less vehicles, 954 (Table 204A).
transmission lines, 218, 332.
tubular heaters (Table 77), 574.
turbines (hydraulic), 214.
urns (Table 77), 574.
vacuum cleaners (Table 76), 573.
vibrators (Table 76), 573.
wall sockets (Table 74), 571.
washing machines (Table 76), 573.
water heaters (Table 77), 574.
water power, 216, 230.
water-tight fittings (Table 75), 572.
wiring for heating and power, 566.
— — lights (Table 67), 565.
wood casing, cleats, 569.
Cotton, 73 (Table 7), 74, 80.
manufacturing and air-conditioning, 647A.
spinning and weaving machinery, 776 (Tables 154 to 156).
-wool air filters, 647A.
Coulomb, 2, 28.
Counterbalances in hoisting, 785.
Counter E.M.F., 132.
Countersinking machines, 775.
Couple, galvanic, 127.
Counterweight pendants, cost (Table 75), 572.
Coupling, hydraulic, Föttinger, and Daimler, 230A, *963.*
— step, 230A.
Cowan-Still transformer, 406.
" Cracore " cable, 820.
Cranes, electric, 786 et seq.
motors for, 787, 789.
types of and data, 789.
Credenda heater, 620.
Creedy converter, 413 (A).
" Creep " in heated tubes, 170.
Creosote, 86, 323.
Crest factor, 30.
— voltmeter, 105.
Crimping iron heaters, 631.
Crompton-Burge " Tru-watt " motor, 697.
Crompton mains system, 277.
Crompton-Parkinson auto-synchronous motor, 696.
Crompton's rule, 33.
Crop treatment, electrical, 857.
Cross-cut saws, 775.
Crossing wires, 324.
Crucible furnaces, 637.
Crude oil, 178, 180.
Crystals and piezo effect, 130.
rectifiers, 417.
Cryto rectifiers, 416.
Cubic meters and feet, 202.
Cubicles, air-conditioned, 647A.
Cumulative and differential compounding, 677.
Cupboards, hot, 628.
Cupro-nickel, 67 (Table 6).
energy for melting, 647 (Table 101).
Curling-iron heaters, 631.
CURRENT (*see also* " Ampere ")—
alternating (*see* " Alternating current ").
and constant-current transformers, 405.
— discharge of cells, 431.
— voltage in all systems, 468.
capacity or charging (*see* " Charging current ").
-carrying capacity of collectors, bow and trolley, 913.
collection on railways, 913.
— — tramways, 912.
continuous (*see* " Continuous current").
danger limit of, 470, 632.
density, 27.
— in carbon electrodes, 641.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

CURRENT (*cont.*)—
density in switches, 369.
direct, *q.v.* (*see also* "Continuous current").
direction of, 33-5, 127, 358.
-displacement motors, 684.
effective, 29, 49.
efficiency in electrolysis, 970.
elementary, 2, 25.
excessive, 337, 338.
flow in electronic devices, 422.
for resistance welding, 664.
fusing, of wires, 342.
heating cables by, 291.
— *by passage of, 637.*
— — *induced, 638, 639.*
-impulse transformers, 405.
in arc welding, 651-7.
induced, for cooking, 629.
lagging and leading, 46, 153 *et seq.* 304.
limitation, 337, 340.
limiter, 272, 374.
-limiting reactors, 340.
magnetism and, 33, 35.
maximum in A.C., 31.
— on short-circuit, 338, 339.
measuring, 98 *et seq.*
-meters for water, 207.
meters, hydraulic, 207.
pressure and, of 3-phase alternator, 143.
primary and secondary in transformer, 391.
rated normal, of oil switch, etc., 369.
rating of cables, 280 (Tables 40A–40K).
rectified, 13, 132, *415 et seq.*
rectifying, 415 et seq.
required by motors, 754.
return, in rails, 389.
reverse, 358.
R.M.S. (root-mean-square), 29.
shunt, 138.
sine wave, 29 to 31.
-transformer testing, 1035.
— *voltage characteristics of arc, 657.*
-transformers, 107, 108, 384, *405.*
virtual, 29.
wattless (*see* "Wattless currents").
— in cables, 312.
Curves, heating and cooling, 1025.
load-duration, electrical, 266.
mass and duration, hydraulic, 209.
Cuscus grass thermantidote, 647A.
CUSEC (*see* Preface to Vol. I)—
and ampere, 25.
equivalents, 202, *768* (*see also* "Water power").
meaning of, 201.
Cutler-Marsden automatic welder, 654.
Cut-outs, fusible, 342, 375.
consumers', 514, 515.
cost of, 570.
I.E.E. rule as to, 516.
in installation, 512.
undertakers', 512.
Cutting and welding, electric (*see Vol. II, Chap. 27*).
by arc, 656-9.
safety in electric, 656, 658.
Cyanamide manufacture, 635, 973.
Cyanide process, 988.
Cyc-arc welding, 666.
Cycles, 12, 135.
Cyclic irregularity in torque, 149, *749.*
Cyclometer dials, 113.
Cylinder gate, 221.

DAIRY WORK, electric, 855.
Dalmarnock station, 196.
Damping and control, 90.
windings, 408, 679.
Damp situations, precautions, 484.
Dams, 219, 225, 244.
sand-filled, for Severn, 230.
"DANGER" defined, 353.
— *in cutting and welding, 656, 658.*
from sawdust, 562.
of faulty earthing, 533.
Dangerous currents and pressures, 470, 632.
Daniell cell, 127.
Darjeeling plant, 256.
D'Arsonval galvanometer, 96.
Dashpots on relays, 344.
Data required for traction projects, 875.
Daylight, 586, 589, 597A.
Daysohm welder, 657.
D.C. (*see* "Continuous current," "Direct current").
Dead-beat instruments, 90.
"*Dead-man's Handle*" *in lifts, 797.*
— — *traction, 741, 897.*
"*Dead water*" *in hot-water supply, 622A.*
in reservoirs, 242.
Deadweight of "electrics," 938.
Deal-splitters, 775.
"Decantation chamber," Uhl., 238.
Deceleration on lifts, 796.
in traction, 899.
"Declared efficiency" defined by B.S.I., 146 note.
Declared pressure and variation, 442, 469.
Decomposition voltage, 970.
Definite time-limit relay, 344.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

DEFINITIONS—
and explanatory matter, Vol. I, *passim.*
B.S.I. for switches and circuit-breakers, 371.
Electricity Supply Regulations, 5, *469.*
general (Chap. 1).
I.E.E., 4.
International, 3, 6.
of controllers, 713, 736, 737.
— electrode boiler, 625.
— starters, etc., B.S.S., 736.
pressure, 22.
service lines, 443.
voltage, 22 ; *revised, 469.*
(*See also* under the heading of the terms defined ; also "British Standards Institution," "International.")
Deflectors, water jet, 255.
"*Dehumidification*" (see also "*Drying*"), *647A.*
De-ion circuit-breakers, 372A.
De-ionizing devices, 372A.
Delivered pressure, 23.
Delon type rectifiers, 1033.
Delta connections, 143, 158, 314.
and star transformer, 394.
Demagnetising, 806 et seq.
Density, current, 27, 369.
of energy concentration, 646A.
(Sp. G.) of materials, 60, 67 (Table 6).
Depreciation and maintenance, 1012, 1013.
Depth, hydraulic mean, 210.
Deri repulsion motor, 702.
traction motor, 896.
Derrick cranes, 786, 789.
Designations of electronic valves (Trade names, etc.), 418.
Desk fans, 758, 760.
testing, 1036.
Detector galvanometer, 96.
"*Detectors,*" *wireless, 417.*
Diagrams, vector, 11, 12A and *passim.*
Dial, cyclometer, etc., 113.
synchoscope, 149.
Diamagnetic, 32.
Dichlo-difluoro-methane, 647A.
Dickens' run-off formula, 204.
Dick (Siemens-Schukert) train-lighting system, 932.
DIELECTRIC—
breakdown, 89.
constant, permittivity, 46, 71.
defined, 4.
hysteresis, 60, 70.
loss in cables, 312.
properties of various, 70 *et seq.*
DIELECTRIC (*cont.*)—
strength, 70, 72.
— of air, 78, 79.
— in oil, 1034.
Diesel-driven ships, 957, 962.
-electric freight ships, 962.
rail cars, 873.
Diesel Engine Users Association, data from 180.
engines, 167, 179, 180.
Difference of potential, 22.
Differential compounding, 657, 677.
Dimming lamps, 586.
resistance, 68.
Dinas bricks, 85.
Diode valves, 419.
Dip and stress, 327, 328, 329.
Diphenyl-oxide cycle, 166.
for binary vapour plant, 191.
— pre-heating, 191.
properties of, 166.
DIRECT—
-acting (main) haulage, 831.
-arc furnace, 640.
-driven lifts, 793.
lighting, 601, 605, 606.
DIRECT CURRENT or D.C. (*see also* "Continuous current").
and A.C. for ship propulsion, 958.
— — — traction, 867, 868.
— alternating distribution compared, 10, 294 *et seq., 475, 478.*
— — in welding, 656.
compared with A.C., 10, 294 *et seq, 475, 478.*
conversion of, 409 et seq.
direction of, 33-5.
elementary, 10, 14.
fluorescent lamps, 591A.
furnaces, 636.
generator (*see* "Dynamo").
main line example, traction, 918.
motors (see "*Motors, D.C.*").
rectification of, 415 et seq.
regenerative braking, 900.
short-time rating, 136.
three-wire system, 461, 463.
traction motors, 896.
tramway return circuit, 903.
transmission, 294, 297, 317.
two-wire system, 460.
vapour lamps for, 589.
wave generator, 420.
Direction of current, 33-5, 127, 358.
Direct lighting, 601, 605, 606.
Disc coal-cutters, 834.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

DISCHARGE—
corona, 316.
rate of lead cells, 431, 432.
— — nickel-iron cells, 433.
— — traction cells, 941.
sluices, 213.
streams, 206.
water in pipes, 232, 246 *et seq.*, *768.*
weirs and notches, 205.
Disconnection of consumer's supply, 512.
"*Discriminator,*" *Scott-Bentley, 718.*
for hoisting, 788.
Dish washers, cost, 573.
Dispersion lenses, 613.
Displacement water-heater, 622A.
Disposal of power applied to a vehicle, 879.
Disputes as to contracts, 1000.
Disruptive critical voltage, 316.
Dissonance coil, 351.
Distance protection, 357, 359.
remote control, 372, 373, 378, *741.*
Distillation products, 983.
Distilling and evaporating electrically, 626.
Distributing main defined, 441.
DISTRIBUTION—
and application of power, 747 (2).
and control in branch circuits, Vol. II, Chap. 22.
and transmission, works cost (G.B.), 269.
boards, 511, 517, 521, 534 (13).
— cost of, 570.
choice of systems of, 474.
from rural lines, 847.
lines, cost of, 575.
main defined, 441.
of power demand in mines, 823.
overhead, 481.
panel, 385.
problems, 456, 473.
system for traction, 892.
underground, in mines, 819.
Divergers, 613.
Diversity and load factor, etc., 262 *et seq.*
factor in group driving, 748.
Diverter control of shunt motors, 717.
Diverting jets, 255.
Dockyards, power for, 779.
Dolomite, 85.
DOMESTIC—
heating (Chap. 26).
light and power on farms, 848.
lighting, 601 (see also "Cooking," "Cooling," "Ventilating," etc.).
uses of motors, 755 (Table 137).
water heating, 621 et seq.
Double-field synchronous motors, 698.
-frequency generation, 390.
squirrel-cage motors, 684.
-stator double-rotor induction motor, 698.
Dowsing clothes warmer, 631.
Draft tube, 214, 218, 220, 232, 233.
Drainage in agriculture, 853.
Dransfield voltmeter, 100.
Drawing-in cables, 290.
Draw-out switchboard, 376, 380.
Dredges, electric, 965.
Dredging equipment, 842.
Drills, 775.
for mining, 836.
Drip-proof motor, 670.
Drive for lifts, 793.
on "*electrics,*" *944.*
DRIVING, ELECTRIC, *Chap. 30.*
adjustable ; multi-speed, 753.
group or individual, 748.
Drop of pressure, 24, 286.
— volts in cables, 286.
Drowned weir, 205.
Drum starter, 736.
Drumm battery, 434B, 873.
DRY—
and wet-bulb temperature, 647A.
battery exploders, 838.
cells, 127.
rectifier, 417.
test of insulators, 330.
DRYING—
by infra-red rays, 648A.
electrical, 634.
-out for tests, 1018.
ovens, 642 et seq.
transformers, 393, 403.
— oil, 403.
Drysdale potentiometer, 95.
wattmeter, 109.
Dry test of insulators, 330.
Dual-frequency induction motor, 693.
lift control, 797.
Duct system, 538, 539.
Ducter Test Set, 119.
Ducts, passage of air through, 765.
Duct-ventilated motor, 670.
Duddell-Mather wattmeter, 109.
Duddell oscillograph, 118.
thermo-ammeter, 99.
Dull-emitter valves, 419.
Duration curves, etc., hydraulic, 209.
load curves, electrical, 266.
Durex wiring system, 552.
Dust, electrical collection of, 996 (see also "Ash").
precipitation in air-conditioning, 647A

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Duty-cycle rating of motors, 670.
Dyes, fluorescent, 591B.
Dynamic braking of synchronous motor, 722.
— *of lifts, 797.*
DYNAMO (*see also* "Alternator," "Generator").
acyclic, 137.
armature, 132, 133.
balancing on 3-wire, 141.
battery charging, 138.
brushes, 133.
characteristic curves, 134, 138.
commutation, 139.
commutator, 133.
compound wound, 134, 138, 148.
efficiency, 146, 167.
elementary, 132.
excitation, 140.
homopolar, 137.
interpoles, 139.
magnets, 32, 35, 40 *et seq.*, 81-3, 133, 138.
parallel running, 148.
power to drive, 164.
rating, 136.
residual magnetism, 81-3, 138.
series and shunt wound, 138.
train-lighting, 729 et seq.
DYNAMOMETER TYPE—
— instruments, 101.
— relays, 358.
— wattmeters, 109.
Dynatron, 420.
Dyne, 2.

EARTH(S)—
and earthed returns in distribution, 482.
conductor defined, 4, 353.
connection, 4, 347, *482.*
current-carrying capacity of, 472.
electrodes, 482.
intermittent, 351.
leakage to, 471, 472.
-leakage trips, 354A, *471, 472, 482, 632.*
leak indicator, 553.
plates, 347, 348.
potential, 24, *472.*
relays, 359.
returns of telegraphs, etc., 908.
shields, 398.
specific resistance of, 907.
testers, 119.
tests in installations, 348, *1026, 1037.*
wires, 324, 347.
Earthed (conductor) defined, 4, 353.
"*Earthed return*" *and* "*earth return*" *explained, 903.*
EARTHING—
accidents, due to bad, 533.
conduit, 544 (*46*).
definition, 4, 353.
in cooking and heating, 632.
— *mines, 821.*
lightning arrester, 346.
— conductor, 348.
metal casings, 533.
neutral, 354, *472.*
— *of transformer, 394, 472.*
posts, etc., 323, 324.
regulations as to, 151, 383.
— *water-heaters, 622A.*
— *water-pipes, 472.*
stays, bearer wires, etc., 533.
"*Easyfix*" *grid-tapping device, 427.*
Ebonite, 73 (Table 7), 74.
ECONOMICS—
— *of high-efficiency in motors, 753.*
— overhead and underground wires, 333.
— power factor correction, 162.
— steam and water power, 217.
— *water heating, 622.*
Economiser, steam, 170.
Economy of electric haulage, 831.
— *3-wire system, 462.*
Eddy currents, 39, 81, 82, 135.
— braking, 114.
— *in transformers, 398.*
Edina alloy, 67 (Table 6).
Edison cells, 434, 939.
lampholders, 486.
Ediswan wiring system, 552.
Effective volts and amperes, 29.
EFFICIENCY (*see also* next entry, "Efficiency of").
control of electric drive, 747 (*3*).
curves of transformer, converter, etc., 425.
defined by B.S.I., 146 note.
economic aspect of, in motors, 753.
frequency and, 135.
fuel and, 166.
power factor and, 155.
power-house, 191.
probable limits, 191.
tests, 1021.
thermal, of induction fluid heater, 639A.
typical, of lamps (*Table 80*), *583.*
EFFICIENCY OF (*see also* preceding entry, "Efficiency").
accumulators, 431, 432, 434.
air and electric working in mines, 833.
alternators, 146.
arc lamps, 583, 594, 595.
boilers, etc., 170.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

EFFICIENCY OF (*cont.*)—
combined sets, 189.
converters, 409, 413, 413A, 425.
Diesel-electric drive on ships, 960.
Diesel engines, 167, 179.
dynamos, 146, 167.
electric lamps, 582.
— processes, 970.
— winding, 827.
electrolytic rectifier, 417.
engines, heat, 167, 179.
gearing, 751.
generators, 146, 167.
glow-lamps, 582, 583 (Table 80).
hot-air drying, 619.
hot-plates, 630.
induced current cooking, 629.
induction furnaces, 639, 971.
industrial processes, 970.
Kaplan turbines, 214.
kenotron, 419.
mercury vapour rectifier, 422.
motor-generators, 388.
motors, A.C. and D.C., 672 (Table 114), (see also "*Motors*").
secondary cells, 431, 432, 434.
sub-stations, 426.
synchronous motors, 679.
thermal storage, 627.
thermo-couples, 165.
traction cells, 939.
transformers, 401, 402, 425.
transverter, 414.
turbines, steam, 173.
— water, 201.
water heating, 624 and note.
— pumps, 768 et seq.
Egg boilers, 628.
E.H.T. (*see* "Extra high pressure").
Einthoven string galvanometer, 96.
Elastic bitumen, 74.
ELASTICITY—
copper, 62, 67 (Table 6).
metals, 67 (Table 6).
wires, 324.
Elaterite, 74.
Electrical Times tables, 194, 269.
ELECTRIC -AL (*see also* "Electricity," "Electric traction," below)—
air-conditioning, 647A.
and mechanical ship propulsion, 957.
— steam winding compared, 827.
bells in mines, 839.
boilers, 625.
brakes, 899.
brazing, etc., 660.
ELECTRIC -AL (*cont.*)—
cooking apparatus, 628.
— on rolling stock, 928 (see also *Chap. 26*).
cranes and hoists, Chap. 31 passim.
cutting and welding (q.v.), *Chap. 27* passim.
Development Association (E.D.A.), 647A.
drills, 836.
driving, Chap. 30 passim.
— advantages of, 747.
— and control, Chaps. 29, 30.
energy, sale of, Chap. 12 passim.
fans, 506, 534, 573, 758 et seq.
— on rolling stock, 928.
— testing, 1036.
furnaces, 971.
heaters, immersion, 623.
— types of, 620.
heating, Chap. 26 (see "*Heating*").
— minor apparatus, 631.
— on rolling stock, 928.
hoisting, Chap. 31 passim.
horse-power, 51.
Inspector of Mines, 823.
installations, cost, Chap. 24 passim.
irons, 574, 631.
kettles, geysers, urns, 624.
lifting magnets, 84, *805* et seq.
lifts, 792 et seq.
lighting, Vol. II, Chap. 25 passim.
— Acts (British), 198, 275, 322, *1040, 1041, 1043.*
— in mines, 840.
locomotives, 872, 873, 894, 919A.
"*Mary Ann,*" *755.*
motors (see "*Motors,*" "*Motors, A.C.,*" "*Motors, D.C.,*" "*Motors, traction*").
ovens and furnaces, 636.
ploughing, 851.
precipitation, 996.
properties of metals, 59-65.
propulsion of ships (*Chap. 37*), see "*Ship propulsion.*"
— of special craft, 965.
pulley blocks, 790.
pumps, 767 et seq.
punkahs, 762.
railways (see "*Railways, electric*").
reduction of iron ore, 976.
refining of metals, 976, 986, 987, 988, 990, 992.
refrigeration, 647A, 773.
road vehicles ("*Electrics*"), see *Chap. 36* passim, "*Road vehicles.*"
separation, 997.
ship propulsion, Chap. 37 passim.
shock, danger of, in welding, 656, 658.
— from earthed circuit, 482.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

ELECTRIC -AL (*cont.*)—
— *pressures, frequencies, etc., 632.*
— *prevention of, in domestic heating, etc., 632.*
shot firing, 838.
signalling on railways, 933.
stacking machines, 802.
steam boilers, 625.
steel, 977, 978.
steering on ships, 964.
supply for arc welding, 656, 657.
— public, 185, 268.
technical terms, Chap. 1.
traction, Chaps. 34, 35 (see below, "*Electric traction*").
treatment of fodder, 852.
winches and capstans, 791.
winding, 827 et seq.
ELECTRICITY—
and agriculture (Chap. 33), see "*Agriculture.*"
— *compressed air compared, 833.*
— *hoisting (Chap. 31),* see "*Hoisting.*"
— *mines (Chap. 32),* see "*Mining.*"
— *processes (Chap. 38),* see "*Processes.*"
— *ship propulsion (Chap. 37),* see "*Ship propulsion.*"
— *vehicles, 927 to 932* (see also "*Road vehicles*").
coal and gas compared, 576, 622, 628.
COMMISSIONERS—
Regulations, *see detailed list under* "Regulations and Rules" (*see also* "Regulations," "Rules," "Wiring Rules").
— *and loans, 1013.*
— — *standardisation, 814.*
— — supply, 185.
— *memorandum on agriculture, 846.*
— *powers of, 1046.*
for luminous tubes, 612A.
regulations (factory and workshop), *see detailed list under* "Regulations and Rules."
static in cotton mills, 647A.
Supply Act, 1919, 198, 322, *1040, 1041, 1043.*
— — 1922, 275.
— (Meters) Act, 270.
"Electrics" (*see* "Road vehicles, electric").
ELECTRIC TRACTION (*see also* "Railways," "Road vehicles," "Tramways")—
acceleration, 879, 882, 883.
— *on local lines, 865.*
adhesion, 871, 890.
air resistance, 879.
automatic sub-stations, 869.
battery locomotives, 873.
ELECTRIC TRACTION (*cont.*)—
bonding, 903, 925.
characteristic curve of traction motor, 886.
classification of systems, 864.
converters for, 869.
data required for projects, 875.
D.C. v. A.C. for, 867, 868.
Diesel-electric cars, 873.
disposal of power on vehicle, 879.
distribution for, 892.
electric locomotives, 872.
energy required for, 878 et seq.
— *stored in vehicle, 882.*
— *used per ton-mile, 887.*
estimates for, 875.
examples of, 880 et seq.
"*full automatic*" *sub-stations, 869.*
general information on, Chaps. 34, 35.
— *expression for power needed, 884.*
generating stations for, 893.
generation for, 867.
goods locomotives, 872.
gradients in, 879, 881, 946.
high-speed circuit-breakers for, 869, 914.
industrial locomotives, 874.
inter-urban railways, 865.
line, systems of supply to, 868.
locomotives, electric, 894.
main lines and local lines, 865.
master control, 871.
mercury-vapour rectifiers for, 869.
metadyne in, 389A.
multiple-unit trains, 871.
oil-electric locomotives, 873.
passenger locomotives, 872.
power and energy calculations for, 878 et seq.
— *required on level, 879, 880.*
— — *for acceleration, 882.*
— — *on gradients, 881.*
practical methods of calculation for, 885, 886.
projects and service, 875 et seq.
protection in, 892.
rail-cars, and motor-coaches, 871, 873.
railway supply, 868.
Ramsay locomotive, 873.
rectifiers for, 869.
regeneration in, 881.
rolling stock for, 876.
— — *and service, 876, 877.*
— — *supply to, 868.*
rotary-converters for, 869.
savings due to, 863.
self-contained locomotives, 873.
shunting locomotives, 873.
speed-time curves, 886.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

ELECTRIC TRACTION (*cont.*)—
statistics of, 863, 865, 874, 887.
steam and electric, compared, 894.
sub-stations for, 869, 893.
suburban railways, 865.
"*supervisory control,*" *869.*
systems of supply for, 866-8.
terminal congestion on, 865.
three-phase locomotives, 872.
tractive coefficient, 879, 890.
— effort, 890.
— resistance, 891.
traffic and energy data, 887-9.
tramcars, 870.
tramway supply, 868.
transmission for, 867.
turbo-electric locomotives, 873.
uniform speed, on level power required for, 880.
ELECTRO-CHEMICAL—
equivalents, 970 (Table 213).
furnaces, 634, 635 (*and* see also "*Processes*").
generator, 127, 128.
instruments, 89 *et seq.*
phase advancer, 160.
processes (see "*Processes*").
series, 127.
Electro-chemistry (see *Vol. III, Chap. 38;* see also "*Processes*").
-chlorination process, gold, 988.
-culture, 857.
Electrode arrangements, 970.
boiler defined, 625.
Electrodes, 66.
battery, 430.
chromium, etc., 597.
earth, 482.
for arc furnaces, 641.
— — welding, 652, 653, 657.
magnesium, 588B.
Electrodynamic units, 2.
braking of motors, 715, 717, 718.
series motors, 718.
shunt motors, 717.
Electro-hydraulic steering gear, 963.
ELECTROLYSIS—
Faraday's laws of, 127, *970.*
in electric boilers, 625 and note.
of brine, 984.
on traction systems, 907.
ELECTROLYTE, 68, 127.
for iron-nickel cells, 433.
— lead cells, 431, 432.
— rectifier, 417.
volume per cell, 431.
ELECTROLYTIC—
alkali, gases, metals, etc., 635, 984.
cell, 127.
copper, 987.
corrosion, 324.
— of lead, 553.
hydrogen and oxygen, 985.
instruments, 89 *et seq.*
iron, 82.
lightning arresters, 346.
meters, 113, 114, *1035.*
meter testing, 1035.
rectifier, 417.
synthesis, 995.
ELECTROMAGNETIC—
clutch, 751.
generators, 132.
hoisting and lifting, 805 et seq.
instruments, 89 *et seq.*
release, 743.
separation, 997.
Electromagnets, 32, 41, 133 (see also *Vol. II*).
in cyc-arc welding, 666.
Electro-mersible pumps, 767.
Electro-metallurgical furnaces, 634, 635, 640 (see also "*Processes*").
Electro-metallurgy (see "*Processes*").
"*Electro-metals*" *furnace, 640.*
Electrometer, 96.
Electromotive force, 22 (*see* "Pressure").
counter, 132.
of thermo-couple, 122.
Electronic devices for control purposes, 418A, 420A.
Electro-osmotic separation, 997.
percussive welding, 665.
Electroplating cell, 127.
processes, 994.
Electro-positive and negative elements, 127.
ELECTROSTATIC—
air-filters, 647A.
capacity of cables, 311.
charge indicator, 104.
flux shield for insulator, 330.
generator, 131.
grading of insulators, 330.
instruments, 89 *et seq.*
ohmmeter, 119.
oscillograph, 118.
separation, 997.
units, 2.
voltmeter, 103, 104, 107.
Electro-technical terms and definitions, Vol. I, Chap. 1.
Electro-typing, 994.
Elementary explanations, 8 *et seq.*

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Elmore process, copper, 987.
Elo (resin plastic), 74.
Elongation in wires, 324.
Elverson oscilloscope, 123, 214.
E.M.F. of accumulators, 430, 431, 434 (see also "*Pressure*," "*Voltage*").
Empire cloth, 74, 287.
Enamel baking ovens, 643.
Enamelled wire, 80.
Enamels, baking and drying, 646A.
insulating, 76.
ENCLOSED—
arcs, 593.
fittings, 484.
fuses, 375.
hot-plates, 630.
motor, defined, 670.
Enclosure of motors, 751.
End contractions in weirs, 205.
turns and surges, 349.
Endless haulage, rope and chain, 831.
Endosmose, electrical, 997.
ENERGY—
conservation of, and "reverse cycle," 647A.
consumption of (*see* next entry, "Energy consumption". *See also* "Power," "Power required for").
defined, 52.
demand for acceleration, 883.
equivalents, 52.
measurement, A.C., 110.
sources of, 126.
stored in field, 57.
— — *moving vehicle, 882.*
transformation and conversion of, 387 et seq.
used per ton-mile in traction, 887.
— — — *with batteries, 940.*
ENERGY (ELECTRIC), CONSUMPTION DATA FOR—
agriculture, 845 et seq., *858.*
air heating, 619, 647A.
— *-conditioning, 647A.*
arc cutting, 659.
— *welding, 652.*
baking ovens, 643, 644.
coal cutters, 834.
cyc-arc welding, 666.
electric cooking, 628.
"*electrics,*" *946.*
escalators, 804 (*Table 173*).
fodder treatment, 852.
haulage, 832.
heating rooms, 619.
— *water, 621* et seq.
hoisting, 784.
induction furnaces, 639.
industrial heating, 635 (*Table 97*).
ENERGY (ELECTRIC), CONSUMPTION DATA FOR (*cont.*)—
lifts, 801.
melting metals, etc., 645 (*Table 98*), *647* (*Table 101*).
mining, 814, 816, 823 et seq.
motor-cars, 946.
ovens and furnaces, 635 (*Table 96A*), *639.*
processes, Chap. 38 passim.
railways, 878 et seq., *888.*
rivet heating, 637.
small water-heaters, 622A.
steel-treating furnaces, 646.
street lighting, 612.
tea manufacture, 619.
tramways, 878 et seq., *889.*
water heating, 621 et seq.
ENGINES, STEAM—
— compared with turbines, 189.
— condensing and non-condensing, 172.
— consumption of steam, etc., 167.
gas and oil, 167, 179, 181.
Ensilage, 852.
Entz booster, 432.
Epicyclic gearing for speed variation, 751.
Equalising circuit for compound dynamos, 148,
connection, 412.
Equipment, permanent way and return circuit, 901 et seq.
railways, overhead, 913 et seq.
— *third-rail system, 920* et seq.
tramways, overhead system, 909 et seq.
Equivalents, electrical and mechanical, 48 *et seq.*
hydraulic, 202.
resistance inductance and impedance of transformer, 392.
Erbia, 583.
Erection of conduit wiring, 543.
Erg, 2.
Erinoid, 73 (Table 7), 74.
Errors of instruments, 92 *et seq.*
Escalators, 804.
"*Escura*" *lamps, 589.*
Estimates, traction, 875.
Eupatheoscope, 620.
Eureka alloy, 67 (Table 6).
Evaporation and distillation electrically, 626.
— in boilers, 170.
Evaporative condensers, 175, *647A.*
Everett-Edgcumbe power factor indicator, 111.
synchroscope, 149.
Evershed earth-circuit continuity tester, 821.
EXAMPLES OF—
lifts, 797, 799.
main line D.C. traction, 918.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

EXAMPLES OF (*cont.*)—
railways with overhead construction, 915 et seq.
speed-time curves in traction, 886.
tariffs, 275.
third-rail traction, 916, 921.
traction, general, 880-8.
Also Vols. 1, 2, 3 *passim.*
Excessive pressure, causes, 345 *et seq.*
Excitation for ship propulsion, 960.
of dynamos, 140.
Exciter, 133, 140.
Exhaust and pressure fans, 763.
turbine, Bauer-Wack system, 963.
EXHAUST STEAM—
in mines, 817.
— turbines, 173.
utilisation of, 176, 185, 188.
Exhausters and blowers, 766.
Expansion of metals, 67 (Table 6), 331.
Expansion-type circuit-breaker, 368A.
Explosion-proof gear, 740.
motors in mines, 818.
switchgear in mines, 822.
tanks, 356.
Explosions in mines, 812.
Export of power, 198.
EXTERNAL AND INTERNAL—
characteristic, 138.
combustion, 166.
resistance, 21.
Extinguishing arc by gas, 368A.
Extra fuel for additional units, low cost of, 265.
Extra high pressure (E.H.T.), 22.
cables, 288, 289.
transmission, 315 *et seq.*
EXTRACTION AND REFINING OF—
copper, 987.
gold, 988.
nickel, 990.
silver, 989.
zinc, 991.
(*See also* "*Processes.*")

FABROLITE, 74.
Face-plate starter, 736, 738.
switches, 374.
FACTOR OF SAFETY—
of conductors, 324.
— insulators, 324.
— overhead wires, 324.
— pipes for water power, 248.
— poles, 324.
— stays, 324, 326.
Factory and Workshop Regulations, 58, 151, 152, 293, 353, 356, 382, *1050* (*see also* "Regulations and Rules").
Failure of insulation and protection, 352.
"*Falco*" *inducer, 629.*
FALL OR HEAD OF WATER—
on canals, 218.
general, 201-3, 215.
high, Chap. 10.
low, 218-23.
medium, 224-33.
variable, 223.
FANS—
ceiling and desk, 534 (*22*), *758* et seq.
— *cost, 573.*
data as to air, 764, 765.
forge, 775.
hours of use and consumption, 761 (*Tables 141, 142*), *764.*
in air-conditioning, 647A.
— *mines, 726, 824.*
— *rolling stock, 928.*
— *series-parallel, 453, 506.*
on shipboard, 963.
series-parallel switches, for, 506.
speed control of, 726 (*Table 134*).
testing, 1036.
Faraday's laws of electrolysis, 970.
Farads, 2 (*see also* "Capacity").
Farms (*Chap. 33*), see "*Agriculture.*"
buildings, distribution for, 847.
machinery and power required on, 885.
FAULTS—
and leakage, 354A, *471, 472, 553.*
general, Chap. 15.
relays and, 344, 354A.
testing, 1026, 1032.
to earth, 351.
Faure plates, 431.
FEEDER(S)—
boosting, 389.
defined, 442.
panels, 385.
railway, 924.
reactance, 340, 370.
return, traction, 906.
services and, 334.
tramway, main and line, 923.
Feeding points, 473.
Feed water, 171.
"*Ferflex*" *cable, 820.*
Ferno alloy, 67 (Table 6).
Ferranti-Field leakage protection, 352.
Ferranti-Hawkins, core balance system, 359.
Ferranti rectifier, 416.
thermal storage, 627.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Ferries, electric, 965.
Ferro-alloys, 635, 979.
-manganese, energy for melting, 647 (Table 101).
-nickel, 67 (Table 6).
Ferrozoid alloy, 67 (Table 6).
Ferry alloy, 67 (Table 6).
Fertilisers, nitrogenous, 973.
Fibre, vulcanised, 73 (Table 7).
Fibroid, 74.
Fibrous insulators, 74.
FIELD—
alternator, 133, 140.
building up, 138.
control, speed variation, 716.
data in traction, 875.
dynamo, 140.
elementary, 32, 40 *et seq.*
general, 133.
magnets, 133.
residual, 81-3, 138.
rheostats, 385, *736.*
strength, unit of, 2, 6.
synchronous motor, 160.
system of motors, 671.
variation speed-control, series motors, 718.
Fiery mines, 818.
Filament (glow) lamps, 156, *583* (*see* "Lamps").
Filtering transformer oil, 403.
FILTERS—
for air, types of, 647A.
— ventilators, 146.
Finance of electric farming, 859.
Fireclay, 85.
Fire risk, 356 (*see* "Regulations and Rules").
Fires in transformer chambers, 404.
Firing explosives electrically, 838.
First charge of batteries, 432.
First-grade instruments, 92.
Firth's steel, 81.
Fish kettles, electric, 628.
paper, 74 (ix).
Fishplates, British standard, 901.
Fittings (Chap. 21).
cost of, 571.
in specification, 534 (18), (23).
wires, 488.
Fixed and "works" cost, 269.
— charge per lamp or k.w., 272.
— coil galvanometer, 96.
Flame arcs, 594, 599.
FLAMEPROOF—
construction for mines, 832.
fuses, 375.
gear, 740.
motors, 670.
FLAMEPROOF (*cont.*)—
switchboards, 376, 379.
switches, 366.
FLASH—
boilers, 170.
— *butt welding, 661.*
lamp, mercury, 589.
-over on rotaries, remedies for, 869.
— voltage, 330, 338.
-point of oil, 1034.
Flat irons, 574, 631.
rate charges for energy, 270.
Fleming's Cantor lectures, 619.
rule, 35, *669.*
valve, 418 et seq.
FLEXIBLE WIRES AND CABLES—
cable and cords distinguished, 525.
cost of, 567.
for vacuum cleaners, 525.
general, 284, 285.
I.E.E. rules for, 284, 285.
in mines, 820 (see also §§ 284, 285).
suspension, 910.
twin wiring system, 549, 550.
unkinkable, 281.
Floating battery, 142.
— weir, 244.
Flood and searchlights, 586, 613.
— discharge, hydraulic, 204.
-light projectors, 586.
— — *cost (Table 75), 572.*
Floor area covered by fans, 761.
— tariffs, 273.
space required by plant, 196.
Flooring machines, 775.
Flotation concentration, silver, 989.
Flour mills and bakeries, power required, 756.
Flow of current, direction of, 33-5, 127, 358.
FLOW OF WATER—
and storage, 234 *et seq.*, 243.
approximations, 202.
from catchments, 204.
in pipes, 232, 246 *et seq.*
over weirs, 205, 244.
through sluices, 213.
Fluctuating loads on motors, 753.
— price of copper, 332.
Flue gas analysis, 171.
Fluid flywheel (Föttinger and Daimler), 230A, *963.*
Fluids, inductive heating of, 639A.
Flumes (water channels), 211, 212, 237.
Fluorescence, 587, 591A.
Fluorescent lamps and powder, 591A.
— *cost (Table 74), 571.*
Fluor-spar, 130.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

FLUX, MAGNETIC—
density, 82.
general, 41, 43.
in transformer, 391.
measures, 121.
meter, Grasset, 121.
of magnetic induction, 2 (Table 1).
shield, 330.
unit, 2, 6.
"*Flying Hamburger" Diesel coach, 873.*
Flywheel, fluid, 230A, *963.*
motors, 751.
storage, 751, 753, 828, 829.
— in winding, 828, 829.
Focussing lamps, 586.
Fodder, electrical treatment of, 852.
Foot-candle defined, 579.
-meter, 580.
Foot-pounds, 2, 48, 50, 52, 53, 201.
-warmers, 631.
Force defined, 2.
lines of, 35, 41.
"Forced draught machine," 4.
— motor, 670.
Ford motor works plant, 196, *646A.*
Forebays, 231, 235, 245.
Forge fans, 775.
Formapex, 74.
Form factor, 30.
Formite, 73 (Table 7), 74, 75.
FORMULA—
for air-heating, 619.
— thermal storage, 627.
— transmission, 295, 297 *et seq.*
— water heating, 621.
(and *passim.*)
Forster magnetic clutch, 751.
Föttinger hydraulic coupling, 230A, *963.*
Four-wire 3-phase supply, 467.
Fractional distillation, 169.
H.P. motors, 670, 680, 710, 755.
— — limits of temperature rise for, 670 (Table 109).
— — speeds and weights of, 710 (Table 128).
Fractionating rain-gauge (Meares), 204.
Fractions in oil, 178.
Frame saws, 775.
Frames and greenhouses, treating soil in, 857.
cotton, power for, 776.
treating soil in, 857.
Francis wheel, 203, 214, 215, 221, 233.
Free-stator starting of synchronous motor, 722.
FREIGHT—
and water-power, 217.
locomotives, cost of, 926.
FREIGHT (*cont.*)—
locomotives on G.I.P. Railway, 918.
railway, British Post Office, 922.
Freon as refrigerant, 647A.
FREQUENCY(IES)—
allowable variation in, 469.
and efficiency of transformer, 401.
— torque of induction motor, 681.
British standard, 1047.
changers or converters, 135, 186, *390.*
-changing speed-control of motors, 725, 728.
coupling, different, 388.
effects of various, 135.
errors in instruments, 92.
for steel furnace, 647.
general, 47.
in arc welding, 656.
measures, 112.
meters, 92, 112, 385.
of mechanical vibration in quartz, 428B.
speed and, 123, 135.
standard, 134, 135, *428B, 477.*
standardisation, cost of, 135.
very low, in ship propulsion, 956.
Fresnel lens, 591A.
Fret saws, 775.
Frick furnace, 639.
Frictional machine, 131.
Friction clutches, 751.
in water pipes, 247, *768.*
tape, 74.
Front and back connections, 363.
Frying pans, 628.
FUEL—
capital costs and, 217.
coke, 168.
combustion of, and efficiency, 166 *et seq.*
Conference, 816, 1058.
consumption and weight of various ship drives, 957 (Tables 206, 207).
— of generating stations in G.B., 1931 and 1936, 191 (Tables 22 and 22(A))
— — internal combustion engines, 179.
costs, 269.
economy of electric-drive on ships, 957.
engines, 179.
extra, for additional units, 265.
gaseous and liquid, 178, 179.
general, 168.
grate area and, 170.
Research Board, 169.
steam consumption and, 167.
Full automatic sub-stations, 869.
Full-wrap traction for lifts, 793.
Fullerboard, 74.
Fuller cell, 127.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Fumes, precipitation of, 996.
FURNACES, ELECTRIC, 156, *971.*
and ovens, 634, 635 (Table 96A), et seq.
arc, 640.
classified, 971.
for treating steel, etc., 646.
induction, 639.
melting, 647.
power factor of arc, 156.
processes, 635, 636, and *Chap. 38* passim.
resistor, 978A.
steel, 977, 978.
transformers for, 405.
FUSE LINKS (*see also* "Circuit-breakers," "Cut outs")—
bimetal, 342.
carbon tetrachloride, 375.
cartridge, 375.
consumers', 514, 515.
copper, tin, lead, 342.
enclosed, 375.
for mine work, 375.
high-tension, 375.
I.E.E. rule as to, 516.
in telephone circuit, 335.
"*M effect*" *in, 515.*
oil-immersed, 375.
standard, B.S.I., 375.
-switch and link defined, 4.
trip relay, 344.
wire, cost, 570.
Fusing currents, 342.
Fusion, latent heat of, 645 (Table 98).
Fynn-Weichel synchronous-asynchronous motor, 697.

G ("*g*"), value of, 2 note.
Galalith, 73 (Table 7), 74.
Gallons and cusecs, 202.
Galvanic couple, 127.
Galvanising, wet, 994.
Galvanometers, 96.
Ganges hydro-electric plant, 216, 218.
Ganister brick, 85.
Gantry Cranes, 786, 789.
Garages, lighting, 613.
"Garty-apex" wind set, 165.
GAS(ES)—
and arc lighting compared, 609.
arc extinction by, in circuit-breakers, 368A.
blast furnace, 167.
coal and electricity, 576, 622, 628.
-discharge lamps, sodium, etc., 587-91, 612.
engines, 167, 179, 181.
GAS(ES) (*cont.*)—
-filled cables, 289, 290A.
— *lamps, 571, 585, 599.*
— — *cost, 571.*
— — *over-running effect, 585.*
-fired boilers, 170.
fuel, 168, 178, 179.
heating of water by, 622.
in mines, 812, 818.
ionized spectrum of, 592.
plant, specification for, 1010.
producer (suction), 167.
town, 167.
turbine, 179, 183.
-warning safety-lamps, 841.
welding in, 655.
Gate interlocks for lifts, 797.
-end loaders, 835.
Gates, water, 221.
Gauge, standard, wire, 279.
hook, 205.
Gauges, rail, in use in mines, 832.
Gauss, 1 (Table 1), 40.
Geared drive for lifts, 793.
tramway motors, 895.
turbines v. *electricity for ships, 962.*
Gearing, efficiency of, 751.
epicyclic, for speed variation, 751.
on ships, 960.
Gearless drive for lifts, 793.
— — *road vehicles (Cedes), 944.*
Gebus system of locomotive motor control, 873.
Geissler tube, 588A.
Gel (gelatinous substance), 647A.
Gem mines, 842.
General conditions of contract, I.E.E. model, 534 note, 999, 1000.
General Electric Co. (U.S.A.), and high-pressure, 315.
General expression for power required for traction, 884.
Generating costs, 194.
sets, Chap. 6 *passim.*
— *self-contained, 929.*
station, automatic, 187.
stations, traction, 893.
Generation and transmission for traction 867.
of power on rolling stock, 929-32.
GENERATORS (*see also* "Alternator," "Dynamo")—
and accessories, Chap. 4.
— *motors, limits of temperature rise in, 670 (Tables 110, 112).*
burning out of, 356.
capacity, in power-house, 189.
delta connection, 314.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

GENERATORS (*cont.*)—
efficiency, 167.
— and ventilation, 146.
electrostatic, 131.
elementary, 132 *et seq.*
for arc welding, 656, 657.
frequency, 135.
high-speed, 145.
metadyne, 389A.
panels, 385.
parallel-running, 148-50.
power to drive, 164.
rating and temperature rise, 136.
reactance, 340.
regulation tests of, 1022.
series, Thury, 317.
specification for, 1001.
star connection, 314.
testing (Chap. 40).
Gennevilliers plant, 173, 196, 288, 356.
Geothermic power, 165.
German silver, 67 (Table 6).
Geysers, electric, 624.
cost, 574.
Gilbert, 2 (Table 1), 42.
Gilles' valve, 346.
Gilsonite (asphalt), 74.
Gin, cotton, 776.
G.I.P. (see "*Great Indian Peninsular Railway*").
Girard wheel, 233.
Girod furnace, 640.
Glasgow system of charging for energy, 273.
Glass, annealing, 636.
insulators, 74, 330.
properties of, 73 (Table 7), 80, *645 (Table 98).*
Globes, reflectors, 599.
"*Glo-clad*" *wiring, 552.*
Glossary of illumination terms, 580.
Glow lamps (*see* "Lamps").
and power factor, 156.
— *efficiency of, 582, 583.*
Neon type of, 588B.
Glue pots, 631.
Glyptal and Glyptal-mica, 74.
GOLD—
extraction and refining of, 988.
plating, 994.
properties of, 67 (Table 6), 127, *645 (Table 98).*
reflectors, 646A.
Goldschmidt process, tin, 993.
Goliath cranes, 789.
lampholders, 486, 487.
Goods lifts, 798.
locomotives, 872.
Governors, water wheel, 221, 255, 256.
Grab buckets, 789.
Grade of cables, 281, and Chap. 13 *passim.*
— insulation defined, 4.
Graded insulation, 289.
Gradients in traction, 879, 881, 946.
power required on, 881.
ruling, 875.
slope equivalent of, 946.
Gramme-centimetre, 2.
equivalent, 970.
GRAPHICAL—
construction for active and reactive components, 12.
— — addition of loads of different P.F., 157.
— — alternating E.M.F. and resistance, 144.
— — effect of synchronous motor, 160.
— — limit of P.F. correction, 163.
— — single-phase lines, 300.
— — 3-phase lines, 303.
— — Varley phase-rotation test, 150.
— — Watt and wattless components, 154.
example of Kelvin's law, 353.
method for power factor and K.V.A., 157, 159.
— — reactance, etc., 300, 303.
symbols, 58.
vectors, 11, 12A.
GRAPHITE, 66.
crucibles, 637.
electrodes, 641.
manufacture, 635, 982.
production, 982.
Graphitised carbon, 66, *639.*
Grasset fluxmeter, 121.
Grate area in boiler, 170.
Gratz connection, 417.
Gravity, value of *g*, 2 note.
control instruments, 90.
Grease-spot photometer, 580.
Great calorie, 48.
Great Indian Peninsular Railway, 916, 918.
Southern Railway of Ireland, 873.
Greaves-Etchells furnace, 640.
Greenawalt process, 988.
Greenhouses and frames, 632.
heating soil in, 857.
Grid-controlled M.A. rectifiers, 315.
Grid supply and private plants, 185.
GRID(S)—
and reduction of reserve plant, 186 note, 189.
balancing and the, 427.
controller rectifiers, 315, *424.*
control of valves, 390, 418, 418A.

GRID(S) (*cont.*)—
cost of, 195.
frequency and clocks, 428B.
in valves, 418.
supply and private plants, 185.
system, British, 135, 194, 197, 198, 269, 275A.
tapping the, 427.
Grinders and grindstones, 774, 775.
Grounds, arcing, 351.
Group and individual drive compared, 748.
Grunsky's coefficients, 207.
Guard brackets, 324.
wire regulations, 1052.
Guarding trolley wires, 909.
Gummoid (plastic), 74.
Guttapercha, 73 (Table 7), 74.
Gyptal, 74.

HAAS–ŒTTEL cell (caustic-alkali), 984.
Haber process, 973.
Hadfield's steel, 83, 84.
— *trackwork, 902.*
Hail prevention, electrical, 857.
Hair-dryers, 631.
cost of (Table 73), 573.
Half and quarter wave transmission, 318.
"*Half-watt*" *lamps, 585, 599.*
Half-wrap traction for lift, 793.
Hall process, 975.
Hamburg Diesels, 180.
Hamilton poles, 323.
Hammer-head cranes, 789.
Hand-lamps, cost (Table 78), 572.
Hand-operated starters, 738.
-rope lift control, 797.
Handyell control system, 372, *428.*
Hard coke, 168.
Hard-drawn copper, 66, 295, 307.
Hard rubber, 74.
metal-sheathed wiring, 556.
Hardening steel electrically, 646.
Harland and Wolff Diesel engines, 180.
HARMONICS—
and resonance, 350.
— *transients in transformer, 394, 407.*
very high, 428B.
Hartford M.-V. plant, 166.
Haulage in agriculture, 854.
— *mines, 831.*
HEAD OF WATER—
canal falls, 218.
definitions, 200.
developments of high, Chap. 10.
— — low, 218-23.

HEAD OF WATER (*cont.*)—
development of medium, 224-33.
elementary, 201.
in pumping, 768.
lost in pipes, 247.
variable, 223.
Headworks, hydraulic, 236.
HEAT—
and power from steam, direct or electrical, 747 (1).
conductivity of building materials, 647A.
— — *krypton, 585.*
consumption per kWh in G.B., 191.
— and plant refinements, 191.
distribution in boilers, 170.
losses in power-house, 191.
low grade and waste, 176, 188.
pump, heating and cooling by, 616, 620A.
removal by hydrogen, 80A, 191, *671.*
run tests, 1023.
stored in water, formula for, 627.
treatment for plants, 857.
— *of steel, 978A.*
unit, international, 52.
Heaters, electric, and P.F., 156.
immersion, 623.
panel and tubular cost (Table 77), 574.
remote control of, at peak, 615.
types of electric, 620.
water (*see* "Water heaters").
HEATING (*see next entry also*)—
and cooling air, 647A.
effect of short-circuit, 338.
electric (*see below*).
of cables, 291, 312, 338.
— insulation, 352.
-surface of boiler, 170.
HEATING, ELECTRIC (*Chap. 26*)—
advantages of, 615.
air, by compression or chemically, 176, *647A.*
and cooking, wiring for, 530.
— *cooling by heat pump, 616, 620A.*
— — *curves, 1025.*
— *melting metals, 645.*
apparatus, cost, 574.
— *minor, 631.*
by induced current, 638, 639.
— *passage of current, 637, 645.*
— — *calculations for, 618, 619, 621, 627.*
cost of wiring for, 566.
effect of short-circuit, 338.
elements, 616, 617.
fluids by induction, 639A.
I.E.E. rules as to, 633.
in vehicles, 928.
— *of metals, 639.*

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

HEATING, ELECTRIC (*cont.*)—
inductive, of fluids, 639A.
industrial, 634 et seq., and *Chap. 38.*
in vehicles, 928.
limitations of, 615.
of air, 619, 647A.
— cables, 291, 312, 338.
— *churches, 619, 620.*
— *cinemas, 620.*
— *converters, 408, 409.*
— *generators and motors, to avoid condensation, 963.*
— insulation, 352.
— *metals, 639.*
— "*pyrotinax*" (*magnesia*), *cables for, 566.*
— *rooms, 619, 620.*
— *various materials, 618.*
— *water, 621* et seq.
safety in, 632.
Hecnum alloy, 67 (Table 6).
Hefner candle, 579.
Height of overhead lines, 324.
— — *trolley wire, 909.*
Helical gearing for lifts, 793.
Helium in lamps, 589.
Hell Gate station, N.Y., 196.
Helsby wiring system, 551, 552.
Henley Manual, 291, 311.
leak indicator, 553.
wiring system, 552, 554.
Henries and millihenries, 2, 36.
Herdecke hydraulic storage scheme, 230A.
Hering melting furnace, 639.
Heroult furnace, 640.
process, 975.
Hertz, 134.
Hewlett insulators, 330.
Heyland induction motor, 688.
High-fall water-power, Chap. 10.
Highfield booster, 432.
transverter, 414, 425.
HIGH-FREQUENCY—
air-core induction furnace, 639.
alternators, 144.
currents, 47 (*see also* "Lightning").
induction motors for tools, 774.
High-intensity neon lamps, 588B.
HIGH PRESSURE, ELECTRICAL—
cables, 287-9.
constant-current in mines, 815.
defined, 22.
extra (E.H.T.), 22, 288, 289.
mercury-vapour lamps, 587.
overhead lines, 481.
transmission, 315 *et seq.*
High pressure and temperature steam, 170, 189, 191, 196.
— — engines, 172.
HIGH-SPEED—
circuit-breakers, 372 (3).
— *in traction, 869, 914.*
Diesel motor coach, 873.
generators, 145.
High-temperature heating, 634.
High-tension machines for crop treatment, 857.
— potentiometer, 95 (3).
-voltage cable tests, 1028.
Hill-shotter demand indicator, 117.
Hipernik, 82.
Hoisting, conveying, etc., *Chap. 31* (*see also* "Lifts").
energy used in, 784.
speed, 788.
Hoists, conveyor, 803.
Hollow walls and air-cooling, 647A.
HOLOPHANE—
"*controlenses,*" *591.*
lumeter, 600.
shades, 599.
HOME OFFICE—
lampholders, 486.
regulations, general, 58, 151, 152, 293, 353, 356, 382, *612A, 658, 1040, 1050, 1051.*
— *for factories and workshops, 1050.*
— — *mines, 812-14, 819-22, 838, 839, 841, 1051.*
— — *ships, 966.*
(*See under* "Regulations and Rules—Home Office.")
wall sockets, 494.
welding dangers and the, 656 note.
Homopolar dynamo, 134, 137.
Honda's steel, 83.
Hook gauge, 205.
Hopkinson tests, 1021.
Hopkinson's law, transmission, 333.
Horizontal and vertical motors, 751.
HORN—
arresters, 346.
fibre, 74.
gap switches, 364.
HORSE-POWER (*see also* "Energy," "Power," and Chap. 6 *passim*).
choice of, 752.
equivalents, 51, 201.
for pumping, 768 et seq.
-hour, 53, 202.
indicated, brake, electrical, etc., 51, 202.
in water-power, 201.
of internal combustion engines, 179.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

HORSE-POWER (*cont.*)—
of motor-cars, 943.
— motors, determining, 752.
— — in mines, 823.
required for mining purposes, 824 et seq.
— — traction, 879 et seq.
HOT—
and cold water transmission analogy, 11.
cupboards, 628.
plates, 628, 630.
— cost of, 574.
spot temperature, 122.
— — in transformer, 402.
water radiator, 620.
— required in houses, 622 note.
well, condenser, 175.
HOT WIRE—
— instruments, 89, *et seq.*, 99.
— oscillograph, 118.
Hours of lighting, 607, 612.
House transformers, 479.
Howard leakage detector, 352.
H-poles, 323.
Hudson Ave. station, N.Y., 196.
Humidifiers, cotton, 647A, 776.
Humidity, control of, 647A.
Humphrey pump, 182.
Hunt cascade motor, 694.
Hunter four-core pilotless and other protective systems, 359.
"*Hunting*" *in converters, 408.*
— synchronous motors, 679.
HYDRAULIC (*see* "Water-power")—
analogies, 8, 9, 11, 24, 46, 260, *444*, *448*.
cloth presses, 776.
Föttinger coupling, 230A, *936*.
laboratory, 214.
mean depth, 210.
rams, 772.
slip-coupling, 230A.
turbines (*see* "Turbines, water").
Hydraulicing in mines, 842.
Hydrautomat for water raising, 230, *772*.
HYDRO-ELECTRIC (*see* "Water storage and Power")—
and thermal storage, 615.
commission of Ontario on heating houses, 615.
costs, 218.
power, Chaps. 8 to 10.
— and thermal storage, 615.
— — tea firing, 619.
— — water heating, 622.
— automatic stations, 187, 217.
pumping to storage for, 230A.
HYDROGEN—
as a cooling medium, 80A, 191, *671*.
electrolytic, 635, 985.
for cooling motors, 80A, *671*.
in barreter tube, 583.
welding in, 655.
Hydrogenation processes, 169.
Hydrographs, 208, 209.
Hypernik, 83.
Hypochlorate production, by electrolysis, 635, 984.
Hysteresis, 34, 81, 82.
dielectric, 312.
in transformer, 398.

ICE-MAKING plant and data, 647A, 773.
Ice on overhead wires, 324, 331.
Ideal alloy, 67 (Table 6).
Idle component, 110.
I.E.C. (*see* "International Electro-technical Commission").
I.E.E. (*see* "Institution of Electrical Engineers").
regulations for the electrical equipment of buildings (see "*Wiring Rules*").
Ignition, 421, 423A.
Ilgner winding system, 829.
Illuminating Engineering Society, 604.
ILLUMINATION—
and the architect, 598, 601, 602.
defined, 580.
for various purposes, 603, 613.
in vehicles, 927.
lumens, 580.
-photometer, 580.
reflection from surfaces, etc., 590.
required, 604, 605.
shades, globes, and reflectors, 599.
terms explained, 598.
Immersion heaters, 617, 623, 634.
— cost of, 574.
— on railway stock, 928.
IMPEDANCE—
cables, 310.
elementary, 44-6.
equivalent, of transformer, 392.
frequency and, 135.
on overhead lines, 299, 302, 307.
permissible in fault circuit, 482.
relays, 359.
switching and, 370.
table of, 307.
Impregnated cables, 289, 290A.
— — rating, etc., 280.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Impregnation, 76, 86, 323.
Impulse protective gaps, 346.
  wheels, hydraulic, 203, 214, 238.
Incandescent lamps and power factor, 156.
Inching starters, 738.
Incrustation of pipes, 247.
Incubation, electrical, 856.
India—
  rainfall and run-off in, 204.
  water-power in, 242.
  — cost of, 216.
  wood poles in, 323.
Indiarubber, 73 (Table 7), 74, 75, 287 (*see* "Cables").
Indicated horse-power, 51.
Indicating devices on switchboards, 373.
Indicator, P.F., 111 (*see also* "Remote control").
  earth leak, 553.
Indirect lighting, 602, 603, 605, 606.
  — fittings, cost of, 572.
Indirectly-compounded D.C. motors, 677 (Table 116).
Individual and group drive compared, 748.
Induced current for cooking, 629.
  — — heating, 638, 639.
  draught motor, 670.
  E.M.F. and frequency, 135.
Inductance—
  cables, 310.
  defined, 2.
  equivalent, of transformer, 392.
  overhead lines, 299, 302, 307.
  resonance and, 350.
  table of, 307.
Induction (*see next entry also*)—
  -alternator, 144.
  -ammeter, 102.
  elementary, 35, 81, 82.
  from traction circuits, 908.
  furnaces, 639.
  — and power factor, 156.
  heating of fluids by, 639A.
  instruments, 89 *et seq.*
  magnetic, 81, 82.
  motor and frequency, 135 (*see next entry,* "Induction motors").
  — — *generators, 388.*
  — — power factor, 156.
  regulator, 142, 406.
  relay, 344, 358.
  self and mutual, 2, 35, 36.
  voltmeter, 102.
  wattmeter, 109.
Induction Motors (*see also* "Motors, A.C.")—
  and frequency, 135.
  — power factor, 156.
  compared with commutator motors, 699 et seq.
  comparison of starting methods, 724.
  control of, 723-6.
  data for, 681 (Table 119).
  general description, 681-96.
  motor-generators, 388.
  on battleships, 958.
  short-circuit tests of, 1020.
  speed control of, 725, 887.
  variable-speed, 728.
  with auxiliary machine, 728.
  — driven stator, 729.
Inductive—
  coils for arresters, 346.
  heating of fluids, 639A.
  localisation of cable faults, 1032.
  reactance and P.F., 156.
  relay, 344.
Inductor generators, high-frequency, 144.
  landing control for lifts, 797.
Industrial—
  air-conditioning, 615, 616, 647A.
  air heating, 619.
  applications of synchronous motors, 679 (Table 118).
  electric heating, 619, 634 et seq.
  load curves, 266.
  loads, characteristics of, 780.
  locomotives, 874.
  power and heat, 747 (1).
  — for farms, 849.
  processes (Chap. 38), see "*Processes*".
  trucks, electric, 951.
I.E.C. (*see* International Electro-technical Commission).
Inflammable gas in mines, 812 (see also "Explosion-proof gear").
Influence machines, 131.
Infra-red—
  lamps, cost (Table 74), 571.
  radiation, 578, 584, 587, 597A, 646A.
  rays, drying and baking by, 646A.
Inherent regulation, 147.
Input and output of transformers (q.v.), 391.
Insects and electrical apparatus, 929.
  destroying electrically, 856.
Installation, construction and cost of (Chap. 24, Vol. II).
Instalment method of loan repayment, 1014.
Instantaneous relay, 344.
Institute of Agricultural Research, 165.
Institution of Civil Engineers, earthing rules, 472.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

INSTITUTION OF ELECTRICAL ENGINEERS—
Cable tables, 280.
model form of general conditions of contract, 999.
"Regulations for the Electrical Equipment of Buildings," here called "Wiring Rules," 4, 58, 152, 280 *et seq.*, 293, 356, 382. For Vols. II and III and details, *see* "Wiring Rules."
Regulations for luminous signs, 612A.
Institution of Gas Engineers, 169.
— *Heating and Ventilating Engineers, 619.*
INSTRUMENT(S) (*see also* Chap. 16, "Switchboards")—
and measuring, Chap. 3 *passim.*
on "electrics," 942.
— *shipboard, 959.*
transformers, 108, 108A, 384, *405.*
INSULATED—
conduit, 539, 568.
wires (*q.v.*) and cables (*q.v.*), 310 *et seq.*
Insulating materials, constants, etc., 70 *et seq.*
paint and varnish, 76.
INSULATION (*see also* "Dielectric")—
cables (*see* "Cables").
class, 283.
equivalent stress with A.C. and D.C., 298.
failure of, 352.
grade of, 281.
graded, 289.
high-pressure cables, 287-9.
material, B.S. classes of, 1018.
— *classified, 670.*
of conductors, 525.
— *transformers, 400.*
— *trolley wire, 911.*
overhead lines (*see* "Overhead lines").
resistance, 119, *470, 471.*
— of cables, 280 (Table 40 A to K), *1029.*
— *tests of buildings, 1037.*
-sheathed wiring, 551.
tests, 1018.
voltage and strain on, 298.
INSULATORS—
and conductors differentiated, 59.
capacity of, 330.
cap type, 330.
condenser type, 368.
for tramways, 911.
general, 74, 330.
solid and plastic, 74.
suspension, 330.
tests, 1033.
Intensity of illumination, 579, 580, 604, 605.
rain-gauge (Meares), 204.
Inter-connection of systems and plant, 186, 257 *et seq.*, 320, *390* (*see also* "Grid").
INTERFERENCE—
from earth return, 482.
— *harmonics, 407.*
with radio, 416.
— *supply by consumer, 512.*
— *telegraphs, 908.*
Interlocked field rheostat, 736.
switchgear, 366 *et seq.*, 373.
Interlocking in mines, 822.
signals, 933.
Intermittent earths, 351.
rating of motors, 670, 787, 895 (see "*Rating*").
Internal and external characteristics, 138.
— — combustion, 166.
combustion engines (*see* "Gas engines," "Oil engines").
resistance, 21.
INTERNATIONAL—
ampere, 2, 3.
candle, 579.
definitions, 3.
Electro-technical Commission, 6, 62, 87, 136, 152, 209, 258, 262, *1056.*
heat-unit, 52.
horse-power, 51.
ohm, 2, 3.
rating of rivers, 209.
standard rating for electrical machinery, 136.
Standards Association, 1057.
Interpoles, 139, 148, *671.*
in converters, 408.
Interrupter and capacitance for grid tap, 427.
Interruptions to supply, 355.
of excessive current, 341 (*see* Chap. 16 *passim*).
Intersheaths, 289, 311, 319.
Inter-urban railways, 865.
Intrinsic brightness, 597, 599.
Invar, 66 (Table 6).
Inverse-speed motors, 670.
Inverse time limit relay, 344.
Inverted running of converters, 408, 412, 413.
— — *mercury arc rectifiers, 424.*
conversion, 388, 408, 412, 413.
synchronous motor-generator, 388.
Inward and outward flow turbines, 233.
Iodoform, 986.
Ionic valves, 418 et seq.
Ionisation, 79, 105, 316.
Ionized air, removal of, 372A, *869.*
gas, spectrum of, 592.
Iridium, 67 (Table 6).

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

IRON—
and nickel cells, 434.
— steel alloys, 979.
— — works, 778.
— thermal storage, 627.
conductors, 331.
-constantan couple, 122.
-cored reactors, 340.
magnetic separation of, 809.
pig, manufacture, 635.
properties, 64, 66, 82, 127, 331, *645 (Table 98).*
reduction and refining, 976.
resistors, 617.
wire as voltage regulator (Barreter), 583.
IRONCLAD—
-exide cells, 939.
reactance, 340.
rectifier, 422, 423.
switchboard and switches, 366, 376, 379.
switchgear in mines, 822.
Irons, flat, 574, 631.
Irrigation by electric power, 853.
Irwin oscillograph, 118.
Isolated neutral, 351.
Isolating switches, 338, 361, 362, 385.
Isoperm alloys, 83.

JACKSON, electric boiler, 624.
Jacob leak-indicator, 553.
J. and P. wiring, 552.
Jet arrester (lightning), 346.
condenser (steam), 175.
Jets and impulse wheels, 255.
Jib cranes, 786, 789.
Jigger conveyors, 835.
Joiners, wood-working, 775.
Joint boxes, 489.
Joints and connections, 488, 489.
cable, 290.
in wires, 534 (10), 536 (30).
pipes, 252.
Johnson valve, 253.
Joule, 2, 57.
Junction boxes, 489.
Jute, 73 (Table 7), 74.
machinery, 776 (Table 158).

KALANITE, 75, 330.
Kaleeco wiring, 552.
Kalkos wiring, 540.
-Stannos wiring, 545, 556.
Kando system, single-phase traction, 919A.
Kanthal, 66 (Table 6).
Kaplan wheel, 215, 223, 230.
KAPP—
method of finding phase sequence, 150.
phase advancer, 160.
Kärmer system, variable speed, 728.
Kataphoresis, 997.
Kathode (Cathode *q.v.*), 118, 127, *970.*
" *Keepalite* " *batteries, 430.*
battery system on ships, 963.
Keighley Cralft 2-speed A.C. lift motor, 734.
Kellner process, 984.
Kelvin balance, 101.
" Kelvin " = kVA or " unit " *q.v.*, 52.
unit of absolute black-body temperature (K), 589, 591A.
Kelvin's law, 333.
Kenotron, 419.
Kettles, electric, 624.
cost of, 574.
Kicking coil, 346.
Kieselguhr, 85.
Kilburn-Scott furnace, 974.
Kilogramme-calorie, 48.
Kilovolt-ampere (K.V.A.), 55, 56.
— reactive (K.V.A.R.), 110A, 116A, 117.
KILOWATT(S) (*see also next entry*)—
connected, 608.
defined, 50.
for tea manufacture, 619.
method of charge, 272.
KILOWATT-HOURS—
and steam in electric boilers, 625.
— consumption in G.B., 191.
generated in U.K., 197.
per ton for melting metals, 645 (Table 98).
— — in chemical and metallurgical processes, 635 (Table 97).
(" units ") 2, 52 (*see* " Energy consumption ").
Kilowatt-year outputs, etc., in processes, 635.
Kinetic generators, 666.
Kingsway wiring, 552.
Kirchoff's Law, 456.
Kjellin furnace, 639.
Klydonograph, 104A.
Knife switches, 363.
Koenemann process, 176.
Korndorfer connection in motor starting, 722.
Kosfi-leading motor, A.C. induction, 688.
Kromore alloy, 67 (Table 6).
Kruppin, 67 (Table 6).
Krypton lamps, 571, 585.
— cost (Table 74), 571.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

K.V.A., 55, 56.
K.V.A.R., 110A, 116A, 117.
kW, kWh (*see* "Kilowatt," "Kilowatt-hour").
Kyanising, 86.

LAC Blanc and Lac Noir scheme, 230A.
Lacour converter, 413.
Lacquers, drying by infra-red, 646A.
Lagging boilers, 171.
  currents, 46, 153 *et seq.*, 304.
Lake Erie and Northern Railway, 917.
Lakes, storage, 244.
Laminated cores, 671.
  transformer core, 398.
La Mont boiler, 170.
LAMPHOLDERS—
  all-insulated moulded resin, 485, 486.
  cost of, 571,
  general, 485-7, 534 (19).
  Home Office pattern, 486.
  I.E.E. rule as to, 487.
  -plugs, 498 (*see also* " Plugs," " Sockets ").
LAMP(S) (*see also* "Arc Lamps," "Lighting")—
  and power factor, 156.
  arc, 583, 591-7, 599.
  " black," 591B.
  arc-incandescent, 597.
  candle, 586.
  carbon filament, 584, 599.
  " coiled-coil," 585.
  cost of (Table 74), 571.
  details of (Tables 83, 83A), 585.
  efficiency of, 582, 583.
  filament (glow), 583-7.
  flood- and photo-, 586.
  gas discharge, 578, 588A–590A, 593, 599, 609.
  gas-filled or *" half-watt," 585, 599.*
  hand-, cost (Table 75), 572.
  hours of use, 607, 612.
  incandescent, I.E.E. rule as to, 587.
  — power factor, 156.
  indicator, 553.
  infra-red, 571, 578.
  in parallel, 449.
  — series, 445.
  krypton, 571, 584.
  life of, 597.
  mercury-vapour, 583, 587 et seq., *612.*
  Moore tube, 588A, 599.
  Neon, 588B.
  number required, 605.
  over-running, 583, 585.
LAMP(S) (*cont.*)—
  " permanent " photo-flash, M.-V., 588.
  pilot, in heating and cooking, 632.
  " pointolite," 597.
  public, in series and parallel, 611.
  searchlights, 613.
  slowing-down oscilloscope, 123.
  sodium gas discharge, 590A.
  special glow, 586.
  spectra of, 587, etc.
  synchroscope, 149.
  titanium, 597.
  tubolite, 586.
  tungsten, 585, 599.
  turn-down, 586.
  under-running, 583, 585.
  vapour-discharge, 578, 583, 587, 590, 591.
Lancashire boiler, 170.
  booster, 432.
" Lancashire " reducer set, 948.
Landing gear for lifts, 797.
Larson's potentiometer, 95 (2).
LATENT HEAT—
  — in evaporation, 626.
  — of fusion, 645 (Table 98).
  — removal of, in air-conditioning, 647A.
Lathes, 775.
Latour traction motor, 896.
Lattice construction, railways, 915.
  pole, 323.
Laundry machinery, power required for, 757.
" Lavalect " basin unit, 622A.
LAW—
  and Regulations (Chap. 41), 1039 et seq.
  Kelvin's and Hopkinson's, 333.
  of electricity, 198, 275, 322 and *Chap. 41 (Vol. III).*
  — — in India and Burma (Meares), 1060.
Laxapana-Aberdeen hydro-electric scheme, 243, *619.*
Layered insulation, 79.
"Lead" and "return," 9 (*see also* "Line" and "Return").
LEAD—
  accumulators, 431.
  and nickel cells for " Electrics," 939.
  burning by " pyrotip," 637, 660.
  corrosion, 553.
  -covered cable, 280, 283.
  fuses, 342.
  hydrate cells, 433.
  peroxide arrester, 346.
  plating, 994.
  properties, 65, 67 (Table 6), 127 *645 (Table 98).*
  refining, 992.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

LEAD (*cont.*)—
sheath as return conductor, 482.
sheathed wiring, 552-5.
— cost of (Tables 68, 69), 566.
vibration and cracking of, 66.
Leading and lagging currents, 46, 153 *et seq.*, 304.
LEAKAGE—
and protection, 352.
currents, 71, 95, 352, *470-2.*
flux, 391.
in instruments, 95.
— mines, 821.
on consumer's premises, 512.
testing for (see "*Testing*").
trips, earth, 354A, *471, 472, 482, 632.*
Leather and boot machinery, 775 (Table 153).
Leblanc phase-advancer, 688.
Leclanché cell, 127.
Leeds-Northrup furnace, 646.
Lethcroid, 73, 74 (Table 7).
Letterpress printing, 647A, 777.
Level and over-compounding, 138.
Leyden jar, 46.
LIFE OF—
lamps, 597.
— with variable voltage, 583, 585, 591A.
lead cells, 431.
plant and depreciation, 1013.
railway rails, 902.
road vehicles, 936.
tramway rails, 901.
wood poles, 86, 323.
Lifting dams, 219, 225.
magnets, 84, *805* et seq.
LIFTS, ELECTRIC—
brakes for, 797.
carrying capacity of, 799.
control of, 796, 797.
counterbalancing, 785, 792.
doors and gates for, 797.
energy consumption of, 801.
escalators, 804.
goods, 798.
I.E.E. rules for, 795.
installations, typical, 800 (Table 171).
Keighley Cralft A.C. motor for, 734.
landing gear for, 797.
methods of driving, 793.
motors for, 796.
passenger, 792.
— two-speed A.C., 734.
speed of, 794.
Light duty circuits, 565.
load losses of transformers, 394.
overhead railway construction, 917.
LIGHT (visual)—
and colour, 578.
— semaphore signals, 933.
"Black," 591B.
sources, intrinsic brilliancy of, 599.
treatment for plants, 857.
— of poultry, 856.
velocity of, 47.
LIGHTING, ELECTRIC (*Chap. 25*), (*see also* "Lamps").
and domestic power on farms, 848.
by vapour lamps, 587-91.
direct, 601, 605, 606.
domestic, office, workshop, 601.
fittings, cost of, 572.
gas v. *arc, 609.*
hours of use, 607.
— monthly and annual, 612.
indirect, 602, 605, 606.
in mines, 840.
— vehicles, 927.
load factor of, 601.
maximum demand of, 265, *608.*
power consumed in, 606, 607.
public, in series and parallel, 611.
semi-indirect, 603, 605, 606.
street, 609, 610, 611.
— by sodium lamps, 590-A.
LIGHTNING—
and buried cables, 334 *note.*
— telephones, 335.
— *traction, 869, 914.*
— *transformers, 400.*
arresters, 45, 334, 335, 346, 385, *421, 512.*
conductors, 348.
protection, 346, *407.*
Lignite, 168.
Lilla Edet H.E. plant, 214.
Lime-silica cement, 75.
"Limes," stage, electric, 586.
Limitation of current, 272, 274, 337, 340.
— starting demand in motors, 744.
Limiter, current, 272, 274.
Limit switch defined, 736.
"Line" and "return" in traction, 903-6.
LINE—
construction, railways, overhead, 914.
fault relays, 359.
feeders, tramway, 923.
systems of supply to traction, 868.
voltage of transformer, 394.
welding, 662.
Linear expansion of metals, 67 (Table 6).
Linesman's detector, 96.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Lines of force, 35, 41.
(supply) overhead and underground, Chap. 14.
Linings for furnaces, 971.
Linked switch defined, 4.
Linolyte, 586.
Lipman frequency meter, 112.
LIQUID(S)—
controllers, 739.
fuel, 178.
heating formula, 621.
insulators, 77.
resistance, 68.
starters, 736.
Lithargo arrester, 346.
Lithium chloride, 647A.
Lithograph printing, 777.
Live steam utilisation, 176.
cable system testing, 1031.
LOAD (*see* "Load-factor" below)—
characteristics of motors, 749.
curves, 265, 266, 266A.
despatcher, 190, 382.
-duration curves, 266A.
LOAD FACTOR—
and consumption, 576.
— efficiency, 191, 194.
— pumping to storage, 230, 230A.
— tariffs, 270.
— *transformer losses, 401.*
— water-power 217.
defined and explained, 261, 263 *et seq.*
diversity and demand, 262 *et seq.*
in air-conditioning, 647A.
— *mines, 814.*.
— *resistance welding, 664.*
— *welding, 664, 667.*
of furnace with thermostat, 636.
— *industrial processes, 969.*
— *various classes of consumers, 780 (Table 167).*
on mains and station, 473.
undertaking, plant and station, 261.
Loaders and conveyors, 835.
Loading coils, 82.
of squirrel-cage motors, 682.
transmission line, half- and quarter-wave, 318.
Loan periods and depreciation, 1013.
repayments, 1014.
LOCAL—
action, 127.
— *in cells, 431.*
Acts of Parliament, 1042.
LOCAL AUTHORITIES—
and companies' supplies, 195.
— — wayleaves, 322.
Location of faults, 1026, 1032.
LOCOMOTIVES, ELECTRIC—
alternating current, 919.
battery, 873.
compared with steam, 894.
cost of, 919A, 926.
Diesel-electric, 873.
for mines, 832.
goods, 872, 918.
haulage by, 831, 832.
industrial, 874.
passenger and freight, 872, 918.
Ramsay, 873.
self-contained, 873.
shunting, 873.
single-phase, 919.
steam and, compared, 894.
three-phase, 872, 919.
turbo-, oil-, and battery, 873.
weight of, 919A.
Loetchberg railway, 919.
Loffler boiler, 170.
Lohys steel, 82.
London P.O. freight railway, 922.
Long distance transmission, 315 *et seq.*
spans, 324 *et seq.*, 329.
Looms, calico, 776.
"Loop" of A.C. defined, 371.
— *tests on cables, 1032.*
Looping back, 543.
in, 488, 492.
— *draw-in conduits, 538.*
Loss of head, hydraulic, 247.
LOSSES—
from hydro-electric power to steam, 625.
— — *via* pumping and back, 230, 230A.
in cables, dielectric, 312.
— *electric air heating, 619* (*see also* "Air-conditioning").
— plant, 191.
— power-house, 193.
— *sub-stations, 426.*
— *transformers, 391, 401.*
light load, of transformers, 394.
Louvre-type fittings, 598.
Low-grade heat, using, 176, 188.
— — *in mines, 817.*
Low (*see below,* "Low voltage")—
frequencies for ship propulsion, 956, 958.
heads, hydraulic, Chap. 9.
oil-capacity circuit-breaker, 368A.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Low (*cont.*)—
-pressure turbines, 176.
— (electric) defined, 22 (*see below*, "Low voltage").
-speed characteristics, motors, 753.
temperature-distillation, 169.
voltage (*see next entry*).
Low Voltage—
and interruptions, 355.
release, 355.
tripping, 372.
Lucere alloy, 67 (Table 6).
Luffing cranes, 786, 789.
Lumen(s) (see *Chap. 25* passim)—
and voltage variation in fluorescent lamps, 591A.
defined, 580.
of gas-discharge lamps, 589-91.
per watt, 578, 582.
Luminous flux, 580.
discharge tubes, 612A.
heaters, 620.
intensity, 579, 580.
Lundberg switching, 502.

"M" *EFFECT in fuses, 515.*
Macfarlane-Burge control, 945.
Machine(s), control gear for, I.E.E. rule, 781.
textile, 776.
-tools, driving, 775 (Table 151).
(*See under* name headings also.)
Machinery, rating of, 136.
Macintosh wiring, 535.
Maconite, 535.
Magazine lamps, 594.
Magnesite, 85.
Magnesium—
by electrolysis, 635.
electrodes, 588B.
hydroxide, 630.
in fluorescent lamps, 591A.
oxide as dielectric, 556.
production, 635, 980.
properties of (Table 6), 67, 127.
Magnet(s)—
ageing ovens for, 642.
elementary, 32, 40 *et seq.*
field, 133.
interpoles, 139.
lifting, 805 et seq.
Maxwell's rule, 32.
polarity and current, 32, 35.
reluctance, 41, 42.
residual magnetism, 81-3, 138.
Magnetic—
blow-out, 365.
brakes for lifts, 797.
chucks, 807.
circuit, 41.
clutches, 751, 808.
field, 40, 92.
— strength, unit of, 2 (Table 1), 6.
flux, 2, 6.
— measures, 121.
— unit, 2 (Table 1), 6.
pyrometers, 122.
separators, 809, 997.
shunts, 107.
steel and non-magnetic, 81 *et seq.*
storage in spot-welding, 662A.
susceptibility, 6.
Magnetisation curve, 81, *1019.*
Magnetism, current and motion, 35.
(*See above* "Magnets," "Magnetic".)
Magnetite lamps, 591, 594.
arc, efficiency of, 583.
Magnetomotive force, 2 (Table 1), 41, 42.
Magnetostriction, 83.
Magnetron, 418A, 421.
Magno-nickel, 67 (Table 6).
Main—
and tail haulage, 831.
distribution boards, 511, 517.
feeders, tramway, 923.
haulage, 831.
line and local traction, 865.
— construction, overhead, 918.
— electrification, 865, 915 et seq., *921 (2).*
switches, I.E.E. rule as to, 510.
transmission lines and "Grid," 195.
water and air-conditioning, 622A.
wires and control, cost of, 570.
Mains (*see* also "Overhead lines," "Cables").
defined, 439.
in distribution, 473.
Maintenance, depreciation, and repairs, 194, *1015.*
"Make-time" of C.B. defined, 371.
"Making-current" of C.B. defined, 371.
Management in power-house, 194.
Mangan-bronze, 335.
Manganese—
-copper, 67 (Table 6).
— electrodes, 591A, 653.
properties, 127.
-steel, 67 (Table 6), 84, *979.*
— trackwork, 902.
Manganin, 67 (Table 6).
Manning's hydraulic formula, 212.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Manœuvring power of electrically-driven ships, 957.
Marble, 73 (Table 7), 74.
Marine boiler, Benson, 170.
Marryat's lift formula, 799.
"*Mary Ann,*" *electric, 755.*
Marx multiplying circuit, 1033.
Marylebone charges, 272.
Mass and weight, 2.
— — duration curves, hydraulic 209.
MASTER—
control, 373.
— *on ships, 957.*
controllers, 736, 741, 897, 957.
in traction, 871.
switching, 504.
Materials and properties, Chap. 2.
power required to heat, 618.
Mather & Platt train-lighting system, 931.
Mats, electrically heated, 631.
Mavor & Coulson wiring, 554.
MAXIMUM—
demand (*see below*).
flow off catchment, 204.
temperature in fabrics, 80.
values in A.C., 31.
— of volt and ampere, 31.
MAXIMUM DEMAND—
abbreviation, M.D., 6.
explanation, 259 *et seq.*
in cooking, 628.
indicator, 117.
limiting, with group of motors, 744.
load and diversity factor (Vol. I, Chap. 11).
measurement of, 117.
of lights, 608.
predicting, 576.
tariffs, 272.
"Maxwell" unit, 2 (Table 1).
Maxwell's rule for magnets, 32.
Maybach Diesel engines, 873.
McColl biassed relay system, 359.
MEAN—
and surface velocity of water, 206, 210.
candle-power, 580, 581.
hydraulic, depth, 210.
value of sine wave, 30.
Meares' fractionating rain gauge, 204.
MEASURING: MEASUREMENTS—
accuracy of, 92.
conductance and resistance, 119, 120.
current and pressure, 98 *et seq.*
electrical, Chap. 3.
instruments, 89 *et seq.*
in power factor, 157.
MEASURING: MEASUREMENTS (*cont.*)—
in power required by motors, 752.
— revolutions, 123.
— supply, 113 *et seq.*
— temperature, 122.
— wave form, 118.
of flow of water, 205, 206, 210, 213.
— flux, 121.
— frequency, 112.
— maximum demand, 117.
— power, 109.
resistance, 119, 120.
standard, 95.
transformer, D.C., 108A.
MECHANICAL—
connectors, 488, 489.
considerations in motors, 751.
control of shunt motors, 717.
effect of short-circuit, 338, 339.
efficiency, 166, 167.
equivalents of heat, 166.
— horse-power hour, 53.
— watt-hours and kilowatt-hours, 52.
— watts and kilowatts, 49, 50.
forces in transformer, 398.
output of motors, 669.
rectifiers, 416.
transmission from motor, 751.
MEDIUM—
falls, water-power, 224.
pressure defined, 22.
— *isolation of terminals, 489.*
resistance steel, 82.
Megger test set, 119.
Megohm, 19.
grade of cables, 281.
MELTING—
by induced current, 639.
furnaces, 634, 635, 639, 640, 646, 647, 978, 978A.
in air-core induction furnace, 639.
metals, 645.
-point of metals, etc., 67 (Table 6), *645 (Table 98).*
Memorandum of Home Office on earthing in mines, 821.
Merchant mills, steel, 778.
MERCURY—
arc (*see below,* "Mercury-vapour").
boiler, 166.
meters, 115.
-*Neon lamps, 587* et seq.
properties, 65, 67 (Table 6), 127.
-steam plant, 166.
thermometers and eddy currents, 122.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Mercury-vapour—
arcs, 587-9.
in thermo-dynamic cycle, 166.
lamps, 587 et seq., *612.*
— *cost, 571 (Table 74).*
— *efficiency of, 583.*
— *fluorescent, 591A.*
— *inverter, 424.*
rectifier, 418 et seq., *422-4.*
— *efficiency curve of, 425.*
— *for traction, 869, 921 (2).*
transmission by grid-controlled, 315.
Merz maximum demand indicator, 117.
-Hunter split-conductor system, 359.
Merz-Price—
balanced voltage system, 359.
circulating current system, 359.
conductors, 288, 290.
Mesh and star condenser connections, 160.
(Delta) connection, 143, 160.
— *transformer, 394.*
Messenger wires, 914.
Metadyne converter, 389A.
Metal(s)—
amount cut by arc per kWh, 659.
deposited in arc welding, 652, 654.
electro-chemical series of, 127.
heating and melting, 645.
properties (*see under* "Copper," etc.), 67 (Table 6), *645 (Table 98).*
rectifier, 417.
sheathed wiring, 556 et seq.
— — *cost of, 565.*
Metal-graphite brushes, 66.
Metallic oxide rectifiers, 417.
Metalliferous mines, 842.
Metallising filaments, 583.
Metallurgical dust and fumes, precipitating, 996 (Table 216).
Metallurgy (see "*Processes*").
Metering energy (*see also* "Meters"), 270.
Meters—
and earthed neutral, 472.
ampere-hour, 114.
certified, 270.
cyclometer dial, 113.
Electric Supply (Meters) Act, 270.
electrolytic, 89, 114.
frequency, 92, 112.
general, 54, 113 *et seq.*
in installation, 512.
kVAh and kVARh, 116A.
load-duration, 266.
maximum demand, 117.
phase, 111.
power factor, 92.
Meters (*cont.*)—
reactive polyphase, 116-A.
reading dials, 113.
recording, 93.
supply, 113 *et seq.*
tampering with seals, 512.
testing, 1035.
Metropolitan electric supply, 317.
"Metropolitan" system of charging, 273.
Metropolitan-Vickers standard power-houses, 185.
— — "translay" protective system, 359.
Mhos, 18, *450.*
Mica, 73 (Table 7), 74, 80.
cloth, 73, 74.
Micafolium, 74.
Micanite, 73 (Table 7), 74, 80.
Micarta, 73 (Table 7), 74.
Michie test for oil, 1034.
Micro-ampere, 26.
Microfarad, 2 (*see* "Capacity").
Microsol, 86.
Middle wire (*see* "Neutral").
Mil, circular, 292 footnote, 309 (Table 45).
Mild steel electrodes, 653.
Mileage and speed of "electrics," 937.
Miles Walker phase advancer, 160.
Miliphot unit, 580.
Milking booster, 432.
machines, electric, 855.
Milliampere, 26.
Millihenry, 2, 36.
Milling machines, 775.
Million-volt transformer, 396.
Millivoltmeter, 106.
Mineral caoutchouc, 74.
Miner's lamps, 841.
Mines Dept. Regulations, 562, 612A, 1051.
Miniature motors, 670, 680, 710, 755.
Minimax plug and socket, 493, 494.
Minimum charges, 271.
Mining, Mines, Electricity in (*Chap. 32*)—
accidents, 812.
advantages of, 812.
applications of, 823.
armouring in, 821.
cables for, 819.
coal cutters, 834.
comparison with compressed air, 833.
constant-current system, 815.
controllers, 822.
conveyors and loaders, 835.
cutters, coal, 834.
distribution of demand in, 823.
— *underground, 819.*
drills, 836.

MINING, MINES, ELECTRICITY IN (*cont.*)—
earthing in, 821.
exhaust steam in, 817.
explosions, 812.
fan, comparison between methods of speed control, 726 (Table 134).
flexible cables for, 820.
flywheel storage for, 828, 829.
fuses for, 375.
gas in, 812.
— utilisation in, 816.
haulage in, 831.
Home Office Regulations for, 1051 (see "*Regulations, Home Office*").
inflammable gas in, 812.
interlocking in, 822.
leakage in, 821.
lighting in, 840.
load factor in, 814.
low-grade heat in, 817.
metalliferous mines, 842.
miners' lamps, electric, 841.
miscellaneous machines in, 837.
motor-generators for, 814.
motors for, 818 (see also "*Motors,*" "*Motors, A.C.,*" "*Motors, D.C.*").
oil switch and fuse for, 375.
pit locomotives, 831, 832.
plant for, 818.
power factor in, 814.
pumping in, 826.
purchase of power v. *plant, 816.*
regulations for, 562, 612A, 1051 (see also "*Regulations, Home Office*").
rotary converters for, 814.
safety in, 812.
— lamps in, electric, 841.
salt mines, 842.
screening in, 837.
sheathing resistance, 819.
shot-firing in, 838.
signalling in, 839.
standardisation in, 814.
statistics of, 812, 816, 823, 834, 841.
switchgear for, 379, *822.*
ventilation in, 824, 825.
washing coal, 837.
winding in, 827-30.
MINISTRY—
of Agriculture 844.
— Transport, as to wayleaves, 322.
— — *Memorandum on car equipment, 899.*
— — *Regulations of, 899, 901, 903, 904, 908, 909, 912, 914, 920, 923, 1052, 1053* (see also detailed list under "*Regulations and Rules, Ministry of Transport*").
Mirror galvanometer, 96.
Mirrors, searchlight, 613.
Miscellaneous mining machines, 837.
Mixed-flow wheels (water), 233.
Mixed-pressure turbines (steam), 173.
Model general conditions, I.E.E., 534 note.
specification for wiring (see "*Specification*").
Modulus of elasticity of metals, etc., 67 (Table 6).
Mœbius process, silver, 989.
Moisture-resisting motors, 670.
MOLYBDENUM—
for furnaces, 636.
properties, 67 (Table 6).
steel, 979.
Mond gas, 169, 178, 195.
Monel metal, 66 (Table 6).
Monochromatic light, 587, 590.
Monocyclic devices, single-phase motors, 730.
Moody ejector turbine, 220.
Moore tube lamps, 588A, 599.
lamp, efficiency of, 583.
-titanium arc, 597.
Morgan crucible, 637, 647 (Table 102).
Mortise machines, 775.
Moscicki condenser, 346.
Mosquito destruction electrically, 856.
Motor buses, trams, and trackless vehicles compared, 954.
cars, batteries for, 432.
— electric (see "*Road Vehicles*" *Chap. 36, Vol. III*).
— rail, 871, 873.
MOTOR-CONVERTERS—
back-to-back test of, 1021.
binary, 413A.
Brush Co.'s method of starting, 413.
cascade, 413.
efficiency curve, 425.
MOTOR-GENERATORS—
as boosters, 142.
back-to-back test of, 1021.
efficiency curve, 425.
flywheel, in rolling mills, 778.
Gebus control for, 873.
general description, 388.
in mines, 814.
MOTOR(S) AND MOTOR CONTROL (*see also below,* "Motors, A.C.," "Motors, D.C.," "Motors, traction")—
A.C. and D.C. compared, 753.
— — — typical characteristics of, 670 (Table 113).
and drive, choice of, 750.
— supply, 754.
applications of, 746.
braking methods for 715.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

MOTOR(S) AND MOTOR CONTROL (*cont.*)—
British standards for, 670.
buses (see above, "*Motor Buses*").
change speed, 670.
characteristic curves (q.v.) *of, 672.*
compared with line-shafting, etc., 747 (2).
construction of, 671.
continuous rating, 670.
control and protection of, Chap. 29 passim.
— *gear, construction of, 738.*
— — *cost of, 711.*
controllers for, in mines, 822.
— — *winding, 827.*
converters (see above, "*Motor Converters*").
cooling systems for, 671.
cost of, 711 (*Tables 128-30*).
drip-proof; duct-ventilated; duty-cycle rating; enclosed, 670.
drying by embedded heater, 963.
efficiency (q.v.) *and power factor* (q.v.) *of 672* (*Table 114*).
elementary, 132.
flameproof, 670.
for coal-cutters, 834.
— *cranes, 787, 789.*
— *electric lifts, 796.*
— *farms, 850.*
— *haulage, 832.*
— *machine tools, 775.*
— *mine pumps, 826.*
— *mining, 818, 823.*
— *portable tools, 774.*
— *printing machines, 777.*
— *pumping, 768* et seq., *826.*
— *railways, 896.*
— *ship propulsion, 958.*
— *steel works, 778.*
— *traction* (see "*Motors, traction,*" below).
— *tramways, rating of, 895.*
— *vehicles, 943.*
— *ventilation, 824.*
forced draught, 4, *670.*
fractional H.P., 670, 680, 710, 755.
frequency and, 135.
general principles, 132, *669.*
-generators, 142, *388, 425, 778, 814, 873, 1021.*
horizontal and vertical, 751.
I.E.E. rules as to, 781.
in series-parallel, 453.
induced draught, 670.
inverse speed, 670.
lift, 796.
mechanical considerations, 751.
meters, 112, 114.
moisture-resisting, 670.

MOTOR(S) AND MOTOR CONTROL (*cont.*)—
open, 670, 818.
output, torque, etc., 669, and Chap. 28 passim.
overloads for, 670 (*Table 111*).
panels, 385.
pipe-ventilated; protected, 4, *670.*
pony, 410.
rating and temperature rise of, 136
ratings for, 670.
— — *traction, 895.*
reversing, 751.
screen-protected, 670.
selection of type and power, 752, 753.
series (q.v.), *shunt* (q.v.), *compound* (q.v.) *and synchronous* (q.v.), *753.*
short-time rating, 670.
small power, 670, 680, 710, 755.
— — *cost of, 573.*
specification of, 1002.
speed variation in (q.v.), *726, 751, 752.*
starters, definition and rating of, 713, 736, 737.
— *cost of, 711* (*Table 130*).
starting conditions of, 714.
submersible, 670.
temperature, rise of, 670 (*Tables, 109, 110, 112*).
torque, output, etc., 669, and *Chap. 82* passim.
— *when starting, 714.*
traction (see below, "*Motors, traction*").
types of, defined, 4.
"*Universal*" (*fractional H.P.*), *710.*
variable-speed (q.v.), *670.*
vertical and horizontal, 751.
with flywheels, 751.
MOTORS, ALTERNATING CURRENT (*see preceding entry and also below,* "Motors, D.C.," "Motors, traction")—
"*All-watt*" *induction, 688.*
auto-compensated induction, 688.
Boucherot induction, 684.
cascade, control of, 727.
— *induction, 694* (see "*Induction*").
characteristics of, 670 (*Table 113*).
clutch, starting of, 722.
commutator type, 699 et seq.
— — *s.-ph. control, 734.*
— — *3-ph. control, 735.*
— — — — *for power factor correction, 687.*
condenser type, s.-ph., 690.
control of, 721 et seq.
Crompton-Burge "*Tru-watt,*" *697.*
Crompton-Parkinson auto-synchronous, 696.
current-displacement (*Boucherot*), *684.*

Motors, Alternating Current (*cont.*)—
definitions of starter, controller, rheostats, rating, 736, 737.
Deri repulsion, 702.
double-fed synchronous, 698.
— *squirrel-cage*, 684.
— *-stator, double-rotor induction*, 698.
dual frequency induction, 693.
efficiency of, 672 (*Table 114*), 700 et seq.
for ship propulsion, 958.
fractional H.P., 710 (see "*Fractional*").
free stator starting, 722.
frequency-changing speed control, 728.
Fynn-Weichsel synchronous-asynchronous, 697.
Heyland induction, 688.
Hunt single-field cascade, 694.
induction type, 681-96 (see also "*Induction*").
— — *Boucherot*, 684.
— — *cascade*, 694.
— — *comparison with commutator type*, 669.
— — — *of starting methods*, 724.
— — *control of; starting*, 723-6.
— — *data of*, 681 (*Table 119*).
— — *double stator double rotor*, 698.
— — *general description*, 681 *et seq.*
— — *Heyland*, 688.
— — *on battleships*, 958.
— — *Osnos*, 688.
— — *short-current tests of*, 1020.
— — *speed control of*, 725.
— — — — *and P.F. correction by 3-ph. commutator*, 887.
— — *with auxiliary machine*, 728.
— — — *driven stator*, 729.
— — *variable speed*, 728.
Krämer system, variable speed, 728.
Kosfi-leading induction, 688.
lift types, 796.
miniature self-synchronising, 680.
monocyclic devices, s.-ph., 730.
no-lag induction, 688.
Osnos induction, 688.
Parkinson "Tork" s.-ph., 689, 691.
phase-splitting for s.-ph., 730.
pistoye triple-synchronous, 698.
"*plugging*," 715.
pole-changing induction, 686.
— *-shedding for s.-ph.*, 730.
polyphase induction, control of, 723-6.
power factor of, 672 (*Table 114*); 700 et seq.
— — *correction for induction*, 695.
— — — *by 3-ph. commutator*, 687.
rating of, 722, 725.
repulsion, control, 733.

Motors, Alternating Current (*cont.*)—
repulsion-induction type, 690, 704.
— *type*, 701-5.
Richter induction, 685.
rotor and stator, 133, 671.
— *currents of induction*, 725 (*Table 132*).
Scherbius system of variable speed, 728.
Schon-Punga single-phase, 692.
series-repulsion single-phase, 703.
— *single-phase*, 700.
shunt-characteristic type, 706.
single-phase induction, 689.
— — *control*, 730.
— *repulsion*, 701.
— *series*, 700.
— — *control*, 732.
— *shunt*, 706.
slip of induction, 681.
— *-rings, etc., for*, 671.
speed of, 672 (*Table 113*), 698 (*Table 125*).
— *control methods compared*, 726.
— *variation in*, 722.
split-phase, single-phase, 690.
squirrel-cage, 681, 682, 684.
starting of, 721 et seq.
— *torque of*, 684 (*Table 121*).
stator and rotor, 133, 671.
super-synchronous, 698.
synchronous, 679, 680.
— *industrial applications of*, 679 (*Table 118*).
— *speeds of*, 679 (*Table 117*).
— *starting and control*, 722.
synchronous-asynchronous, 696.
— *control*, 731.
— *-repulsion*, 705.
terminal markings, B.S.I., 671.
three-phase commutator, 707-9.
— *series*, 708.
— *shunt*, 709.
Torda type, 688.
"*Tork*," 691 (*Table 123*).
Torque, etc., of, 672 (*Table 113*).
traction, 896 (see below "*Motors, traction*").
typical characteristics of, 672 (*Table 113*).
variable-speed induction, 694, 728, 729.

Motors, Direct Current (*see also above*, "Motors and Control," "Motors, A.C.," and *below*, "Motors, traction")—
armature (q.v.), *commutator* (q.v. *and brushes*, 671.
characteristics of, 670 (*Table 113*).
compound-wound, 677, 720, 753, 796.
— *starting and speed control*, 720.
constant-current, 678, 753.
control of, 716 et seq.
efficiency of, 672 (*Table 114*).

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Motors, Direct Current (*cont.*)—
efficiency weight, speed and H.P. of shunt, 675 (Table 115).
field system of, 671 (see "*Field*").
for hoisting, 787.
— ship propulsion (q.v.), *958.*
fractional H.P., 670, 680, 710, 755.
indirectly-compounded, 677 (Table 116).
lift types, 796.
permanent-magnet type, 673.
separately-excited (q.v.), *674.*
series-wound, 669, 676 (see "*Series*").
— starting and speed control, 718.
shunt-wound, 669, 675 (Table 115), 753.
— starting and speed control, 717.
speed of, 675 (Table 115), 677 (Table 116).
— variation in, 716 et seq.
starting of, 716 et seq.
— resistance calculations, 719.
terminal markings, B.S.I., 671.
torque, etc., 672 (Table 113); 675 (Table 115).
typical characteristics, 672 (Table 113).
Ward-Leonard control, 716.
weight, etc., 675 (Table 115).
Motors, Traction (*see also above*)—
A.C. railway, 896.
cascade coupling for, 898.
control of, 895.
— — A.C., 898.
— — D.C., 897.
D.C. railway, 896.
Deri, 896.
Latour, 896.
master controller for, 897.
multiple unit connection, 897.
polyphase, 896, 897.
rating of, 895.
reduction gear for, 895.
regenerative, 900.
single-phase railway, 897.
standard, B.S.I., 895.
tramway, 895.
Moulded type insulators, 75.
Mouldensite, 74.
Moulders, 775.
Mountain railways, 919.
Moutiers Lyons scheme, 317.
Movable-blade (Kaplan) wheel, 214, 223, 230.
Moving-coil instruments, 96, 101.
-iron ammeter and voltmeter, 100.
power-factor indicator, 111.
Moving stairways, 804.
Muffle furnaces, 646.
Multiblade fans, Pitter, 763.
Multiple—
gap arresters, 346.
knife switches, 363.
switching, 503.
switch starter and controller, 736.
-unit trains, 871, 897, 921.
— working, 921.
Multi-speed driving, 753.
Multivibrator, 428B.
Multiway switches, 374.
Mumetal, 82 (Table 7B), *979* (7).
melting, 639.
Murray loop test, 1032.
Mutual inductance, 2, 35 (*see* "Induction").
MVA. rating, 371.

NAGLER turbine wheel, 215.
Nalder and Thompson frequency meter, 112.
Nalder-Lipman power-factor indicator, 111.
Names of electronic devices, 418A.
Naphthaline, 403.
Natural frequency, 47.
gas, 167, 178.
steam, 165.
Navigation lights, 964.
Needle valve, 255.
Negative—
acceleration, 899.
— in lifts, 796.
and positive poles, battery, 127.
— — — magnet, 32.
boost, 389.
boosters, 142, *389, 906.*
characteristic of arc, 657.
-glow Neon lamps, 588B.
resistance of arc and vapour lamps, 587, 591.
Neon—
in vapour lamps, 587, 588B.
lamps, 588B.
— cost of, 571.
— efficiency of, 583.
-mercury lamps, 588.
Nernst lamps, 583.
Network—
defined, 441.
interconnected, 142.
nominal voltage of, 24.
problems, 456, 473.
Neutral; Neutral Point—
conductor, 4.
earthing, 354, 472.
— in mines, 821.
in 3-phase, 4-wire system, 467.
— 3-wire system, 461, 463.

NEUTRAL; NEUTRAL POINT (*cont.*)—
of three-wire system, 141.
— — — *testing insulation alive, 1031.*
— *transformer, 394.*
— — *earthing, 394.*
zone and interpoles, 139.
Newspaper printing, 777.
Niagara falls, 226.
Nichrome, 67 (Table 6), 122.
in ovens and furances, 635 (Table 96A), 636.
resistors, 617.
NICKEL—
and lead cells for "electrics," 939.
as conductor or resistor, 65, 67 (Table 6), 81, 127.
-cadmium alkaline accumulators, 434A.
-chrome, 67 (Table 6).
energy for melting, 647 (Table 101).
extraction and refining, 990.
-iron alloys, 83.
cells, 433, 434.
melting, 639.
-nichrome couple, 122.
-plating, 994.
properties of, 645 (Table 98).
— steel, 979.
-silver, 67 (Table 6).
-steel, 65, 67 (Table 6), 82, 84.
Nickelin alloy, 67 (Table 6).
Niederwartha hydraulic storage scheme, 230A.
Nilgiri Railway (India), 919.
Nitric acid, atmospheric, 635.
— production, 973, 974.
Nitrogen fixation, 974.
for cable filling, 290A.
products, 973.
Nitrophoska, 973.
Nodon valve, 417.
No-lag motor, A.C. induction, 688.
No-load losses in transformer, 391.
tests, 1019.
No-mag iron, 67 (Table 6).
steel, 84.
Nominal voltage of network, 24.
Non-arcing metals, 346.
"Nonazo" cables, 281 (*Table 68*), *552*, *566*.
Non-association cables, 281, 284.
Non-condensing engines, 172.
Non-inductive coils, 35.
"Normal current" of switch or C.B. defined, 371.
Norwegian water-power, 219, 243.
Norwich system of charging for energy, 273.
Notches, discharge of, 205.
Notodden, 219.
No-voltage release, 355.
Nozzles for Pelton wheels, 253.
Nystrom's table, wind, 324.

OERSTEDS, 2 (Table 1), 43.
Office lighting, 601.
Official Regulations (*see* "Regulations and Rules" of "Electricity Commissioners" and "Home Office," etc.).
Off-peak energy, 264, 269.
Ohm (*see also* "Resistance"), 2, 3, 17, 19.
international, value of, 2, 3.
-farad, 71.
Ohm's law, 17, 21, 24, 25, 28, 40, 44, 49.
Ohmer, 119.
Ohmeters, 97, 119.
Oil-break switches and circuit-breakers, 366 *et seq.*
OIL (*see also below,* "Oil Engines").
and air immersion of transformers, 400.
-bath furnaces, 646.
-blast, air-blast and steam switches, 372A.
-break switches, 366 *et seq.*
circuit-breakers, 367 *et seq.*
— defined, 371.
-electric locomotives, 873.
engines (*see below,* "Oil Engines").
-filled cables, 289.
for transformers, 403.
fuel, 168, 178, 179.
-immersed fuses, 375.
— starters, 738.
insulators, 77.
isolating switch defined, 371.
switches, 365, 367 *et seq.*
— clearances in, 371.
— defined, 371.
switches, rated normal current in, 369.
-tankers, electric, 962.
tests, 1034.
turbine, 179, 183.
varnish, 76.
waste, etc., cost, 269.
Oiled tape and cloth, 74.
OIL ENGINES—
Diesel, 167, 178, 179, 180.
effect of altitude, 179.
efficiency, 180.
fuel consumption, 167.
paraffin, 167, 180.
petrol, 178.
plant, specification of, 1010.
semi-Diesel, 180.
Omega testing sets, 119.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Ondograph, 118.
Opal bowls, cost of, 572.
  glass, efficiency of, 599.
OPEN (*see also* next entry)—
  -air boiler plants, 170.
  arcs, 592B, 599.
  channels, *see below.*
  circuit, 9, *438, 599.*
  — *characteristics of generators, 1019.*
  — *localisation in cables, 1032.*
  delta transformer, 394.
  displacement-type water-heaters, 622A.
  hot-plates, 630
  fuses, 375.
  penstock, 218.
  sparking, 375.
  -type motor defined and classified, 670.
  — *motors in mines, 818.*
OPEN CHANNELS FOR WATER—
  and pipes, 251.
  Bazin's formula, 210.
  calculating size, 211, 237.
  general, 211, 237, 251.
  gradient, 211.
  Manning's formula, 212.
"Opening time" of circuit-breaker defined, 371.
Operating, duty of C.B., 371.
  mechanism of switches, 372.
Operation of lead cells, 432.
Optical pyrometer, 122.
Ore concentration, magnetic, 809.
"Orthojector" circuit-breaker, 368*a*.
Oscillating discharge, 346.
Oscillation period, 47.
Oscillator, triode, 420.
Oscillogram of 3-ph. short-circuit, 371 (Fig. 83-A).
Oscillograph, 118.
Oscilloscope, 123, 214.
  Elverson, 214.
Osnos motor, A.C. induction, 688.
Ostwald process, nitric acid, 973.
Outdoor sub-stations, 427.
  switchgear, 376, 381.
  transformers, 481.
Outer wire, 4, 141 (*see also* "Concentric").
Outlet sockets, 492-8, 534 (11).
  changing type, 952.
  — — *for mines, 820.*
  "*Minemax*," *492.*
Output and input of transformers, 391.
  — *consumption data of processes, 635* (see "*Processes*").
  of converters, 409.
Outward flow wheel, 233.
OVENS (*see also* "Furnaces")—
  and furnaces, 628, 634 et seq.
  — — *635 (Table 96A).*
  cost of, 574.
  for drying and ageing, 642.
  industrial, 636.
Overcharge of lead cells, 432.
Over-compounding, 138.
Over-excited synchronous meter, 160.
Overhanging turns in transformer, 395.
Overhead Lines Association, 322, *846.*
OVERHEAD LINES AND CONSTRUCTION (*see also* next entry and Chap. 14, "Transmission of Power")—
  aluminium, 308.
  breakage of, 324.
  cables *v.*, 334.
  capacity, 305-306.
  conductors other than copper, 308, 309, 331 (*see also* under the various metals).
  construction, 324.
  copper conductors, 307.
  cost of, 332, 334.
  dip and stress, 328, 329.
  distribution and services, 481.
  earthing poles, 324.
  factor of safety, 324.
  general, 324 *et seq.*
  high-tension, tapping, 427.
  impedance, inductance, etc., 299 *et seq.*
  insulators, 74, 330, 368 (*see* "Insulators").
  on railways (see below, "*Overhead system for traction*").
  — *tramways, 909* et seq.
  poles for, 329.
  reactance, etc., 299 *et seq.*
  Regulations for, 324, *1048, 1049.*
  rural lines, 846.
  safety devices for, 324.
  service lines, 481.
  setting out, 324.
  specification for, 1007.
  tapping, 427.
  transmission, Chap. 14 *passim.*
  wind and, 324.
OVERHEAD SYSTEM FOR TRACTION—
  A.C. railway lines, 919.
  railways, 913, 914.
  — *equipment, cost of, 926.*
  — *examples of, 915* et seq.
  tramways, 909 et seq.
Overheating insulation, 352.
OVERLOAD—
  capacity of mercury-vapour rectifier, 422.
  — — *motor-generator, 388.*
  — — *transformer, 402 (Table 55A).*

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

OVERLOAD (*cont.*)—
defined, 670.
general, 338.
in group and individual drive, 748.
rating and, 136.
relays, 344, 357 *et seq.*
release, 743.
sustained, in industrial generators and motors, 136, *670 (Table 111).*
tripping, 372.
Over-running gas-filled lamps, 583, 585.
Oxide film arrester, 346.
Oxygen and hydrogen electrolytic, 635, 985.
Ozone production, 985.

PADDLE-WHEEL ships, electrically-driven, 965
Paint, drying by infra-red, 646A.
insulating, 76.
Palladium, 67 (Table 6).
Pancake coils, 398.
Panels, arrangement of switchboard, 385.
Panel-type radiators, 620.
— cost (Table 77), 574.
switchboards, 376, 377.
Pantograph collector, railway, 913.
PAPER—
as dilectric, 73 (Table 7), 74, 80, 287.
filter for air-conditioning, 647A.
insulated cables, 283, 287, 311 (*see* "Cables").
-making machines, 777 (Tables 159, 160).
Para- and diamagnetism, 32.
Parabolic reflectors, 613.
— for drying, 646A.
Paraffin, 178, 179.
engines, 167, 180.
wax, 73 (Table 7), 74.
PARALLEL—
beams from reflectors, 613.
-block train lighting, 931.
connections, elementary, 448.
converters, 412.
coupling lamps in, 445, 449.
flow wheels, water, 233.
operation of mercury-vapour rectifiers, 422.
— — public lamps, 611.
— — transformers, 394, 397.
running of alternators, 149, 150.
— — dynamos, 148.
-series coupling, 452-4.
— — of fans, 453, 506.
transmission lines, 321.
Parallelogram rule in vectors, 11.
Parkinson "Tork" motor, 689, 691.
Parsons-Reyrolle arc-suppressor, 407.
Passenger lifts, 792.
locomotives, 872, 918.
— cost of, 926.
— on G.I.P.R., 918.
ship auxiliaries, 678, 964.
— electric drive for, 963.
Pasted plates, 431.
Pasteurising, electrically, 855.
Pattern-makers' lathes, 775.
Pauling process, 974.
Paxolin, 73, 74.
PEAK—
factor, 30.
in lighting, 608.
load power plant, 177.
— and interconnection between private and public plant, 186, 191.
Pelton wheels, 203, 214, 215, 238, 253.
nozzles, 253.
Pendants, cost, 572.
lampholders, 485.
Pendulum meters, 115.
Penstock, open, 218.
Pentode valves, 418A.
Perborate of soda, etc., 986.
Perchlorate of soda, etc., 984.
Percolators, cost, 574.
Percussive coal cutters, 834.
drills, 836.
Performance of electrical machines, 1017.
Periods; Periodicity, 12, 135.
Permalloy, 82.
melting, 630.
PERMANENT—
magnet, 83.
— motors, 673.
magnet ammeter and voltmeter, 101.
way and return circuit, 901 et seq.
Permanganate of sodium and potassium, 986.
Permatron, 421.
Permax bird-guards, 324, 330.
Permeability, 40, 43, 81, 82.
Perminvar, 82.
Permittivity, 46, 71.
Peroxide of hydrogen, 985.
Persulphate production, 986.
Pestarini, metadyne, 389A.
Peterson earth coil, 351.
Petrol, 178, 179.
and electric cars compared, 943.
-electric vehicles, 953.
engines, 167, 180.
from coal, 169.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Petroleum, 73 (Table 7), 77, 178, 179.
and thermal storage, 627.
engines, 167, 180.
Phanotron, 418A, 419.
PHASE—
advancers, 160.
connections, 150.
-converter for 3-phase locomotive, 919A.
error in instrument transformers, 108.
general, 11, 56.
meters, 111, 157.
rotation, 150.
-splitting for s.-ph. motors, 730.
Phenix alloy, 67 (Table 6).
Phosphor-bronze, 66 (Table 6), 331, 335.
Phosphorus (*see above, also* "Phosphor-bronze").
alloys, 979.
manufacture, 635.
production, 983.
PHOTO—
-electric cells, 420A, 430A, 743.
— — *for control gear, 743.*
— *photometer, 580 (2).*
enlarging lamps, 586.
-flash lamps, M.-V., 589.
flood lamps, 586.
printing light, 578.
Photometers, 580 (2).
Photometric terms and units, 580.
Piezo-electric effect, 130.
— *used in clocks, 428B.*
Pig-iron furnaces, 635.
Pilot exciter, 141.
lamps for heating and cooking, 632.
wires, 359.
Pin and suspension insulators, 330.
Pinch effect, 639.
PIPES—
and losses in water-heating, 627.
water turbine, friction in, 768.
— — general, 232, 246 *et seq.*
— — joints, 252.
— — line, example, 249.
— — special, 250.
— — *specifications for, 1011.*
Pipe-ventilated motor, 4, *670.*
— *in mines, 818.*
Pisa geothermic station, 165.
Pistoye motor, 698.
Pitch, 73 (Table 7), 75.
Pit locomotives, 832.
Pitter multiblade fan, 763.
Planers, 775.
Plans, wiring, 531.
PLANT (*see under* various heads)—
cost of, 195.
depreciation of, 1013.
for agriculture, 845.
PLANT (*cont.*)—
— *mines, 818.*
general, Chap. 7.
load factor, 261.
maintenance of, 1015.
oil and gas, specification for, 1010.
refrigerating (q.v.), 773.
self-contained, for vehicles, 929.
space required, 196.
spare, 190.
statistics, *see below.*
steam, Chap. 6 *passim.*
— *specification for, 1008.*
statistics, 173, 195, 197, 198.
Plante plates, 431.
Plaskon, 74.
Plastic insulators, 74.
Plating vat, 127.
Platinoid, 67 (Table 6).
PLATINUM—
for furnaces, 636
properties of, 65, 67 (Table 6), 127, *645 (Table 98).*
thermometer, 122.
Platinum-iridium, 67 (Table 6).
-rhodium, 67 (Table 6), 122.
-silver, 67 (Table 6).
Pliable cables, 820.
Pliotron, 420.
Ploughing, electric, 851.
"*Plugging*" *A.C. motors, 715, 722.*
Plugs and sockets (now called "outlet sockets"), 492-8.
— *charging type, 952.*
— — *for mines, 820.*
— — "*minimax,*" *493.*
Pneumatic drills, 836.
"Point" in wiring defined, 4, *565.*
"Point-five" tariff, 273.
Pointolite lamp, 597, 599.
Point welding, 662.
Polar curves of candle-power, 581.
Polarisation, 89, 127.
Polarised instruments, 127 *et seq.*
Polarity and flow, 33.
in arc welding, 651, 652, 656.
of transformer, 397.
Pole-changing induction motor, 686.
— — *for speed control, 725.*
Pole-shading of s.-ph. motor, 730.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

POLES—
and brackets for tramways, 910.
— towers for overhead lines, 86, 323, 324 *et seq.*, 329.
(battery), 127.
(magnetic), number of, 32, 138, 254.
preserving wooden, 86, 323, *846.*
Pollopas, 74.
Polymerisation, 646A.
POLYPHASE (*see also* "Alternating current," "Alternators," "Motors, A.C.," "Three-phase," etc.)—
motors, 681-96 (see also "*Motors, A.C.*").
— control of, 723, 724, 898.
— for traction, 896 (see also "*Motors, traction*").
v. *single-phase transformers, 399.*
Poncelet wheel, 233.
Pony motor starting, 410.
Population and units sold in G.B., 197 and Table 29B.
PORCELAIN—
fuses, 375.
general, properties, 73 (Table 7), 74, 80.
insulators, 330.
PORTABLE—
cells, 432.
fittings, 484.
motors and line-shafting on farms, 850.
sub-stations, 427.
tools, 774.
Portland cement, 75.
Positive boost, 389.
and negative boosters, 906.
— — poles of battery, 127.
— — — — magnet, 32.
Post- and pre-war prices, 530(h), 564.
POST OFFICE—
freight railway, 922.
recommendations as to electrolysis, 907.
technical instructions, 324.
Wheatstone bridge, 120.
Posts (*see* "Poles").
POTASSIUM—
chlorate by electrolysis, 635.
production, 980.
properties of, 127.
POTENTIAL (*see also* "Pressure")—
and current transformers, 108, 384.
difference of, 2, 22.
— in arc welding, 651-7.
divider, 95, 107.
earth, 24.
gradient on insulators, 330.
— — *ground, 482.*
POTENTIAL (*cont.*)—
transformer, 405.
— tests, 1035.
Potentiometer, D.C., A.C. and high-tension, 95.
Potentiometer-type field rheostat, 736.
Poultry farming, electricity in, 856.
Poundal, 2.
Powell process for timber, 86.
POWER (*see also below*, "Power factor," "Power-house," "Power required for")—
Acts and Companies, 1041, 1044.
and energy used on railways, 888.
— heat in industry, 747 (1).
— process installations, 188.
— speed on ships, 957.
— work, 48.
apparent and true, 153.
applied to vehicles, 879.
by-product, 776.
calculations for traction, 878 et seq.
— — — practical methods, 885, 886.
circuits, 518.
consumed by instruments, 94 *et seq.*
cost of wiring for, 566.
costs with electric drive, 747 (3).
demand in mines, 823.
distribution and application, 747 (2).
elementary, 2, 48, 55, 56.
factor (*see below*, "Power factor").
from pumped water, 230A.
— sun heat, 165.
— tropical sea water, 165.
generation in carriages, 929-32.
-houses (*see below*, "Power-houses").
lost by corona, 316.
on petrol and electric cars, 943.
per wage-earner, statistics of, 780.
plant data, Chaps. 6 and 7.
required (see below, "*Power required for*").
sources of, Chap. 6.
-station output in acceleration, 883.
stations, Chap. 7.
— small standard, 185.
supply in agriculture, 845.
— — mines, 814.
transmission, Chap. 11.
water (*see* "Water-power").
"*Power Acts,*" *1044.*
Power companies, 1041.
POWER FACTOR—
and condensers, 480.
— improvement, Chap. 5.
— tariffs, 270, 274.
— voltage regulation, 155.
average, 116A.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

POWER FACTOR (*cont.*)—
avoidance of low, 158.
capacity, condensance and, 156.
causes of low, 156.
correction, 159-62, 274, *388*, *390*.
— *of, for induction motors, 695.*
dielectric, 71A.
effects of, 155.
efficiency and, 155.
elementary, 55, 56.
errors of instruments, 92.
excitation and, 140.
for electric processes, 969.
high, in motors, 753.
improvement, Chap. 5.
in cables, 1030.
— *furnaces, 636.*
— *group and individual drive, 748.*
— *mines, 814.*
— *relation to weight of conductors, 468.*
— *welding, 661, 667.*
indicators, 111, 157, 385.
low, charging for, 270.
measurement of, 157.
meters, 92.
of butt welders, 661.
— *converters, 411, 413.*
— *electrolytic rectifiers, 417.*
— *fluorescent lamps, 591A.*
— *high-frequency furnace, 639.*
— *inductive fluid heating, 639A.*
— *kenotron, 419.*
— *mercury vapour rectifier, 422.*
— *motors, 672* (*Table 114*), see also "*Motors, A.C.*").
— — *induction, 681.*
— — *open delta, 399.*
— — *synchronous, 679.*
— power line, 300, 303.
— various loads, 157.
reactance, condensance and, 156.
tariffs and, 270, 274.
three-phase, 110A.
POWER-HOUSE—
buildings, 196.
data of plant, Chap. 7.
design, 191.
efficiency, 192, 193.
general, Chap. 7.
losses, 191.
output of, in traction acceleration, 883.
plant (*q.v.*) generally, Chaps. 6 and 7.
standard plant for small, 185.
POWER REQUIRED FOR—
acceleration, 882.
agriculture, 845 et seq., *858.*
POWER REQUIRED FOR (*cont.*)—
air-heating, 619.
baking ovens, 643, 644.
cement mills, 779.
charging cables, 311.
coal cutters, 834.
collieries, 779.
compressors, 766.
concrete mixers, 779.
cotton machinery, 776 (*Tables 154-6*).
dockyards, 779.
driving generators, 164.
electric cooking, 628.
— driving, 164 *and Chap. 30.*
— *processes, Chap. 38* passim.
escalators, 804 (*Table 172*).
excitation, 140.
fans, 761, 764.
farms, 848, 849, 850.
ferro-alloy production, 979.
flour mills, bakeries, etc., 756.
gradients in traction, 881.
haulage, 831.
hoisting, 784.
hot-plates, 630.
incubators, 856.
induced current cooking, 629.
industrial heating, 635 (*Table 97*).
instruments, 94 *et seq.*
iron and steel works, 778.
jute machinery, 776 (*Table 158*).
laundries, 757.
lifting magnets, 806.
lighting, 606, 607, 612.
locomotive haulage, 832 (see also "*Electric traction*").
machine tools, 775 (*Table 151*).
magnetic chucks, 807 (*Table 175*).
mining, 814, 816, 823 et seq.
ovens and furnaces, 635 (*Table 96A*).
paper-making and printing, 777.
processes, 969 (see "*Processes*").
pumping, 768 et seq., *826.*
resistance furnaces, 646.
rivet heating, 637.
ship auxiliaries, 779.
tea manufacture, 619.
textile machinery, 776.
traction, 879 et seq.
— *general expression for, 884.*
tramways, 889.
uniform speed on level track, 880.
ventilation, 824 (see "*Air-Conditioning*").
water heating, 621 et seq.
winding, 827.
wool and worsted machinery, 776 (*Table 157*).

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Power transmission, Chap. 14.
Pramaxwell, 2.
"*Precalorie" welding process, 661.*
Precipitation, electric, 647A, 996.
of dust, in air-conditioning, 647A.
test, 330.
Preece's formula for fuses, 342.
Preface, v-viii.
Pre-heating in arc welding, 652.
Premier welder, 657.
Prepayment meter, 116.
Prescot wiring system, 552.
Preserving timber, 86, 323, *846.*
Pressboard (Presspahn), 73 (Table 7), 74.
Presses, printing, power for, 777 (Tables 161, 162).
PRESSURE (ELECTRICAL), E.M.F. VOLT(AGE) P.D. (*see also* Volt).
and current of alternator, 143.
British standard, 1047.
danger limit of, 480, 632.
declared, variation in, 442, 469.
definitions and elementary, 22, 24.
drop and frequency, 135.
— in cables, 286.
— — *installation, 534* (7).
— — *rail return, 903.*
effective, 29.
excess, causes of, 345.
for arcs, 595.
gradient, 72, 368.
high, medium, and low, 22, 23.
in arc welding, 651, 657.
insulation and, 297.
maximum, 31.
nominal, in network, 23.
reducing coil, 95, 107.
regulation, 147.
— by booster, 142, 147.
R.M.S. (root-mean-square), 29, 30.
standard (British), 23, 134.
variation allowed in mains, 442.
— *in vehicle lighting, 927* et seq.
virtual, 29.
PRESSURE, MECHANICAL, etc.—
and exhaust fans, 763.
— Piezo effect, 130.
in water pipes, 248, 249.
on poles, wind, 324, 329, 331.
steam, 174.
— standards, 170.
-type water heaters, 622A.
Prices (*see* "Cost of").
pre- and post-war, Note on, 530(h), 564.
Primary and secondary current in transformer, 391.
cells, 127, 128.
Prime movers, Chap. 6 *passim.*
— choice of, 189.
Printing and air-conditioning, 647A.
— *machinery, 777 (Tables 161, 162).*
"Prior Regulations," 469, 625.
Prismatic shades, 599.
PRIVATE—
and public supply, 185 *et seq., 458.*
plant v. purchase of energy in mines, 816.
— *for farms, 845.*
"Process," steam, 176, 188, *776.*
— *for textiles, 776.*
PROCESSES, CHEMICAL, ELECTRO-CHEMICAL AND ELECTRO-METALLURGICAL—
abrasives, 981.
alkali, 984.
alloys, 979.
aluminium, 975.
arc, 635.
bipolar electrodes for, 970.
brine products, 984.
calcium by electrolysis, 635.
— *carbide, 635, 973.*
carbon bisulphide, 635.
cheap power essential for, 969.
copper production, 987.
— *plating, 994.*
definitions, 970.
distillation products, 983.
efficiency of, 970.
electrolytic processes, 984-94.
— — *efficiency of, 970.*
electro-plating and typing, 994.
equivalents, chemical and electro-chemical, 970 (Table 213).
ferro-alloys, 979.
furnace products, 973-83.
furnaces for, 973-93 (see also *Vol. II, §§ 634 to 647).*
— *processes, 973-83.*
gold extraction and refining, 988.
— *plating, 994.*
graphite, 982.
hydrogen and oxygen, 985.
iron reduction and refining, 976.
— *and steel alloys, 979.*
lead plating, 994.
— *production, 992.*
linings for furnaces, 971.
load factor in, 969.
mercury vapour and steam for, 166.
metallic products, 975-80.
nickel extraction and refining, 990.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

PROCESSES, CHEMICAL, ELECTRO-CHEMICAL AND ELECTRO-METALLURGICAL (*cont.*)—
nickel-plating, 994.
— -steel, 979.
nitrogen, fixation, 974.
— products, 973, 974.
output and consumption data, 635.
oxygen production, 985.
parallel electrodes for, 970.
potassium production, 980.
power factor in, 969.
precipitation, electric, 996.
quartz, 981.
separation, various methods, 997.
silver extraction and refining, 989.
— plating, 994.
sodium and potassium, 980.
steel alloys, 979.
— from arc furnaces, 977.
— — induction furnaces, 978.
summary of, 972.
synthesis, electric, 995.
timber preservation, 86, 323, *846*.
tin recovery, 993.
zinc extraction 991.
— plating and wet galvanising, 994.
Producer gas, 167, 178, 181.
Projectors, 613.
cost of (Table 75), 572.
flood lighting, 586.
Projects and service in traction, 875 et seq.
Propeller pumps, 771.
— water turbines, 214, 215, 223, 230.
PROPERTIES OF MATERIALS (*see* Chapter 2, "Materials")—
for thermal storage, 627.
of metals, etc., 60, 66 (Table 6), *645* (*Table 98*).
Propulsion of ships (see "*Ship propulsion, electric*").
Protected machine defined, 4.
— motors, 670.
— — in mines, 818.
Protection of circuits and apparatus, Chap. 15.
— low-tension circuits, 398.
— motors, 713 et seq., *743*.
on traction systems, 892.
PROTECTIVE—
cable, 346.
devices for motors, 743.
— — earth leakage, 354A.
reactance, 340.
systems in mines, 819.
Systems, 359, *viz.*
Beard-Hunter sheathed-pilot, (*d*);
Beard self-balance, (*g*);
PROTECTIVE (*cont.*)—
Systems (*cont.*)—
Bowden-Thompson sheathed-cable, (*k*);
B.T.H. biassed-transformer, (*i*);
Distance protection, (*l*);
Ferranti-Hawkins core-balanced, (*j*);
Hunter four-case pilotless, (*f*);
McColl biassed-relay, (*h*);
Merz-Price balanced voltage, (*a*);
Merz-Price circulating-current, (*c*);
Merz-Hunter split conductor, (*e*);
translay, (*b*).
Provisional orders, 1040, 1041, 1043.
PUBLIC—
lamps in series and parallel, 611.
supply, 185 *et seq.*
— and private supply, 458.
— connection to, 512.
Pulley-blocks, electric, 790.
Pull-out torque, 752.
Pulverised coal, 168.
PUMPING; PUMPS—
electric, 767 et seq.
Humphrey, as auxiliary, 182.
in agriculture, 853.
— irrigation, 853.
— mines, 826.
power for, 768 et seq.
small, cost, 573.
to storage for power 230A.
Punches, 775.
Puncture tests, 1033.
Punkah pullers, 764.
Purchase of energy, 185 *et seq.*
— — or private plant in mines, 816.
Push-button lift control, 797.
Pyranol, 77.
Pyrheliometer, 647A.
Pyro-electric conductor, 72.
Pyrometry, 122, *646A*.
"*Pyrotenax*" (*magnesium*) *cables, 558.*
Pyrotip heating, 637.

"Q" in duration curves, 209 (ii).
Quadruplex air compressors, 766 (*Table 144*).
Quarter- and half-wave transmission, 318.
Quarries, electric working in, 811, 842.
Quartz, 73 (Table 7), 74, 130.
clocks, 428B.
glass, 981.
mercury-vapour lamps, 588.
Quasi-arc welding, 653.
Quick-break switches, 363 *et seq.*

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

RADIANT and convected heat, 616, 620.
insulation against, 616.
Radiation pyrometer, 122.
— *and convection losses in rooms, 620.*
Radiators, 620.
— *cost of, 574.*
Radio (*see* "Wireless"), 47.
Rail-bond resistance, 120.
Rail cars, Diesel-electric, 873.
motor coaches, 871.
RAIL(S)—
-brakes, 899.
conductor, railway, 902.
railway, 902.
resistance and weight of, 901.
return for A.C., 905.
standard, British, 901.
tramway, 901.
voltage drop in, 389.
Railway shunting yards, lighting, 613.
RAILWAYS, ELECTRIC (*see also* "Electric traction," "Motors, traction," "Tramways").
adhesion, 890.
alternating current, 919.
Bombay, Baroda and Central India, 868, 915.
braking on, 899, 900.
Brighton line, Southern Railway, 921 (2).
Budapest section, 919A.
Chicago, Milwaukee and St. Paul, 863.
classification of, 864, 865.
cost of, 926.
current collection on, 913.
electric and steam compared, 894.
examples of, 915 et seq.
feeders for, 924.
Great Indian Peninsular, 916, 918.
Hungarian State, 919A.
Kandó system, single-phase, 919A.
Lake Erie and Northern, 917.
line construction, 914.
locomotives for, 872-4, 894.
Loetschberg, 919.
main and suburban, 865, 915 et seq., *921 (2).*
motors and control for, 896, 898 (see also "*Motors, traction*").
Nilgiri (India) rack, 919.
permanent way and return circuit, 902, 904, 905.
Post Office (London) freight line, 922.
power and energy calculations, 878 et seq.
projects and service for, 875, 877.
rails and permanent way, 902.
regulations as to, 904, 908, 914, 920, 1052.
RAILWAYS, ELECTRIC (*cont.*)—
return circuit on, 904.
rolling stock on, 871-4.
— — *and service, 877.*
signalling on, 933.
Southern Railway, 921, 933.
speed-time curves, 885, 886.
street railways (see "*Tramways*"), *862.*
supply of power to, 868.
third-rail system, 920 et seq.
tractive effort, resistance and coefficient, 890, 891.
train lighting systems on, 927 et seq.
tube, 904.
tunnels on, 902, 914.
Rainfall and run-off, 204.
— storage, 241.
Rain-gauge, fractionating (Meares), 204.
Ram pumps, 768, 769.
Ramsey locomotives, 873.
Rate of electric welding, 654, 655.
Rateable value charges, 273.
"Rated normal current" of oil switch, etc., 369.
RATING—
intermittent, 670, 787, 895.
International standard of, 136.
of cables (Tables), 280.
— circuit-breaker, 369, 371.
— *crane and hoist motors, 787.*
— *hot-plates, 630.*
— *lamps, etc., 534 (8), 585.*
— machinery, 136.
— *motors, continuous and short-time, 670.*
— oil switches, 369.
— *pole-changing synchronous motor, 722 (Table 131).*
— rivers (B.S.I.), 209, *1058.*
— *starters, controllers, rheostats, 737.*
— switch defined, 371.
— *tramway motors, 895.*
— *transformers, 402.*
Ratio error in instrument transformer, 108.
— *of voltages in transformer, 391, 394.*
Rayo alloy, 67 (Table 6).
Rays, infra-red and ultra-violet, 578, 587 et seq.
REACTANCE—
alternators, 147.
cables, 310.
capacity, 46, 135, 304.
coils, 346.
component, 110, 154.
elementary, 44-6.
in starting induction motors, 724.
of short circuit, 370.
overhead lines, 299 *et seq.*
protective, 340.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

REACTANCE (*cont.*)—
  switching and, 370.
  table of, 307.
  transformers, 391 et seq. *and Chap. 17* passim.
Reactive components, 12A (*see* V.A.R.).
  — current, charging for, 270.
Reactors, current limiting, 340.
Recalescence, 64, 84.
Reciprocating and rotary compressors, 766.
Reclamation pumping, 853.
Recording instruments, 93, 97.
Records in power-house, 192, 193.
Recovery plants, 169.
  of tin, 993.
"Recovery-voltage" defined, 371.
Rectangular weirs, 205.
Rectified current, 13, 132.
RECTIFIER(S)—
  copper oxide, 417.
  — — *for lift brake control, 797.*
  Crypto, 416.
  crystal, 417.
  dry, 417.
  for traction, 869.
  general, 415 et seq.
  in cable tests, 1028.
  instruments, 101A.
  magnetron, 421.
  mercury vapour, 422-4.
  metal, 417.
  pliotron, 420.
  steel tank, 424.
  triode, 420, 424.
Rectifying matting, 417.
Rectigon, 418A, 419.
Recuperation of battery under reduced discharge, 431.
Redmanol, 74.
Red rope paper, 74.
Reduction gearing on ships, 960.
  — — *tramway motors, 895.*
  of iron ore, 697.
  ratio of transformers, 391, 394.
Reductor, 479 note.
Reed frequency meter, 112.
REFINING—
  of copper, 987.
  — *gold, 988.*
  — *iron, 976.*
  — *lead, 992.*
  — *nickel, 990.*
  — *silver, 986.*
Reflecting power of surfaces, 600.
Reflection ratio, 580.
REFLECTORS—
  — *cost of, 572.*
REFLECTORS (*cont.*)—
  for infra-red drying, etc., 646A.
  searchlight, 616.
  shades, etc., 599.
Refractories and linings, 85, *971.*
REFRIGERATION—
  air-conditioning and, 647A.
  machinery, 773 (Tables 149, 150).
  — *cost of (Table 76), 573.*
  — *on ships, 9624.*
  power used for, 647A.
  refrigerants used, 647A.
Refuse as fuel, 168.
Regeneration, 881.
  from propeller, 962.
Regenerative boiler heating, 166.
  braking, 715, 900, 945.
Register gate, 221.
Regulating water storage, 234, 239.
REGULATION (*see below*, "Regulations and Rules")—
  alternators, 147.
  furnace electrodes, 641.
  inherent, 147.
  of voltage in mercury vapour rectifiers, 422.
  tests of generators, 1022.
  transformer, 392.
  turbines, low fall, 221.
  — Pelton, 255, 256.
REGULATIONS AND RULES—
  Electricity Commissioners (formerly Board of Trade) *official*—
    bibliography, 293, 336.
    earthing, 472, 478.
    — *neutral, 472.*
    for rural lines, 1048, 1049.
    frequency standardisation, 135.
    general, for statutory undertakings, 1048.
    — — *non-statutory undertakings, 1049.*
    leakage, 470.
    luminous tubes, 672A.
    overhead lines, 324, *481.*
    safety of public and ensuring proper supply, 469.
    statistics, 191, 195, 197.
    supply organisation, 198.
  Home Office, *official*—
    arc welding, 658.
    bibliography, 58, 152, 293.
    cutting and welding, 658.
    earthing metal, 353.
    fire risk, etc., 356.
    general, factory and workshop, 1040, 1050.
    — *lampholders, 486.*
    — *mines, 1040, 1051.*
    generators, motors, etc., 151.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

REGULATIONS AND RULES (*cont.*)—
mines (*see also below*, "Unofficial"), *562.*
— *cables in, 819.*
— *earthing in, 821.*
— *general, 812, 813, 814, 1050, 1051-3.*
— *safety lamps, 841.*
— *shot firing, 838.*
— *signalling, 839.*
— *switchgear, 822.*
— *trailing cables, 820.*
ships, 966.
switchgear, etc., 382, *822.*
wall sockets, 494.
Minister of Transport (*official*)—
as to interference, 923.
for light railways, 1052.
railways, conductor rails, 920.
— *line equipment, 914.*
— *overhead work, 908.*
— *track and return circuit, 904.*
tramways, brakes, 899.
— *car equipment, 912.*
— *overhead work, 908.*
— *permanent way, 901, 1052.*
— *track and return circuit, 903, 909.*
Unofficial—
Institution of Civil Engineers as to earthing, 472.
Institution of Electrical Engineers, for the electrical equipment of buildings (*see* "Wiring Rules").
of licensing authorities, 632.
Regulators, speed, for fans, 759.
induction, 406.
Re-heating steam, 191.
Reinforced concrete poles, 323.
Relays, 124, 343 *et seq.*, 354A, 357 *et seq.*, 368.
induction, 344.
inverse time, 344.
Reluctance, 2, 6, 41, 42.
unit of, 2 (Table 1).
Remanent magnetism, 81-3, 138.
Remote control, 359, 372, 373, 378, *741.*
— *at peak, of lights, etc., 608, 615, 622.*
Rennerfelt furnace, 640.
Repairs and maintenance, 194, 269.
Repayment of loans, various methods, 1014.
Report on heating of houses, 615.
REPULSION—
between conductors, 338.
induction motors, 704.
motors, 701, 703.
— *control of, 733.*
Research, 59.
Reserve plant and the Grid, 186 note, 189.
RESERVOIRS—
and storage, 239 *et seq.*
— balancing, 240.
— pumping, 230A.
"dead water" in, 242.
Residual magnetism, 81-3, 138.
— *value of plant, 1013.*
Resins, 73, 74.
moulded lampholders, 485, 486.
Resista alloy, 67 (Table 6).
RESISTANCE(S)—ELECTRICAL—
alloys, 67 (Table 6).
copper, 62, 307.
current, and power of lamps, 583.
due to skin effect, 905.
elementary, 2, 8, 17, 19-24.
equivalent of transformer, 392.
furnace processes, 635, 636.
furnaces, 971.
I.E.E. rule as to resistances, 781.
insulation, 119.
materials, 66 (Table 6).
measurements, 119, 120.
metals and alloys, 67 (Table 6).
negative, of arc and vapour lamps, 587, 591, 592.
of alloys, 67 (Table 6).
— *carbon electrodes, 641.*
— *conductor rails, 901, 902, 920.*
— copper, 62, 307.
— hard-drawn copper, 307.
— *human body, 632.*
— *track rails, 903.*
reactance (*q.v.*), impedance (*q.v.*), 44-6.
shunt, 138.
starting, 719.
tests, temperature method, 1024.
thermometers, 122.
tractive, 891.
unequal, in parallel, 450.
welding, 660-4.
zero, 166 note.
Resistivity, 18.
Resistor furnaces, 978A.
Resistors, nichrome, carbon, silit, iron, etc. 617.
Resonance, 47, 318, 350, *428B.*
Restricted hour tariff, 272.
"Re-striking voltage" defined, 371.
Retardation, power absorbed in, 899.
RETURN CIRCUIT—
A.C., 905.
and permanent way, 901 et seq.
by rails, railway, 904.
— — *tramway, 903.*
defined, 9.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Return Circuit (*cont.*)—
earthed, 903.
feeders and boosters, 906.
Revenue from light, power, heating, etc., in G.B., 197 and Table 29C.
Reverse current and power relays, 357, 358.
-cycle refrigeration, 647A.
Reversible boosters, 432.
driving, 753.
field rheostat, 736.
Reversing motors, 751.
— ships, 957.
Revolutions, measuring stroboscopically, 123.
Reyrolle switchgear, 380.
Rheostats, 138, 385.
B.S.I., definition of, and rating, 736, 737.
Rheostene and rheotan alloy, 67 (Table 6).
Rhodamine, 589.
Richter induction motor, 685.
Ring mains, 383.
for farms, 846.
Rip saws, 775.
Rivers (*see* "Water Storage and Power")—
rating of, 209, *1058 note.*
— — curves, etc., 209.
Riveted and welded pipes, 248.
Riveting machines, 775.
Rivets, heating, 637.
replaced by electric welds, 649.
Rjukam plant, 243.
R.M.S. (virtual) values, 29, 56.
Road lighting (*see* "Street lighting").
Road Vehicles, Electric (*Chap. 36*)—
battery-charging for, 948-50.
— vehicles, 936 et seq.
— weight of, 938.
brakes for, 945.
cells for, 941 et seq.
comparison with petrol, 943, 954.
— of various types, 954.
deadweight of, 938.
drive of, 944.
energy consumption of, 946.
general information as to (*Chap. 36*), passim.
horse-power of, 943.
industrial trucks, etc., 951.
instruments on, 942.
life of, 936.
mileage and speed, 937.
motors for, 943.
petrol-electric, 953.
public service, 937.
road surfaces, 946.
running costs of, 947.
service data as to, 937.
Road Vehicles, Electric (*cont.*)—
speed control of, 945.
tractive resistance to, 946.
Roechling-Rodenhauser furnace, 639, 647.
Roller bearings in haulage, 832.
Rolling drum compressors and exhausters, 766.
steel, power for, 778.
weir, 244.
Rolling Stock, Traction—
and service, railways, 877.
— — tramways, 876.
generally, 870 et seq.
lighting, etc., on, 927 et seq.
on B.B. and C.I. line, 915.
— Brighton line, 921.
— G.I.P. line, 916.
supply on, 868.
Rolls, bending, 775.
Rooms, warming, 619.
Root-mean-square (R.M.S.) values, 29, 56.
Rope drive, 164.
— speeds in winding, 827.
for haulage, 831.
haulage ploughing, 851.
Rosin oil, 74.
Ross Institute, 647A.
Rotary and reciprocating compressors, 766.
condenser, 160.
drills, 836.
Rotary-converters, 135, 156, *408* et seq., *667.*
back-to-back tests of, 1021.
efficiency curve of, 425.
in mines, 814.
— traction, 869.
— welding, 667.
Rotating and rocking furnaces, 640.
boiler, 170.
Rotation, phase, 150.
Rothamsted experimental station, 857.
Rotor, 133, *671* (*see* "Motors, A.C.").
currents of 3-h.p. induction motors, 725 (*Table 133*).
starters, 738.
Rousseau's method and figure, 581.
Rubber, 73-5, 287 (*see* "Cables").
tough (*cab-tyre*), *551.*
Rubbered tape, 74.
— cost (*Table 74*), *571.*
Ruhmkorffcoil, 588A.
Rule—
Ampere's, 33.
Crompton's, 33.
Fleming's 35.
Maxwell's, 32.
parallelogram, in vectors, 11.
Wilmshurst's, 619.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

RULES (*see also* " Regulations and Rules ")—
as to switchgear, 382.
for rural lines, 1048, 1049.
of the Electricity Commissioners; the Home Office; the Ministry of Transport (*see detailed lists under* " Regulations and Rules, official ").
Regulations of the Institution of Electrical Engineers for electrical equipment of buildings (*see* " Wiring Rules ").
" *Ruling gradients," in traction, 875.*
Running costs of " electrics," 947.
speed of lifts, 794.
Run-off, Barlow's method, 204.
Runways, 786, 790.
Ruping process, 86.
Rupturing capacity of switches, 369-71.
RURAL LINES—
cost of overhead, 332 (Table 50).
distribution by, 847.
for agriculture, 845 et seq.
regulations for, 1048, 1049.
transformer and consumer data for, 846 (Table 179).
transmission by, 846.
Russell's method for candle-power, etc., 581.
Rutger process, 86.
Ruth's steam storage, 625.

SAACHEM plant, 243.
Saccharine process, timber, 86.
SAFETY—
devices, 324.
in A.C. and D.C. welding and cutting, 656, 658.
— mining, 812.
lamps in mines, 841.
Mines Research Board, 812.
rules for tramcar equipment, 912.
Sag of overhead lines, 328, 329.
Sale of energy, 268, 270 *et seq.*
— — in G.B., statistics, 197.
Salt-bath furnaces, 646.
Salt mines, 842.
Sampling coal for analysis, 168.
Sand and thermal storage, 627.
in H.T. fuses, 375.
traps, in water power, 238, 240.
Sandberg steel rails, 902.
Sandpaper machines, 775.
Saturation density, 81, 82.
Saucepans, electric, 628.
Savings due to electricity, 863.
— — *regeneration, 900.*
SAWDUST—
as fuel, 168.
danger from, 562.
Saws and saw-sharpeners, 775.
SB alloy, 67 (Table 6).
Scales for instruments, 91.
Schedule of wiring, 522.
Schenectady M.-V. plant, 166.
Scherbius phase advancer, 160.
system, variable speed, 728.
Schering bridge for P.F. tests, 1030.
Schönherr process, 974.
Schön-Punga single-phase motor, 692.
School of Hygiene; air-conditioning, 647A.
Sciaky welder, 662A.
Scoop-type scraper loader in mines, 835.
Scott-Bentley discriminator, 718.
Scott connection, 394.
Screened type E.H.T. cables, 289.
Screening coal, 837.
Screen-protected motors, 670.
Screwed conduit, 539 et seq.
Screw-eyes, cost (Table 74), 571.
Screw-type pumps, 771.
Sealing-wax heaters, 631.
Seals, tampering with, 512.
Seam welding, 660, 663.
Searchlights, 613.
Sea-water, power from tropical, 165.
Secondary and primary of transformer, 391.
SECONDARY BATTERIES; CELLS—
acid loss in, 432.
alkaline, in safety lamps, 434, 434B, 841.
— and primary, 127.
ampere-hour efficiency, 431, 432, 434.
backward cells, 432.
bare connections for, 561.
boosting, 432, 949.
capacity of, 430 et seq.
— for " electrics " 941.
care of, 432.
charging, 432.
— for vehicles, 948.
— tariffs for, 950.
curves of voltage recovery, 431.
discharging, 431, 432.
Drumm 434(b), 873.
Edison, 433.
efficiency of, 431, 432, 434.
electrolyte for, 431-3.
elementary, 127.
E.M.F. of, 430, 431, 434.
fallacies about, 432.
Faure, 431.
first charge of, 432.
for " electrics," 936 et seq., *948-50.*

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

SECONDARY BATTERIES; CELLS (*cont.*)—
for railway carriage service, 929.
I.E.E. rules as to, 431.
in parallel, 451.
— series, 447.
— series-parallel, 454.
" *Keepalite* " *system, 430.*
lead, 431 et seq.
lead-hydrate, 433.
locomotives, 873.
— for mines, 832.
motor car types, 432.
nickel-iron, 433.
Planté, 431.
portable, 432.
propelled public-service vehicles, 937.
recuperation under reduced discharge, 431.
road cars (see "*Road vehicles, electric*"), *936* et seq.
specification for, 1004.
sulphating of, 432.
traction (*Chap. 36*), passim.
tractors and trucks, 951.
trickle charging, 430, 432, 583.
truck cranes, 789.
vehicles, running costs of. 947.
watt-hour efficiency of, 431, 434.
zinc-alkaline, 873.
Second-foot (*see* "Cusec").
Sectionalising of overhead line, 909.
Seed treatment, electrical, 857.
" *Seelco* " *wiring, 552.*
Seewer turbine governing, 255.
" Selected stations," British, 268.
Selection of suitable motors, 752, 753.
Selective protection, 357 *et seq.*
Selector switches, 362.
— *for lifts, 797.*
Selenium, 65.
calls, 420A.
Self-balance system, protective, 359.
-contained locomotives, 873.
Self-exciting, 133, 140.
-inductance, 2, 35.
" *Selsyn* " *motors, 680.*
Semi-coke, 168.
Semi-Diesel engine, 179, 180.
Semi-enclosed machine, 4?
Semi-indirect lighting, 603, 605, 606.
Semi-storage cookers, 628.
Separate excitation, 133, 140.
— *of motors, 674.*
— *ships' dynamos, 960.*
Separation, electrical, 997.
Separators, magnetic, 809.
SERIES—
boilers in, 191.
connections, 444, 445.
dynamos, 138.
— in parallel, 148.
insulators in, 330.
lighting, 446.
motors, 676, 753.
— starting and control of, 718, 873.
-parallel coupling fans and lights, 452-4.
— — — — switches for, 506.
public lamps, 611.
-repulsion motors, 703.
resistance in arc welding, 656, 657.
— — furnaces, 636.
— — voltmeter, 107.
single-phase motors, 700.
— — control of, 731.
-type commutator motors, A.C., 708.
winding, 134, 317.
Serpek process, ammonia, 973.
Serra hydro-electric plant, 216.
SERVICE—
data of "*electrics,*" *937.*
— and rolling stock on railways, 877.
— — traction projects, 875 et seq.
— lines (see next entry).
— on tramways, 876.
SERVICE LINES—
cost, 575.
defined, 443.
general, 443, 481, 512.
" *Service value* " *in fans* (*B.S.I.*), *1036.*
" Service voltage " of system defined, 371.
Setting out overhead lines, 324.
Severn Barrage, 214, 230.
SHADES—
" *controlens,*" *591A.*
cost of, 572.
reflectors, etc., 572, 599, 616, 646A.
Shaft cables, 819.
signalling in mines, 839.
Shafts for lifts, 792.
Shaker conveyors, 835.
Shaped conductor cables, 311.
Shapers, 775.
Shaving-water heaters, 631.
Shears, 775.
Sheath as earth return, 482.
Sheathed cables, 359 (*see* "Intersheaths"), *819*
pilot system, 359.
Sheathing resistance of cables, 819.
Shellac, 73 (Table 7), 74, 75.
Shell-type transformer, 398.
Sherringham daylight, 578.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Ship auxiliaries, power for, 779.
welding plates in, 649.
Ship Propulsion, Electric—
A.C. and D.C. for, compared, 958.
advantages of, 957.
auxiliaries and accessories for, 964.
barges, dredgers, ferries, tugs, 965.
battleships, 961.
by towing, 965.
cables for, 959, 964.
cascade connection for, 958.
colliers, 957.
compared with mechanical drive, 957, 962.
— — *geared turbine drive, 962.*
control for, 959.
Diesel engines in connection with, 957, 960, 962.
dredgers, 965.
excitation for, 960.
ferries, 965.
fuel consumption and economy of, 957.
induction motors for, 958 (see also "*Motors, A.C.*").
low frequencies for, 958.
manœuvring power with, 957.
master control for, 957.
passenger vessels, 963.
reduction-gearing for, 960.
reversing with, 957.
rules and regulations for, 966.
signalling, ship's telegraph, 957.
steam consumption with, 960, 961.
towing barges, etc., 965.
tugs, 965.
turbo-electric, 960.
warships, 961.
Ship's telegraph, 957.
Shock danger in welding, 656, 658.
dangerous pressure, frequency, etc., 632.
from earthed circuit, 482.
prevention in domestic heating, etc., 632.
Short Circuit—
caused by birds, 915.
current of transformer, 393.
forces in transformer, 398.
general, 25, 337, 338.
in switches, 368.
isolating switches and, 338.
location, 1026.
reactance, 370.
tests, 1020.
time lag, 344.
Short-circuiting switch, 480.
Shortt clock, 428B.
Short-time ratings, two different, 136.
— — *of motors, 670.*
— — — switch or C.B., 371.
Shot-firing in mines, 838.
Shrinking on tyres, heat for, 638.
Shunt (Electric)—
current, 138.
discharge path, 367.
dynamo, 138.
— in parallel, 148.
explanation of, 455.
-field rheostat, 736.
in instrument design, 107.
resistance, 138.
-type commutator A.C. motor, 709.
-winding, 134.
-wound motors, 675 (Table 115), 753 (see also "*Motors, D.C.*").
— — *for lifts, 796.*
— — *starting and control of, 717.*
Shunting locomotives, 873.
yards, lighting, 613.
Shunts in instruments, 107.
Side- and under-running trolleys, 912.
Side contact rail, railway, 920.
— *-pole construction, tramways, 909, 910.*
Siemens-Halske process, gold, 988.
Siemens (horn) arrester, 346.
— unit, 18.
"*Sieray-dual*" *lamp, 589, 612.*
Signalling, electric on railways, 933.
— *in mines, 839.*
Signals, three-aspect colour, 921.
Signs and symbols, conventional, 6, 7.
Silica, 73, 74, 85, 375.
-gel, aquagel, aerogel, 647, 647A.
properties of, 645 (Table 98).
Silico-manganese, 979.
Silicon-bronze, 67 (Table 6), 329, 331, 335.
— *trolley wire, 909.*
Silicon production, 981.
— — *for trackwork, 902.*
Silicon-steel, 67 (Table 6), *979.*
Silit, 67.
resistors, 617.
Silk, 73 (Table 7), 74, 80.
Silo treatment, 852.
Siloxicon ; silundum, 981.
Silt traps, 238, 240.
Siluminite, 73 (Table 7), 74.
Silver—
energy for melting, 647 (Table 101).
extraction and refining, 989.
melting, 639, 647.
-plating, 994.
properties of, 65, 67 (Table 6), 127, *64[illegible] (Table 98).*
Simla, water problem, 622.
"Simplified unit" train-lighting, 931.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Sine-wave, 11, 30, 350.
Single-core, cable, 319.
SINGLE-PHASE (*see also* "Alternating current," "Transmission of power")—
alternator, 134, 143.
and 3-phase compared, 476.
capacity and charging current, 305.
commutator motor, 706.
elementary, 11.
furnaces, 639.
induction motor, 689.
— — control, 730.
motor control, 730, 731, 898.
power, 110.
railway construction, 919.
regenerative braking, 900.
repulsion motors, 701.
series motors, 700.
— — control, 731.
shunt-characteristic motors, 706.
supply, 464.
traction type motors, 896.
— — — Kandó system, 919-A.
transformers, 399.
transmission, 297, 299 *et seq.*
v. *polyphase transformers, 399.*
Single-pole switch defined, 4.
Single-way switching, 500.
Sinking funds, 1012.
— and loans, 1014.
Sirocco fans, 764.
Six-phase transmission, 319.
Size of wires, 279, 307.
Skin effect, 38, 135, 309, *637.*
— in induction furnaces, 639.
— rails, 905.
Slag pits for boilers, 191.
Slate, 73 (Table 7), 74.
Sliding scale, 1044.
Slip and stroboscope, 123.
changing for speed control, 725.
— of induction motor, 681.
— drying ceramic, 647A.
Slip-ring(s), 133, *671.*
of induction motors, for lifts, 796.
— motors, 681.
— polyphase motors, 683.
Slipper brakes, 899.
Slope of stream bed, 210.
Slotters, 775.
Sludge in oil, 1034.
Sluices, 213.
Snow on wires, 324, 331.
Snyder furnace, 640.
Soapstone, 74.
Socket-outlets, adapters, and wall plugs, 492-8.
Soda, caustic, manufacture, 635.
Soderberg electrodes, 641.
SODIUM AND POTASSIUM—
gas-discharge (vapour) lamps, 587, 590.
cost of, 571 (Table 74).
production, 127, *635, 980.*
properties, 127, *590.*
-silicate, 647.
— cement, 75.
Soldering, electric, 631.
— irons, cost, 574.
— "Pyrotip," 637.
Sole electrodes, 641.
Solenoids, 355.
in cyc-arc welding, 666.
type starters, 738.
Solid insulators, 74.
laid cables, 290.
Solignum, 86.
Sources of energy and prime movers, Chap. 6.
Southern Railway, Brighton main line, 921 (2).
— — signalling on, 933.
— — third-rail, work on, 921.
Space-heat application, 616.
Space occupied by cells, 431.
— — — plant, 196.
Spacing of overhead lines, 327.
Span and dip of overhead lines, 324, 327, 329.
Span-wire construction, 909, 910.
Spare plant, 189, 190.
SPARK GAP—
arresters, 346.
general, 89.
voltage, 78.
voltmeter, 105.
welding, 665.
Sparkless commutation, 139.
Spear and nozzle for water turbine, 255.
Special Acts, 1044.
Orders, 1040, 1041, 1043.
pipes, hydraulic, 250.
switches, 374.
SPECIFICATIONS (*see also* "British Standards Institution").
batteries, 1004.
bodies issuing, 1053.
boilers, 1009.
B.S.I., of transformer, 402.
— of switchgear, 365, 369-72.
cables, 1006.
generators, 1001.
model wiring, for cleat system, 547.
— — — conduit system, 544.
— — — for metal conduit, 558.
— — — wood casing, 536.
— — general clauses, 534.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

SPECIFICATIONS (*cont.*)—
motors, 1002.
oil and gas plant, 1010.
overhead lines, 1007.
secondary batteries, 1004.
steam plant, 1008.
street lighting, I.E.E., 1054.
switchboards, 1005.
switchgear, 365, 369-72.
transformers, 1003.
water-power plant, 1011.
SPECIFIC (*see two following heads*)—
heat of air, 619.
— — *metals, etc., 645 (Table 98).*
inductive capacity, 46, 60, 70.
resistance, *see below.*
speed (water turbines), 214, 215, 233.
SPECIFIC GRAVITY—
of electrolyte for lead cells, 431.
— metals, etc., 67 (Table 6).
— *thermal storage materials, 627.*
SPECIFIC RESISTANCE—
dielectrics, 70, 71.
"*earth,*" *907.*
electrolytes, 68.
general, 59.
metals, etc., 67 (Table 6), 82.
steel and iron, 82.
Spectra of arc lamps, 592B.
— *lamps, 587* et seq.
Spectrum of arc and vapour lamps, 592B.
SPEED (*see also* "Velocity").
and energy demand in traction, 888.
— frequency, 123, 135.
— head, water turbines, 223.
— *mileage of "electrics," 937.*
— *poles of converter, 409.*
— *torque variation, 749.*
— *weight of fractional H.P. motors, 710 (Table 127).*
control and braking on "electrics," 945.
— *methods compared, 726 (Table 134).*
— *on A.C. motors, 699.*
— — *group and individual drive, 748.*
— — *lifts, 796.*
— — *shunt motors, 675.*
— — *three-phase commutator for, 687.*
measurements, 123.
of cranes, 788.
— *haulage, 831.*
— *lifts, 794.*
— *motors, 672 (Table 113), 698 (Table 125).*
— — *adjustable, 753.*
— *suburban railways, 921.*
— *synchronous motors, 679 (Table 117).*
— turbines (steam), 145.
SPEED (*cont.*)—
of turbines, water wheels, 222, 254.
reduction for motors, 751.
regulation defined, 713 note.
— *of fans, 759.*
specific (turbines), 214, 215, 233.
time curves for power calculations, 886.
variation by pole changing, 686.
— *of D.C. motors, 716* et seq.
— — *motors, 751, 752.*
— — *synchronous motors, 722.*
Sperry arc lamp, 613.
Spherical candle-power, 580, 581.
Spindles, cotton; spinning machines, 776 (Tables 154 to 156).
Spinning boilers, 170.
Spiral casing, 233.
Spirit varnish, 76.
Split conductor system, 288, 290, 359.
— *-phase starting, 689, 690.*
"*Spot lights,*" *586.*
Spot welding, 660, 662, 662A.
Spouting velocity, water, 214.
Spray filters for air, 647A.
Spring control instruments, 90.
operated fuses, 375.
— circuit-breakers, 372.
Spur-gear for lifts, 793.
Square-mile-foot as hydraulic unit, 202.
Squirrel-cage motors, 681 (Table 119), 684 (Table 120).
— *polyphase motors, 682.*
— *rotor, double, 681.*
Stabilit, 74.
Stability windings, 389A.
Stacking machines, 802.
Stainless steel, 978.
Stairways, moving, 804.
Stalling torque, 752.
Stalloy, 82.
STANDARD—
ambient air temperature, 402.
— temperature in oil switch, etc., 369.
British Standards Institution (B.S.I. formerly B.E.S.A.), 5, *1055* (*see* "British Standards").
candle, 579.
cells, 95, 128.
charging plugs and sockets, 952.
conductors, 279.
copper (I.E.C.), 62.
frequency, 134, 135.
instrument transformer, 108.
measurements, 95.
method for resistance of steel rails, 901.
of time, precision, 428B.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

STANDARD (*cont.*)—
oil-break switches, 371.
pressures (British), 23.
price and dividend, sliding scale. 1044.
rating, 136.
resistance, 20, 95, 106.
station pressure, 134.
steam pressures, 170.
switchgear, 365, 369-72.
time, 428B, 602.
tramway poles, 910.
trolley wheel and groove, 912.
voltages (British), 23, 134.
wire gauge (S.W.G.), 279.
Standing charges, 269, 272.
Stand-pipe, hydraulic, 232, 249, 251.
Stannos system, 545, 556.
STAR-DELTA; STAR AND DELTA—
connections, 143, 158, 314.
starter rated, B.S.I., 736, 737.
— cost of, 711 (Table 130).
— defined, 713.
starters, 738.
switching for starting induction motors, 724.
transformer, 394.
STARTING—
characteristics of series-repulsion motors, 703 (Table 126).
converters, 410-13 (a).
current of squirrel-cage motor, 681.
demand, limiting, 744.
resistance calculations, 719.
sheet (cathode), in electrolysis, 970.
torque of motors (Chap. 28), passim.
— — lift motors, 796.
Stassano furnace, 640.
Static balancer, 141.
condenser and power factor, 160.
transformer, 391 (*see* "Transformers").
Station pressure, 23.
load factor, 261.
STATISTICS—
agriculture, 844, 858.
boiler plant, 170.
coal cutters, 834.
dairy work, 855.
industrial locomotives, 874.
mining, 812, 816, 823.
plant, 170, 173, 195, 197, 198.
power, 165, 192, 193.
quarries, 842.
railways, energy used on, 887.
safety lamps, 841.
sale of energy, 197.
traction, 863, 865.
Stator-rotor starters, 738.
Stators and rotors, 133, *671.*
Stay wires, 326.
— earthing, 533.
STEAM (*see also* "Boilers")—
accumulator, 177.
— and exhaust steam in mines, 817.
— electric traction compared, 894.
— — winding compared, 827.
— water-power compared, 217.
— pumping, 230A.
-blast switches, 372A.
boilers, 170 (*see* "Boilers").
— electric, 625.
condensers, 175, 191.
consumption, engines, 167.
— in battleships, 961.
— of geared and electric turbo drive, 960, 963.
— turbines, 167, 173.
cycle, 166.
-electric winding system, 830.
from volcano, 165.
fuel and, consumption, 167.
high pressure and temperature, 170, 174, 189, 191, 196.
per kWh in electric boilers, 625.
plant, specification of, 1008.
pressure transformer, 176.
turbines (*see* "Turbines, steam").
— consumption, 167, 173.
— cost, 195.
Steatite, 74.
— and thermal storage, 627.
STEEL—
alloys, 979.
arc furnace, 635.
Baily furnace for, 636.
conductors, 328.
conduit and casing, 538, 539, 541-5.
— cost of, 568.
contact wire on railways, 917.
-core cables, 481.
-cored aluminium cables, 917.
electrodes, 653.
energy for melting, 647 (Table 101).
for conductor rails, 64.
— transformer plates, 398.
from arc furnaces, 977.
— induction furnaces, 978.
heat treatment of, 978A.
magnetic and non-magnetic, 81 *et seq.*
overhead wires, 328, 331.
pipes, water (*see* "Pipes, turbine").
plate cutting, 659 (Table 105).
poles, 323.
properties, 64, 82, *645 (Table 98).*
rails, skin effect in, 905.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

STEEL (*cont.*)—
skin effect, 309, *905*.
special, for rails, 902.
stainless, 978.
tank rectifiers, 424.
treating furnaces, 646.
wires, 331.
— constants of, 309.
works, 778.
Steeple-type turbo-generators, 196.
Steering, electro-hydraulic, 963.
Step-down transformer, 108.
— *for heating, 637.*
Sterilisers, 631.
cost of (*Table 77*), *574.*
Stewpans, 628.
Still engine, 179.
Stirling boiler, 170.
Stobie furnace, 640.
Stokes' Law, 591A.
Stone insulators, 74, 330.
Stone's system of train lighting, 930.
STORAGE (*see also* "Secondary batteries," "Storage of water," "Thermal storage")
batteries, specification of, 1004.
by pumping, for power, 230A.
flywheel, 751, 753, 828, 829.
magnetic, in welding, 662A.
of energy, 230A (see also *Chap. 18*).
— fuel, 168, 196.
thermal (*see* "Thermal Storage").
STORAGE OF WATER—
approximations, 202.
as power accumulator, 230, 230A.
dams and, 225.
flow and, on medium head plants, 229.
— — — high head plants, 234 *et seq.*
for reserve power, 230A.
mass curves and, 209.
plants depending on, 241 *et seq.*
regulating, 239.
Severn Barrage, 230.
Strapping wires, 502.
Stream-lined windmill blades, 165.
Streams, discharge of, 206.
STREET LIGHTING—
by vapour (*gas-discharge*) *lamps, 589, 590, 612.*
general, 590A, 609-11.
I.E.E. clauses for, 1054.
remote control of, 608.
Street railways, 862.
Strength of poles, 325.
Stress (*see* "Breaking stress").
String electroscope, 96.
galvanometer, 96.
Stroboscopes, 123, 215, *1035*.
Stroboscopic meter testing, 1035.
Stubbs-Perry winding system, 830.
Sub-divided circuits, 524.
— *I.E.E. rule as to, 523.*
lights, 501.
Submarine cables, 198, 292, 329.
— *lifting magnets, 806.*
Submarines and Diesel drive, 960.
Submerged pumps, 826.
Submersible motors, 670.
SUB-STATIONS—
automatic, 428.
cost of, 926.
description, 426-8.
efficiency of, 426.
for traction, 869, 893, 916, 918.
on G.I.P. Railway, 916, 918.
outdoor, 381.
Sub-standard instruments, 92, *427*.
types of, 427.
Suburban railways, 865.
— *description of, 915, 916.*
— — — *third-rail, 921.*
Suction (producer) gas, 167.
head, 214, 218, 220, 232, 233.
on windmill blades, 165.
Sulphation of battery plates, 432.
Sulphur, 73 (Table 7).
Sulzer engine, 172.
monotube boiler, 170.
Summation meters, 116.
panels, 385.
Summer time, 612.
Sumpner wattmeter, 109.
Sunlight, 599, 604.
Sun-power, 165.
Superheat and fuel saving on ships, 957 (*Table 206*).
Superheated and high-pressure steam, 170, 172, 174.
Super-imposed or topping plants, 191.
"Superior" alloy, 67 (Table 6).
Super-synchronous motors, 698.
Supervisory control sub-stations, 869.
SUPPLY, ELECTRIC (see also *Vol. II, Chap. 20*)—
charges for (*see* "Tariffs").
disconnection of consumer's, 512.
in relation to motors, 754.
interruptions to, 355.
meters, 113 *et seq.*
systems of (*Vol. II, Chap. 20*).
— — *for traction, 866* et seq.
Surface condenser, 175.
velocity of stream, 206, 210.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

SURGES (ELECTRICAL), 45.
absorbers, 346.
and choking coils, 45.
— *transformers, 400.*
arrester, 421.
lightning, 346.
switching, 349.
Surge tanks and towers, hydraulic, 232, 249, 251.
Susceptibility, 6.
Suspension and insulation of trolley wire, 911.
insulator, 330.
of mine cables, 819.
Sustained overload defined, 136.
Svir H.E. plant, 214.
Sweated joints, electrical, 660.
S.W.G. (Standard Wire Gauge), 279.
SWITCHBOARD(S) (*see also* "Switches" below)—
and switchgear, Chap. 16.
cost of small, 570.
defined, 4.
in mines, 822.
outdoor, 921 (*2*).
rules as to, 382.
specification for, 1005.
SWITCHES AND SWITCHES (*see also* "Circuit-breakers" and *Vol. II, Chaps. 21, 22*)—
all on one pole, 499.
— *or part, 501.*
and accessories (*Chap. 21*).
automatic, 507.
branch, 507.
Calvete tele-switch, 505.
charge and discharge, 431, 432.
circuit-breakers (*q.v.*).
cost of, 570, 571.
general, 362 *et seq.*
I.E.E. rules as to, 508, 510.
in earthed conductor, 499.
— *installations, 534* (*11*), (*16*).
intermediate, 502, 503.
lampholder, 486, 492.
Lundberg, 502.
master control, 504.
miscellaneous, 505.
multiple, 363, *503.*
oil for, 77.
— *tests for, 1034.*
plugs, "anti-flash," 493.
pressel, 507.
ratings, 369.
series-parallel, 506.
single-way, 500.
special types. 505.
-starter, B.S.I. definition of, 736.
subdivision of, lights, 501.
SWITCHES AND SWITCHES (*cont.*)—
surges in, 349.
three-point, 503.
time, 622.
tumbler, 363.
twinob, 501.
two-way, 502.
Switching transients, 400, 407.
Symbols and signs, conventional, 6.
Synchronising, 149, 321, *419.*
SYNCHRONOUS—
A.C. boosters, 411.
asynchronous motors, 696.
— *control, 731.*
alternators, 143.
condenser, 679.
— hydrogen-cooled, 911.
motor-generators, 388, 425.
motors, 679, 680, 753 (see also "*Motors, A.C.*").
— and power factor, 156, 158, 160.
— over-excited, 160.
— *industrial applications of, 679* (*Table 118*).
— *speeds of, 679* (*Table 118*).
— *starters, 738.*
— *starting and control, 722.*
— *two-pole, 722.*
-repulsion motor, 705.
speed and frequency, 135.
Synchroscope, 149, 385.
Synthesis, electrolytic, 995.
SYNTHETIC—
insulators, 74.
resins, 75.
Syntony, 47.
"System" defined, 4.
SYSTEMS OF—
distribution, choice of, 474.
hot water supply, 622A.
supply (see *Vol. II, Chap. 20*).
— *approval of, 1047.*
— *for traction, 866* et seq.
train lighting, 929 et seq.
winding, 827 et seq.
wiring (see *Vol. II, Chap. 23*).

TABLE lamps, cost of, 572.
Tables, list of, xi.
Tail race, 257.
Talc, 74.
Tandem mills, steel, 778.
— turbo-sets, 196.
— *worm-drive for lifts, 793.*
Tangent galvanometer, 96.
Tank arrester, 346.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Tanks for circuit-breakers, 368.
Tantalum, 67 (Table 6).
— *alloys, 979.*
— *lamps, 583.*
Tap-changing in transformers, 395.
Tape, adhesive and rubber, cost (Table 74), 571.
Tapping overhead lines and "grid," 324, *427.*
Tappings on transformers, 395.
TARIFFS FOR ELECTRIC SUPPLY—
according to room areas, 273.
and costs, Chap. 12.
— load factor, 270.
— power factor, 274.
— private supply, 185.
— *welding load, 667.*
examples of, 275.
fixed charges per kw. or per lamp, 272.
flat rates, 270.
floor area, 273.
for agricultural supply, 860.
— *battery charging, 950.*
— *traction, 925.*
— *welding load, 667.*
general, Chap. 12.
Glasgow, 273.
Grid, 275A.
maximum demand, 272A.
Metropolitan, 273.
minimum charges, 271.
Norwich, 273.
point-five, 273.
power factor and, 274.
rateable value, 273.
restricted hour, 272.
standing charge plus unit, 272.
"telephone," 272, 273.
Wright's, 272.
Tarnac alloy, 67 (Table 6).
Tar oils, 169, 178, 180.
precipitation of, 996 (Table 216).
Tarpon paper, 74.
Tea-firing electrically, 619.
Tee-connection in transformer, 394.
Telegraph, ship's, 957.
— *and telephones, interference with, 407, 908.*
TELEPHONE(S)—
general, 335.
in mines, 839.
interference, 407, 908.
loading, 82.
localisation of cable faults, 1032.
system of charging, 272, 273.
Tele-switch, Calvete, 505.
TEMPERATURE—
absolute (K), 166, *591A.*
and colour, 646.
TEMPERATURE (*cont.*)—
and consumption in industrial heating, 635.
"black body," 589.
coefficient of carbon and tungsten, 583.
— — — *electrodes, 641.*
— — copper, 62.
— — electrolytes, 68.
— — metals, etc., 60, 61, 66.
dielectric loss and, 312.
due to sun's heat, 647A.
electrical measurement of, 122.
errors of instruments, 92.
for comfort; eupatheoscope, 620.
in large generators and motors, 670 (Tables 110 and 112).
— *mining motors, 818.*
— *ovens and furnaces, 635 (Table 96A).*
limits, insulators, 80.
machine, mean, 122.
of arc, 591.
— — *furnaces, 640.*
— *Kelvin scale (K), 591A.*
— *transformers and altitude, 402.*
regulation in furnaces, 636.
rise, cables, 291.
— *in fractional H.P. motors, 670 (Table 109).*
— *of transformers (B.S.I.), 402.*
— overhead line, 328.
— standard rating and, 136.
— switches, 369.
specific resistance and, 71.
standard ambient, in rating switches, 369.
— *of air, 402.*
steam, 170, 172, 174.
tests, 1024.
Tempering, electrical, 646.
Tenders, competitive, for wiring, 565.
Tenoning machines, 775.
Tensile strength of metals, etc., 67 (Table 6).
Terminal congestion on railways, 865.
insulator, 330.
markings of motors, 671.
stays, 326.
Tertiary winding in transformer, 394, 396.
Tescari system of ploughing, 851.
Tesla transformer for testing, 1033.
Testers, earth, 119.
TESTS: TESTING (Chap. 40)—
cable, 1027 et seq.
constants in meters, 1035.
drying out for, 1018.
earth, 1037.
— plates, 348.
efficiency, 1021.
fans, 1036.
faults, 1026, 1032, 1033.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

TESTS: TESTING (*cont.*)—
flame-proofness, 812.
for leakage to water pipes, 472.
heating, 1023.
Hopkinson back-to-back, 1021.
induction motors, 1020.
installation wiring, 534 (9), 1037.
insulation, 1018, 1029.
insulators, 330, *1033.*
lead cells, 432.
live cable systems, 1331.
loads on standard poles, 910.
loop cable, 1032.
meter, 1035.
motor-converter; motor-generator, 1021.
Murray, 1032.
no-load, 1019.
oil, 1034.
open-circuit, 1019, 1032.
performance, 1017.
regulation, 1022.
rotary-converter, 1021.
sets, 106.
— *cost of (Table 74), 571.*
short-circuit, location of, 1026.
— *machine, 1020.*
temperature, 1024.
tinning, 282.
transformer, 405, 1020, 1035.
turbo-alternator, 1021.
Varley, 1032.
wiring and installation, 1037.
Tetrode, etc., valves, 418 et seq.
Textile machinery, power for, 776.
works and humidity, 647A.
Thallium, 67 (Table 6).
Theory and practice in water heating, 622.
Therapeutic rays, 578.
lamps, cost (Table 74), 571.
Therlo alloy, 67 (Table 6).
Therm, 48, 178.
THERMAL—
conductivity, 85.
contact in hot-plates, 630 note.
efficiency, 166, 167, 181, 183, 188, 191.
— internal combustion engines, 179.
— *of water heating, 621.*
— steam turbines, 173.
— water turbines, Chaps. 8-10 *passim.*
instruments, 89 *et seq.*
-maximum demand indicator, 117.
relay protection, 743.
steam accumulators, 177.
storage, 177.
— *and water-power, 615.*
— *heaters, cost of, 574.*
THERMAL (*cont.*)—
systems, 621, 627.
— and cooking, 122.
Thermantidotes, 647A.
Thermionic valves, 418 et seq.
— *for motor control, 743.*
— — *generator for induction furnace, 639.*
— *in welding, 662.*
THERMO—
ammeter, 99.
-couples (*see* "Thermopile" *below*).
— *in heat runs, 1023, 1024.*
-electric generators, 165.
THERMOMETER—
tests, 1024.
Thermometers, mercury and spirit, 122.
hydrogen, 589.
Thermopile (thermo-couple), 89, 99, 122, 129, 165, *591A, 646A, 1023, 1024.*
THERMOSTAT(IC)—
control, 615, 618, 620, 636.
— *of furnaces, 636.*
— *in air-conditioning, 647A.*
— — *industrial heating, 634.*
— — *room heating, 620, 647A.*
Thermo-tank punkah louvres on ships, 963.
Therol thermal storage, 627.
Thickness of water-pipes, 248, 249.
Third harmonics in transformers, 394.
-rail system, 920 et seq.
— *collectors, 920.*
Thomas transmission, 953.
Thompson watt-hour meter, 115.
Thoria, 583.
Three-core cables, 311.
Three-electrode "Pointolite," 597.
— *valves, 420, 424.*
THREE-PHASE (*see also* "Alternating currents, 3-phase")—
and single-phase compared, 476.
auto-transformer, 396.
commutator for power-factor correction, 687.
— *motors, 707, 708, 709.*
— — *control, 735.*
elementary, 10 *et seq.*
induction motor data, 681 (Table 119).
locomotives, 872.
motors for lifts, 796.
railway construction, 919.
supply, 465-7.
to one-phase transformation, 394.
transformer, 394.
Three-pin sockets, 492.
Three-way switching, 503.
Three-winding transformer, 394.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Three-wire D.C. system, 4, *461-3.*
— *system in cooking, 632.*
— *3-phase supply, 466.*
Throw-over switch, 363.
Thury system, 289, 294, 317.
— (*Kenotron as substitute*), *419.*
Thyratron, 418A, 420.
Thyrite, 346.
Tidal power, 230.
Tilling-Stevens vehicles, 953.
Timber preservation, 86, 323, *846.*
TIME—
constant, 44, *402.*
— *of transformer* (*B.S.I.*) (*Table 55A*), *402.*
element fuses, 342 *et seq.*
— relays, 344, 357 *et seq.*
precise measurement of, 428B.
switches, 272, 372, 374, *622.*
— *and mains clocks, 622.*
— *cost of* (*Table 74*), *571.*
— *for water heating, 622.*
Tin, 65, 67 (Table 6), 127, 342.
fuses, 342.
properties of, 645 (*Table 98*).
recovery, 993.
Tinning on copper and testing, 282, *525 note.*
— *test, 525 note.*
Tirril regulator, 147, 160.
Titanium alloys, 979.
and tungsten arcs, 597.
Toasters, 628.
cost of, 574.
Toggle mechanism in circuit-breakers, 372 (Fig. 84).
Tools, machine, 775.
— *portable, 774.*
Top-contact rail, 920.
Topping or superimposed plants, 191.
"*Topping-up*" *accumulators, 432.*
Torda type motor, 688.
"Torev," 50.
"*Tork*" (*Parkinson*), *motor, single-phase, 689, 691.*
TORQUE—
and speed variation, 749.
high-starting, 753.
in crane and hoist motors, 787.
— *magnetic clutches, 808 and* (*Table 176*).
of lift motors, 796.
— *motors, 669, 672* (*Table 113*).
— *single-phase motors, 689.*
— *steel mills, 778.*
stalling, 752.
synchronous motors, 679.
"Total break-time" of C.B. defined, 371.
Totally enclosed motor, 4, *670.*
— — *in mines, 818.*
Tough rubber compound (C.T.S.), 74, 283, *551.*
Tourmaline, 130.
Towel-heating rails, 631.
Tower-type cranes, 789.
Towing, electrical, 965.
Town gas, 178.
refuse as fuel, 168.
Track-circuiting for signals, 921, 933.
Track equipment, cost of, 926.
Trackless-trolley vehicles, 954.
Track rail resistance, 903.
Track-sectioning cabins, 918.
— — *cost of, 926.*
Track, tramway, cost of, 925.
TRACTION (*Chaps. 34, 35*), (*see above* "Electric traction," "Railways," "Road vehicles, electric," "Traction cells" *and below,* following entries and "Tramways").
motors (*see* "Motors, traction").
power and energy calculations for, 878 et seq.
sheave for lifts, 793.
Traction cells, 938.
— *capacity of, 940, 941.*
— *discharge rate of, 941.*
— *lead and nickel, 939.*
Tractive coefficient, 879 et seq.
effort, 890.
resistance, 891.
— *on roads, 946.*
Tractors, electric, 951.
for farms, 851, 854.
— *ploughing, 851.*
Traffic and energy data, 887 (*Table 190*).
control on railways, 933.
TRAIN LIGHTING SYSTEMS—
Dick, 932.
dynamos for, 929 et seq.
general, 927 et seq.
Mather and Platt, 931.
Stone, 930.
Trains, multiple-unit, 871.
Tramcars, 870 (see also "*Tramways*").
cost of, 925.
TRAMWAYS, ELECTRIC (*see also* "Electric traction")—
bonding on, 903, 925.
boosters for, positive and negative, 906.
bow collectors for, 912.
brakes and braking, 899.
B.S.I. standard rails, 901.
B.S.I. standard trackwork, 901.
cars for, 870, 925.
centre, side and span construction, 909.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

TRAMWAYS, ELECTRIC (*cont.*)—
comparison with buses and trackless, 954.
copper in line feeders for, 923.
cost of, 925.
current collection on, 912.
earthed and earth returns, 903.
electrolysis on, 907.
feeders, main and line, 923.
flexible suspension on, 910.
guarding on, 909.
insulators for, 911.
"*interference,*" *908.*
motor buses and trackless vehicles compared, 954.
motors and rating, 895 (see "*Motors, traction*").
overhead equipment, 909.
permanent way and return circuit, 901.
poles and brackets for, 910.
power and energy used in, 889.
— supply to, 868.
pressure drop on return circuit, 903.
rails, 901.
regeneration on, 900.
regulations as to, 899, 901, 903, 908, 909, 912, 1052.
return circuit on, 903.
— feeders and boosters, 906.
rolling stock and service on, 876.
side and span construction, 909.
supply of energy to, 868.
track, cost of, 925.
trackless, 954.
trolley wire, 909, 911.
— buses, 954.
Transformation and conversion of energy (see *Vol. II, Chap. 17*).
TRANSFORMERS, TRANSFORMING—
air-cooled, 400.
arrangements in 3-phase commutator motors, 708.
auto-, 396, 479, 495.
boosting and bucking, 142.
connections, 394, 397.
constant-current, 405.
cores and coils, 398.
current, 108, 384, *405.*
data for rural lines, 846.
— general (Table 54A), 401.
d.c. measuring, 108A.
double-wound, house, 479.
efficiency of, 401, 425.
elementary, 35 *et seq., 391.*
fires in, 404.
for concentric wiring, 479.
— luminous signs, 612A.
TRANSFORMERS; TRANSFORMING (*cont.*)—
for resistance welding, 660.
frequency of, 135.
harmonics in, 407.
house, 479.
in Falco cooker, 629.
insulation and cooling of, 400.
in welding, 667.
line calculations and, 313.
location of, 404.
losses in, 391, 394, 401.
measuring, D.C., 108A.
metadyne, 389A.
no-load losses of, 394.
oil for, 77.
oil-immersed, 403.
oil tests, 1034.
outdoor, 481.
polarity and parallel operation of, 397.
potential, 108, 384, *405.*
power factor and, 156.
— — of open delta, 399.
primary and secondary current in, 391.
principle of, 35 et seq., *391.*
rating of, 136, *402.*
regulation of, 392.
Scott, 394.
short-circuit current of, 393.
— tests of, 1020.
special types of, 405.
specification for, 1003.
step-down, for heating, 637.
tap-changing, 395.
tappings on, 395, 636.
testing (Chap. 40), passim.
transients and harmonics in, 400, 407.
variable tappings in, for furnaces, 636.
voltage control of, 392.
water-cooled, 400.
weatherproof, 404.
weight of, 401.
Transients and harmonics, 400, 407.
Transil oil, 77.
Translay protection, 359.
Transmission line (see also next entry).
cost of, 218, 332, 334.
defined, 440.
lines, main, and "grid," cost, 195.
mechanical, on ships, 957.
— from motors compared, 751.
TRANSMISSION OF POWER (*see also* "Overhead lines" and preceding entries)—
aluminium conductors for, 308, 324, 328, 331.
bronze conductors for, 331.

TRANSMISSION OF POWER (*cont.*)—
by inverted grid-controlled mercury arc rectifier, 315.
— *rural lines, 846.*
cables for, 310 *et seq.*
C.C. and A.C. calculations, 294 *et seq.*
control and, Chaps. 13-16.
copper conductors for, 66, 295, 307.
cost of, 196, 218, 332, 334, *926.*
for traction, 867.
half- and quarter-wave, 318.
high pressure, 315 *et seq.*
hydraulic analogy, 9.
lines, cost, 332, 334, *926.*
— and frequency, 135.
— parallel, 321.
quarter-wave, 318.
six-phase, 319.
steel conductors for, 309.
water analogy, 11.
— -power and, 217.
works costs of distribution and, G.B., 269.
Transport, Minister of (*see detailed list under* "Regulations and Rules—Ministry of Transport").
Transporter cranes, 786, 789.
Transposition of telephone wires, 335.
Transverters, 414.
efficiency curve of, 425.
"Travel" in circuit-breakers defined, 37.
Travelling cranes, 786, 789 (Table 168).
Tree system of wiring, 515.
Triangular notch measures, water, 205.
Trickle-charging of batteries, 921 (2).
Triode valves, 420, 424.
Trip-coil, 343 *et seq.*
earth leakage, 354-A.
mechanism, 372.
Triple expansion engines, 172.
-synchronous motors, 698.
TROLLEY—
buses, 954.
locomotives for mines, 832.
poles and wheels, tramway, 912.
suspension and insulation of, 911.
wheels on railways, 913.
-wire system, tramways, 909.
— copper; silico-bronze, 909.
— guarding, 909.
Truck type switchgear, 380.
Trucks, electric, 951.
True and apparent power, 56.
"*Tru-watt*" *Crompton-Burge induction motor, 697.*
"*Tube*" *railways, 904.*
Tubes, heating electrically, 637, 645.
Tubolite, 586.
TUBULAR—
heaters and radiators, 620.
— — — cost (Table 77), 574.
lamps, 586.
— cost (Table 74), 571.
-poles, 323.
Tudor accumulator, 432.
Tugs, electrical, 965.
Tumbler switch, 363, *500, 507* (*see also* "Switches").
Tungar rectifier, 418A, 419.
TUNGSTEN—
alloys, 83.
and titanium-tungsten arc, 597.
arc-incandescent lamp, 597, 599.
— (open type), 595A.
filament lamps, 585, 599.
— — efficiency of, 583.
— — over-running effects, 585.
for furnaces, 636.
properties of, 65, 67 (Table 6), *645* (*Table 98*).
-steel, 65, *979.*
temperature coefficient of, 583.
Tungstone accumulator, 431 note.
Tunnelling in water-power, 228, 242.
Tunnels (railway) and overhead lines, 914.
effect of, on life of rails, 902.
Turbines, gas, and oil, 179, 183.
TURBINES, STEAM—
and alternators, 145, 146, 173.
engines compared with, 189.
exhaust steam, 173, *963.*
general, 173, 174, 196.
specification for, 1008.
speeds, 145.
steam consumption, 167.
TURBINES, WATER—
Banki, 233.
general, 182, 201 *et seq.*, 214.
Girard, 233.
governors for, 256.
Kaplan, 215, 225, 230.
Nagler, 215.
Pelton wheel, 203, 214, 215, 238, 253.
propeller type, 214, 215, 223, 230.
specification for, 1011.
specific speeds, 214, 215, 233.
speeds for driving alternators, 254.
Turbine-driven ships, 957.
Turbine pumps, 768, 770.
Turbines, exhaust steam, 173.
Bauer-Wach system, 963.
Turbo-alternators, 145, 146, 173.
testing by wattless loading, 1021.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

Turbo-electric and Diesel-electric ship propulsion, 960.
locomotives, 873.
warships, 961.
Turbo-generators, steeple-type, 196.
— *on railway stock, 929.*
"Turbulator" for circuit-breaker, 368.
Turn-down lamps, 586.
Turpentine, 73 (Table 7).
Two-electrode Pointolite, 597.
valves, 419.
Two-phase, 16.
transformers, 394.
Two-pin sockets, 492.
Two-pole synchronous motors, 722.
Two rate meter, 116.
Two wattmeter method, 110.
Two-way switches, 502.
Two-wire D.C. system, 460.
TYPE(S)—
of coal cutters, 834.
— *filament lamps, 583.*
— instruments, 89 *et seq.*
— *motor, choosing, 753.*
Tyre-heating, 638.

UHL River scheme, 238, 243.
Ulbricht sphere, 581.
ULTRA-VIOLET LIGHT; RAYS—
general, 578, 658.
— *in fluorescent lamps, 587* et seq., *591.*
lamps, 571, 587 et seq.
protection in welding, 658.
Unbalanced A.C. circuits, 110.
Under- and side-running trolleys, 912.
-contact rails, 920.
Under- and over-running lamps, 583, 585.
UNDERGROUND—
cables, *q.v.*
distribution in mines, 819.
motor rooms, 825.
railways (tube), 904.
service lines, cost, 575.
switchgear, 822.
transmission, Chap. 14.
ventilation, 824, 825.
"UNDERTAKERS," ELECTRIC—
and supply, 268, *469.*
— wayleaves, 322.
(See also *Chap. 41,* "*Law.*")
Undertaking load factor, 261.
law regarding, 1040 et seq.
Under-water cables, 329.
— *cutting, electric, 659.*
Uniflow engines, 172.
Uniform speed on level, etc., power for, 880.
"Uninsulated" defined, 4.
returns, 903, 904, 907.
Unit air-conditioners, 647A.
UNITS—
absolute and practical, 1.
— temperature (K), 166, *591A.*
and definitions, Chap. 1.
British Thermal (B.Th.U.), *q.v.*
generated and sold, 197, 269.
Kelvin, kilowatt-hours (kWh); (B.O.T. or B.T.U. units), 52; (*see* "Energy consumption").
photometric, 580.
temperature (K), 589.
"*Universal*" *fractional H.P. motors, 710.*
Unkinkable flexibles, 281.
Unwin's hydraulic coefficients, 206.
Upset butt welding, 661.
Upward light, fittings for, 572.
Uranium alloys, 979.
electrodes, 597.
in titanium arc, 597.
Urns, 624.
cost of, 574.
Utilisation factors, 605.
of primary energy, 747 (1).
— *reflectors, 646A.*

VACUUM—
cleaners, 755.
— *cost of, 573.*
— *flexibles for, 525.*
— *wiring for, 525, 530.*
impregnation in, 76.
in mercury-vapour lamps (Tables 83, 83A), 585.
— — — *rectifier, 423.*
lamps, 583, 584.
— *cost (Table 74), 571.*
turbine, 174.
valves, 418 et seq.
Valve rectifiers in cable tests, 1028.
VALVES—
in quartz clock, 428B.
thermionic, 418 et seq.
— *for control, 743.*
vacuum, 418 et seq.
Vanadium alloys and steel, 979.
Vapour-discharge lamps, 578, 587-91, 599 (Table 86), 609.
V.A.R. (volt-ampere reactive), 110A, 116A, 117.
Vargon H.-E. plant, 214.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

VARIABLE—
heads, water, 223.
ratio tappings, 142.
-speed driving, 753.
— — induction motors, 670, 694, 722, 728, 729.
— — motors, 670.
— — synchronous motors, 722.
Variation allowed in declared pressure, 442, 469.
Variator windings, 389A.
Varley loop test, 1032.
Varley's method for phase sequence, 150.
Varnish, dielectric, 73 (Table 7), 76, 287.
Varnished tape and cloth, 74.
cambric, 288.
Varnishes, baking and drying, 646A.
Vector diagrams, 11, 12*a* and *passim.*
parallelogram rule in, 11.
Vee curves, 679.
-groove for lifts, 793.
VEHICLES—
electrical equipment of, 927.
electric road (see Chap. 36, "*Road Vehicles*").
heating and ventilation in, 928.
power generation in, 929-32.
trackless-trolley, 954.
VELOCITY (*see also* "Speed")—
and pressure of wind, 324, 329, 341.
head in fans, 764 note, 1036.
— — Kaplan wheel, 214.
— — pumps, 770.
in pipes, 232, 247.
of approach, of water, 205.
— streams, 206, 210.
spouting, of water, 214.
wind, 324, 329, 341.
Velox boiler, 170.
VENTILATION—
in air-conditioning, 647A.
— mines, 824.
— ships, 963.
— underground motor rooms, 825.
— vehicles, 928.
of generators, 146, 356.
Vermork plant, 243.
Vertical and horizontal motors, 751.
Vibrating reed rectifier, 416.
Vibration galvanometer, 96.
of quartz, 428B.
Vibrators, cost (Table 78), 573.
Violet-ray lamps, cost (Table 74), 571.
V.I.R. cables, 280 (*see* "Cables").
Virtual (R.M.S.) values, 29, 56.
Viscosity of oil, 1034.
Viscous filters for cleaning air, 647A.
Vitreous insulators, 74.
Volcanic steam raising, 165.
Volt, 2, 3, 8, 17 (*see also* "Pressure," "Voltage").
-ampere, 153.
— reactive (V.A.R.), 110A, 116A, 117.
average and maximum value, 30, 31.
drop in mercury vapour rectifier, 422.
effective or virtual (R.M.S.), 29.
— international, value of, 2.
VOLTAGE (*see also* "Pressure, Electric" "Volt")—
allowable variation of, 442, 469.
and current in all systems, 468.
— torque of induction motor, 681.
boosting, 142, *389.*
-control, for speed variation, 716.
— of converters, 411.
— — transformers, 392, 395.
-current characteristics of arc, 657.
decomposition, electrolytic, 970.
definition of, revised, 469.
drop in cables, 280.
— in rails, 389.
efficiency in electrolysis, 970.
for cable tests, 1027, 1028.
high medium and low, 23.
nominal, in network, 23.
of cells, 430, 431, 434.
— transformers, 392, 395.
ratio of converters, 409.
— — transformer, 391, 394.
recovery of batteries, curves, 431.
regulation and power factor, 155.
— in mercury-vapour rectifier, 422, 424.
— of alternators, 147.
— — transformers, 392, 395.
regulators, 147, 160, 339.
resonance, 350.
standard (British), 23, 134.
transformer (instrument), 108, 384.
variation speed-control, series motors, 718.
— of, in vehicle lighting, 927 et seq.
Volt-box, 95, 107.
VOLTMETERS—
electrostatic, 103, 104, 107.
general, 97-100, 385.
hot-wire, 99.
recording, 93, 97.
spark-gap, 105.
synchroscope, 149.
Volts lost in cables, 24, 286.
Volume and capacity of power stations, 196.
— speed, pressure of air, 764, 765.
Vorce cell for caustic alkali, 984.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–658. Volume III contains §§ 669–1060.

VULCANISED—
bitumen, 74, 283, 287.
cables, *q.v.*
— *in mines, 819.*
fibre, 73 (Table 7), 74.
indiarubber, 74.
— cables, 283, 287 (*see* "Cables").
Vulcanite, 73 (Table 7), 74.

WAGES, power-house, 194, 269.
Wage-earners and power statistics, 780.
Wall-kall wiring system, 552.
Wall-papers, reflection from, 600.
WALL (OUTLET) SOCKETS AND PLUGS—
charging type, 952.
cost, 571.
for mines, 820.
general, 492-8, 534 (17).
Home Office pattern, 494.
"*Minimax,*" *493.*
Walls in installation, 534 (14), (15).
Ward-Leonard control, 716, 827, 829.
— *in mines, 827.*
— *of motors, 716.*
Warming of rooms, 619.
Warship auxiliaries, 964 (see "*Ship propulsion*").
turbo-electric, 961.
Wash-boilers, 574, 724.
Washer-type air filters, 647A.
Wash-houses, heating in, 632.
Washing coal, 837.
machines, cost, 573.
Waste gas as fuel, 168.
heat utilisation, 176, 188.
of energy, determining, 747 (3).
WATER (*see below* "Water storage and power")—
and thermal storage, 615, 627.
arc cutting under, 659.
circulating, 175.
conditioning for boilers, 191.
constants of, 202.
-cooled generators, 146.
— *high-pressure M.V. lamps, 589.*
— *transformer, 400.*
data as to, 768.
deep well, in air-cooling, 647A.
discharge through pipes, 768.
electrolyte, 69.
evaporation, 50, 52, 53.
-gas, 178.
— *production, 985.*
glass, 983.
-hammer in turbines, 214.
WATER (*cont.*)—
heaters, classified, 522A.
— *cost, 574.*
heating, electrically, 621 et seq.
— — *accelerator for, 627.*
— — *and time switch control, 622.*
— *remote control of, 622.*
— *states of association with solids, 647A.*
-jet arrester, 346.
pipes, power, friction in (*see* "Pipes turbine").
-pipes, 768 (see also "*Pipes, turbine*").
— *regulations (Inst.C.E.) as to earthing, 472.*
-proof lampholders, 486.
pumping and coal raising, 826.
pumps, 767 et seq.
raising, mechanical, 230, 772.
supply for farms, 853.
tight fittings, cost, 572.
-tube boiler, 170.
WATER STORAGE AND POWER (*see* previous entry, "Water")—
and electric heating, 615.
— *tea-firing, 619.*
— *thermal storage, 615.*
automatic plants, 187.
auxiliary pumping, 230A.
balancing reservoirs, 240.
Barlow's formula, 204.
Bazin's formula, 210, 211.
bends in rivers, 228.
canal falls, 218.
canals and forebays, 231.
classification, 203.
combination of falls, 227.
consumption, low head, 222.
cost, 216, 230.
cusec, 25, 201, and Preface.
discharge of sluices, 213.
— of streams, 206.
duration curves, 209.
economics of steam and water power, 217.
falls, 226.
flow and storage combined, 243.
— on high falls, 235.
forebays, 231, 245.
general, Chaps. 8-10.
governors, hydraulic, 255, 256.
head, 201, 218-33, 247.
headworks, 236.
high falls, Chap. 10.
Kelvin's law and, 333.
level recorders, 208.
low falls, 218-23.
Manning's formula, 212 (Table 34).
mean and surface velocity, 206, 210.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

WATER STORAGE AND POWER (*cont.*)—
measuring flow, 205 *et seq.*
medium falls, 224-33.
meters, current, 207.
nozzles, 253.
open channels, 211, 212, 237.
Pelton wheels, 203, 214, 215, 238, 253.
pipes and joints, 232, 246 *et seq.*
plant, specification for, 1011.
power and head, 201, 223.
— cost, 216.
pumping in conjunction with, 230A.
rainfall, gauges, and run-off, 204, 241.
rating of rivers for (B.S.I.), 209, *1058.*
regulating storage, 239.
regulation of impulse wheels, 255, 256.
reservoirs, balancing, 240.
— main storage, 244.
rivers, low fall, 219.
— rating of (B.S.I), 209.
Severn barrage, 230A.
speed of turbines, 254.
standard rating (B.S.I.) of rivers, 209.
steam *v.* water power, 217.
storage, 202, 209, 225, 229, 230A, 234 *et seq.*, 241 *et seq.*
surge tanks, 232, 251.
tail race, 257.
Tata (Bombay) plants, 241.
thickness of pipes, 248, 249.
tidal power, 230.
turbines, 182, 201 *et seq.*, 214, 215, 221, 222, 233, 256.
Uhl river, 238, 243.
variable heads, 223.
watershed crossings, 242.
weight of pipes, 248, 249.
wood-stave pipes, 250.
Waterproof lampholders, 486.
Watkin switch, 586.
WATT(S)—
and lumens, 578, 582, 583.
— power factor, 153.
— wattless component, 110, 117, 154 (*see below,* "Wattless current").
candle-power and lumens, 578, 582, 583.
definition and elementary, 2, 3, 48-50.
equivalents, 2, 48.
kilo- (*see* "Kilowatt").
-meters, 97, 109.
per cubic foot for heating rooms, 619.
WATT-HOUR—
efficiency of cells, 431, 434.
equivalents, 52.
meters, 97, 113, 115, 385, *1030.*
Wattless component, 110, 117, 154.
WATTLESS CURRENTS—
and tariffs, 274.
centralised production of, 161.
general 37.
in cables, 312.
Wattmeter for cable P.F. measures, 1030.
Wave form, 30.
Wave-lengths in spectrum, 578.
Ångstrom unit of (Å), 589, 591A.
Waxes, insulating, 74.
Wayleaves, 322.
Wear of tramway rails, 901.
Weather-proof transformers, 405.
Weaving machinery, cotton, 776 (Tables 155, 156).
Weber, unit, 2.
Wedge drive for lifts, 793.
WEIGHT—
and fuel consumption of ship drives, 957.
— mass, 2.
— *speed of fractional H.P. motors, 710 (Table 127).*
of accumulators, 430, 431.
— *air, 619.*
— *batteries, in "electrics," 938.*
— copper wire, 62, 307.
— *electric irons, 631.*
— — *locomotive, 919A.*
— *metal deposited in arc welding, 652, 654.*
— oil switches, 371.
— *secondary cells (q.v.), 430, 431.*
— *steel rails, 901.*
— *tramway poles, 910.*
— *transformers, 401.*
— water pipes, 248, 249.
"*Weir Committee," traction, 1041.*
Weir, discharge of, 205.
floating, 244.
Welbourn's construction, 303.
Welded and riveted pipes, 248.
— boiler drums, 191.
WELDING—
and cutting (*Chap. 27,* see also "*Arc welding*").
arc, 650-6.
as central station load, 667.
butt, spot, seam, 660, 662, 662A.
cyc-arc, 666.
Daysohm, 657.
electrodes for, 652, 653, 657.
percussive, 665.
"*Precalorie," 661*
premier, 657.
railbonds, 903.
resistance, 660-4.
safety in, 656, 658.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

WELDING (*cont.*)—
spark or electro-percussive, 665.
spot, seam, etc., 660-2.
with metal electrodes, 652, 657.
Well-water for air-conditioning, 647A.
Westinghouse lift control, 797.
WESTON—
cell, 128.
— standard, 128.
frequency meter, 112.
synchroscope, 149.
Wet- and dry-bulb temperatures, 647A.
Wet galvanising, 994.
Whalebone paper, 74.
Wheatstone's bridge, 97, 120, 348.
Wheel brakes, 899.
White lead, 992.
Wicket gate, hydraulic, 221.
Wild-Barfield furnace, 646.
Wild frequency changer, 112.
Wilkinson "change-circuit" system, 264, *662.*
Wilmshurst's rule for heating rooms, 619.
Wimshurst machine, 131.
Winches and capstans, electric, 791.
Windage and hydrogen atmosphere, 191.
in tests, 1019.
Winding for lifts, 792, 793.
drums for lifts, 793.
in mines, 827 et seq.
Windings (coils, etc.), 133.
Wind power, 165.
overhead lines and, 324.
pressure, 324, 329, 331.
velocity and pressure, 324.
Wireless (radio), 47.
detectors, 417.
Wire ropes for haulage, 831.
WIRES AND CABLES (*see also* "Cables," "Conductors," "Overhead lines")—
aluminium, 290, 324, 328, 331.
and poles, 324 *et seq.*
bare, 4.
bronze, 331.
copper, 279 *et seq.*, 307 (*see also* "Copper").
earth, 347.
flexible, 284, 285.
fusing currents in, 342.
-gauge, 279.
general, Chap. 13.
hard-drawn copper, 307.
heating electrically, 637, 645, 646.
— *in oil bath, 646.*
overhead (*see* "Overhead wires").
phosphor-bronze, 66, 331, 335.
pilot, 359.
WIRES AND CABLES (*cont.*)—
silicon bronze, 67, 329, 331, 335.
steel, etc., 331.
WIRING (*see below*, "Wiring rules," "Wiring systems")—
and control of circuits (Chap. 22).
— *safety in heating and cooking, 632.*
branch circuits (Chap. 22).
capacity of conduits, 541.
cost of, 565 (Table 67), 566.
details, 526 et seq.
diagrams, 519.
model specification for (see "*Specification*").
of buildings, testing, 1037.
plans, 531.
"points," 4, *565.*
WIRING RULES (I.E.E. "Regulations for the electrical equipment of buildings")—
abstract of headings, 484.
accessories, 562.
accumulators, 431.
arcing, 562.
arc lamps, 596.
armoured conductors, 557.
bare conductors, 561.
base blocks, 562.
bathrooms, 562.
batteries, 431.
boilers and water-heaters, 622A.
branch switches, 507.
bunching, 537.
cable runs, 562.
— *socket, 562.*
cables and flexible, 285, 513, 525.
cables, wires, and flexibles, 280, 283, 285, *513, 525* (*see* "Cables").
cab-tyre cable, 283, 551.
casing, 537.
ceiling roses, 491.
cleated wiring, 548.
concentric wiring, 560.
concrete, 562.
conductors, 513 (*see* "Cables").
conduit system, 541, 545.
connectors, 498.
control, 510.
cooking, 633.
cut-outs, 516.
damp places, 562.
— *defined by electricity commissioners, 469.*
definitions from, 4.
distribution boards, 517
earthing, 562.
— *electric signs and luminous tubes, 612A.*
extensions, 562.
fittings, 484.

References are to numbered paragraphs, not to pages.

Volume II contains §§ 387–668. Volume III contains §§ 669–1060.

WIRING RULES (*cont.*)—
flexible cords, 285, *525*.
fuses, 516.
general, 562.
heating and cooking, 633.
incandescent lamps, 587.
in model wiring specification, 534 (1).
installation testing, 1037.
joint boxes, 498.
joints, 488, 562.
lampholders, 487.
lamps, 587 (*see* "Lamps").
lifts, 795.
machine control gear, 781.
mercury-vapour lamps, 587 et seq., *612* (*see* "Mercury-vapour").
metal-sheathed wiring, 555, 557, 562.
motors and machine control, 781.
objects of, 4.
plugs and connectors, 498.
précis of, 1054.
secondary batteries, 431.
ships, 966.
specified in model specification, 534 (1).
sub-division of circuits, 523.
testing installations, 1037.
water-heaters and boilers, 622A.
wires and cables, 280, 283, 285, *513, 525*.
wood casing, 537.
WIRING SYSTEMS (*Vol. II, Chap. 23*)—
casing, 535-7.
cleated, 546-8.
concentric, 554, 559, 560.
conduit, 538-43.
duct, 539.
Durex, 552.
Ediswan, 552.
Flexible, 549, 550.
Glo-clad, 552.
Helsby, 551, 552.
Henley, 552, 554.
insulation sheathed, 551.
J. & P., 552.
Kaleeko, 552.
Kalkos-Stannos, 545, 556.
Kingsway, 552.
lead-sheathed, 552-5.
Macintosh, 535.
Mavor and Coulson, 554.
model specification for (*see* "Specification").
Prescot, 552.
Stannos, 545, 556.
Wall-kall, 552.
WOOD—
as dielectric, 73 (Table 7), 74.
fuel, 168.
poles, 86, 323.
preservation, 86, 323, *846*.
-working machinery, 775 (Table 152).
WOOD CASING—
— cost, 569.
wiring, 535-7.
— cost of, 565.
Woodhouse steel casing, 538.
Woollen machinery, 776 (Table 157).
Work and power, 2, 48, 52.
Working costs, distribution of in G.B., 194 (Tables 25, 26).
— of tramways and trackless vehicles, 954 (Table 205A).
"Works" and "fixed" costs, 194, 269.
Workshop lighting, 601.
World Power Conference, 209, *833, 1058*.
Worm-driven lifts, 793.
Worsted machinery, 776 (Table 157).
Wright's M.D. indicator, 117, 272.

X-RAY examination of welds, 649.

Y-CAPACITY, 306.
Y-connection, 143.
Yields in various processes (*Chap. 38*), passim.
Young's modulus, 324.
Yttrium, 583.

ZERENER "torch," 650.
Zig-zag transformer connections, 394.
ZINC—
-alkaline (Drumm) battery, 434B, 873.
electrodes, 591A.
extraction, 991.
plating and wet galvanising, 994.
properties of, 65, 67 (Table 6), 127, 346, *645 (Table 98)*.
Zirconium, 67 (Table 6), 85, *583*.
alloys, 979.
Zodiac alloy, 67 (Table 6).

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