ELECTRICAL PHOTOMETRY AND ILLUMINATION.

ELECTRICAL PHOTOMETRY AND ILLUMINATION.

A TREATISE ON
LIGHT AND ITS DISTRIBUTION, PHOTOMETRIC APPARATUS, AND ILLUMINATING ENGINEERING.

BY

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TO

SIR CARRUTHERS BEATTIE, D.Sc., F.R.S.E.,

PRINCIPAL AND VICE CHANCELLOR

OF THE

UNIVERSITY OF CAPE TOWN.

PREFACE TO THE SECOND EDITION.

THE first edition of this book was sold out some years ago, and the delay in publishing the second one was mainly due to pressure of work in other directions, and to the rapid progress in illuminating engineering. The latter made it necessary to rewrite a large part of the book and to include many additions. The author hopes that the new volume will have the same friendly reception which the first edition had throughout the Engineering World. All constructive criticism—unfortunately often wanting in reviews of technical publications—has been utilised as far as practicable, and further suggestions will be gratefully considered.

The author is greatly indebted to the General Electric Company of Schenectady, to whose energy and enterprise a good deal of progress in illuminating engineering during the last ten years is due, and whose public spirit enabled him to make use of numerous articles and illustrations, without which the book would be incomplete. He is especially grateful to Mr J. W. Kirkland, Vice-President of the South African General Electric Company, through whose offices he has procured most of the valuable work carried out by the world-known experts of the General Electric Company. Without such help it would to-day be almost impossible to publish a complete and up-to-date treatise.

He must also express his sincere thanks to Mr L. Simons, D.Sc., who kindly checked part of the manuscript and made valuable suggestions, and to Mr F. L. Lief for the reading of proofs.

H. B.

UNIVERSITY OF CAPE TOWN.

PREFACE TO THE FIRST EDITION.

THIS book is primarily intended as a text-book for second year engineering students. It contains in an amplified form the lectures delivered by the author during the session 1911.

The subject of photometry and illuminating engineering has been somewhat neglected in the past, and whereas one finds scores of books on electrical machinery, there have been very few on photometry and lighting. Yet this subject is as important as, or even more so than, the design of dynamos and motors. It is useless to raise the efficiency of generators and motors by 1 or 2 per cent. and afterwards to waste the power by improper illuminating engineering.

Illuminating engineering is a combined science of physics and physiology. This has been far too little understood in the past, with the result that physiology has hardly been considered. Our knowledge of physiological science is still very meagre. We neither possess any apparatus with which we can measure the physiological quality of an illumination, nor have we been able to remove the difficulties which we encounter when lights of different colours are compared. For a long time —while engineers were busily engaged in perfecting the generating plant and the light-producing devices—the subject of illuminating engineering was left in the background, with the result that one often finds the finest buildings poorly lighted, not so much from the physical, as from the physiological standpoint. Especially, architects are to blame in this direction; any illumination is often considered good enough, as will be gathered from the fact that for a particular building costing £20,000 the sum allocated by the architects for the lighting was only £100, in spite of the building being largely wanted for entertainments at night.

Although the book is primarily intended for college students, it is hoped that it will be found useful by others interested in illuminating engineering, such as medical men, architects, teachers, and even the general public. The mathematics have been kept as elementary as possible, and persons not acquainted with higher mathematics may skip the deductions of the formulæ without detriment.

Much material has been collated from various sources, and of these I should like to mention the writings of Messrs Steinmetz, Trotter, Norden, Högner, Monasch, Dow, Sharp, Bloch, Bell, Hyde, Drysdale, J. T. Morris, Millar, and last, but not least, the articles appearing in the *Illuminating Engineer*. Since the appearance of this paper and the formation of the Illuminating Engineering Society by Mr Leon Gaster, method has been introduced into the researches for the advancement of illuminating engineering science, and it is to be hoped that in future valuable information will be obtained from this source.

A great many of the tests described in this book were carried out in the laboratory of the South African College,[1] Cape Town; some of them appear here for the first time. Where the results of tests of other experimenters are included, mention is made in the text or by foot-notes wherever possible. Although the metric system of units has been employed throughout the book, all principal figures are supplied with two scales, so that the book will be found equally useful by persons preferring the English system. Figures are numbered according to chapters, *i.e.* fig. 5.06 indicates the sixth figure of the fifth chapter. Time-wasting explanations and errors are thereby largely avoided. As no definite system of photometric units has so far been adopted, the system mainly employed in Europe has been used.

The author is very much indebted to Mr Leon Gaster, Editor of the *Illuminating Engineer*, and to various other persons and firms mentioned in the text, who have so kindly supplied particulars of their apparatus or experiments, supplied electrotypes, or in any other way assisted in the production of this book; and especially to his colleagues, Professor T. P. Kent, M.A., and Professor A. E. Snape, M.Sc., and his senior student, Mr P. J. de Wet, for checking the manuscript. Without such co-operation the book would lose much of its value.

H. B.

CAPE TOWN,
July 1912.

[1] Now the University.

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LIST OF PRINCIPAL SYMBOLS.

A = emissivity
a = absorption coefficient
$2a_1$ = distance between lamps
c, c_1, c_2, c^1 = constants or coefficients
D, d = diameter
E = illumination
$\bar{E}$ = average illumination
E′ = surface brightness
E_h = horizontal illumination
$E_{vertical}$ = vertical illumination
h = height of lamp above testing plane
i = intrinsic brightness
I = intensity in any direction
I_H = horizontal intensity (mean)
I_n = normal intensity
I_O = mean spherical intensity
$I_{\smile}$ = mean hemispherical intensity (lower)
$I_{\frown}$ = mean hemispherical intensity (upper)
I_c = current in amperes
m = reflection coefficient
K_r, K_1, K_2, etc. = constants

$$K_u = \frac{\text{maximum illumination}}{\text{minimum illumination}}$$

K_λ = visibility
l, l_0, L, L_1, L_2, L_0 = lengths
n = number of divisions or refractive index
p = percentage voltage fluctuation
p, P, P_1, P_2 = power absorbed
P_R = radiated power
Q = quantity of light
R, r, r_0 = radii or distances
S, S_1, S_2, s = areas
t = temperature
t_f = temperature at the finish
t_b = temperature at the beginning
V = voltage
V_0 = constant voltage
α, β, γ, θ = angles

$$\gamma = \frac{\text{distance between lamps}}{\text{width of street}}$$

ω = spherical angle
ϕ = flux
ϕ_r = reflected flux
ϕ^θ = flux included in region swept out by rotating θ round the vertical

$$\phi^1 = \frac{\phi^\theta}{2\pi}$$

λ = wave-length
π = 3·14159
ε = 2·71828
η = watts per candle
$\cos\phi$ = power factor

Any other symbols are fully explained in the text.

ELECTRICAL PHOTOMETRY AND ILLUMINATION.

CHAPTER I.

PHOTOMETRIC QUANTITIES, UNITS, AND STANDARDS.

1.01. GENERAL CONSIDERATION.—In photometry we compare sources of light with regard to either their luminous intensity or their power of producing illumination. Usually these comparisons are not made directly, but instead, a comparison is made of the brightness of two surfaces, one of which is illuminated by some standard of light, and the other by the light in question. Such measurements, or rather comparisons, depend therefore upon the physiological properties of the human eye, which has to judge the relative brightness of the two surfaces, the accuracy of the judgment becoming the more difficult the more the lights differ in colour.

Photometric measurements require the use of

(*a*) Photometric Units.
(*b*) Standards of Light.
(*c*) Photometers.
(*d*) Systems of Measurements.

For simplicity we shall assume that all sources of light are points, this assumption being allowable if the distance of the photometer from the light is more than twenty times the greatest dimension of the light, otherwise the inverse square law does not hold (see also paragraphs 7.10 and 7.11).

1.02. PHOTOMETRIC QUANTITIES.*—The principal quantity is "*Luminous Flux*," or the rate of emission of radiant energy (or radiant power) evaluated according to its capacity to produce the sensation of light. It is the total *visible* radiant power issuing from the illuminant. Its unit is called the *Lumen*.

* See also the report presented by the Committee on Nomenclature of the Illumination Engineering Society, U.S.A., 18th September 1916 (*Illuminating Engineering*, October 1916, p. 309).

The lumen has hitherto been an arbitrary unit, chiefly because there has been no absolute standard of light, and it has been found extremely difficult to determine accurately the mechanical equivalent of a lumen. The difficulties are augmented by the fact that human eyes, which, after all, have to judge the illumination caused by a given luminous flux, are not all alike, so that in the determination of the mechanical equivalent of light the stimulus curve of an *average eye* is required (see fig. 5.12). But even with such a curve different experimenters have found different values for the mechanical equivalent of light. The most reliable results are probably those by Ives and his collaborators,* who place the lumen as equivalent to a rate of radiation of energy of 0·00159 watt. Until this result has been verified and established, or until a more accurate one has been obtained, the unit of luminous flux will probably remain to be the lumen. The watt as the unit would greatly simplify notation and calculation. A watt of luminous flux, according to Ives, thus represents 629 lumens. From the lumen (or watt) all other quantities may now be derived.

Unfortunately, although the luminous flux is the principal quantity with which we have to deal in lighting, its use is not yet common in all countries. In some countries the luminous intensity or candle-power is still placed first, so that as a result the radiant power of lamps is designated by different units in different countries.

From a scientific standpoint the radiant power of lamps should be designated by a unit which gives a true indication of the value of the lamp as a light-producing body, without further lengthy explanations. If a person buys a pound of a certain commodity he knows what quantity he will receive, but this is not the case if he purchases a lamp rated at, say, 100 candles, which may mean almost anything and which gives no true idea of the quantity of light the lamp is capable of emitting per second. This will be seen at once from the definition of luminous intensity.

1.03. LUMINOUS INTENSITY—or candle-power—of a point source of light is the solid angular density of the luminous flux emitted from the source in the direction considered ; or it is the flux per unit solid angle. The unit of luminous intensity is called the *candle*.

Imagine a hollow sphere of radius $R=1$ with a surface $4R^2\pi=4\pi=12{\cdot}57$, and that the point source in the centre of the sphere radiates light energy (uniformly in all directions) at the rate of 12·57 lumens, then the luminous intensity of the lamp is one candle.

The *candle* is thus a point source which emits a flux of one lumen (or

* See also Ives, Coblentz, and Kingsbury, *Physical Review*, April 1915, p. 152 ; Ives and Kingsbury, *ibid.*, November 1915, p. 319 ; Pirani and Miethling, *Verh. der D. Phys. Ges.*, vol. xiii., 1915, p. 219 ; Meyer, *ibid.*, xxi., 1915, p. 384 ; Langmuir, *Physical Review*, January 1916, p. 152 ; Ives and Kingsbury, *ibid.*, September 1916, p. 254.

0·00159 watt) through unit solid angle. Let I be the intensity, ϕ the flux, and ω the solid angle, then

$$I=\frac{d\phi}{d\omega},$$

or, if the intensity is uniform,

$$I=I_{c}=\frac{\phi}{\omega} \qquad . \quad . \quad . \quad . \quad 1.01$$

The total flux from a light source is therefore

$$\phi=4\pi I_{o}, \qquad . \quad 1.02$$

since the solid angle surrounding a sphere is 4π. I_o is the mean spherical (sometimes called the average) candle-power (M.S.C.P.).

The unit of intensity, the standard candle, is now the same in England. France, America, and the British Dominions; it is also called the International candle. In Germany the Hefner candle is employed. which is equal to 0·9 International candle.

The quality of a lamp from the standpoint of producing light may therefore be defined accurately only by the number of lumens emitted, or by the mean spherical candle-power, but not by the candle-power in any direction unless the source radiates light uniformly in all directions.

We must remark that in some cases—as, for instance, in street lighting, where little or no light emitted into the upper hemisphere is reflected and made useful—a comparison of luminants as regards their light-producing efficiencies by employing the lumens or mean spherical candles per watt as a basis might easily lead to wrong conclusions. A true comparison of various illuminants should be based, in the first place, on the *usefully available* lumens or mean spherical candles per watt, after deducting losses in ballast resistances, reflectors, etc. Other commercial considerations will influence these results (see paragraph 8.01).

The usual practice in England has been to derive the lumen from the candle. One lumen represents the $\frac{1}{4\pi}$th part (approximately 8 per cent.) of the whole light emitted from a source giving one candle in every direction.

Equation 1.02 is analogous to the one for the flux from a permanent magnet. If we place a unit pole inside a hollow sphere of radius unity and surface 4π, and combine the magnetic emanations through unit area to one line of force, the total flux is 4π; from a pole M it is $4\pi M$ lines of force. Here we combine the light radiations through unit area from a point source of one candle to one lumen, and thus obtain from a source of I_o candles the total flux $4\pi I_o$ lumens.

1.04. ILLUMINATION, on a surface, is the luminous flux density over that surface, or the flux per unit of intercepting area. The unit is termed the *foot-candle* or *metre-candle*, the latter being also called *lux*. Thus a unit of illumination is obtained if a surface of unit area (one square foot or one square metre) receives a flux of one lumen uniformly distributed over this area. Let E be the illumination and S the area, then

$$E=\frac{d\phi}{dS},$$

and, when uniform,

$$E=\frac{\phi}{S} \quad . \quad . \quad . \quad . \quad . \quad . \quad 1.03$$

For a sphere,

$$E=\frac{\phi}{S}=\frac{4\pi I_o}{4\pi R^2}=\frac{I_o}{R^2} \quad . \quad 1.03a$$

which means that the illumination varies inversely as the square of the distance. This holds generally, and is easily understood when it is remembered that by doubling the radius of a sphere the surface increases fourfold, so that for a given flux the flux per unit area, or flux density, is only one-fourth.

For $I=1$ and $R=1$, $E=1$, which means that an illumination of one foot-candle is produced on an area placed normally to the incident rays a foot away from a light source of one candle-power, assuming that no absorption takes place, as might be the case outside in foggy weather.

Let a uniform luminous flux ϕ strike a surface S perpendicularly; then the illumination is $\frac{\phi}{S}=E$. This same flux illuminates an inclined surface $S_1=\frac{S}{\cos\theta}$ (see fig. 1.01), the illumination being now $E_1=\frac{\phi}{S_1}$, whence

$$E_1=E\cos\theta \quad . \quad . \quad . \quad . \quad . \quad 1.04$$

We see that the illumination is proportional to the cosine of the angle of incidence. The latter is the angle between the ray and the normal to the plane of incidence. This is *Lambert's law.*

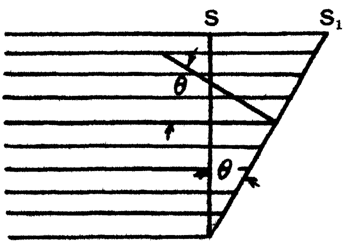


Fig. 1.01.—Lambert's Law.

1.05. QUANTITY OF LIGHT is the product of the flux by the time, and is therefore measured in lumen-seconds or lumen-hours.

1.06. TIME ILLUMINATION, or exposure, is the product of the illumination by the time, and may be measured in foot-candle-seconds or lux-seconds.

1.07. INTRINSIC OR PRIMARY BRIGHTNESS, *i*, of an element *ds* of a luminous surface from a given position, is the luminous intensity per unit area of the surface projected on a plane perpendicular to the line of sight, using an area negligibly small. It is measured in candles per unit area of the projected area.

Let θ be the angle between the normal to the surface and the line of sight, then

$$i=\frac{dI}{dS\cos\theta} \quad . \quad . \quad . \quad . \quad . \quad 1.05$$

The normal intrinsic brightness is

$$i_n=\frac{dI}{dS},$$

or, when uniform,

$$i_n=\frac{I}{S} \quad . \quad . \quad . \quad 1.06$$

Empirically we may state as proof that a luminous sphere appears as a uniformly luminous disc.

This law, also due to *Lambert*, is correct for perfectly matt surfaces only, for which the reflection coefficient is independent of the direction of the rays. For other surfaces the law holds approximately only.

1.08. COEFFICIENT OF REFLECTION is the ratio of the total luminous flux reflected by a surface to the total luminous flux incident upon it. It is thus an absolute number. Reflection may be regular or diffuse (see Chapter II.).

Let m be the coefficient of reflection (regular or diffuse), E the flux received, and E′ the flux reflected, per unit area, then

$$m=\frac{E'}{E} \quad . \quad . \quad . \quad . \quad . \quad 1.07$$

1.09. SURFACE OR SECONDARY BRIGHTNESS, E′, represents the product of the illumination E and the absolute reflection power m. $E'=mE$. The unit of surface brightness is the Lambert, and may be defined as the degree of surface brightness of a white unpolished surface having a reflecting power of 100 per cent. which receives a light flux of one lumen per square centimetre.

For practical purposes, the milli-Lambert is a preferable unit. In Great Britain the unit of surface brightness is the foot-candle, or in the metric system the lux, which may be defined as the brightness of a perfectly diffusing surface which receives an illumination of one foot-candle (or one lux). Such a surface will have a brightness of 1·076 milli-Lamberts.

The relationship between primary and secondary brightness is given by

$$\pi i=mE=E' \quad . \quad . \quad . \quad . \quad . \quad 1.08$$

found as follows: Let a matt white surface S_1 of unit area (see fig. 1.02) receive an illumination E, and thus a total flux E, then it emits light to the extent of mE, where m is the reflection coefficient. This is also the surface brightness.

Let the candle-power of this area be I, which is equal to the intrinsic brightness i, as we are dealing with unit area, then the illumination of an elementary area $(a\ b\ c\ d)$ on the surface of a hemisphere of radius R is $\frac{I}{R^2}\cos\theta$, where θ is the angle between the direction of the rays with the normal on S_1. The total flux received by $(a\ b\ c\ d)$ is therefore

$$\frac{I}{R^2}\times\cos\theta\times\text{area }(a\ b\ c\ d).$$

The light flux received by the whole hemisphere is the sum of the light fluxes on all areas $(a\ b\ c\ d)$ which make up the surface of the hemisphere, or equal to $\Sigma\frac{I}{R^2}(a\ b\ c\ d)\cos\theta$. But $(a\ b\ c\ d)\times\cos\theta$ is the projection of the area $(a\ b\ c\ d)$, viz. $(a^1\ b^1\ c^1\ d^1)$, and the sum of all areas $(a^1\ b^1\ c^1\ d^1)$ is the area of the circle, πR^2. Thus $\Sigma(a\ b\ c\ d)\cos\theta=\pi R^2$, and the total light emitted is $\frac{I}{R^2}\times\pi R^2=\pi I=\pi i$. But this light was also found to be equal to $mE=E'$, so that $\pi i=mE=E'$. If the surface brightness is in milli-Lamberts and the intrinsic brightness in candles per square centimetre, the numerical relationship is

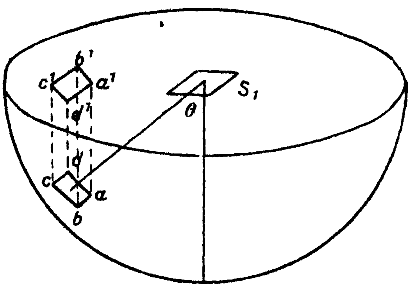


FIG. 1.02.—Relationship between Primary and Secondary Brightness.

$$\pi i=\frac{mE}{100} \quad . \quad 1.09$$

If the surface brightness is expressed in foot-candles and the intrinsic brightness in candles per square inch, we have

$$\pi i=\frac{mE}{144} \quad . \quad . \quad . \quad . \quad . \quad . \quad 1.09a$$

For lux and candles per square centimetre we have

$$\pi i=\frac{mE}{10{,}000} \quad . \quad . \quad . \quad . \quad . \quad 1.09b$$

The above deductions hold correctly only for matt surfaces for which the cosine law is true. For semi-matt metallic surfaces, opal glass illuminated from the back, etc., surfaces for which the candle-power in any direction is not proportional to the cosine of the angle at which they are viewed, the above relations hold approximately only.

1.10. SPECIFIC LUMINOUS RADIATION is the luminous flux density emitted by a surface, or the flux emitted per unit of emissive area. It is expressed in lumens per unit area. Let E′ be the specific luminous radiation, then

$$E'=\pi i_n \quad . \quad . \quad . \quad . \quad . \quad . \quad 1.10$$

1.11 VISIBILITY, K_λ, of radiation, of a particular wave-length, is the ratio of the luminous flux to the radiant power producing it.

1.12. MEAN VALUE OF THE VISIBILITY, $\bar{K}_\lambda$, over any range of wave-lengths, or for the whole visible spectrum of any source, is the ratio of the total luminous flux (in lumens) to the total radiant power (in ergs per second, or more commonly in watts).

1.13. MEAN HORIZONTAL CANDLE-POWER, $\bar{I}_h$, of a lamp is the average candle-power on the horizontal plane passing through the luminous centre of the lamp.

It is here assumed that the lamp (or other light source) is mounted in the usual manner, or, as in the case of an incandescent lamp, with its axis of symmetry vertical.

1.14. MEAN SPHERICAL CANDLE-POWER, $I_\circ$, of a lamp is the average candle-power of a lamp in all directions in space It is equal to the total luminous flux of the lamp in lumens divided by 4π.

1.15. MEAN HEMISPHERICAL CANDLE-POWER, $I_{\smile}$, $I_{\frown}$, of a lamp (lower or upper) is the average candle-power of a lamp in the hemisphere considered. It is equal to the total luminous flux emitted by the lamp in that hemisphere divided by 2π.

1.16. MEAN ZONAL CANDLE-POWER, I_θ, of a lamp is the average candle-power of a lamp over the given zone. It is equal to the total luminous flux emitted by the lamp in that zone divided by the solid angle of the zone.

1.17. SPHERICAL REDUCTION FACTOR of a lamp is the ratio of the mean spherical to the mean horizontal candle-power of the lamp.

1.18. STANDARDS OF LIGHT.* – The most important primary flame standards are the British, German, and French candles, or the pentane, amyl-acetate, and colza oil or carcel lamps.

Besides these flame standards there exist a number of incandescent, or secondary, standards, of which we shall consider the platinum and the carbon standards.

1.19. FLAME STANDARDS.—A flame standard should fulfil the following conditions:—

(1) The combustible should be pure and easily procurable.

(2) It should be burnt under conditions which can be easily controlled and defined.

(3) Changes in atmospheric conditions should have no influence on the candle-power, or the variation should be capable of being easily defined.

(4) The colour of the light should be such that no difficulty is experienced in comparing it with the more common sources of light.

It may be said that none of the above flame standards fulfil all these conditions.

* See also Mr C. C. Paterson's paper, *Journal of the Inst. Elect. Engr.*, vol. xxxviii. 271; E. Liebenthal, *Zeitschrift für Instrumentenkunde*, vol. xv., 1895, p. 157.

1.20. THE BRITISH OR PENTANE STANDARD.—This lamp was invented by Vernon Harcourt * and is constructed to give 10 candle-power It is used for reference at the National Physical Laboratory, hence we may express the British candle as the tenth part of the 10-candle-power pentane lamp The lamp is illustrated in figs 1 03 and 1 04 Liquid pentane is contained in the rectangular saturator at the top of the lamp Air passes in at one of the cocks, and, being drawn

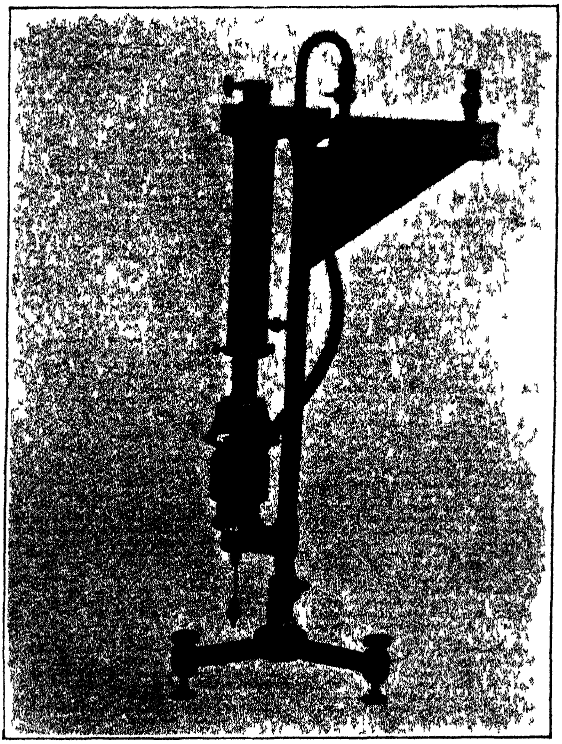


FIG 1 03 —The Pentane Standard

round baffle plates over the surface of the pentane, mixes with pentane vapour and passes by gravity down a rubber tube to an argand burner. The air supplied to the outside of this flame is drawn through the cylindrical box enclosing the steatite burner, whilst that feeding the inside of the flame is heated by its passage up the annular space between the outer and inner metal chimneys It then passes through the rectangular box seen at the top of the chimneys, and through the hollow supporting pillar to the middle of the burner The extent to which a variation in the dimensions of any part of the lamp affects the candle-power is being investigated at the present time, but no results have as yet been published.

The chimney tube CC should be turned so that no light passing

* *Proc. of British Assoc*, 1877, pp. 51 and 426 ; 1898, p. 845.

through the mica window near its base can fall upon the photometer. The lower end of this tube should, when the lamp is cold, be set 47 millimetres above the steatite burner.

A cylindrical boxwood gauge, 47 millimetres in length and 32 in diameter, is provided with the lamp in order to facilitate this adjustment.

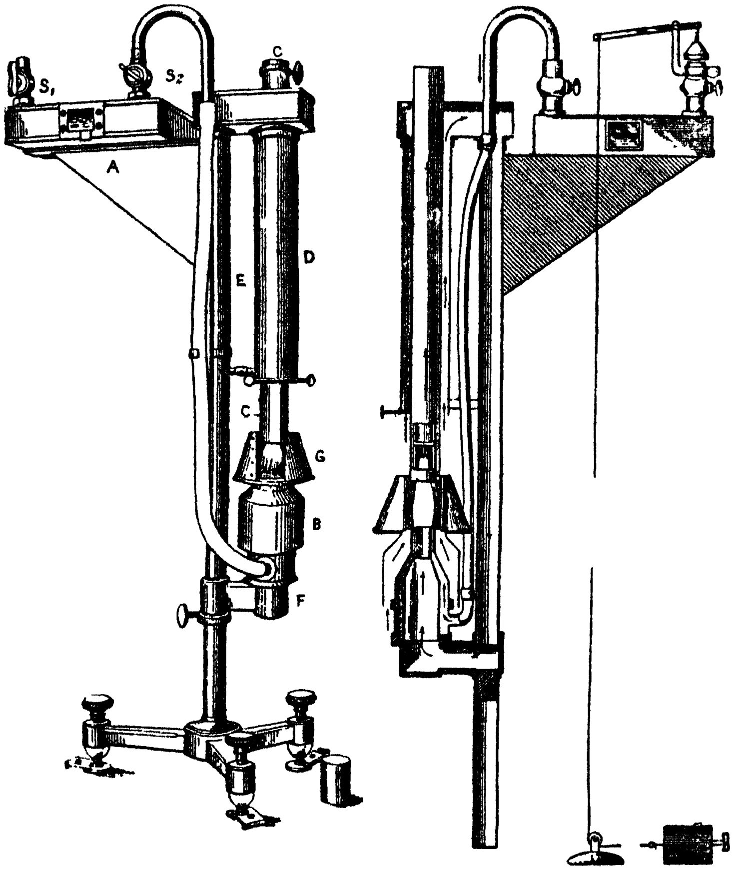


FIG. 1.04.—The Pentane Standard.

The conical shade G should be so placed that the whole surface of the flame beneath the tube C may be seen at the photometer through the opening.

The adjustment of the lamp is as follows: The lamp is set up plumb at the end of the bench by means of a plumb-line passed through the chimney, and made to coincide with its central axis by means of a centring plug at the top. The lamp is then levelled till the plumb-bob hangs exactly over the middle of the burner. The exact distance of the lamp from the photometer is measured by means of the burner, and at the other end by a shoe, the top of which must graze some known point on the photometer.

The manipulation of the lamp is extremely simple. All that is necessary is to put into the reservoir a pint of pentane, to open both the stop-cocks, and after a few moments to light the jet of vapour at the burner, and then to regulate the flow of air and vapour by the stop-cocks until the tip of the flame is seen at the middle of the mica window.

By affixing a piece of rubber to the air inlet cock, and regulating the flow of air through it by an ordinary screw clip, a most sensitive means of flame adjustment is obtained. The candle-power of the lamp is a maximum when the flame is at its proper height, but a slight increase or decrease does not materially affect the candle-power.

1.21. THE AMYL-ACETATE OR HEFNER LAMP (GERMAN OFFICIAL STANDARD).—A section of this lamp, which was invented by Hefner von Alteneck, is shown in fig. 1.05. The combustible is amyl-acetate ($C_7H_{14}O_2$), which has a very mobile flame, so that—since the lamp is used without a chimney—it must be carefully protected from draughts. The combustible is contained in a cylindrical reservoir which forms the base of the lamp. A wick dips into this and passes up the thin-walled German-silver tube projecting from the centre of the base, into which it fits without being screwed. The tube is of 8 millimetres inside, and 8·3 outside diameter, and is 25 millimetres high. The wick consists of 15 to 20 strands of untwisted cotton yarn, which just fill the tube without squeezing. The wick, however, does not rise above the top surface of the tube, but, keeping about level with it, serves to conduct the liquid to the point of ignition.

The exact height at which the flame gives one Hefner candle (0·9 English candle) is 40 millimetres

In order to adjust the flame to the correct height, the lamp is fitted with a sighting arrangement, by means of which an image of the top of the flame is cast on a ground-glass disc, and adjusted to a cross line.

Considerable care and skill must be employed in judging whether the flame is at its correct height, since the flame shows a tendency to vary its shape from one which is high and pointed to one which is somewhat depressed and flattened at the top.

The height of the flame is of great importance, since a variation of 1 millimetre alters the candle-power by 2·3 per cent.

As the lamp is also widely used in Great Britain, on account of its simplicity and cheapness, it is advisable to describe fully how the height of the flame is adjusted to exactly 40 millimetres.

Each lamp is provided with a gauge, shown in fig. 1.06. When it has been placed over the tube containing the wick and the observer looks through the slot S in the gauge, he should just be able to distinguish a light between the tube and the wall of the gauge, the space being less than one-tenth of a millimetre. The upper edge of the gauge then just reaches to the little mark in the middle of the sighting arrangement.

The lamp should be burnt at least ten minutes before it is used, and the temperature of the room should be between 15 and 20 degrees C The height of the flame is correct when the visible tip of

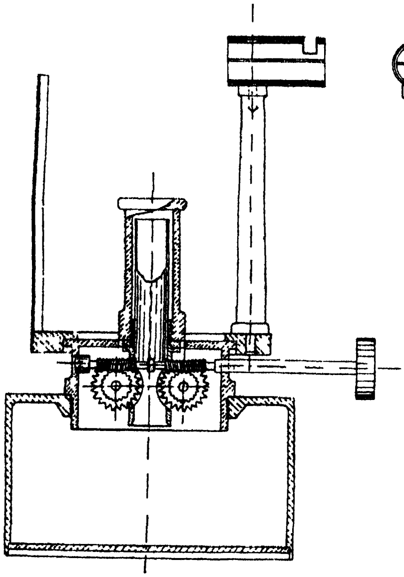


Fig 1.05—The Hefner Standard

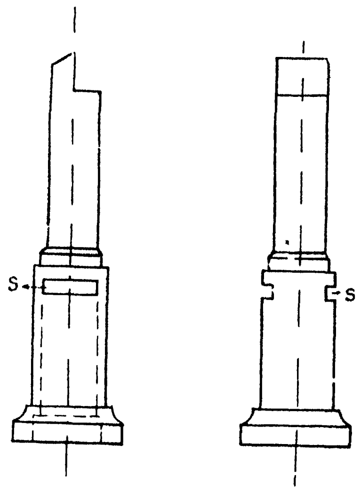


Fig 1.06—Gauge for Hefner Standard.

the flame just touches the mark on the ground glass in the sighting arrangement

The residue which collects at the top of the German-silver tube near

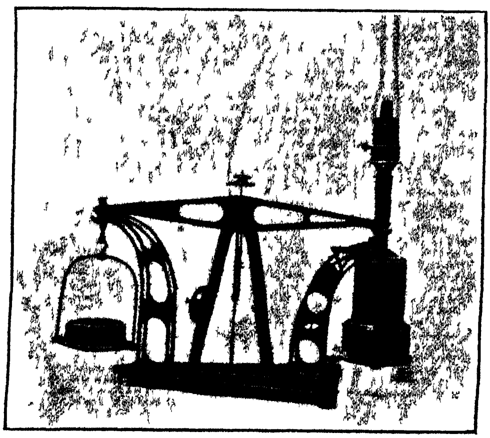


Fig 1.07.—The Carcel Standard.

the wick should be taken off before the lamp has cooled down, and the lamp should be frequently cleaned in order to ensure accuracy

1.22. THE CARCEL LAMP. —A photograph of this lamp, the working standard of the French gas industry, is shown in fig 1.07 It has a glass chimney and a wick of annular cross section, to which a continual supply of pure colza oil is maintained by means of a clock-work pump. According to the official instruction, the wick should stand 10 millimetres above the wick-holder, but in practice this is found to give too great a consumption of oil, and it is necessary to lower it to 7 or 8 millimetres. The chimney is made of thick glass and reduced in diameter to 7 millimetres above the wick.

The lamp should give its standard candle-power when consuming 42 grams of oil per hour. This adjustment is difficult to obtain, and a correction is made if the consumption falls within 37 to 46 grams.

For each experiment the oil and wick must be new, and the latter must be perfectly dry. As soon as a full stream of oil is circulating over the wick, the latter should be charred to an even depth of about 2 millimetres all round by means of a flat flame burner. The lamp may then be lighted, turned very low, and the chimney fixed so that the neck presses close down on to the wick.

Under these conditions there is only a very shallow ring of flame, which tends to equalise the intensity all round the wick. After about 15 minutes' burning in this condition, the chimney is raised, and the wick turned up; after 20 minutes' burning the lamp is counterpoised on a balance on the photometer bench. A mass of 10 grams is then added to the scale on which the lamp is fixed, and the time observed before the balance again swings over.

The correct time for a consumption of 10 grams is 14 minutes 17 seconds.

Mr Paterson, of the National Physical Laboratory, states that even with extraordinary care he was unable to make readings from the lamp agree with certainty to within ± 3 per cent.

1.23. INFLUENCE OF ATMOSPHERIC CONDITIONS ON THE CANDLE-POWER OF FLAME STANDARDS.—(*a*) **Variation Due to Carbon Dioxide.**—The effects of humidity and barometric pressure on the Hefner standard were considered carefully by Dr E. Liebenthal in 1895.* Since then further investigations have been carried out on this lamp and also on the pentane standard. According to investigations by W. J. A. Butterfield, J. S. Haldane, and A. P. Trotter,† the candle-powers of the pentane and Hefner lamps are reduced by 1 per cent. when the volume of carbon dioxide reaches 0·035 and 0·045 per cent. respectively. The diminution in light is practically uniformly proportional to the volume of carbon dioxide up to about 2 per cent. of carbon dioxide. We see therefore that good ventilation is essential.

(*b*) **Water Vapour.**—The results obtained by C. C. Paterson ‡ have been practically confirmed by the above experimenters. The effect of

* E. Liebenthal, *Zeitschrift für Instrumentenkunde*, 1895, p. 157.
† *J.I.E.E.*, vol. xxxviii. p. 271.
‡ *The Illuminating Engineer*, 1911, p. 509.

moisture on the pentane and Hefner standards is shown in figs. 1.08 and 1.09 respectively. As it is necessary to know the aqueous pressure in

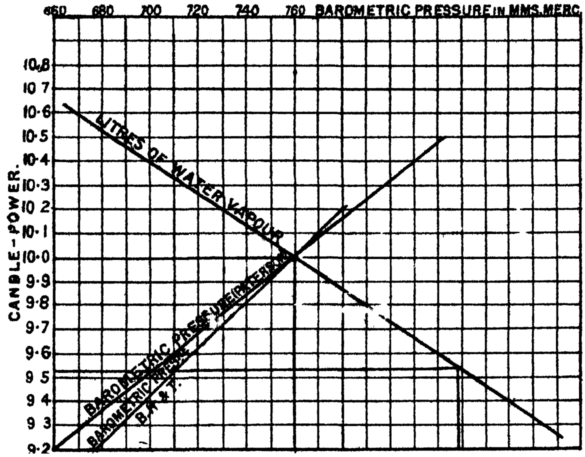


FIG. 1.08.—Variation in Candle-Power of the Pentane Lamp with Humidity and Barometric Pressure.

order to find the amount of water vapour, fig. 1.10 has been plotted, which holds for a wet- and dry-bulb thermometer.

(c) **Barometric Pressure.**—According to the investigations by Mr

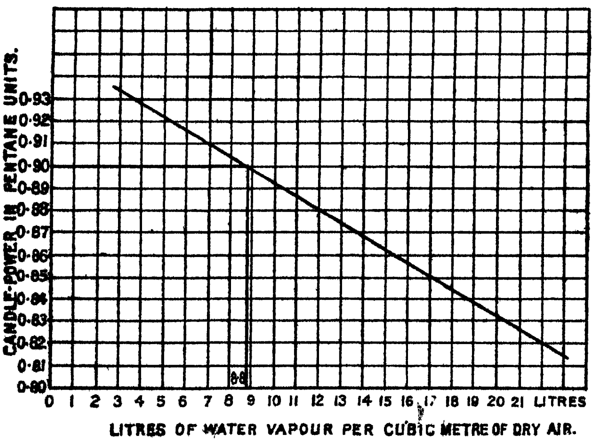


FIG. 1.09.—Variation in Candle-Power of the Hefner Lamp with the Humidity.

Paterson, the candle-power falls uniformly with a reduction in the barometric pressure, as shown for the pentane and Hefner lamps in figs 1.08 and 1.11 respectively. The investigations by the above three experimenters show, however, somewhat different results, as is indicated in the same figures.

(*d*) **General Formulæ for Corrections.**—According to the investigations by Butterfield, Haldane, and Trotter we have:

For the pentane lamp *—

$$I' = \frac{100 - \left(\frac{a-A}{0·16} + \frac{c-C}{0·035} - \frac{b-B}{12·5}\right)}{100} \times I \quad . \quad . \quad 1.11$$

For the Hefner lamp—

$$I' = \frac{100 - \left(\frac{a-A}{0·16} + \frac{c-C}{0·045} - \frac{b-B}{25}\right)}{100} \times I \quad . \quad . \quad 1.12$$

in which

A = the accepted normal percentage of aqueous vapour in the air (10 litres per cubic metre of dry air for the pentane lamp, 8·8 litres for the Hefner lamp).

B = normal barometric pressure (760 millimetres).

C = the accepted normal percentage of carbon dioxide in the air; no standard value is given, and with good ventilation the influence of carbon dioxide may be neglected. No flame standard should be relied upon which has been burned for over 15 to 20 minutes in a closed room.

a = the prevailing percentage of aqueous vapour in the air when the lamp is in use.

b = the prevailing atmospheric pressure.

c = the prevailing percentage of carbon dioxide in the air.

I = normal candle-power (10 for the pentane, 0·9 for the Hefner lamps).

(*e*) **Height of Flame.**—The variation of the candle-power of the Hefner lamp for different heights of the flame is shown in fig. 1.11. For the pentane lamp no reliable results are available, but the influence on the candle-power of a slight increase or decrease in the height of the flame is small.

In the Hefner lamp, which is not guarded against draughts, great care has to be taken to keep the height of the flame constant. A variation in the height is best noted with a thermo-electric couple fixed about 5 millimetres above the tip of the flame (when the flame is 40 millimetres high) and connected to a galvanometer. There is then a certain deflection corresponding with the correct position and height of the flame. If the flame sinks or moves to one side, the reading of the galvanometer changes. The galvanometer may be combined with an audible signalling arrangement.

* A redetermination at the National Physical Laboratory (*Phil. Mag.*, July 1915) gives $I' \{= 1 + 0·0063(8-e) - 0·00085(760-b)\} I$, where e is the humidity of water vapour in litres per cubic metre of *moist* air, and b the barometric pressure. The results obtained with this formula differ slightly from those given by equation 1.11. Rosa and Crittenden at the Bureau of Standards (see *Illuminating Engineer*, September 1918, p. 214) give for the correction of water vapour the figure 0·0057, possibly due to the fact that they employ a ventilating duct above the lamp to carry away the products of combustion, which is not the case at the National Physical Laboratory.

Example.—For the pentane lamp let A=10 litres or 1 per cent.,

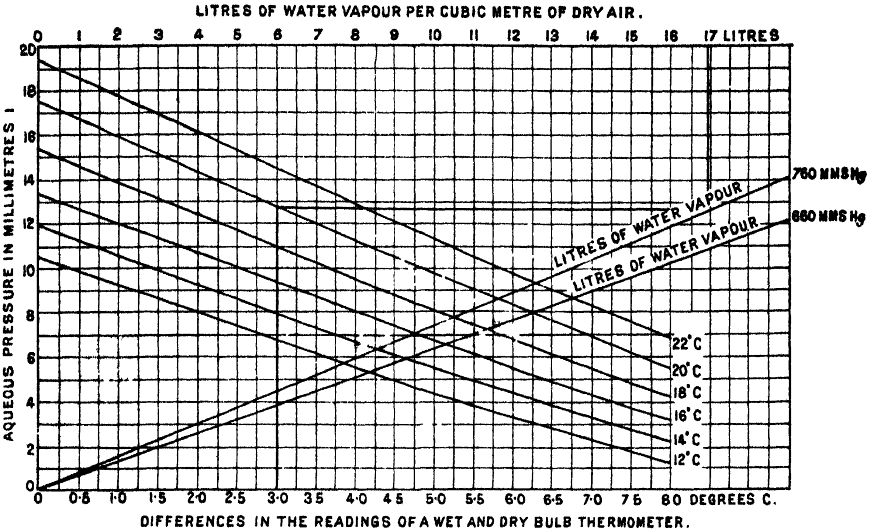


FIG. 1.10.—Aqueous Pressure for Different Readings of a Wet and a Dry Thermometer.

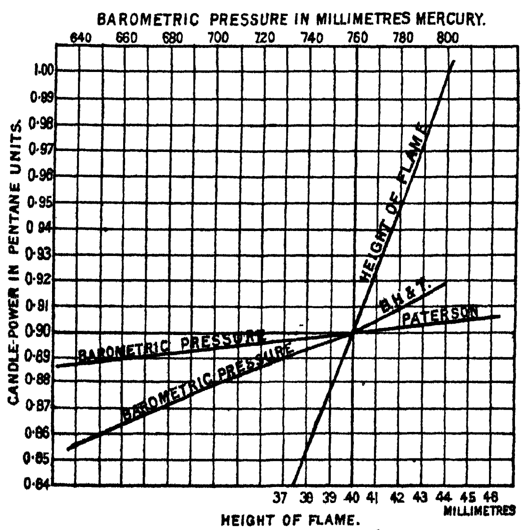


FIG. 1.11.—Variation in Candle-Power of the Hefner Lamp with Barometric Pressure and Height of Flame.

a=20 litres or 2 per cent., b=710 mms., B=760 mms., then (neglecting the influence of carbon dioxide) we have

$$I' = \frac{100 - \left(\frac{2-1}{0{\cdot}16} - \frac{710-760}{12{\cdot}5}\right)}{100} \times 10$$

$$= 8{\cdot}975 \text{ candles.}$$

1.24. COMPARISON AND CRITICISM OF THE VARIOUS LAMPS AS STANDARDS. The accompanying table (1.01) shows the relationship between the values of the various standards in use.

1.25. GENERAL CONSTRUCTION.—The Hefner lamp is much simpler than the pentane lamp, smaller in size, and more easily manufactured to standard dimensions. Its price is about one-seventh of that of the pentane lamp. (The Carcel lamp does not give sufficiently accurate readings, and will not be further considered.)

Ease of Regulation and Working. The pentane lamp is easier to adjust, and its candle-power remains more constant while observations are being made than that of the Hefner lamp, because the latter, burning as it does without a chimney, is not guarded against draughts.

TABLE 1.01.—CONVERSION TABLE FOR STANDARDS OF LIGHT.*

1 Pentane Candle = 1 American Candle = 1 International Candle = 1 Bougie Decimale = 1·11 Hefner Candle = 0·104 Carcel Candle.

Results expressed in	Factors for Conversion into				
	1 German Lux.	2 Hefner Foot-candle	3 International Foot-candle	4. International Metre-candle or Lux.	5. Carcel Metre-candle.
1. Hefner metre-candle (German lux) . .	1·0	0·0929	0·0837	0·9009	0·093
2. Hefner foot-candle .	10·76	1·0	0·9009	9·71	1·001
3. International foot-candle . . .	11·95	1·11	1·0	10·76	1·034
4. International metre-candle, bougie-metre, lux	1·11	0·103	0·0929	1·0	0·104
5. Carcel metre-candle .	10·75	0·9986	0·966	9·61	1·0

Effects of Atmospheric Changes.—As regards changing humidity, the two standards are nearly equally affected. The pentane lamp is, however, more sensitive to barometric variations than the Hefner.

The Nature of the Light.—The pentane lamp has a whiter light than the Hefner lamp.

The fact that the candle-power of the pentane lamp is about eleven times that of the amyl-acetate lamp makes it of about the same order of magnitude as the lights which are tested against it.

This—and the better colour of the light—are advantages not to be underrated.

1.26. INCANDESCENT STANDARDS OF LIGHT.†—It would go

* Dr B. Monasch, *Illuminating Engineer*, 1909, p. 742.

† See also J. S. Dow, *Electrician*, vol. lvii., 1906, p. 855; Dr Flemnig, *J.I.E.E.*, vol. xxxii., 1903, p. 119.

beyond the scope of this book to consider the many incandescent standards which have been suggested. It may suffice to consider the two principal ones—the primary platinum standard by M. Violle, and the secondary carbon standard due to Dr Fleming.

The Platinum Standard.—M. Violle proposed in 1881 to define the unit of light as the light radiated normally from one square centimetre of platinum at its melting-point. The essential conditions for the reproduction of the platinum standard are that—

(1) The platinum must be chemically pure.

(2) The mass must not be less than 500 grams.

(3) The crucible must be made of pure lime.

(4) The hydrogen burnt must contain no carbon.

(5) The gases should be burnt in the ratio of 4 volumes of hydrogen to 3 of oxygen.

The process of producing the unit of luminous intensity by the platinum standard consists in melting this mass (500 grams) under the above conditions. This is, however, extremely difficult, and could be done only at special laboratories.

The candle-power of the platinum standard is about twenty English candles.

A modification of the Violle standard was suggested by Messrs Lummer and Kurlbaum. It was to be the light emitted from a square centimetre of solid platinum when brought by an electric current to such a temperature that 10 per cent. of its radiation, as measured by a bolometer, could pass through a layer of water two centimetres in thickness contained in a cell with quartz sides. The spectral quality of the light is, however, not very satisfactory for a standard, and the adjustments are very difficult.*

1.27. FLEMING'S INCANDESCENT STANDARD.—This consists of an ordinary incandescent carbon glow lamp, with a specially aged filament in a large glass bulb, as illustrated in fig. 1.12.

The candle-power of the glow lamp alters with—

(1) Changes in electric resistance of the filament.

(2) The nature of the surface of the filament.

(3) The deposit of carbon on the interior of the bulb.

(4) The temperature of the atmosphere surrounding the lamp.

When, however, a good filament is run in a lamp at normal, or slightly above the normal, voltage for 50 hours or so, it attains a condition in which a small further use will not much alter the candle-power of the filament. By this time the glass globe has been somewhat blackened and the lamp is reduced in candle-power. The filament is then taken out and placed in a large clear globe, for which the blackening on account of the large size is practically negligible. The lamp is then calibrated with a pentane standard for a definite voltage, and the voltage

* See J. E. Petavel, *Proc. Roy. Soc.*, vol. lxv. p. 478.

and candle-power are marked on the globe. The statement of a definite temperature would appear to be necessary, since an increase of the surrounding temperature slightly augments the candle-power. Subsequent tests seem, however, to indicate that the influence due to external temperature fluctuations is negligible.

Experiments on carbon incandescent standards made by C. C. Paterson show that such lamps are suitable for low voltages up to 110

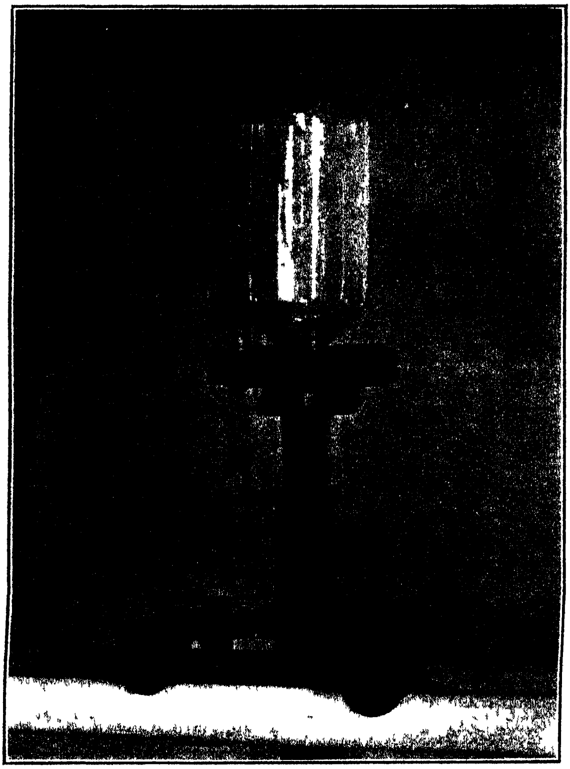


FIG. 1.12.- Fleming's Electric Lamp Standard.

volts, so that it can be made in a single loop, if they are properly manufactured and provided they are not used for more than ten minutes a day for five days in the week; in this case they will last for two or three years and longer without recalibration. No excess voltage must ever be applied.

Carbon filament secondary standards are now chiefly employed as working standards. They may be obtained from various makers, with a certificate from the National Physical Laboratory as regards their candle-power at a given voltage.

1.28. ABSOLUTE STANDARD.—The want of an absolute standard of light is very much felt, and various proposals for supplying this want are made from time to time. Dr Strache * suggests that, if the total radiation from a black body be received on a thermo-couple joined to a galvanometer, a deflection proportional to the entire radiation is received. This radiation should now be cut down, so that only visible radiation remains, and the latter should be resolved in a spectrum; by means of diaphragms the light at each point of the spectrum should be cut off to such an extent that the remaining intensities coincide with the Lummer curve. The latter represents the relative sensitiveness of the eye to light as a function of the wave-lengths (see also paragraph 3.04). The spectrum should next be reassembled by means of a cylindrical lens. In this way the illuminating value may be expressed in terms of the visible radiated energy. The Lummer curve varies, however, for different individuals, so that an average value would have to be taken, as represented in fig. 5.12.

Dr Houston † proposes the following definition :—

The unit of light intensity is that source the total intensity of radiation from which, at an optical distance of 1 metre, after passing through an ideal filter, would be X ergs/cm.^{2} sec.; the ideal filter to be one possessing the light-absorbing properties of a 3 per cent. thick aqueous solution of $CuSO_4 . 5H_2O$ of strength 0·200 gramme-molecule per litre, and a one-centimetre thick aqueous solution of potassium bichromate ($K_2Cr_2O_7$) of strength 0·0025 gramme-molecule per litre, but neither to reflect nor to absorb any light in any other way.

These solutions have the property of stopping the infra-red and ultra-violet radiations and of cutting down the energy of the visible spectrum in the inverse ratio of the light-producing effect.

The value of X is about 0·8 in the units specified.

In the experiments by Ives for the determination of the mechanical equivalent of light, the absorption medium whose transmission was almost identical with the luminosity curve of the normal energy spectrum (average eye) consisted of a solution of 60 grams of cupric chloride, 1·7 gram of potassium chromate, 7·5 grams of cobalt ammonium sulphate, 15 cubic centimetres of nitric acid of specific gravity 1·05, and the remainder of water in 1 litre of solution. The lamp used was a carbon filament using 4·85 watts per mean spherical candle-power, or 2·59 lumens per watt. Such a lamp may thus also constitute an absolute standard when burned at a definite temperature and under given conditions.

In a communication to the German Physical Society, Professor E. Warburg recently made some proposals for a new form of standard of light. He recognises that, while its reproducibility is sufficient for practical purposes, the Hefner lamp has no rational basis; it involves many variable factors, such as the construction of the lamp, the constitution of the liquid fuel, height of flame, etc.

* *Illuminating Engineer*, 1911, p. 513.
† *Ibid.*, 1911, p. 618.

Accordingly, he proposes to take as a standard the brightness of a surface, maintained at a specified temperature, and forming the interior of a cavity (capable of observation through an aperture). The brightness of such a surface depends only on its temperature and not on the radiating substance.* The brightness being thus specified, in a direction normal to the surface, one can obtain any desired candle-power by specifying a convenient area. Thus, if it is desired to approach the brightness of an ordinary metal filament, the temperature of the cavity must be 2300 degrees absolute. We should then obtain a convenient candle-power by using an area of about one twenty-fifth of a square centimetre, but the value of the light source can be adjusted by altering the size of the aperture.

As a means of controlling the temperature, Professor Warburg recommends the use of the photo-electric potassium cell of Elster and Geitel, which is stated to be much more sensitive than any thermic method.† The relation between intensity of light and deflection is of no consequence, the cell with its galvanometer serving only as an indicator, and the intensity of light falling on the cell being altered by means of a rotating sector-screen. It is suggested that in this control only light of a wave-length $65 \cdot 6 \times 10^{-6}$ cms. (the red hydrogen line) should be used. It is calculated, however, that in order to afford a reliable standard, the light must be measurable to within 1 in 1000, and the wave-length measured with somewhat greater accuracy. These requirements border on the unattainable, so that the operation of the standard would require considerable care.‡

* Presumably this refers to black-body radiation, *i.e.* radiation derived from the blackened interior of a hollow sphere, raised to incandescence.

† See paragraph 5.28.

‡ From *Illuminating Engineer*, August 1918, p. 195.

CHAPTER II.

RADIATION AND ITS EFFECTS.

2.01. NATURE OF LIGHT.- According to Newton, light consisted of minute particles thrown off at great velocities by light-giving bodies. This corpuscular theory is, however, no longer employed, as many phenomena cannot be satisfactorily explained thereby. For instance, in order to explain refraction, the speed of light in the optically denser medium would have to be greater than in an optically less dense substance, which is obviously wrong.

Another theory, originated by Euler, considers light to be a wave-motion, and early in the nineteenth century Young employed it to explain interference, while Fresnel, by assuming the transverse nature of light waves, was able to explain the polarisation of light.

In 1873 Maxwell propounded the electro-magnetic theory, and the conclusions foreseen by him—that both, electro-magnetic and light phenomena, are of the same nature—were experimentally confirmed by Hertz in 1888. Subsequently to Hertz, Lebedew, Nichols, and Hull proved experimentally that light exerts a pressure which is equal to that calculated on the basis of Maxwell's theory.

Assuming the theory of wave-motion as valid, there must be a medium which is moving, and, as the movement is of extraordinary rapidity, it follows that the medium must have an extremely high elasticity; it must also have a very low density, so as to penetrate all substances. To this hypothetical medium has been given the name "ether." It is essentially a carrier of energy, and hence, looked at from this standpoint, we may consider ether to be matter.

Until 1900 the Maxwell-Hertzian conception of light radiation had been found to be self-sufficient, but in 1901 Planck published a paper in which he showed that the ordinary electro-dynamical methods of heating with radiation did not lead to results in agreement with experimental results on the relation between energy distribution and wave-lengths as obtained from the measurements on the spectra exhibited by heated bodies. The revolutionary effect of Planck's work was supported by Nernst and Einstein, who found that an absolutely continuous emission and absorption of radiant energy was incompatible with the newer discoveries. Thus originated the atomic structure of energy of the theory of light quanta.

Einstein's investigations are known under the name of Principle of Relativity. The latter tells us that in the description which we make of physical phenomena, there remains always an indefiniteness, a quantity, which we may dispose of as we please, and which relates to the movement of matter in ether. As a result a number of physicists have come to the conclusion that it would be better to drop the idea of the existence of the ether altogether firstly, because it is no material medium in the sense of the old mechanics; and, secondly, because it contains that indefiniteness which prevents us from stating definitely whether a body moves in it or not. In reality, however, the universal character of the principle of relativity probably points more clearly than anything else to the idea that the physical world does not consist of separated independent atoms, but that there is in existence a substance, which fills all space, of which noticeable substances are only a special development. This world substance is the ether.

There are two kinds of wave-motions to be considered: longitudinal and transverse. Light is of the latter type, since it shows different properties in two directions, at right angles to each other and to the direction of propagation; whereas for longitudinal motion, such as sound, the air particles vibrate in the direction of propagation only.

The speed of light, which can be fairly accurately calculated, is 3×10^{10} centimetres per second. Experience shows that light, or radiation, possesses different wave-lengths, and hence also different frequencies, since the speed is constant.

Within the visible range this shows itself by different colours. Red light has a greater wave-length than yellow light, and blue or violet lights have still shorter wave-lengths.

When the wave-length attains values lying within certain limits, the radiation becomes visible. The range of waves in the visible part of the spectrum is, however, very small compared with the whole range of known electro-magnetic waves. The visible wave-lengths lie between 75×10^{-6} and 38×10^{-6} centimetres,* which gives a range of frequencies of

$$\frac{3 \times 10^{10}}{75 \times 10^{-6}} = 4 \times 10^{14} \text{ to } \frac{3 \times 10^{10}}{38 \times 10^{-6}} \text{ to } 7{\cdot}9 \times 10^{14}.$$

Heat radiation of energy, however, commences long before it becomes visible, *i.e.* long before the red light appears. This radiation is called infra-red. The visible radiation begins at the red end of the spectrum and reaches to the violet, and that which occurs beyond the violet is called ultra-violet, after which come the X-rays. If we divide

* The wave-length is frequently expressed in terms of μ, which is equal to $\frac{1}{1000}$th of a millimetre, or $\mu\mu$, equal to one-millionth of a millimetre; or in Angström units (10^{-10} metres).

the whole range of radiation into octaves, we have about 56 between a 50-cycle alternating current and the X-rays, and of these only about one octave is visible. Of sound waves, on the other hand, the ear distinguishes eight octaves, so that the eye is relatively less sensitive than the ear.

The wave-motions which cause the sensation of light are themselves invisible, a fact which may easily be proved by letting a beam of light enter a dark room. If there is no dust whatever floating about, the beam, when looked at sideways, will be invisible. If dust is present, the dust particles reflect light, and the beam of light may be traced.

On the basis of the electron theory, light may be explained as follows : All atoms of so-called elements are complicated structures of positively charged protons or nuclei around which are rotating in orbits negatively charged electrons. The simplest atom is the hydrogen atom, which consists of one positive core charge and one electron. Electrons have choice of many orbits. The paths are labelled from inner to outer, K, L, M, etc., or 1, 2, 3, etc., and any one of these may be occupied. Nothing apparently connects these orbits. If a substance is heated, the electron may or may not jump from one orbit to another, the radii of which are in the ratio of the squares of the natural numbers (1, 4, 9, etc.), but it will not take up any intermediate position.

The greater the diameter of the orbit, the less the energy connected with the electron and the more easily can it be detached. The closer an electron lies to the nucleus, the less liable it is to be disturbed. To get it out of this, energy must be supplied. When a substance is being heated, energy is supplied to the electrons, but nothing happens until a definite amount of energy has been supplied, when a sudden jump to a larger orbit occurs. To cause a jump from an outer to an inner orbit, energy is emitted in the shape of radiant energy. As the frequencies of rotation are, however, different for different orbits, since the rate of cutting out areas by the radii-vectors joining the nucleus with the electrons is constant for all electrons, it means that different energies must be necessary to cause a jump from, say, the 16th orbit to the 15th, to a jump from the 3rd to the 2nd. But this energy is always a definite multiple of the universal constant (Planck's constant) h, and is equal to hf, where f is the frequency of vibration. As this frequency is the higher the closer the orbit lies to the nucleus, it follows that the spectrum lines, which are emitted by a particle disturbed from the innermost orbit, represent a very rapid vibration, high up in the ultra-violet or even X-ray region of the spectrum, while the spectrum line, corresponding to some outer orbit, will be far down in the spectrum below the red. The frequencies of vibration connected with the second orbit of the hydrogen atom are in the visible part of the spectrum, with lines in the red, the green, and the blue. The series of lines instead of a single one is due to the fact that electrons may drop, not only from orbit 3 to orbit 2, but from 4 to 2, 5 to 2. Dropping from orbit 3 into orbit 2 gives the red line, from orbit 4 into 2 the green line, and from 5 to 2 the blue line. If an electron should drop from infinity (*i.e.* any reasonable distance) into orbit 1, we obtain a much higher series (X-rays). Hence the series is determined by the orbit into which the electron drops, and the position in the series depends upon the radius of the orbit whence it drops. (See also paragraph 2.05.)

The reason why energy is radiated when an electron drops from an outer to an inner orbit is due to the fact that the electron gains a surplus of energy in the fall, this energy gained being double the difference of energy possessed in the two orbits, hence the balance is available and appears as light radiation, equal to hf, where h is Planck's constant and f the frequency of vibrations.

The probable reason for our not being able to perceive more than a certain octave is that vision would not be helped but rather hindered, inasmuch as many white objects as now seen would be dark or black under the shorter rays, and many transparent articles, such as glass, would be opaque. Objects would be similarly false in their effects, and therefore misinterpreted, if waves lower than the red were visible. Evolution has determined the range so visible as being best suited to the need of the organism.

The following table gives the wave-lengths of the various radiations:—

TABLE 2.01.—RADIATIONS OF DIFFERENT WAVE-LENGTHS.

Type of Wave.	Cycles.	Wave-Length in Vacuum or Air in cms.
Alternating current	50	6×10^8
Wireless telegraphy waves	10^5 to 10^7	3×10^5 to 3×10^3
Limit of electric waves	5×10^{10}	0·6
Residual waves	3×10^{13}	$1{\cdot}0 \times 10^{-3}$
Infra-red rays	3×10^{14} to 4×10^{14}	$1{\cdot}0 \times 10^{-4}$ to 75×10^{-6}
Visible rays	4×10^{14} ,, $7{\cdot}9 \times 10^{14}$	75×10^{-6} ,, 38×10^{-6}
Ultra-violet rays	$7{\cdot}9 \times 10^{14}$,, 30×10^{14}	38×10^{-6} ,, 10×10^{-6}
X-rays	30×10^{14} upwards.	10×10^{-6} downwards.

The gap between the infra-red and the electro-magnetic wave is probably due to the difficulty in making an electro-magnetic detector of sufficiently small dimensions, and of isolating longer heat waves. The ultra-violet light from incandescent hydrogen is thought to be the longest type of X-rays known.

Light travels at a speed of 3×10^{10} centimetres per second in a vacuum or free ether, and approximately at this speed in air and gases. When it strikes a denser medium, the speed is reduced, and, since the vibration takes place at right angles to the direction of travel, it follows that the edge of the beam, which strikes the denser medium first, is retarded, in the same way as the near side of a vehicle when turning a corner. We say that the light is refracted, and the ratio of the sine of the angle of incidence to the sine of the angle of refraction (which is also equal to the ratio of the speeds in the two media) (see fig. 2.01) is called the refractive index between the two media.

We have

$$\frac{\sin \theta_1}{\sin \theta_2}=\frac{v_1}{v_2}=n \quad . \quad . \quad . \quad . \quad 2.01$$

When light passes into a less dense medium, it is either refracted or reflected. Reflection takes place when the angle of incidence exceeds a limiting value, called the "critical angle." If the refractive indices of two contiguous media be n_1 and n_2, n_1 greater than n_2, then the critical angle for any incident ray in the dense medium is the angle whose sine is $\frac{n_2}{n_1}$. This principle is made use of in prismatic globes and reflectors.

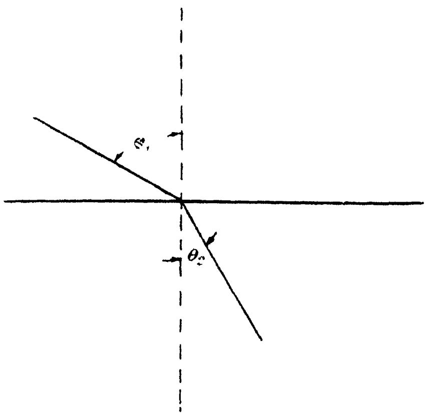


FIG. 2.01. Refraction of Light.

2.02. SPECTRA.—We notice further that the waves of higher frequency are retarded more than those of a lower order, as one would naturally expect. If we send a current of a very high frequency through a choking coil the damping action is enormous, whereas for a frequency of one or two cycles per second it is hardly noticed. It is this phenomenon which makes it possible to resolve a resultant ray into its constituent components, *i.e.* into a spectrum.

Light from different sources produces different spectra. For a tungsten filament, the spectrum is a continuous one, *i.e.* it shows all the radiations from the red to the violet without separate lines. But the spectrum from a mercury vapour lamp shows only a number of lines on the dark background, of which the yellow-green and the indigo-violet are the most pronounced, the red lines being almost completely absent.

A third spectrum is the band spectrum, which shows a number of bright bands, separated by dark spaces; but each band usually shows a number of colours, or radiations of different frequencies. Such spectra are obtained with gases at high pressure.

If we have two lights, of which one is a gas through which the other is studied, it will be found that the gas absorbs those radiations of the other, which it produces itself, while it is transparent for all other radiations. The minute particles of the gas, which have the same frequency as the radiations of the other light, are set in motion and absorb the energy of the impinging rays, whereas the other particles do not respond. We may therefore expect that the spectrum, looked at through a vapour light, will appear as dark lines on a bright background. In this case absorption has taken place, and we have a "reversed" spectrum.

2.03. REFLECTION AND COLOURS. -Besides refraction and absorption we have reflection, which may be of a twofold nature. If we use a polished silver mirror, it will be found that a ray of light which impinges on it is reflected as a single beam, and that the angles of incidence and of reflection are equal. If, however, we take a sheet of

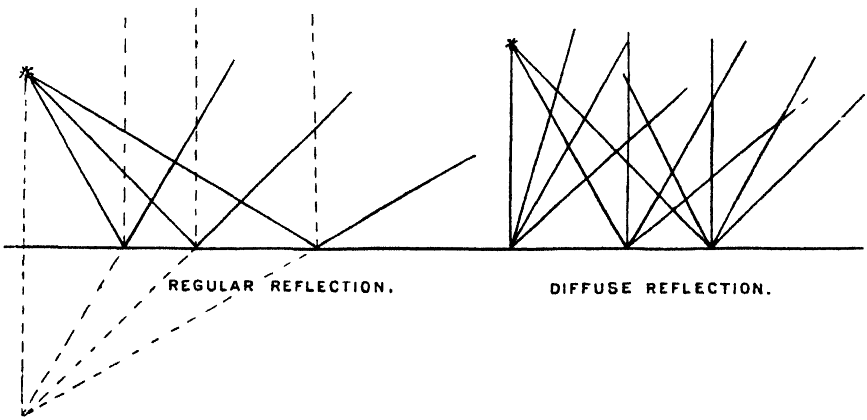


FIG. 2.02.—Reflection of Light.

white drawing-paper, the beam of light is scattered in an irregular manner. The first reflection is called regular, the latter irregular or diffuse reflection (see fig. 2.02). In both cases it must be observed that the intensity of the reflected light is less than that of the incident light, showing that either absorption or transmission, or both, have taken place. In the case of the silvered mirror it will be absorption only, at least as far as visible radiation is concerned, whereas for the drawing-paper it will be both.

On the basis of the electron theory we may explain reflection as follows: When light impinges on an object, some or all of the incident ether waves are stopped by the revolving electrons of the substance at or near its surface. If the latter consists of a material such that the electrons are capable of rotating at such speeds that they can vibrate at the same rate as the impinging ether waves, they will do so, and new trains of waves are generated in the object. We say the light is reflected.

Light radiations consist of radiations of different frequencies, distinguished by different colours. In dealing with these we must consider two questions, of which one refers to colour as a quality of a substance—we speak in this case of actual or objective colour, and it is independent of the nature of the light - and the other to the sensation of colour; in other words, the apparent or subjective colour. In the latter class we must place the sensation given by a black body, while such substances which, although they are in the way of rays impinging on the eye, do not cause the sensation of colour, are colourless.

For a given substance or body we must distinguish between surface (or opaque) and internal (or transparent) colours. In both cases the colour depends upon the influence of the substance upon visible rays (except when ultra-violet rays influence the colour).

As regards surface colour we have the following: When rays impinge upon the surface of a body, a part is regularly reflected. Another part enters the substance to a certain depth, whereby a fraction is absorbed and the radiant energy is transformed, usually into heat. Another fraction is now returned and added to the regularly reflected rays, and on this depends the surface colour of the body and not on the regularly reflected rays. This is proved by the fact that a well-polished surface or mirror is itself invisible and shows no colour. If the fraction of the rays returned shows an excess of a given frequency, the body appears of that particular colour, which by no means implies that the body actually possesses this colour. The apparent colour depends upon the nature of the light. Thus, if the rays returned consist chiefly of radiations with a wave-length between 55×10^{-6} and 60×10^{-6} cms., the object appears yellow. White light is the resultant of a number of rays of various frequencies in definite proportions, and if such light strikes a substance, and if in the reflected rays this proportion is not altered, the article will appear white. A perfectly white body, which reflects all rays and absorbs none, does not exist. Even the whitest magnesia slab will absorb 5 to 10 per cent. of the light. Also an absolutely black body, which absorbs 100 per cent., has not yet been found.

We usually consider diffused daylight as white, and a substance appears to the eye in its actual colour when viewed in this light.

The internal or transparent colour of a body depends upon the light transmitted through the body, or upon the absorption of definite rays within this substance. We even notice this effect in so-called opaque bodies, if we view a sufficiently thin layer of them. A thin gold leaf allows green, one of silver light blue, rays to pass. This subject is of importance chiefly in connection with solutions. A slight change in the chemical nature often entails a considerable alteration in the absorption of light rays, and thus in the colour seen. When only a part of the light is transmitted or returned, but this part includes the various radiations in equal proportions, the substance appears grey.

Radiation is energy, hence it follows that substances which absorb light must become heated, and black bodies more so than coloured and grey ones. This is one of the reasons why we wear white clothes in summer, dark ones in winter.

Substances which reflect or absorb (or do both) all the light are called opaque, and those which transmit visible radiations, transparent to visible light. Perfectly opaque or perfectly transparent substances probably do not exist. Quartz is very transparent, whereas glass is only so for a number of radiations, being opaque for others. For instance, invisible ultra-violet rays are largely passed by quartz, but little ultra-violet light passes through glass. Other substances reflect light irregularly within themselves, but do not transmit it; they are termed *translucent* As has already been pointed out, a substance does not always have the same subjective colour. This depends largely on the nature of the light in which the body is viewed. Thus an opaque red substance, viewed in the green light of a mercury vapour lamp which possesses few red radiations, appears black. It would therefore be useless to employ such light where colours have to be distinguished, unless the missing radiations are supplied by other illuminants, as is the case in the Bastian lamp, to which is added an underrun incandescent carbon filament rich in red rays.

Table 2.02 will give some idea of how some daylight colours will appear under various artificial lights.

TABLE 2.02.—DAYLIGHT COLOURS AS THEY APPEAR IN ARTIFICIAL LIGHT.

Daylight Colour.	Colour of Incident Light.					
	Red.	Orange.	Yellow.	Green	Blue.	Violet.
White . .	Red	Orange	Yellow	Green	Blue	Violet
Red . .	Intense red	Scarlet	Orange	Brown	Violet	Violet, with a red tint
Orange . .	Orange-red	Intense orange	Yellow-orange	Yellow with a green tint	Violet-brown	Light red
Yellow . .	Orange	Yellow-orange	Yellow	Yellowish green	Green	Brown, with a slight red tint
Green . .	Reddish grey to black	Yellowish green	Yellow-green	Intense green	Greenish blue	Blue-grey
Blue . .	Violet to purple	Orange grey	Green to slate	Green-blue	Intense blue	Violet blue
Violet . .	Purple	Red-maroon	Yellow-maroon	Bluish brown	Blue-violet	Intense violet
Black . .	Purple-black	Deep maroon	Olive-yellow	Brown (green tint)	Blue-black	Violet-black

An interesting paper on colour discrimination was read by Th. E. Ritchie before the Illuminating Engineering Society in London on

16th January 1912. The results are embodied in Table 2.03, which should be compared with Table 2.02.

TABLE 2.03. CHANGES IN THE APPEARANCE OF COLOURED OBJECTS UNDER DIFFERENT LIGHTS (RITCHIE).*

Description of Light Used.	Appearance.	Colour.					
		Brown	Red.	Green.	Mauve	Blue.	Orange and Yellow.
Bright diffused daylight.	Bluish white or pure white	Normal	Normal	Normal	Normal	Normal	Normal
Inverted O.I. arc lamp	Bluish white or pure white	Normal	Slightly brighter than normal	Normal	Slightly darker than normal	Normal	Normal
Enclosed arc lamp	Bluish white	Darkened	Lightened several shades	Darkened considerably	Darkened slightly	Darkened slightly	Darkened slightly
Metallic filament incandescent lamps	Yellow-white	Lightened and changed to reddish tint	Lightened many shades	Darkened and changed to a yellower tint	Changed to redder tint	Darkened and changed to purplish colour	Brightened and changed to a more orange shade
Inverted incandescent gas	Greenish yellow	Darkened	Lightened many shades	Darkened and changed to a yellower tint	Darkened and changed to a redder tint	Darkened and changed to a more navy blue	Brightened many shades
Carbon filament incandescent lamps	Orange-yellow	Reddened in tint	Lightened many shades	Darkened and changed to a yellower tint	Darkened and changed to a pinker tint	Darkened and changed to a much more purple colour	Brightened and changed to a deep orange
Ordinary gas light	Yellow	Reddened in tint	Lightened considerably	Changed to a yellower green	Changed to a pink rose-coloured tint	Darkened and changed to a more navy blue	Brightened and changed to orange
White flame arc lamp	Bluish white	Slightly reddened in tint	Lightened many shades	Changed to a yellower tint and lightened slightly	Changed to a bluer and darker shade	Brightened and changed to a more intense blue	Changed to a deeper and more orange colour
Yellow flame arc lamp	Deep yellow	Darkened slightly	Changed to a brick red	Deadened and changed to a yellower colour	Darkened considerably and changed to a purple	Darkened and changed to a more navy blue	Changed to a deeper and more orange colour
Mercury vapour lamp	Pale blue-green	Changed to a greenish colour	Changed to almost black	Lightened considerably	Changed to a slate-blue grey	Deadened	Changed to a greenish yellow

In Table 2.04 are given the relative intensities of the various frequencies for different illuminants.

It will be seen from this table that for colour-distinguishing purposes the flame arc with white light is nearest to daylight. The pure carbon arc with inclined carbons and the Moore tube with carbon dioxide are,

* *Illuminating Engineer*, February 1912, p. 63.

however, even better, and should certainly be employed where the recognition of colours is of great importance (see also fig. 6.50).

TABLE 2.04.—RELATIVE INTENSITIES OF VARIOUS FREQUENCIES FOR DIFFERENT ILLUMINANTS.

Type of Light.	Red.	Yellow-green.	Green.	Blue.
Daylight	1·0	1	1·0	1·0
Petroleum	2·1	1	0·73	0·12
Incandescent gas	1·21	1	0·88	0·22
Incandescent electric (carbon)	1·9	1	0·77	0·22
Tungsten	1·6	1	0·80	0·30
Nernst	1·7	1	0·74	0·18
Pure carbon arcs, with vertical carbons	1·35	1	0·97	0·45
Flame arcs, with inclined carbons (white light)	0·97	1	1·21	1·05
Mercury vapour arc	..	1	0·78	0·58

2.04. PRODUCTION OF LIGHT. TEMPERATURE RADIATION.*—As far as electric lighting is concerned, we have to consider, in the majority of cases, heat radiation. If we heat a substance more and more, the frequency of the major radiation emitted is increased until the radiation itself becomes visible. Thus in the lowest temperature it commences in the red, passes then into the yellow, and finally into the white. A further increase in the temperature produces a bluish-white light, *i.e.* the blue-violet rays predominate if the substance has not already fused. For a given power input the temperature keeps on increasing, but the rate of increase decreases with the rise in temperature due to dissipation, and when a given temperature has been reached the rate of dissipation of energy equals the rate of generation, and no further increase in the temperature takes place.

The dissipation is due to radiation, convection, and conduction. If the radiator is placed in a vacuous globe, as is the case with most incandescent lamps, the dissipation can take place by radiation only, so that the power of radiation must be equal to the input, neglecting the slight losses through the leading-in wires.† This radiated power is, according to Stefan, for a perfect radiator or black body expressed by

$$P_R = AS(t_f^4 - t_b^4) \qquad . \quad . \quad . \quad . \quad 2.02$$

in which t_f is the absolute temperature of the radiator, t_b that of the surrounding media, S the radiating surface, and A a constant.

* An excellent article on "Modern Theories of Light," by S. Dushman, will be found in the *General Electric Review*, 1914, p. 185.

† This is allowable for long filaments.

In lighting we deal mostly with high temperature, so that t_b may be neglected and

$$P_R = AS t_f^4 \quad . \quad . \quad . \quad . \quad 2.03$$

Stefan's law remained for a considerable time unconfirmed. Lummer and Pringsheim, in 1897 and 1900, proved that it is perfectly correct for an absolutely black body. For other bodies the law holds very approximately only.

The value of A is $5{\cdot}32 \times 10^{-12}$ watts per square centimetre.

A perfectly black body, which absorbs all radiations and reflects none, is, of course, an ideal conception. Lamp and platinum black approach it, however, within 2 per cent. The conception of such a body is of great convenience, since it affords a standard for comparison. Suppose we have a closed opaque tube containing two substances and the whole maintained at the same given temperature, then the radiation of one and absorption by the other must be counterbalanced by the emission of the second and absorption by the first. It does not matter what the substances are. One may be carbon (with high absorption) and the other quartz (highly transparent). If the quartz absorbs little, it follows that the carbon must emit little, and if the carbon absorbs practically all the radiation falling upon it from the quartz, the emission from the latter must be small. As the temperature is increased, not only is the total radiation increased, but also that of each wave-length. If we call the radiant energies P_q and P_c for quartz and carbon respectively, and a_q and a_c the absorption coefficients, we have $\frac{P_q}{P_c} = \frac{a_q}{a_c}$. If now we replace the carbon by a perfectly black body we get $P_q \div P_b = a_q \div a_b = a_q$, since a_b for a black body is unity.

Speaking generally we thus have

$$P = P_b \times a \quad . \quad . \quad . \quad . \quad . \quad 2.04$$

This means that we can study the laws of radiation of any substance by comparing it with a black body.

Lummer and Pringsheim constructed a special apparatus which took the place of a black body. It consisted of a closed opaque tube with a small hole at one end, the hole being small compared with the cross section of the tube. Any radiation entering the hole is either absorbed directly or after repeated reflection, so that the tube acts as a black body. Consequently, any radiation emanating from the hole is the same as that from a black substance.* Experiments carried out over a range from about 100 to 1200 degrees C. showed results agreeing well with the figures calculated from Stefan's formula.

* See also D. Owen, *Recent Physical Research*, p. 105, for a description of Keene's receiver.

If p_λ is the energy radiated for a wave-length λ, then

$$P_R = \int_0^\infty p_\lambda d\lambda = AS(t_r^4 - t_b^4) = 5{\cdot}32 \times 10^{-12} S(t_r^4 - t_b^4) \text{ watts} \quad . \quad 2.05$$

Plotting the energy distribution as function of the wave-lengths we obtain the curves in fig. 2.03.

It will be seen that the maxima of the curves if joined together would give a line which bends towards the direction of shorter wave-length. In other words, the more we raise the temperature, the shorter becomes the wave-length for which the energy radiated is a maximum.

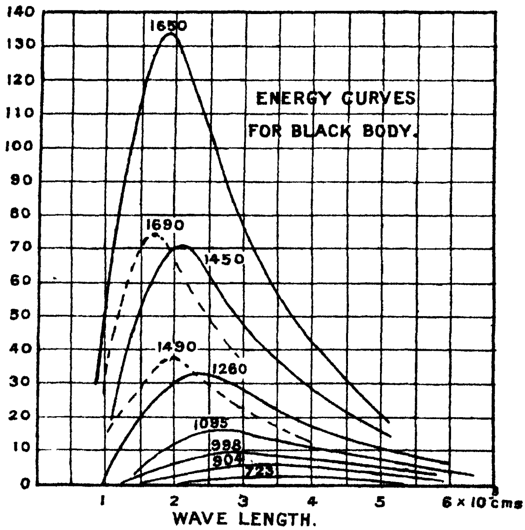


FIG. 2.03.—Energy Distribution in Black-Body Radiation.

Wien has connected these quantities; he stated that the wave-length for which the radiant energy of a black body is a maximum is inversely proportional to the absolute temperature, or

$$\lambda_{max.} \times t = \text{constant} = A' \quad . \quad . \quad . \quad 2.06$$

In other words, if we plot the power as function of $\lambda_{max.}\,t$ instead of λ, we obtain curves whose amplitudes have all the same abscissa.

Combining this with Stefan's radiation law we obtain

$$P_{R\,max.} \times t^{-5} = \text{constant} = B' \quad . \quad . \quad . \quad 2.06a$$

Equation 2.05 is also called Wien's displacement law.

From equation 2.04 it will be clear that at any given temperature the black body radiates the greatest possible amount of energy, since a is greatest. This, however, does not mean that it is also the best material to be employed. Carbon is the substance which, from the standpoint of utility for temperature radiation, approaches the black body most closely.

But although it is the most refractory body known, it unfortunately evaporates at comparatively low temperatures and deposits carbon on the inside of the vacuous globe, which partly absorbs the light, and as the resistance increases with a reduction in the size of the filament, a further decrease in the current and in the candle-power results. When a reduction of 20 per cent. has been reached, the lamp is usually considered useless. This reduction is obtained the sooner, the higher we raise the temperature, and hence the latter is limited for commercial reasons. Where the price per unit of current is high, it pays to run the lamps at a high efficiency, even if they last for a comparatively short time. Five hundred to seven hundred hours used to be considered an average economical life for carbon filament lamps. Wherever light is to be produced, we should see that all the power input is radiated and none conducted away or lost by convection; consequently, the use of a vacuous globe, even if a filament would last in air, is still to be recommended to prevent conduction and convection losses. In the gas-filled lamp the convection losses are reduced by winding the filament in a helix.

Hence, although carbon is the most refractory body we have, it does not follow that it is the best material for incandescent lamps. A material may have a lower melting-point than carbon, and yet the temperature at which it commences to evaporate may be higher. Carbon cannot be worked commercially at a higher temperature than 1800 degrees C., but tungsten can, since its evaporation-point does not lie much below its melting-point, which is 3360 degrees C.* when the intrinsic brightness is 7200 candles per cm.^{2}. We can raise the temperature of a tungsten lamp until it absorbs 1·25 watts per mean spherical candle against 5 for the carbon lamp. As tungsten does not evaporate, the lamp does not blacken, as long as the vacuum remains good, and it may be kept on until the filament breaks. A blackening is always caused by an imperfect vacuum, which, however, does not always develop immediately after the installation of the lamp, but may occur after the lamp has been worked for a considerable time.

We see from these remarks that the efficiency of incandescent lamps can be further increased by discovering a substance which is still more refractory than carbon and tungsten, and has an evaporation-point near its melting-point.

Equations 2.06 and 2.06*a* do not tell us anything about the actual distribution of energy as function of the wave-length. Moreover, the law, according to which the area of the curve between the limits of the visible spectrum varies, is different from that governing the total area of radiant energy. In addition, the radiations of different wave-lengths have various values as regards their power of producing the impression of light.

Lummer and Pringsheim have shown that the luminosity at low temperatures increases proportionally to the thirtieth power of the

* Worthing, *Journal of Franklin Institute* (181), p. 417, 1916.

temperature, whereas at high temperature the exponent is only 12. Wien has connected the intensity of radiation, the wave-length, and the temperature of a black body by the following formula :—

$$P_R = AS\lambda^{-5}\epsilon^{-\frac{C}{\lambda t}} \quad . \quad . \quad . \quad . \quad . \quad 2.07$$

in which P_R is the power radiated in watts, A and C are constants, S is the radiating surface, λ the wave-length, t the absolute temperature. The value of C is 1·47.

If we consider this equation, we see that when λ is large, the first factor $(AS\lambda^{-5})$ decreases very rapidly, and is zero for λ=infinity. But the other factor $\left(\epsilon^{-\frac{C}{\lambda t}}\right)$ rises to unity for λ=infinity. On the other hand, when $\lambda=0$, the second factor is 0 and the first one grows to infinity. Between these two limits P_R rises and falls. If we integrate from $\lambda=0$ to λ=infinity, we get

$$P_R = ASt^4 \quad . \quad . \quad . \quad . \quad . \quad 2.08$$

The maximum power is radiated at temperature t for a wave-length $\lambda = \lambda_{max.}$ given by

$$\frac{dP_R}{d\lambda} = 0, \; t\lambda_{max.} = \frac{1{\cdot}47}{5} = 0{\cdot}294,$$

and

$$\lambda_{max.} = \frac{0{\cdot}294}{t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 2.09$$

With this equation we can find the wave-length of a black body for any given temperature, or the temperature corresponding to a given wave-length.

Take a carbon filament (considered a black body) 100-watt lamp with a radiating surface of 1 square centimetre. The temperature is expressed by formula 2·03, viz.

$$t_f = t = \sqrt[4]{\frac{100 \times 10^{12}}{1 \times 5{\cdot}32}} = 2080 \text{ degrees absolute or } 1807 \text{ degrees C.}$$

$$\lambda_{max.} = \frac{0{\cdot}294}{2080} = 141 \times 10^{-6} \text{ centimetres,}$$

which is outside the range of visible wave-lengths. The eye is most sensitive to wave-lengths of the order of about $54{\cdot}5 \times 10^{-6}$ cms. (for average intensities), whence

$$t_{max.} = \frac{0{\cdot}294}{54 \times 10^{-6}} = 5420 \text{ degrees absolute}$$
$$= 5147 \text{ degrees C.,}$$

which is far above the temperature even carbon will withstand. This is about the temperature of the sun.

While for a given temperature a black body radiates most power, platinum is at the other end and radiates least. The substances to be employed for temperature light radiation must thus lie between these two, and it is important to know also the laws of radiation for platinum. We have

$$P_R = A_p S t^5 \qquad . \quad . \quad . \quad . \quad 2.08a$$

$$\lambda_{max.} = \frac{0{\cdot}263}{t} \qquad . \quad . \quad . \quad . \quad 2.09a$$

In fig. 2.03 two dotted curves are given for platinum, which show that whereas the total energy radiated by a black body for a given temperature is greater than for platinum, the curves for the latter move closer to the visible end of the spectrum which lies to the left of abscissa *1*, so that the light-giving efficiency of platinum is greater than that of an absolutely black body. In fact the latter is the most uneconomical of all substances. This advantageous quality of platinum is called "selective emission."

Lummer has recently been able to obtain exceptionally high temperatures by placing the electric arc under high pressures. The following figures give some relative indications in round figures of the results obtained :—

Pressure in Atmospheres.	Absolute Temperature in Degrees Centigrade.	Intrinsic Brightness. (Relative.)
1	4300	1·0
2	4600	2·0
3	4800	3·0
4	5000	4·0
5	5100	5·0
10	5500	9·9
15	5700	13·6
20	5900	17·0
22	6000	18·0

It remains to be seen how far this property may be usefully employed for practical purposes.

We see from this that, as far as temperature radiation is concerned, we should raise the temperature of substances as high as possible; the material does not matter so much as long as it can withstand the temperature, and does not evaporate. On account of evaporation, carbon, which is more refractory than tungsten, must nevertheless be run at a lower temperature than tungsten if such a filament is to be a commercial article.

Obviously, the best substance would be the one for which the fraction of *visible* radiation is high. Looking at fig. 2.03, we see that of the total radiation the part lying between 38×10^{-6} and 75×10^{-6}, representing the visible spectrum, would be small indeed. For an ideal radiator the curve representing the radiant power as function of the wave-length should reach a maximum within or near the visible spectrum, as indicated in fig. 2.04 by curve B for the firefly.* Curve A represents the energy curve of a carbon glow lamp. The shaded and black areas represent the energy radiated as light for firefly and glow lamp respectively. We see the enormous efficiency of the former compared with the latter. Curve B is, however, no longer governed by the laws of black-body radiation, and we speak in this case again of selective, instead of temperature, radiation. The ordinary arc lamp is a temperature radiator, and the maximum light is obtained from a crater in which the carbon is near the boiling-point. If, however, the carbon is impregnated with salts, we have, besides temperature radiation, a considerable amount of selective radiation, or luminescence, with a result that the light-giving efficiency is greatly increased. The light is now chiefly emitted by the flame and not by the crater, and the magnitude of selective radiation is sufficient to affect the colóur of the radiation, and is thus readily noticed. In the ordinary arc selective radiation is small, and could be determined only by measuring the radiation of each wave-length and comparing the result with black-body radiation. The subject will be further considered under luminescence.

In incandescent lamps the radiation is chiefly of the temperature type, and the colour of the light depends mainly thereon and not on the substances employed. The higher the temperature, the whiter and more efficient the light.

In fig. 2.04*a* energy curves for various illuminants are given as function of the frequency, which are self-explanatory.

2.05. CORRECTNESS OF RADIATION FORMULÆ.--Neither Wien's formulæ (2.07) nor that suggested by Rayleigh, viz.

$$P_R = AS\lambda^{-4}t \qquad . \qquad . \qquad . \qquad 2.10$$

give results which agree with experimental results over the whole range of radiation. The former is correct only for low values of λt, and is thus applicable in the visible region of the lower spectrum at lower values of t. Rayleigh's formula gives results agreeing with experimental results only when λt is large. Yet both formulæ are based on logical arguments from the principles of thermo-dynamics, such as the principle of the equipartition of energy; the existence of radiation pressure, the magnitude of which is calculable from electro-dynamic equations; the second law of thermo-dynamics, which says that a colder substance cannot part with energy to a hotter one without an external agent; and the Doppler principle of the change in wave-length of a ray with change in position of the source.

The failure of both these formulæ to account for experimental data showed conclusively that ordinary methods were not applicable in attacking this problem; but as the method of reasoning adopted in

* H. E. Ives and W. W. Coblentz, *Bull. of Bureau of Standards*, vol. vi.

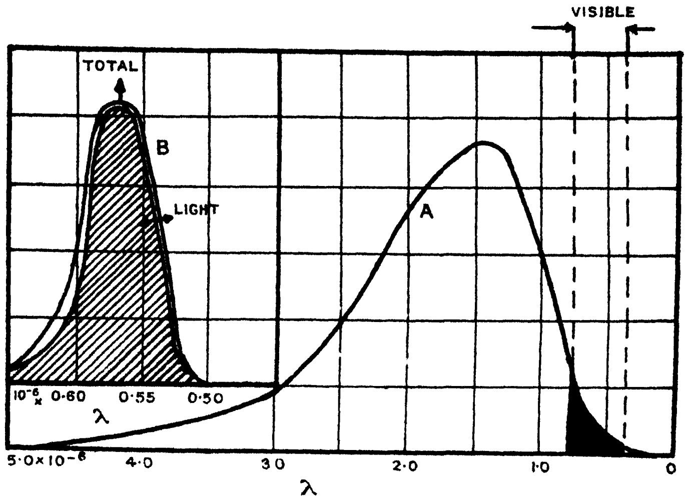
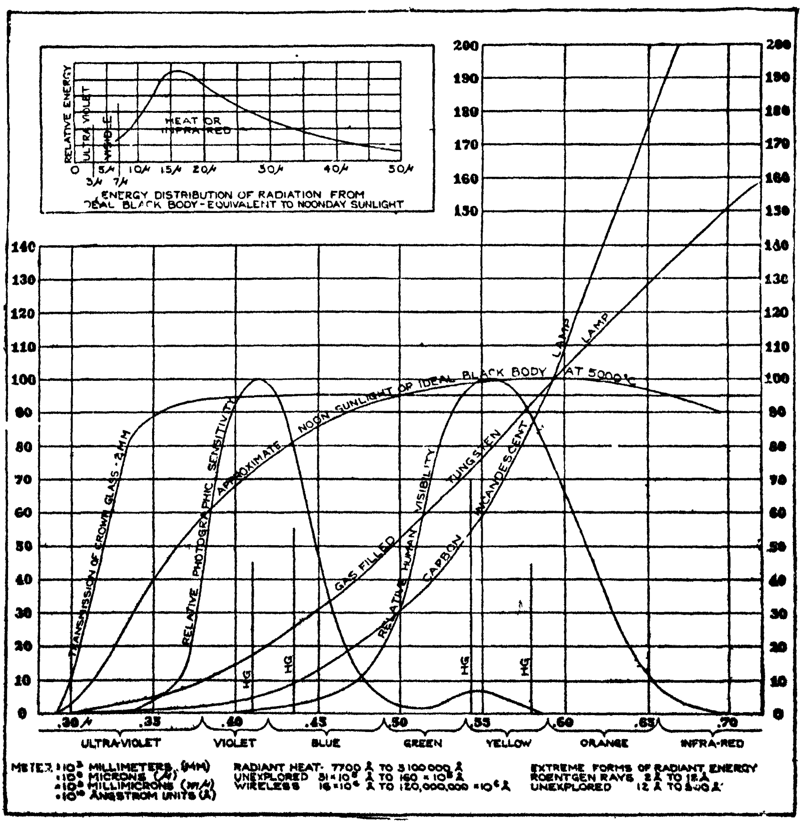


FIG. 2.04.—Selective Radiation.



Energy Distribution in Various Illuminants.

FIG. 2.04*a*.—Radiant Energy Curves.

arriving at these equations was perfectly logical, the only result could be a questioning of the accuracy of the fundamental principles upon which the argument was based.

Planck started by denying the general validity of the principle of the equipartition of energy, which states that for any system in equilibrium the total energy is divided equally amongst the different degrees of freedom of the system, yet made use of the fundamental electro-dynamical equations which rest thereon. Such a theory may justly be questioned, yet the results obtained agree with experimental results over the whole range of radiation. Planck's theory implies that, since energy is always contained in the oscillator in exact multiples of an energy unit, both the absorption and emission of energy by the oscillator must take place *discontinuously*. Planck subsequently assumed that emission alone takes place discontinuously, while the absorption is continuous. At the instant at which a quantity of energy, hf, where h is Planck's unit or constant$=6{\cdot}54\times10^{-27}$ erg, and f the frequency of vibration or radiation, has been absorbed, an oscillator has a chance of emitting the whole of its unit, a chance which, however, it does not necessarily take. If it misses fire, it has no other chance until the absorbed energy has risen to $2hf$, when it has again a chance of throwing out its two whole units, but nothing less, and so on. The ratio between the chance of not emitting when crossing a multiple of hf and the chance of emitting is assumed to be proportional to the intensity of the radiation which is falling upon the oscillator.

Einstein has termed the quantity of energy, hf, a light quantum. This view of light emission and absorption requires thus a complete reversal of our conception of the structure of light, and we have here an atomistic theory of energy, which is now largely confirmed by the investigations of Rutherford, Bohr, and others. At sufficiently low temperatures the atomic heat decreases with the temperature and tends to become zero at the absolute zero of temperature, at which bodies are really solid, since the movement of the electrons around their nuclei ceases.

Planck's formula of radiation reads

$$P_R = AS\frac{\lambda^{-5}}{\epsilon^{\frac{c_2}{\lambda t}}-1} \quad . \quad . \quad . \quad . \quad 2.11$$

in which $$c_2=\frac{ch}{k}=\frac{3\times10^{10}\times6{\cdot}54\times10^{-27}}{1{\cdot}34\times10^{-16}}=1{\cdot}47,$$

c being the velocity of light, h Planck's constant, and k a universal constant equal to $1{\cdot}34\times10^{-16}$ erg per degree; t represents again the absolute temperature. This formula gives correct results for the whole range of radiation.

It is of interest to know that, while the application of the quantum theory to radiation suggests emission and absorption of energy, which is discontinuous as regards *time*, the observations on emission of electrons by X-rays and ultra-violet light leads to the conclusion that the discontinuity exists also as regards *space*. This means that, in order to account for the fact that the X-ray carries over unimpaired the energy of the electron which produced the X-ray to another electron which is ejected by the ray, it is necessary to assume that the amount of energy represented by it keeps together as an entity or quantum throughout the different transformations. As Planck said in a lecture in 1919: "What becomes of the energy of a light-quantum after completed emission? Does it spread out in all directions in the sense of Huygen's wave theory until it is lost in infinite rarefaction, or does it move like a projectile in a single direction according to Newton's corpuscular theory? In the first case the quantum is no further able to concentrate its energy on a single space sufficiently in order to eject there an electron from its nucleus; while in the second case the triumph of Maxwell's theory, the continuity between the static and dynamic fields, and the full understanding into the phenomena of interference would have to go, both disagreeable consequences."

The principal substances employed for temperature radiation are carbon (a metalloid) and tungsten (or Wolfram, a metal). Platinum and iridium are not sufficiently refractory to give good efficiencies, but tantalum and osmium have been used. Osmium has an evaporation-point close to its melting temperature, and may thus be run at a higher efficiency than carbon; but it is a very rare metal, and the demand could not be supplied. On the whole it is held that as regards metals for temperature radiation the limit of efficiency is set by the melting-point, whereas in carbon it is the evaporation temperature. Agreement on this point does, however, not exist. It is quite possible that the greater efficiency of metal filaments depends on the greater density. The more space a substance fills, the greater are the losses and the more power must be conducted to the filament to maintain a given temperature. Also the less dense a material, the worse is the contact between the particles of which the filament consists, and hence the greater is the resistance at the points of contact, and thus also the greater is the heat generated. This means that the temperature inside the filament will be the greater the less dense its structure, and may reach values which lie near the melting-point when the outside temperature, which alone can be measured, is far below this value. This is largely proved by the fact that the pasted tungsten filament cannot be run at such a high temperature as the more dense drawn-wire lamp.

Rare earths, such as the oxides of yttria, zirconia, erbia, and thoria, are also employed as glowers in temperature radiation.

2.06. MANUFACTURE OF INCANDESCENT LAMPS, CARBON FILAMENTS.—Pure zinc-chloride with acid reaction is dissolved in water to a specific gravity of 1·800. It is then placed in a vessel having a water-jacket so as to keep the solution at a temperature between 70 and 100 degrees C. In this solution best cotton-wool or Swedish filter-paper is dissolved, employing 80 to 150 grams of cotton-wool to 1000 cubic centimetres of zinc-chloride solution—the quantity depending on the temperature and size of the final thread. This solution should be stirred to hasten the process. When it shows a uniform consistency and appears like treacle it is withdrawn into glass flasks. The latter possess stoppers with two holes, into one of which fixes a tube connected to an evacuated vessel, while the other contains a feeding-pipe leading from the zinc-chloride solution of cellulose. Means are employed to secure the proper filtering of the mass into the flasks. When they are about two-thirds full the feeding-pipe is disconnected and the mass is kept under a vacuum, the heat being maintained at about 80 degrees C. The vacuum removes all air and uncombined water. When this process is complete we have a thick paste ready for squirting. This is done by joining the flasks to a source of air pressure, which forces the mass through the other tube and a number of distributing tubes connected thereto, and then through jets of various sizes, depending on the size of the filament. The jets are placed over glass cylinders containing methylated alcohol with a little hydrochloric acid, in which the filament sets or becomes hard. The hydrolised cellulose is dehydrated by the alcohol. The thread is then carefully removed from the cylinders, thoroughly washed, and dried on drums. A good thread should now be transparent and strong. It is next cut to the required length and wound on rods of carbon or porcelain. A number of these rods are then embedded in charcoal or plumbago, within crucibles; the latter are placed in furnaces, the temperature of which is raised to 300 and then to 500 degrees C., this temperature being maintained for ten hours, and then to 2500 degrees C. for six hours. This process is called *carbonising*. The filament is now hard and homogeneous, but requires uniformity in thickness. This is obtained by *flashing*—a process in which the filament is placed in an atmosphere of hydrocarbon gas, such as coal-gas, or benzine, and heated to incandescence by an electric current. The thinner, and consequently hotter, parts of the filament receive a greater share of the carbon deposit from the gas than others, and uniformity in thickness results. The latter stage is shown by the automatic opening of a switch in the circuit of the lamp. The carbon filament is usually run at about 4·5 to 5 watts per mean spherical candle.

Carbon has a negative temperature coefficient, from which it follows that the candle-power of such a lamp varies greatly on a variable supply pressure. The filament may, however, be metallised by firing it in an electric furnace after squirting, at a temperature of over 3000 degrees C., before and after the flashing process. In this way a coating is produced which, although it consists of carbon, possesses the qualities of metals, *i.e.* it has a positive temperature coefficient. Its resistance is also lower than that of ordinary carbon. The specific current consumption for commercial working is about 3·0 watts per mean spherical candle.

After flashing the filament, it is placed in a bulb which is exhausted, first with a powerful air-pump and completely with mercury pumps. The final flashing occurs in the bulb. To remove all traces of oxygen, a solution of red phosphorus in alcohol is forced from an orifice in a revolving vertical tube into the sealing tubes, which are placed over it in turn. On heating the bulb with a burner, the phosphorus evaporates, combines with the remaining oxygen, and is deposited in a transparent state inside the bulb. Connections to the filament through the glass are made by means of platinum wires, which have the same expansion coefficient as glass.

2.07. THE NERNST LAMP.—The filament consists of rare earths, usually a mixture of two or more of the metallic oxides of yttria, zirconia, erbia, and thoria, the correct proportions being of importance. These earths do not conduct the current when cold, but become fairly good conductors at high temperatures. As metallic oxides do not oxidise further when glowing in air, the vacuous bulb is not necessary. A disadvantage of this lamp lies in the preheating of the filament, for which a special heater is required. It consists of a fine platinum wire wound spirally (to get the necessary length) on a porcelain core and being covered with a thin coating of porcelain. The heater, which requires from 35 to 100 watts, raises the temperature of the filament to about 700 degrees C. It is automatically cut out when the filament lights up. The filament is produced by mixing the oxides in a fine pulverised state with any binding substance to obtain a paste, from which the rods are formed—being about 1 millimetre in diameter for a current of 1 ampere -which are then burned, causing the rods to sinter somewhat, and to harden. The resulting surface is a rough one. The length of the filament depends upon the voltage.

The Nernst lamp burns in series with a ballast resistance in order to avoid damage to the filament with voltage fluctuations. To keep the filament aglow, a certain P.D. is required. If the latter is increased, the current rises; but for a given P.D., called the critical one, the current rises although there is no further rise in the pressure. The filament is thus in an unstable condition and in danger of burning through. The resistance is all the more necessary since metallic oxides are electrolytes, and possess therefore negative temperature coefficients. It consists of iron worked near red heat, for which the specific resistance increases very rapidly, so that a slight increase in the voltage, and thus of the current, causes a considerable increase in the value of the ballast resistance, and therefore keeps the voltage across the filament fairly constant. The burner must be so chosen that the sum of the P.D.'s of burner and resistance is not less than the highest working pressure. To prevent oxidation the heater is sealed up in a glass tube filled with hydrogen.

The specific consumption of the complete lamp is about 3 watts per mean spherical candle.

In spite of this resistance the candle-power varies considerably on a fluctuating voltage.

2.08. METAL FILAMENT LAMPS. TANTALUM FILAMENT. -The tantalum filament, due to Werner von Bolton, consists of drawn tantalum, obtained originally as a black powder, which is reduced to the metallic form in the electric furnace with the exclusion of air. In this state it is sufficiently ductile to be drawn into thin wires. Its specific resistance is about 12 microhms per square centimetre per centimetre at ordinary temperature, and more than five times this value at proper incandescence temperature. The thickness of the filament for a 25-candle lamp is about 0·05 millimetre, and it requires a length of about 6 millimetres per volt.

2.09. THE PASTED TUNGSTEN LAMP is made by different processes, that of the Osram lamp being as follows: Paste of finely divided tungsten with gums of dextrine is squirted through diamond jets under very high pressure. The resulting thread is heated, with the exclusion of air, by means of the electric current, which causes the filament to sinter. This sintering is carried out in gases which attack the binding material, so that finally pure metal is left.

The diameter of the jet is 0·055 millimetre, that of the resulting thread 0·05. This shrinks after sintering to 0·03 millimetre. The amount of shrinking depends upon the quantity of the binding material, and is usually 84 per cent. in volume and 65 per cent. in length.

The filament is elastic, but brittle ; it can be bent round rods 1 centimetre in diameter, and after bending it returns to its old form. It is fastened to the leading-in wires by melting the ends of the latter to globules to surround the filament. This is accomplished with the electric arc.

The exhausting of the globe takes longer than that of the carbon filament, as more gas is occluded.

2.10. JUST-WOLFRAM LAMP.—The manufacture of the Just-Wolfram lamp is somewhat different. A thin carbon filament of 0·02 to 0·06 millimetre in diameter is placed in an atmosphere of volatile tungsten compounds and hydrogen. The compounds are chlorides and oxychlorides of tungsten. The filament is then heated by the electric current, causing tungsten to be deposited on it and the compounds to be reduced by the hydrogen. To reduce the filament to pure tungsten, it is placed in hydrogen gas, having a pressure of about 20 millimetres of mercury, and heated by means of the current to a white incandescence. The carbon then combines with the tungsten to form a carbide, and the change is so complete that the filament is left tubular, without a trace of carbon being detectable. The filament is next placed in an atmosphere of hydrogen with a little steam and raised to a high temperature, which causes the carbon to oxidise so that tungsten alone remains. The filament is fixed to the leading-in wires by a paste consisting of finely divided tungsten and coal-tar or gum. These paste mounts are dried and made red-hot before the filament is placed into the bulb.

2.11. MANUFACTURE OF DRAWN TUNGSTEN LAMPS.—The original material consists of oxides of tungsten. Before it can be made into wires, the material must be pure, *i.e.* it must be free from oxide, iron, and nickel, and contain not more than 0·05 per cent. of carbon. The latter requirement makes it impossible to melt the material and draw it in the manner in which iron wire is manufactured, as carbon crucibles would have to be used. The material must also be free from sulphur, phosphorus, arsenic, antimony, selenium, and tellurium. The metal must be homogeneous before it can be drawn, and this can be obtained very gradually only. Air must be excluded as much as possible. There are six stages in the manufacture.

(*a*) **Manufacture of Metallic Powder.**—The raw material is a trioxide of tungsten, and this is reduced at a high temperature in a stream of pure hydrogen into pure tungsten. The higher the temperature, the more of the trioxide evaporates and the coarser are the resulting crystals. If the temperature is below 1000 degrees C., not all oxygen is removed. 1000 degrees C., or a little more, gives a fine black powder.

(*b*) **Pressing the Powder into Bars.**—The powder is pressed into bars 4 millimetres thick (square) and 13 centimetres long in special hydraulic presses at a pressure of 5000 Kg./cm.^{2}. Even now the resulting bars easily fall to pieces, especially if the powder is too fine or too coarse. Air must be excluded as much as possible, as air bubbles break the bars when they are taken out of the press.

(*c*) **Hardening of the Bars.**—The bars are so loose that even rough touching will make them fall to pieces. To prevent this they are placed into ovens (tubular) and heated for one hour to a temperature above that to which they were previously subjected ($>$1000 degrees C.). This is done gradually, first to a red heat and then up to the required value. What happens during this process is not quite clear. It is probable that traces of steam cause (by partial oxidation) the formation of gaseous oxide, and a repeated reduction a recrystallisation of the metal, which leads to a greater density of the bar.

(*d*) **Sintering of the Bars.**—This takes place in an electric oven with the exclusion of air and the inclusion of hydrogen. The temperature is gradually raised to about 2850 degrees C. The oven consists of two tubular terminals, between which the bar is stretched without tension. The terminals are water-cooled. The inside of the oven can be filled with hydrogen gas, the oven being made gas-tight with mercury. The current finds the highest resistance where the particles of tungsten are in contact. The current here causes a melting of the corners, the crystals move close together, the resistance drops, also the temperature. The current is then increased and the process is repeated. This goes on until the material has become dense and homogeneous. This process must be carried out carefully and slowly. The reduction in volume of the bar during the sintering process is about 14 per cent. To heat bars of 16 to 20 square millimetres section a current of 53 amps./mm.^{2} is required for 2650 degrees C., and of 57 amps./mm.^{2} for 2730 degrees C.

(*e*) **Hammering and Rolling Process.**—The sintered bars are still brittle and break if dropped from a height of 30 to 40 centimetres. They can be worked now at a temperature of 1200 to 1300 degrees C. But at this temperature they oxidise easily, so that also the ensuing mechanical treatment must be done with the exclusion of air. The hammering takes place in special machines. Two hammers are resting in a rotating drum. At a speed of 250 revolutions per minute the hammers fly outwards by centrifugal force; by doing so they come into contact with rollers which throw them back against the bar under treatment. The bar rotates also, and is moved quickly forward so that about 4000 beats per minute work the bar very uniformly. It is heated previously in an oven filled with hydrogen gas up to 1300 degrees C. and then quickly placed in the hammering-machine. The latter itself is fed with a stream of hydrogen. The feeding of the bar must be rapid enough to prevent two beats on the same spot. A bar of 6 millimetres diameter has to be passed through the machine about fifty times before it is reduced to 1 millimetre diameter. About sixteen swages are wanted for this. When a diameter of 0·75 millimetre is reached the wire has become sufficiently ductile to be drawn.

(*f*) **Drawing Process.**—The drawing-machine consists of a circular piece of metal in which a diamond die is fixed. The metal is fixed in two clamps and surrounded by a circular gas tube, which has a number of jets whereby the metal piece is heated. Before the wire enters the die it is passed through a slot in a cylindrical bar, which is also heated by a gas jet. The die is lubricated with graphite lubricant, consisting of flaked Acheson-graphite in water. Before the wires enter the die, they must be pointed. This could be done on a carborundum wheel, but is usually done chemically, by using the ends as electrodes placed in molten potassium-nitrite or a diluted solution of potassium cyanide (thin wires). The dies decrease in diameter for wires from 0·65 to 0·35 millimetre by 0·0125 millimetre; for wires from 0·35 to 0·1 by 0·0065 millimetre; for wires from 0·1 to 0·075 by 0·003 millimetre; for wires from 0·075 to 0·035 by 0·0025 millimetre, and for thinner wires by 0·00125 millimetre. Thus a hundred dies are wanted to reduce a wire to 0·025 millimetre from one originally 0·65 millimetre thick. The temperature for wires from 0·65 to 0·45 millimetre should be 650 degrees C.; for 0·25 millimetre, 500 degrees C.; and finally 400 degrees C. The wire is blue-black when finished, largely due to the graphite lubricant. To make it bright it is passed through a glass tube, filled with hydrogen, passing it over two rollers sufficiently hot to heat the wire to a red heat.

Drawn-wire tungsten lamps are extraordinarily strong and ductile, and a wire of 0·015 millimetre would support 100 grams before breaking, which is equivalent to a breaking stress of over 60 tons per square centimetre. With an increase in the thickness the breaking stress drops, and is only 25 to 30 tons per square centimetre for wires 0·1 millimetre thick.

2.12. GAS-FILLED LAMPS.* —A tungsten filament 0·127 millimetre thick, when run at a temperature of 2850 degrees absolute, will last from two to five hours when burned in a vacuum, with a consumption of 0·40 watt per candle, whereas in an inert gas at atmospheric pressure, such as nitrogen, it will last eighty to a hundred hours, showing a consumption of about 0·65 watt per candle. If the size of the filament is increased, the results are further considerably improved, the lamp now lasting several hundreds of hours, whereas the relative current consumption is diminished. This clearly shows that the efficiency of incandescent lamps may be greatly improved by running lamps at a high temperature in an inert gas to reduce evaporation, if care is taken that the convection losses are kept small. The relative loss of efficiency caused by convection is the greater the thinner the filament, and the life depends on the relative and not absolute decrease in the diameter caused by evaporation. If the rate of evaporation per unit area of filament were the same for large and small wires, the lives of lamps run at the same temperature would be proportional to their diameters. Actually they are approximately proportional to the square of the diameters.

This being the case, we must endeavour to obtain a large diameter for the filament. The wire for a high-voltage lamp is, however, very thin, so that the desired result is best obtained by winding the filament in a close helix. The diameter of such a helix is limited by sagging, which occurs if the mandril used is too large. The weight would pull out the helix and alter the characteristic of the lamp. If there should be a weak spot in such a filament, and the latter open out in this position, convection and radiation losses would increase and prevent local overheating.

The gas-filled lamp is provided with a long neck, so that any tungsten which evaporates is deposited there by convection currents in the gas. Consequently, the globe itself remains clear for a considerable time, and the useful life of the lamp is almost equal to that of the ordinary vacuous globe filament.

The greater the diameter of the filament the smaller is the specific consumption, and with wires carrying 20 amperes it is only half a watt per mean spherical candle. For these heavy currents platinum as

* See also Langmuir and Orange, *General Electric Review*, December 1913, p. 956.

leading-in wires have in some cases been discarded, and alloys having the same expansion coefficients as glass have been tried. Special glasses, into which tungsten or molybdenum wires can be sealed directly, are also employed. The supports for the helix usually consist of tungsten also. The loss through these is small.

Gas-filled lamps may to-day be obtained from 30 watts upwards at 220 to 250 volts, and for almost any intensity at voltages below 110.

The light from these lamps is much whiter than from ordinary tungsten lamps, on account of the higher temperature, and approaches nearer to that of daylight in appearance (see fig. 6.50).

2.13. CHARACTERISTICS OF TUNGSTEN FILAMENTS.*– Consider first an ideal filament, *i.e.* a long, straight thread with a uniform circular cross-section, of diameter d and length l, consisting of pure tungsten with a definite resistance at a given temperature, with a highly polished surface, and assume that the terminals are at the same temperature as the filament, so that no heat is conducted away. The candle-power I and the power P will be proportional to the surface, and we may place $I = Kld$ and $P = K_1 ld$, where K and K_1 are coefficients depending solely on the temperature. The total lumens radiated by a filament are equal to $\pi^2 I$ (see Chapter IV., paragraph 4.04), or $\pi^2 I = \pi^2 Kld$. The mean spherical candle-power is $\frac{\pi^2 I}{4\pi} = \frac{\pi}{4} Kld$. The resistance is expressed by $R = K_2 \frac{l}{d^2}$, and as $P = I_c^2 R = \frac{V^2}{R}$, or $I_c = \sqrt{\frac{P}{R}}$, and $V = \sqrt{PR}$, where V is the voltage and I_c the current, we obtain

$$V = \sqrt{K_1 K_2 \frac{l^2}{d}} = K_3 \frac{l}{\sqrt{d}} \qquad . \quad . \quad . \quad 2.12$$

and

$$I_c = \sqrt{\frac{K_1 l d^3}{K_2 l}} = K_4 d^{\frac{3}{2}} \qquad . \quad . \quad . \quad . \quad 2.13$$

Equation 2.12 tells us that for a constant temperature we must apply a P.D. proportional to the length and inversely proportional to the square-root of the diameter. Similarly, equation 2.13 informs us that the current required at constant temperature is proportional to the three-halves power of the diameter.

From the values for P and I follows

$$\frac{P}{I} = \frac{K_1}{K} \text{ watts per mean horizontal candle} \qquad . \quad . \quad 2.14$$

The watts per mean spherical candle are $\frac{4}{\pi} \times \frac{P}{I}$.

The diameter of the wire is best found by weighing, as even a micro-

* See also J. Langmuir, *General Electric Review*, March 1916, p. 208, and *Physical Review*, 1912, p. 401.

meter gauge is not accurate enough. If w is the weight of the wire in milligrams per centimetre length, then $d=0{\cdot}008186\sqrt{w}$, which is based on a density of 19·0 for tungsten, a value obtained by measurements on filaments which have been run a considerable time in lamps.

In an actual filament the cooling effect of the leads has to be taken into account. For a given current passing through the lamp the candle-power is reduced by an amount

$$\Delta I=\frac{0{\cdot}00074}{V}I(t-300) \qquad . \quad . \quad . \quad 2.15$$

where V is the total voltage on the filament, I the total candle-power, and t is the absolute temperature of the central part of the filament; 300 is the absolute temperature of the surroundings (27 degrees C.).

For a filament with a loop the distribution is altered, but not the total flux. If, however, the filament is wound into the form of a helix, the watts and mean spherical candles for a given length of filament are decreased.

If the filament is heated in vapours of carbon compounds we obtain an increase in the emissivity, and the candle-power is augmented. Traces of carbon in the filament increase the specific resistance and lower the current.

In vacuous lamps, the amount of gas present does not cause conduction of any noticeable degree. For vapour pressures of less than 0·7 millimetre mercury the heat conducted from a hot filament by the gas is expressed by

$$P_g=K_5p(t-t_0) \text{ watts} \qquad . \quad . \quad . \quad . \quad 2.16$$

where p is the pressure of the gas in bars. A bar is equal to 0·00075 millimetre of mercury pressure (=1 dyne/sq. cm.). $K_5=24{\cdot}9\times10^{-6}$ for nitrogen, $12{\cdot}5\times10^{-6}$ for argon, $6{\cdot}3\times10^{-6}$ for mercury. t is the absolute temperature of the filament, and t_0 that of the bulb; $t-t_0$ is thus the temperature rise.

The following table, 2.05, gives values for K, K_1, K_2, K_3, K_4, and $\frac{P}{I}$, corresponding to various absolute temperatures t.

Additional columns show the ratio: resistance hot to resistance at 20 degrees C. (8); the pressure in bars (or dynes per square centimetre) (9); the evaporation of tungsten in grams per square centimetre per second (10); the maximum current in amperes per square centimetre that can be obtained (11); and the ratio of the lengths of a filament at a given temperature to the corresponding length at room temperature (20 degrees C.).

For $t=2500$ degrees C., $p=1$, the amount of heat carried away by the gas is 0·055 watt for nitrogen, 0·028 for argon, 0·014 for mercury. Hydrogen cannot be used as it is dissociated above 1500 degrees absolute.

TABLE 2.05.—CHARACTERISTICS OF THE "IDEAL TUNGSTEN FILAMENT."

1.	2.	3.	4.	5.	6.	7.	8.	9.	10.	11.	12.
t.	K_1.	K.	K_2.	K_3.	K_4.	P. T.	R. R.	p bars.	m g. cm.[2] sec.	i amps. cm.[2]	$l\,l_o$.
273°K	..	..	6·37 × 10^{-6}	..	..	..	0·907	..	..	..	..
300	0·00034	..	7·24	0·00005	6·9	..	1·031	..	..	..	1·00000
400	0·0112	..	10·43	0·00034	33	..	1·486	..	..	..	1·00026
500	0·0424	..	13·76	0·00076	56	..	1·960	..	..	.	1·00053
600	0·1131	..	17·23	0·00140	81	..	2·454	..	..	..	1·00082
700	0·2606	..	20·83	0·00233	112	..	2·967	..	..	..	1·00111
800	0·5420	..	24·55	0·00365	149	..	3·497	..	..	..	1·00142
900	1·043	..	28·36	0·00544	192	..	4·040	..	..	..	1·00173
1000	1·885	0·0001	32·24	0·00780	242	13,460·0	4·593	..	..	12·0 × 10^{-15}	1·00206
1100	3·225	0·0012	36·20	0·0108	298	2,680·0	5·156	..	..	1·48 × 10^{-12}	1·00240
1200	5·258	0·0074	40·23	0·0145	362	712·0	5·731	..	..	82·0 × 10^{-12}	1·00275
1300	8·207	0·0346	44·34	0·0191	430	237·0	6·316	..	..	2·56 × 10^{-9}	1·00311
1400	12·32	0·1325	48·52	0·0244	504	93·0	6·912	..	..	46·3 × 10^{-9}	1·00349
1500	17·87	0·4243	52·77	0·0307	582	42·1	7·517	..	..	0·58 × 10^{-6}	1·00387
1600	25·17	1·179	57·13	0·0379	664	21·35	8·138	..	..	5·42 × 10^{-6}	1·00427
1700	34·55	2·928	61·61	0·0461	749	11·80	8·776	..	..	37·8 × 10^{-6}	1·00468
1800	46·34	6·552	66·19	0·0554	837	7·074	9·429	..	..	214·0 × 10^{-6}	1·00510
1900	60·98	13·46	70·89	0·0658	928	4·530	10·10	..	..	0·00103—	1·00553
2000	78·87	25·90	75·67	0·0772	1021	3·045	10·78	8·60 × 10^{-9}	114·0 × 10^{-15}	0·0042	1·00597
2100	100·5	46·8	80·52	0·0900	1117	2·147	11·47	111·0 × 10^{-9}	1·44 × 10^{-12}	0·0151	1·00642
2200	126·3	80·6	85·41	0·1039	1216	1·568	12·17	1·13 × 10^{-6}	14·4 × 10^{-12}	0·0483	1·00689
2300	157·1	133·3	90·41	0·1192	1318	1·179	12·88	9·4 × 10^{-6}	117·0 × 10^{-12}	0·1377	1·00736
2400	193·2	209·8	95·39	0·1357	1423	0·921	13·59	65·7 × 10^{-6}	798·0 × 10^{-12}	0·365	1·00785
2500	235·5	319·6	100·48	0·1538	1531	0·737	14·31	392·0 × 10^{-6}	4·67 × 10^{-9}	0·891	1·00835
2600	284·5	471	105·56	0·1733	1642	0·604	15·04	2·02 × 10^{-3}	23·6 × 10^{-9}	2·044	1·00886
2700	341·1	675	110·69	0·1943	1756	0·505	15·77	9·27 × 10^{-3}	106·0 × 10^{-9}	4·35	1·00938
2800	406·3	944	115·83	0·2169	1873	0·430	16·50	0·0381—	429·0 × 10^{-9}	8·33	1·00991
2900	480·5	1290	120·9	0·2410	1993	0·372	17·22	0·141	1·57 × 10^{-6}	17·1	1·01046
3000	565·2	1729	126·1	0·2669	2117	0·327	17·96	0·483	5·23 × 10^{-6}	31·7	1·01101
3100	660·7	2272	131·2	0·2944	2244	0·291	18·69	1·52	16·3 × 10^{-6}	57·2	1·01158
3200	768·8	2941	136·2	0·3236	2376	0·2615	19·40	4·45	46·7 × 10^{-6}	101	1·01215
3300	889·6	3763	141·1	0·3543	2511	0·2364	20·10	12·1	126·0 × 10^{-6}	171	1·01274
3400	1025·0	4725	146·0	0·3868	2649	0·2169	20·80	31·2	320·0 × 10^{-6}	275	1·01334
3500	1176·0	5869	150·9	0·4213	2792	0·2004	21·50	76·3	769·0 × 10^{-6}	437	1·01396
3540	1241·0	6373	152·8	0·4355	2850	0·1948	21·77	107·0	0·00107	510	..

The heat absorbed by dissociating gas is very much larger; at one bar pressure it would be about 1 watt, and as K_1 for 2500 degrees absolute is 235 watts, even this 1 watt is less than ½ per cent. Chemically inert gases do not influence the relationship between resistance and temperature, or between candle-power and temperature.

For pressures above 500 bars (0·375 millimetre mercury) formula 2.16 does not hold.

As regards gas-filled lamps, the convection losses are considerable. According to Langmuir * the losses per centimetre may be expressed by

$$P_g = c(\phi_2 - \phi_1) \quad . \quad . \quad . \quad . \quad 2.17$$

in which c is a function of the diameter of the helix, but otherwise constant

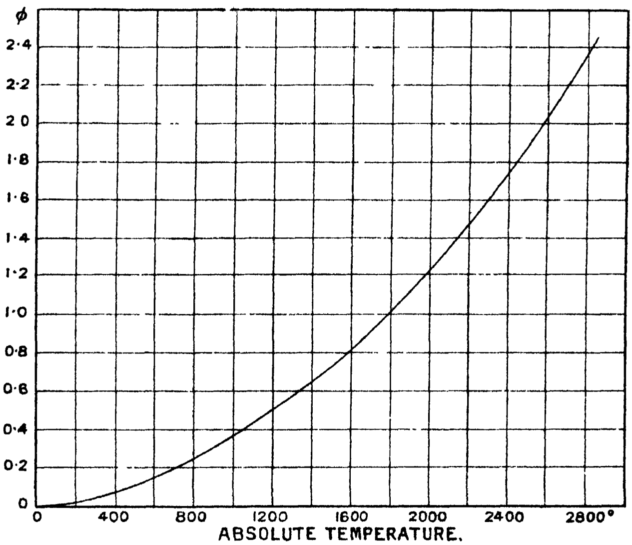


FIG. 2.05.—ϕ as Function of the Absolute Temperature.

for any particular gas, and $\phi = 4{\cdot}19\int_0^t k dt$, in which k is the heat conductivity of the gas at the absolute temperature t, in cal./cm. degrees C., ϕ_2 is taken at the temperature t of the filament, and ϕ_1 at that of the surroundings. For nitrogen ϕ may be taken from fig. 2.05 and c from fig. 2.06.

The interior portions of the helix have a brightness about twice that of the mantle surface, not due to increased temperature, but to reflection. The efficiency of a helix will thus be less than that of a straight wire, other conditions being equal.

With the aid of figs. 2.05 and 2.06 we are able to calculate approximately the size of a filament of a gas-filled lamp. It must, of course,

* *Physical Review*, June 1912, p. 401.

be understood that all these calculations are only very approximate, and that the results of tests and experience are the final criterion. By winding the filament into a close helix, the internal surface of the coil is largely useless from a light-giving standpoint, so that the efficiency is considerably reduced. Gas-filled lamps are run at about 2850 degrees absolute, or 2577 degrees C. A straight filament in a vacuum would then require about 0·4 watt per mean horizontal candle, but a filament wound in a helix and placed in strong nitrogen requires more.

From experiments it has been found that the ratio of the current in the nitrogen-filled lamp to that which would be required to heat the

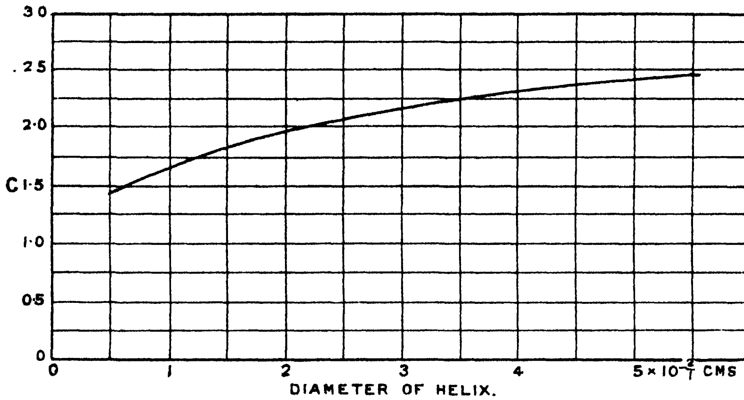


FIG. 2.06.—C as Function of the Diameter of a Helix.

same wire to the same temperature in a vacuum after uncoiling is about 0·95.

2.14. EXAMPLE.—We are asked to determine approximately the length and diameter of an ordinary tungsten lamp filament producing about 1257 lumens or 100 mean spherical candles, to be run from a 220-volt circuit and to absorb 1·257 watt per mean spherical candle.

The energy required is 125·7 watts, and the current therefore $\frac{125 \cdot 7}{220} = 0 \cdot 57$ ampere. 1·257 watt per mean spherical candle is 1·0 watt per mean horizontal candle of a straight filament lamp.

The temperature, according to table 2.05, is then about 2360 degrees absolute, so that, according to equation 2.13,

$$d^{\frac{3}{2}} = \frac{I_c}{K_4} = \frac{0 \cdot 57}{1370} = 0 \cdot 000416,$$

whence $$d = 0 \cdot 0055 \text{ centimetre},$$

and $$l = \frac{V}{K_3}\sqrt{d} = \frac{220}{0 \cdot 128}\sqrt{0 \cdot 0055} \fallingdotseq 127 \text{ centimetres}.$$

The cooling effect of the terminals affects the candle-power of the lamp by about 1 per cent.

Example.—We are required to produce a 220-volt gas-filled lamp giving 160 mean spherical, or about 200 mean horizontal, candles at 0·825 watt per mean spherical candle. Thus $I_c = 0{\cdot}6$ ampere. The filament is to be wound in a spiral with an outside diameter of $d_s = 0{\cdot}025$ centimetre; the length of the spiral will then be expressed by $l = \frac{I}{Kd_s} = \frac{200}{1100 \times 0{\cdot}025} = 7{\cdot}27$ centimetres, assuming a temperature of about 2850 degrees absolute. The heat loss by convection is expressed by

$$\begin{aligned} P_g &= 7{\cdot}27c(\phi_2 - \phi_1), \\ &= 7{\cdot}27 \times 2{\cdot}05(2{\cdot}44 - 0{\cdot}04) = 36 \text{ watts.} \end{aligned}$$

The energy radiated is then $160 \times 0{\cdot}825 - 36 = 96$ watts.

The same filament in a vacuum and uncoiled would require about 5 per cent. more current, hence, if we want to use the formulæ for vacuous lamps, we must place in equation 2.13

$$d^{\frac{3}{2}} = \frac{I_c}{K_4} = \frac{\frac{1}{0{\cdot}95} \times 0{\cdot}6}{1930} = 0{\cdot}00327,$$

whence $d = 0{\cdot}0045$ centimetre,

and $l = \frac{220}{0{\cdot}239}\sqrt{0{\cdot}0045} = 64{\cdot}4$ centimetres.

The number of convolutions required to make up this length is $n = \frac{64{\cdot}4}{\pi d_m} = \frac{64{\cdot}4}{\pi(0{\cdot}025 - 0{\cdot}0045)} = 1000$. These take up a length of $1000 \times 0{\cdot}0045 = 4{\cdot}5$ centimetres, so that there is for spacing between the convolutions $7{\cdot}27 - 4{\cdot}5 = 2{\cdot}77$ centimetres available, the distance between two convolutions thus being 0·00277. We may check our calculation by seeing whether the resultant resistance is correct.

$$R = K_2 \frac{l}{d^2} = \frac{117{\cdot}5 \times 64{\cdot}4}{10^6 \times 0{\cdot}0045^2} \fallingdotseq 370 \text{ ohms},$$

$$R = \frac{V}{I_c} = \frac{220}{0{\cdot}6} \fallingdotseq 370 \text{ ohms}.$$

When a filament is very short the cooling effect due to the leads is of great importance. The subject has been fully investigated by G. Stead, M.A., whose results are found in *Journal of Inst. of Electrical Engineers*, vol. lviii. p. 107, to which the reader is referred.

2.15. CANDLE-POWER AS FUNCTION OF THE VOLTS, AMPERES, WATTS, AND WATTS PER CANDLE.—The accompanying table, 2.06, shows the results obtained with various lamps.

TABLE 2.06.—RESULTS OF TESTS ON INCANDESCENT LAMPS.

Carbon Lamp.	Nernst Lamp.	Tantalum Lamp.	Osram Lamp.
$\bar{I}_h = 5{\cdot}08 \times 10^{-16} V^{7}$	$\bar{I}_h = 0{\cdot}28 \times 10^{-20} V^{9{\cdot}35}$	$\bar{I}_h = 0{\cdot}11 \times 10^{-7} V^{4{\cdot}4}$	$\bar{I}_h = 0{\cdot}16 \times 10^{-6} V^{4{\cdot}0}$
$= 16{,}000 I_c^{5{\cdot}5}$	$= 536 I_c^{2{\cdot}6}$	$= 16{,}700 I_c^{6{\cdot}0}$	$= 16{,}000 I_c^{6{\cdot}0}$
$= 39{\cdot}2 \times 10^{-6} P^{3{\cdot}1}$	$= 3 \times 10^{-3} P^{2{\cdot}15}$	$= 6{\cdot}4 \times 10^{-3} P^{2{\cdot}15}$	$= 5{\cdot}8 \times 10^{-3} P^{2{\cdot}32}$
$= 124 \eta^{-1{\cdot}476}$	$= 160 \eta^{-1{\cdot}87}$	$= 80{\cdot}7 \eta^{-1{\cdot}87}$	$= 52 \eta^{-1{\cdot}77}$
$R = 610 I_c^{-0{\cdot}214}$	$R = 310 I_c^{-0{\cdot}72}$	$R = 580 I_c^{0{\cdot}36}$	$R = 562 I_c^{0{\cdot}5}$

in which $\bar{I}_h$ = luminous intensity in mean horizontal candles,
V = volts at the terminals of the lamps,
I_c = current in amperes,
P = watts absorbed,
η = watts per candle,
R = resistance in ohms.

They are correct only as long as the variations about the normal values are not large. For instance, the candle-power voltage relation does not give a constant value for the exponent. A more correct result has been worked out by F. E. Cady, expressed by

$$\frac{I}{I_1} = \left(\frac{V}{V_1}\right)^{x_1}\left[1 + B\frac{V - V_1}{V_1} + C\left(\frac{V - V_1}{V_1}\right)^2\right],*$$

where I_1 is the candle-power at the normal voltage V_1, and x_1 is the value of x at this voltage, as given in the above table. B = 0·05 for treated carbon, 0·024 for tantalum, and 0·02 for tungsten. C = 1·2 for carbon, 0·65 for tantalum, and 0·5 for tungsten. On the whole it is more convenient to reckon with the simple equation $I = KV^x$ and to plot x as function of the percentage voltage. For Mazda tungsten lamps the exponent may be taken from the table below:

TABLE 2.07.– VARIATION OF EXPONENT x.

Percentage voltage .	60	70	80	90	100	110	120	130	140
x	3·68	3·63	3·58	3·54	3·50	3·47	3·44	3·41	3·38

We see that as long as the voltage fluctuations are small we do not make much of a mistake by assuming x constant.

Table 2.08 gives further information about the variations of Mazda lamps.

* *Electrical Review and Western Electrician*, vol. lix. p. 1087, 1911.

TABLE 2.08.—VARIATIONS IN MAZDA LAMPS.*

Dependent Variable.	Independent Variable.	Symbol.	Definition.	Value.
Candle-power . .	Volts	x	Taken as fundamental.	3·48
Amperes	,,	t	,,	0·582
Lumens per watt . .	,,	g	$g = x-(1+t)$	1·90
Watts	,,	n	$n = 1+t$	1·58
Ohms	,,	q	$q = 1-t$	0·418
Candle-power . .	Amperes	y	$y = x/t$	5·98
Lumens per watt . .	,,	j	$j = \frac{x-(1+t)}{t}$	3·26
Ohms	,,	m	$m = \frac{1-t}{t}$	0·718

Thus candle-power = constant × volts $^{3·48}$; lumens per watt = constant × amperes $^{3·26}$.

2.16. POINTOLITE ARC-INCANDESCENT LAMP.†—This is illustrated in fig. 2.07, and consists of a filament B B' of tungsten mixed with some refractory earths, acting as ioniser, and an electrode E of pure tungsten, the whole being placed in an inert gas such as nitrogen or argon. The filament gives off strong negative discharges (electrons) and ionises the medium around it until a current passes between the filament and the positively charged electrode. This current increases in strength until the cut-out is operated, breaking the ioniser circuit and causing an arc to be set up between the filament and the electrode, which becomes incandescent and gives off an intensely bright light, since the whole is concentrated on a small area, which in the 100-candle lamp is only $\frac{1}{10}$th inch in diameter. The heat rising from the arc causes the expansion strip F to warp, and this moves the arc to another position on the ioniser. On switching off the tungsten electrode returns to its original position, having left the inactive part

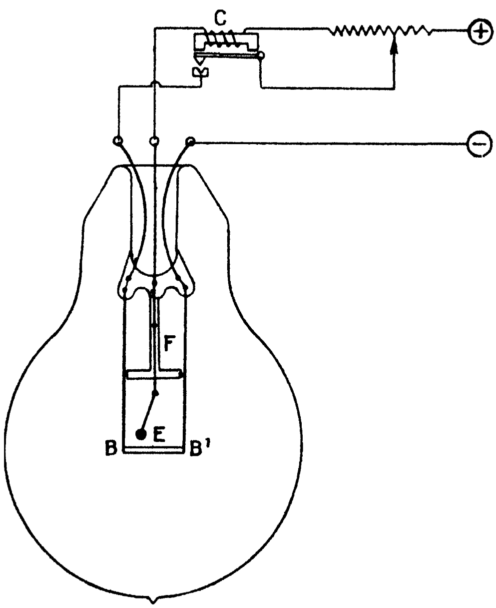


FIG. 2.07.—Pointolite Arc-Incandescent Lamp.

* E. J. Edwards, *General Electric Review*, 1914, p. 282.

† *J.I.E.E.*, vol. liv. pp. 15–19, 1st December 1915; *Electrical Review*, vol. lxxxvi. pp. 9–10, 2nd June 1920.

of the ioniser and coming to rest opposite the still active portion of the ioniser ready for a restart. The characteristics of the lamp are shown in fig. 2.08. They are similar to those of other types of arcs. The lamp is very useful for optical use and might find a field for projection work, as the intrinsic brightness is about 10,000 candles per square inch.

2.17. ARC LAMPS.—The ordinary pure carbon arc lamp may also be classified under temperature radiation, since most light is emitted from incandescent parts of the hot carbon. In the direct-current lamp about 85 per cent. of the luminosity comes from the incandescent part of the

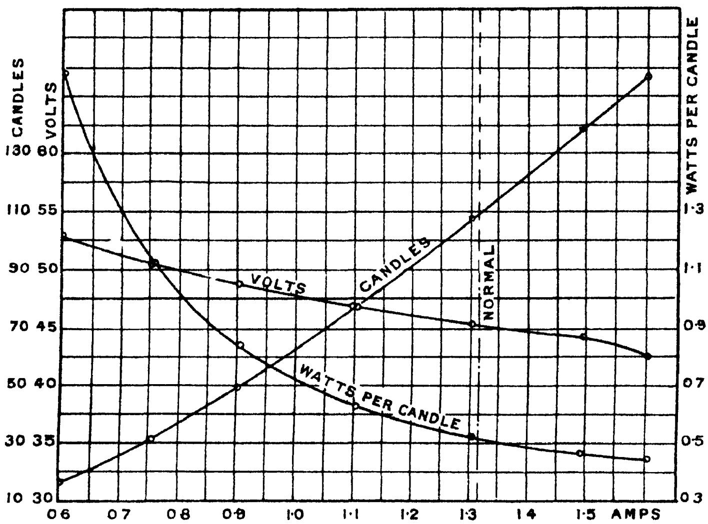


Fig. 2.08.—Characteristics of a Pointolite Lamp.

positive pole. This is due to the fact that this pole becomes very hot, the temperature being near the melting-point of the carbon. Where the temperature is highest, a crater is formed, which is the maximum light producer. Its light is white with a slight bluish tint, and from this point of view it is good for distinguishing colours, as its light approaches in appearance that of daylight. Even the latter has a bluish tint where there is reflected skylight.

On account of the high temperature of the positive electrode, a rapid consumption takes place by combustion, which is about twice as great as that of the negative carbon. This combustion may be reduced by enclosing the arc in an air-tight glass globe, with just enough ventilation to keep an equilibrium of pressure. The arc must now be supplied with a higher pressure (75 volts against 45), the length of the arc is greater, and as the temperature of the positive electrode is now lower, no crater is being formed, and consequently the quantity of light emitted is less. The colour of the light is bluer than before, since a greater portion is obtained from the arc itself, and it is the latter that chiefly supplies the blue part of the spectrum.

As the light is mainly due to temperature radiation, we should employ a temperature as high as possible, and employ carbon of the highest purity. But even with the highest attainable temperatures and the best material, the efficiency procured is not high and—taking the losses in steadying resistances and lamp mechanisms into account—the specific consumption is not even as low as that of the gas-filled incandescent lamp. As a matter of fact we need have no hesitation in saying that the arc lamp, with pure carbon electrodes and producing light chiefly by temperature radiation, is a thing of the past, except for search-lights and motion-picture work.

2.18. LUMINESCENCE.—When energy is directly changed into light without being first converted into heat we refer to the phenomenon as luminescence. The colour of the light is now no longer due to temperature, but depends upon the chemical composition of the substance. We are here mainly concerned with electro-luminescence of gases and vapours. These become luminescent when being used as conductors of electric currents. As the radiation no longer depends solely on the temperature which can be obtained, but mainly upon a peculiar property of the atom of the gas or vapour, it should be possible to obtain efficiencies considerably higher than those possible with temperature radiation.

Luminescence may be caused in three ways, by continuous conduction, heat evaporation from the terminals, and intermittent or disruptive conduction. Examples of the first kind are the magnetite and titanium luminous arcs, and the mercury vapour lamps. Of the second type we have the various flame arc lamps, and the third category is represented by Geissler and Moore tubes.

The arc which is set up between the electrodes is a stream of vapour, which has to be produced before conduction can take place. This starting of the lamp may be accomplished by increasing the potential difference between the electrodes until it is high enough to bridge the space, or by bringing the electrodes momentarily together. The starting could also be effected by temporarily conducting an auxiliary vapour stream between the electrodes.

The current crosses the space between the electrodes through a stream of vapour coming from the negative electrode as a high-velocity blast. The arc stream is conducting only in this direction, and the arc is thus a unidirectional conductor. This property of the mercury vapour arc is employed for rectifying alternating currents.

In the continuous-conduction type of lamp the negative electrode supplies the material which carries the current in the arc stream, and hence the light-giving material must be found in the negative electrode. It is carried into the stream by electro-conduction and not by heat, so that the temperature is of little importance, and the electrodes may as a matter of fact be made large enough so as to remain comparatively cool and give little or no light.

In flame arc lamps the light-giving materials are surrounded by carbon so that the heat of the high-temperature carbon arc evaporates them, passes them into the arc stream, and gives them the corresponding colour, whereby the efficiency is raised above that of the pure carbon arc. The spectra of flame arc lamps are thus the combined ones of positive and negative electrodes. The higher the temperature the more chemicals are evaporated, and, consequently, the greater the amount of light given. In so far the efficiency is thus dependent upon the temperature. As the positive electrode is the hotter one, the chemicals should be chiefly placed into this electrode. The negative electrode may or may not be impregnated, as this does not affect the light to anywhere near the same extent as similar changes would cause in the positive pole. The arc of such a lamp is thus a mixture of carbon vapour and the vapours of the chemicals, but it cannot be as efficient as an arc from pure chemicals would be.

To obtain a high efficiency in all these lamps and the desired colour of the light we must thus search for those chemicals which have the desired properties.

The following table gives the names of the materials used in arc lamps in the order of their efficiencies as producers of light.

TABLE 2.09.—CHEMICALS AS LIGHT PRODUCERS.*

Material.	Main Colour of Arc.
Titanium	White.
Calcium	Yellow.
Mercury	Green.
Cerium and rare earths	White.
Iron	White.
Barium	Greenish-white.
Magnesium	White.
Zinc	Bluish-green.
Copper	Green.
Aluminium	White.
Boron	Green.
Carbon	Purple.

The arc thus depends upon the ionising action of boiling electrodes. The heat is caused by the impact of the ions coming from the opposite electrode at very great speed. As the current is mainly due to the parting of electrons or negative ions from the hot cathode, it is possible to pass the current between the latter and a second cold anode. The

* See also *General Electric Review*, 1913, p. 497, from which Table 2.09 and figures 2.09 and 2.11 have been taken.

bombardment of the second anode with negative ions raises the temperature, and the first anode may be put out of circuit. This principle is employed in the two-anode rectifier.

From this table it follows that the most efficient arcs are those obtained with titanium, calcium, and mercury, and the corresponding lamps are at present the most efficient light producers on the market. The nature of luminous arcs makes them on the whole unsuitable for alternating currents. In such circuits the current drops to zero and then rises in opposite direction, so that the conditions at the two electrodes are reversed, which requires energy and a high voltage. The arc is thus extinguished and has to be established in opposite direction every half-period. The voltage required to do this depends on the temperature, decreasing greatly at high temperatures. If, therefore, the cooling action of the terminals is great, the voltage required for a restart will also be high. In fact, carbon is practically the only substance which will maintain an alternating current arc at a low voltage at atmospheric pressure. But even with carbon the voltage curve shows a high peak at the instant the current passes through zero. This is well illustrated in fig. 2.09, which shows an oscillogram for a titanium arc. The peak in the voltage curve is due to the fact that the titanium lowers the temperature of the arc stream and thus increases the sparking voltage required to re-establish the arc. The peak also grows with the length of the arc. In flame arcs there is a plentiful supply of soft carbon ready to volatilise quickly, and the peaks of the voltage curves are less pronounced. The frequency of carbon arcs should, however, not be less than thirty, as below this frequency the lamps usually pump and the flickering becomes unbearable.

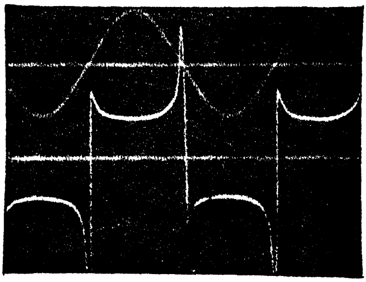


FIG. 2.09.—Oscillogram for Titanium Arc.

It will be seen from the oscillogram that the lamp voltage at the beginning of a period rises almost instantaneously to a high value. If this is not the case, the current curve remains in the abscissa axis a little time until the required value of the pressure for a restart is reached.*

With inductance (choking coil) in the lamp circuit the peak is also less pronounced, as, on account of the phase displacement of the current, the voltage has time to reach a sufficiently high value.

Although current and volts are in phase, the power factor is not unity on account of the distortion of the voltage curve.

2.19. FLAME ARCS.—A flame arc with yellow light for direct

* See paragraph 6.25.

current is shown in fig. 2.10. The feeding of the arc stream with luminescent material by heat evaporation has the advantage of producing a steady arc, since carbon is the most refractory material known and changes directly from the solid state into vapour without first melting. The carbon also makes the lamp suitable for direct and alternating currents, and any stable compound, whether conducting or not, may be used for impregnation. Thus, in the yellow flame lamp, calcium fluoride, oxide, borates, or sodium salts; in the titanium arc, the oxide or the carbide may be employed.

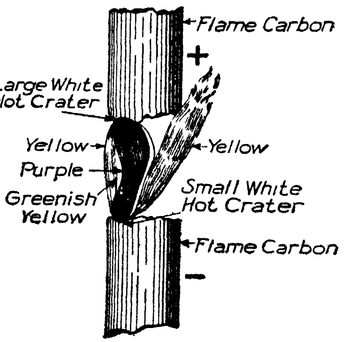
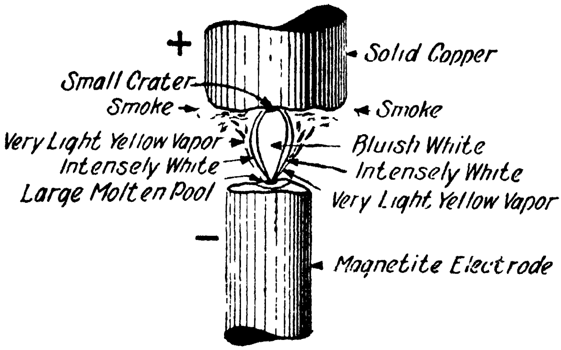


FIG. 2.10.—Flame Arc for Direct Current.

A disadvantage is, however, the rapid consumption of the electrodes and the frequent recarboning required By using the air over and over again, after passing it through a smoke-depositing chamber, as is the case in so-called regenerative lamps, the consumption may be considerably reduced.

2.20. MAGNETITE ARC.—In the magnetite arc lamp the positive electrode consists of copper, large enough to keep sufficiently cool to prevent oxidation and consumption, and hot enough for preventing condensation of the vapour. The negative pole consists of an iron tube, filled with a mixture consisting of 68 per cent. powdered iron oxide (magnetite), 28 per cent. oxide of titanium, and 4 per cent. oxide of chromium. The tube acts as a conductor, the oxide of iron gives conductivity to the mixture when cold, the oxide of chromium prevents the otherwise rapid consumption and the flickering of the arc—the latter by keeping the melted magnetite in a constant position. The oxide of titanium makes the arc luminous. The arc of such a lamp is illustrated in fig. 2.11. The internal arc conductor (bluish white) issues from a large molten pool formed on the surface of the negative terminal. This pool is always in motion and consequently causes a great deal of flickering, a quality inherent to all arcs in which the negative terminal is fusible. The movement is due to the velocity of the vapour from the negative electrode, producing a depression and driving the current up the sides of this depression, thereby shifting the arc. It is for this reason that chromite is mixed with the other materials, as it is more refractory than magnetite. It remains solid and holds the melted magnetite like a sponge. The lamp is suitable for outdoor work only. The oxides are completely converted, but they condense immediately after leaving the arc as a reddish soot. It is therefore essential that the lamp be provided with such ventilation as will carry this soot away into the atmosphere. The maximum amount of light comes from the flame and the negative electrode, as one would expect. The length of the arc is about an inch.

2.21. TITANIUM ARC.—Another luminous arc is the titanium arc,



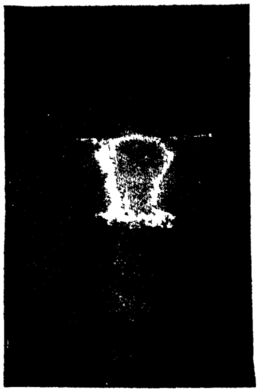


FIG. 2.11.—Magnetite Arc.

as illustrated in fig. 2.12. It may be made suitable for alternating current by making one electrode of carbon and the other of titanium carbide. The electrodes then remain hot enough to allow the working pressure to restart the arc when the current rises in opposite direction. The arc shown in the figure is an alternating one.

Both the magnetite and titanium arcs, evolved by Dr Ch. P. Steinmetz,

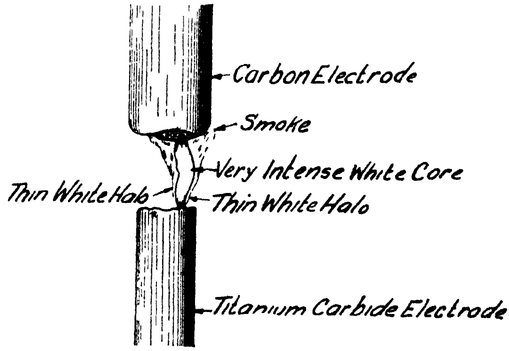


FIG. 2.12.—Titanium Arc.

have been employed in America only, chiefly due to the peculiar conditions reigning there.

Recently a patent * has been taken out by W. R. Mott for arc-lamp electrodes which contain uranium as an ingredient, together with calcium fluoride. It is stated that these electrodes yield an intense snow-white light of extraordinary photographic power, 50 per cent. greater than that of the titanium arc.

* U.S.A. Patent No. 1235996.

2.22. MANUFACTURE OF ELECTRODES FOR ARC LAMPS.*— The proper working and the efficiency of an arc lamp depend chiefly upon the quality of the electrodes employed. Until the beginning of this century plain carbon was exclusively used. The raw material consisted of retort carbon, soot, and tar, carefully chosen and prepared to fulfil definite physical and chemical conditions. The best quality of such carbons contained little retort carbon, but possessed the disadvantage of burning rapidly away, which under certain conditions might counterbalance the advantage of additional light obtained.

The retort carbon is finely ground and then mixed with soot and tar. Lamp-black, on account of its extreme fineness and purity, and very pure finely pulverised petroleum coke, uniformly mixed with sugar syrup or coal-tar, also yield a good quality of carbons.

The mixture should be well kneaded and squirted at a high pressure through steel dies into rods of the required diameter. If the carbon is to be cored, a needle is placed into the centre of the die over which the paste is forced, leaving a central canal in the rod. The rods are usually cut in lengths of about 100 centimetres (39 inches), tied up into bundles and packed upright into fireclay crucibles in which they are carefully baked, the temperature in the crucibles rising gradually to about 1400 degrees C. in about twenty-four hours, the cooling down period taking another twelve to sixteen hours before the rods are removed. The baking is usually done in gas-fired furnaces working on the regenerative principle.

The baked carbons are cut to the required length, sorted, to remove the defective ones, ground flat at one end and pointed at the other. In the case of cored carbons a mixture of finely ground carbon and concentrated potassium silicate is squirted into the canal under high pressure, and the carbons reheated to about 150 degrees C. in order to dry the core. The latter is somewhat softer than the solid carbon and tends to burn away a little faster, holding the crater in the centre of the electrode tips and making the arc steady.

The potassium silicate has also a steadying effect on the arc. It gives a whiter light than sodium salts.

With the open arc the upper carbon soon becomes pointed, owing to the great draught of air pushing continuously against it, thus accelerating the consumption beyond the quantity necessary to maintain the arc, a phenomenon called "washing." If the upper (positive) carbon is electroplated with copper or zinc, the washing is reduced and the life of the electrode increased. On direct current, only the positive carbon is cored.

The quality of carbon which may be suitable for open lamps, may give poor results in enclosed lamps, in which only the very best class of

* See also "Arcs and Electrodes," by Blake and Couchey, in the *General Electric Review*, July 1913, p. 497, and the *General Electric Review* on "Searchlights," September 1919.

electrodes gives real satisfaction. Both carbons are usually solid, but a cored positive is also used.

In flame lamps it is desirable to use as large a percentage of chemicals as possible, but as these are non-conductors at low temperatures, a certain amount of carbon must be employed in order to obtain the necessary heat for volatilising all the chemicals used, to prevent the tips of the electrodes from being covered with a non-conducting slag. It was largely for this reason that the first flame arc lamps were provided with inclined instead of vertical carbons. If there is an excess of chemicals it can drop away from the electrodes, whereas with vertical carbons the non-conducting deposit might prevent the arcs from restarting.

Inclined carbons possess, however, the disadvantage of having to be thin, since an arc drawn between the lower points of two converging electrodes can change its length too much with thick electrodes, and become unsteady by shifting to different points on the tips. This would cause flickering for the arc and changes in colour of the light. When the arc is on the carbon edges, the light is white; when coming from the chemical core, yellow (for calcium-fluoride). The life of thin carbons is naturally short.

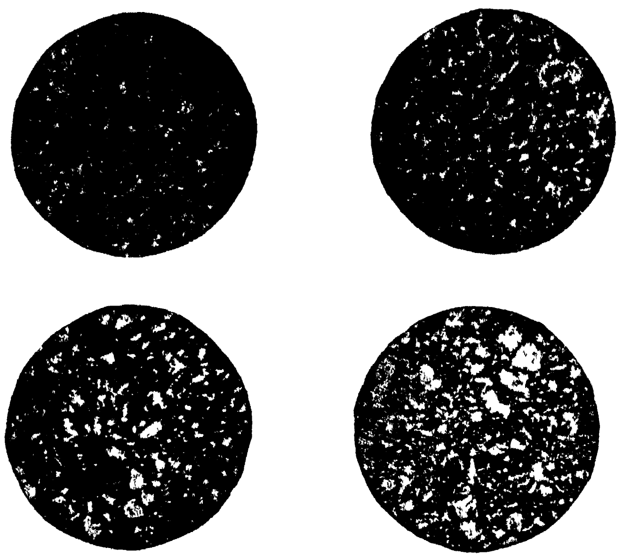
The flame between the inclined carbons is usually spread out by means of an *economiser,* which consists of a saucer-shaped piece of metal having holes through which the carbons pass, and possessing a lining of refractory material. It prevents also the rapid passing away of the vaporised salts and diminishes the rate of consumption of the electrodes. The spreading of the arc is frequently assisted by a blowing magnet, which forces the flame downwards. The arc is thereby always kept in the proper position, *i.e.* it comes chiefly from the core, instead of from the edges of the electrodes, so that the burning is steady.

As the specific resistance of the core is a good deal higher than that of carbon, and the drop along the electrodes would be high, flame electrodes are frequently supplied with zinc or brass wire cores, which are flattened out and bent over at the butt end in order to make good contact with the holders.

The core of chemicals has a diameter of from one-third to one-half of the diameter of the electrode, containing about 50 per cent. of fluoride (calcium for yellow, cerium for white lights). In the Blondel carbon, however, the core takes up a much greater percentage of space—about two-thirds of the total diameter—and both the positive and negative electrodes are the same. The mixture employed is such that a deposit of non-conducting slag of sufficient magnitude on the carbons is prevented, so that the restarting with vertical carbons offers no difficulty. Borates and other alkali salts have been found helpful in this respect, and boracic acid is especially good. The carbons have also a greater thickness than the flame lamps with inclined electrodes, varying from 10 to 20 millimetres in lamps taking from 6 to 15 amperes, so that for the same length of carbons a greater life is obtained than in lamps with inclined electrodes.

In America the cored carbon has in many cases been superseded by the homogeneous impregnated electrode, a result obtained after a great deal of research. Fig. 2.13 represents a microphotograph of flame carbon development. Fig. *a* shows a cross-section of a pure carbon electrode, *b* of a successful flame carbon, *c* and *d* of coarse texture of unreliable flame carbons. If the mineral matter contained is too large in

a *b*



c *d*

FIG. 2.13.—Development of Carbon Electrodes.

proportion it boils out in form of slag, which is non-conducting when cold. The mixture must be such that the whole matter boiled out is volatilised. The colour of the light from homogeneous flame arcs is constant throughout the life, except during the first half-hour. This is due to the fact that at starting there is an excess of light-giving material at the tips of the electrodes, since the carbons become very hot over the first half-inch, and the temperature is high enough to boil out the mineral matter over such distance. After this the impregnating material remains undisturbed until the heat of the arc volatilises it and drives it out of the electrode.

Flame arcs with yellow light are more efficient than those giving white light, as one would expect from Table 2.09, excepting the titanium arc.

For high-intensity search-lights the electrodes have to be especially carefully prepared, as the conditions under which they work are very severe. In these cases beams of enormous intensities are often required, and as the limits as regards the optical system have long been reached (large mirrors and apertures to catch the maximum possible amount of light, intensive concentration to reduce the beam to as small an angle as possible), progress was possible only by increasing the intrinsic brightness of the arc. This is not procured by simply increasing the current, as this enlarges the crater but does not improve the brightness.

Lummer achieved the desired result by working the arc under high pressure (see paragraph 2.04), whereby the boiling-point is raised, but the practical difficulties when applying this principle are so great that the system is not used. To work an arc in a large mirror with an aperture of at least 90 degrees under a pressure of 80 to 100 lbs. per square inch, with water-cooling for such electrodes, to carry about compressed gas for refilling when carbons are replaced, was found to be practically impossible.

Beck improved the intrinsic brilliancy by overloading the electrode with metallic salts, and using large currents, but limiting the size of the crater by cooling the positive electrode near the tip by means of alcohol or town-gas vapour. In this manner the intrinsic brilliancy is increased about threefold.

The Sperry search-light is worked on similar principles. The data for 36 and 60 inches drum type projectors are about as follows :—

The positive electrode is 43 inches (1100 millimetres) long, $\frac{5}{8}$ inch (16 millimetres) in diameter for a current of 150 amperes, with a core of 0·31 inch (8 millimetres) consisting of flaming salts. Shell and core are pressed separately, and the one-piece core is inserted in the shell with a minimum of clearance, and firmly cemented. The core must be straight, or any curvature must be evenly distributed along the whole length, and must not exceed 2 millimetres.

Due partly to an angular setting of the axis of the negative electrode relatively to the axis of the positive electrode, an extremely deep crater is formed, which contains the gas. This is facilitated by the employment of the softer core. In all probability the pressure within the deep cavity is above atmospheric, so that the increased brilliancy is somewhat due to this.

A further overloading of the electrodes with salts and the employment of larger currents was found impossible for some time. To-day this has been achieved, and $\frac{5}{8}$-inch carbon will now carry 225 and even 300 amperes without sooting, yielding an intrinsic brilliancy of over 1100 candles per square millimetre, corresponding to a black-body temperature of 5100 degrees absolute. Moreover, this has become possible without the employment of a vapour blast, as now the oxidation of the red-hot positive electrode outside the crater is prevented by the use of a tube, which is pushed over the electrode, consisting of fireproof material, within which a protective layer of CO is formed after a superficial oxidation. For the 2-metre search-light and a current of 300 amperes, a beam of 1800 million candles has been obtained. Fixed on the moon such a beam would appear as a star of 6th magnitude, so that light-signalling through space may after all become possible.*

For medium-intensity arcs pure carbon electrodes are still used, and in order to obtain good results there should be an even distribution of temperature over the face of the crater.

Also the titanium arc has been developed for search-lights, the light coming then mainly from the arc proper, so that the parabolic reflectors of such projectors must be deep.

A full investigation into the qualities of pure carbon electrodes for search-lights appeared in the *Journal of the Institution of Electrical Engineers*, vol. lviii. p. 83.† The average candle-power current curves are all straight lines, of the form

$$\text{candle-power} = AI_c + Bs + C, \text{ for uncoppered carbons,}$$

where A, B, and C are constants, I_c the current, and s the nominal cross-sectional area of the positive electrode in square millimetres. For seven carbons tested A=150, B= −5, and C= −2000.

It is seen that the average number of candles per ampere tends to increase with the area for a given current density. Thus, candles per ampere $=150-\frac{5}{I_c s}-\frac{2000}{I}$, and if $\frac{I_c}{s}=p=$ a constant current density, candles per ampere $=150-\frac{5}{p}-\frac{2000}{p\sqrt{s}}$.

It appears that no appreciably greater efficiency can be obtained by increasing the diameter of the positive electrode beyond 28 millimetres, and it was also found that the maximum current which any uncoppered carbon could carry without overheating was given approximately by $I_{cmax.}=1{\cdot}8d^4$ amperes, where d is the diameter of the anode in millimetres, which for a 25-millimetre diameter electrode would mean about 0·3 ampere per square millimetre.

With coppered carbons the current density may be raised 10 to 15 per cent.

2.23. MERCURY VAPOUR LAMP.—The mercury vapour lamp was invented by Arons in 1860 and developed chiefly by Cooper-Hewitt, the General Electric Company in America, and by Dr Küch of the firm of Heraeus in Germany. One type consists of an exhausted glass tube, with a positive metal electrode—iron or mercury—and a negative electrode of mercury. On tilting the lamp, so as to bring the mercury in contact with the positive electrode by a thread of mercury, the circuit is closed, and mercury vapour is produced which afterwards keeps the current flowing when the lamp has been tilted back. The voltage required depends on the length of the tube. With a tube 120 centimetres long

* G. Gehlhoff, *E.T.Z.*, 1921, p. 1315.

† *Carbon Arcs for Search-lights*, by Messrs Paterson, Walsh, Taylor, and Barnett.

and 2½ centimetres in diameter, a P.D. of about 110 volts is required. The lamp then uses about 3 to 3·5 amperes. By using a larger diameter of tube and heavier currents the same voltage may be sufficient for longer tubes. The resistance of the lamp consists of three parts: (1) the resistance of the anode, (2) the resistance of the vapour, (3) the resistance of the cathode.

The resistance of the anode is inversely proportional to the current, so that the drop across it is practically constant for all currents, being about 5·7 volts. The same holds for the cathode, as long as the current is not too small, the drop of potential being about 5·3 volts. The resistance of the vapour is proportional to the length of the tube, but decreases with an increase in the diameter, although not exactly inversely. The decrease is rapid if the current is small and the diameter is small. It also decreases with an increase in the current, and more rapidly when the current and diameter are small and the vapour pressure high. The latter is usually 1 millimetre mercury, as it has been found that for this pressure the light-giving efficiency is a maximum.

The equipment and connections of a glass mercury lamp are shown in fig. 2.14,* and the characteristics in fig. 2.14A. The action of such a lamp is as follows: During operation the tube is filled with mercury molecules, mercury ions, and electrons. The ions are molecules which have gained or lost one or more electrons or unit negative charges of electricity, thereby being left charged either negatively or positively as the case may be. These molecules, ions, and electrons move with various characteristic velocities and in individual directions determined by their collisions with their fellows according to the kinetic molecular theory of gases. The commotion is complicated by the fact that because of the heat of the cathode and the impact of the electrons, ions, and molecules on each other, and on the electrodes, more electrons and ions are produced than are needed to carry the current. The effect is a drift of electrons from the cathode to the anode and a relatively much slower movement of positive ions towards the cathode. The result is a gradual short circuit, an increase in the current, and a decrease in the voltage. This is especially noticeable for small currents, but as these increase we finally pass through a minimum potential difference, after which the voltage rises with the current. The conditions are thus similar to those of ordinary arc lamps, and steadying resistances or reactances are essential.

In fig. 2.14 the steadier consists of an induction coil in series with a resistance, the former being also used for starting purposes. In fig. 2.14A, curve F U E O D represents the tube voltage, line B O″ R the resistance E.M.F. of the steadier, and curve C H O′ M the resultant of the two. The system cannot be worked on the left of point H, and for maximum light efficiency the lamp is operated on the point of minimum tube voltage.

* *General Electric Review*, September 1920, p. 741.

The resistance is made adjustable to make the lamp suitable for operation on various voltages.

To start the lamp it is necessary to start and maintain the formation

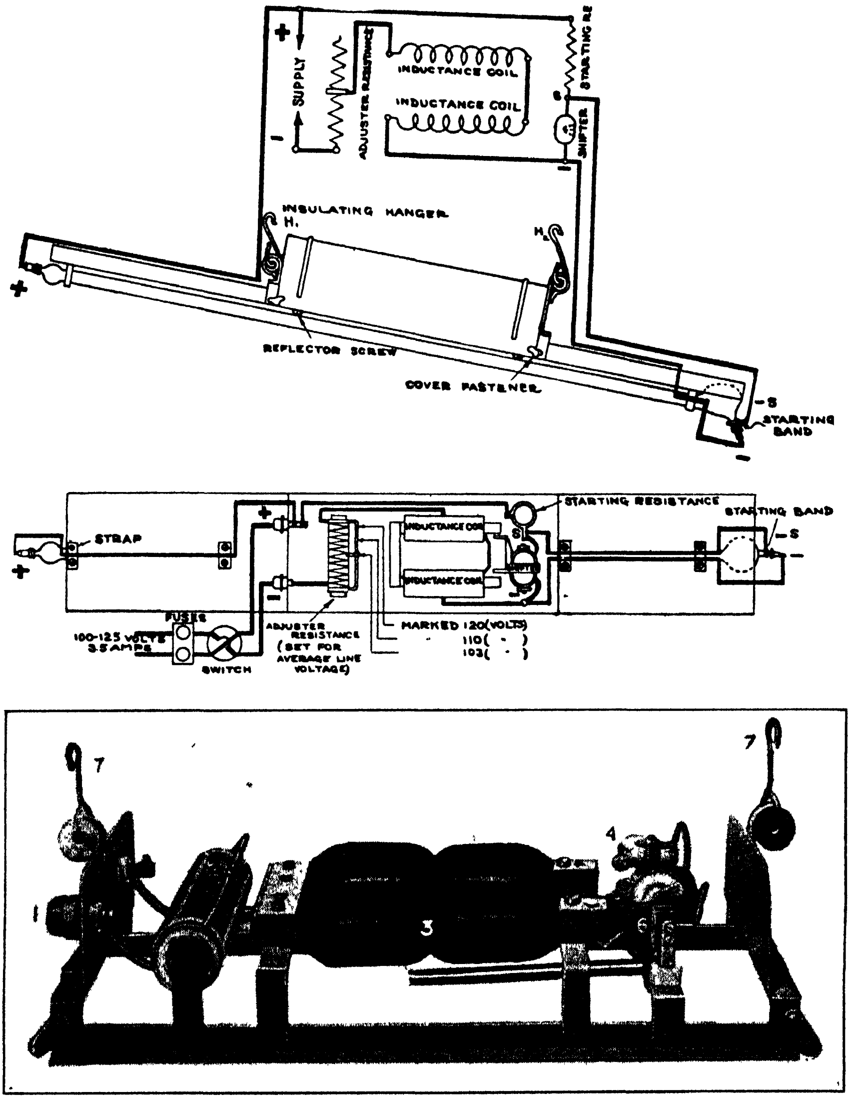


FIG. 2.14.—Connections for a Self-Starting Mercury Vapour Lamp.

of electrons in a so-called "hot spot" on the surface of the mercury cathode. The temperature of this spot is very high on account of the small cross-section of it and the fact that about 18 watts are converted into heat in this small area. This condition is obtained by tilting, which may be done automatically. For long glass tubes the starting with an induction coil is simpler (see fig. 2.14). On connecting the system to the network, the induction coil is charged through a shifter, which immediately afterwards interrupts this circuit, the induced E.M.F. being sufficient to start a localised cathode discharge, and the arc is formed. This is facilitated by a starting-band placed on the outside of the cathode end of the tube and connected to the positive side of the supply, thereby increasing the electrostatic capacity of the cathode, and hence to give a greater current density to the induced high potential discharge when it is localised to form an arc.

The shifter is itself a small mercury vapour arc. It is so mounted as to be easily rotated by an armature actuated by the field of the induction coil. The advantage of this shifter is the very rapid break of the circuit, and hence the production of a high P.D. with a very moderate inductance. A high resistance in the shifter circuit keeps the shifter starting current well below a minimum arc maintenance value, and hence there is no arcing across the shifter.

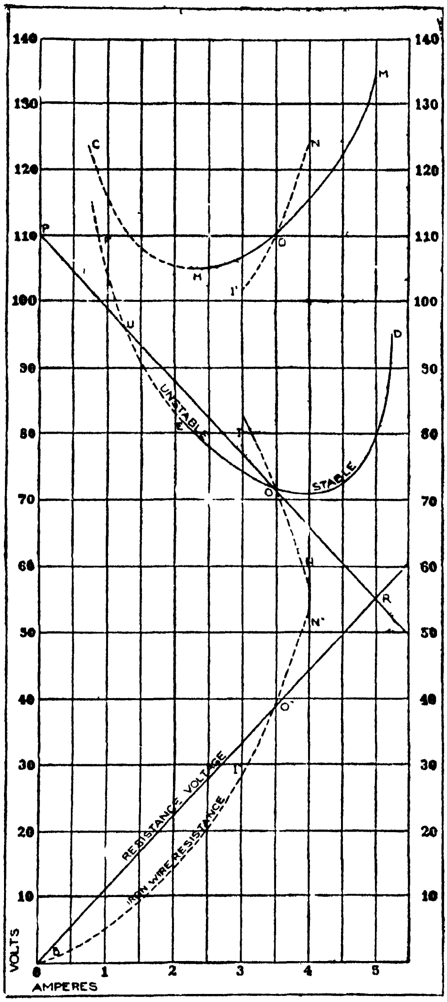


FIG. 2.14A.– Characteristics of Mercury Vapour Arcs.

Of importance are the purity of the substances used in the manufacture, and the vacuum. Contamination during glass-blowing might considerably affect the constancy of the light-giving quality. On the whole, one may reckon a decrease in the luminosity of 1 per cent. with every 100 burning hours. The evacuation of the tube is as follows : The tube, containing about twice the final amount of mercury, is hung vertically in an upright hot-air oven and connected by a tube at the upper end near the anode through a mercury trap to an ordinary vacuum. As the tube heats up to the boiling-point of mercury the relatively heavy mercury vapour rises in it, displacing the remaining traces of foreign gases and water vapour. The temperature is brought as near the melting-point of glass as possible, and kept there until the process has resulted in the necessary distillation from the tube of a measured amount of mercury. The bulb is then sealed off at the tube. To free the metal electrodes from occluded gases they are heated to a white-hot temperature by operating the lamp on an alternating current at some 4000 to 6000 volts during the pumping process. The heat of the cathode hot spot is highly localised, so that the arc column temperature varies from some 500 degrees C. in the centre to about 125 degrees C. at the surface of the tube.

2.24. QUARTZ-MERCURY VAPOUR LAMP.—Fig. 2.15 illustrates the characteristic of a mercury lamp which is worked normally near the

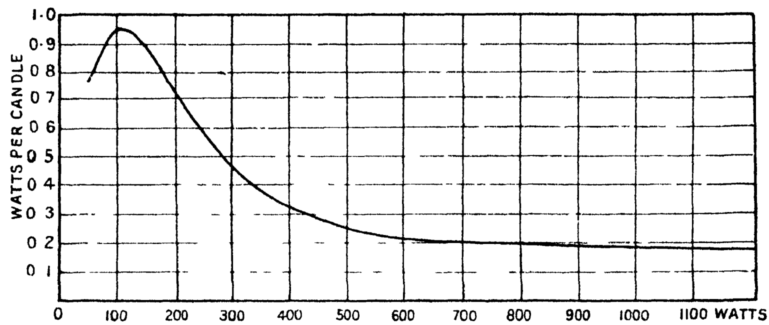
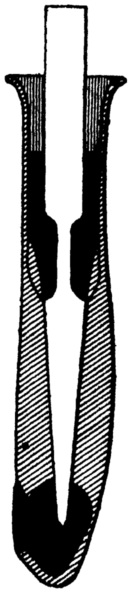


Fig. 2.15.—Specific Consumption of a Quartz Vapour Lamp.

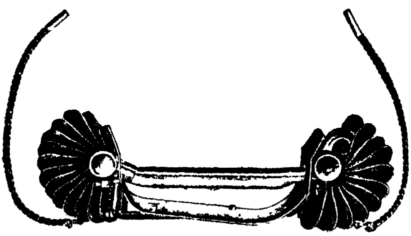
800-watt ordinate. The cooler this lamp, the greater is the specific consumption, until a maximum is reached near 100 watts. From there the specific consumption decreases again and reaches soon another minimum (not shown), about twice as great as given at 800 watts. At that point the glass mercury lamp is worked, the temperature being such as glass will withstand.

By restricting the cooling and using a sufficiently high P.D., the temperature and candle-power beyond the 100-watt ordinate increase rapidly, and glass is no longer suitable. Quartz is then used, as it withstands extremely high temperatures, but this introduces various difficulties, the chief one lying in the method of conducting the current to the electrodes, which in the Heraeus type of lamp consist both of mercury. The expansion coefficient of platinum is about twenty times that of quartz, so that the quartz tube would soon break due to the expansion of the platinum leading-in wires. The difficulty was solved by the use of a nickel-steel alloy called "invar," which has an expansion coefficient approaching that of quartz. The alloy must, however, not be brought to a red heat, as it then loses its property, and it cannot therefore be sealed in in the ordinary way. The method employed consists in grinding in a tapered rod of invar into a conical quartz tube and thus forming a mechanical seal, which is protected by a mercury cup closed with cement. This is shown in fig. 2.16, *a*.

As the fall of potential at the anode is greater than at the cathode, the former will get hotter, and mercury would be deposited on the latter until the anode had disappeared. This is prevented by a conical construction at the negative electrode, the apex of which is towards the luminous tube. If mercury collects at the cathode, the level rises in the cone, the arc is formed over a smaller surface, the temperature rises and the vaporisation increases, thus preventing the accumulation of



a



b

FIG. 2.16.—Burner and Leading-in Conductor for Quartz-Mercury Vapour Lamp.

mercury. The reverse action takes place if the level falls. The construction is illustrated in fig. 2.17.*

As the heat produced is great and the vapour pressure increases with the temperature, equilibrium must be obtained before an excessive temperature is reached. This is accomplished by supplying the terminals with radiators, as illustrated in fig. 2.16, *b*, or by fitting the burner with a chamber in which the mercury vapour condenses and falls back into the electrode in liquid form.

If the lamp is employed for outdoor work the radiator is made smaller, as the cooling is more effective.

The connections of a 220-volt 3·5-ampere Heraeus (Küch) lamp are given in fig. 2.18, and the characteristics of the lamp in 2.19.† At the

* *Illuminating Engineer*, 1912, p. 469.

† *Zeitschrift des Vereins Deutscher Ingenieure*, December 1913, p. 1983.

instant of switching in, the lamp is cold and the pressure low, the voltage at the burner being only about 30. Gradually the arc temperature rises,

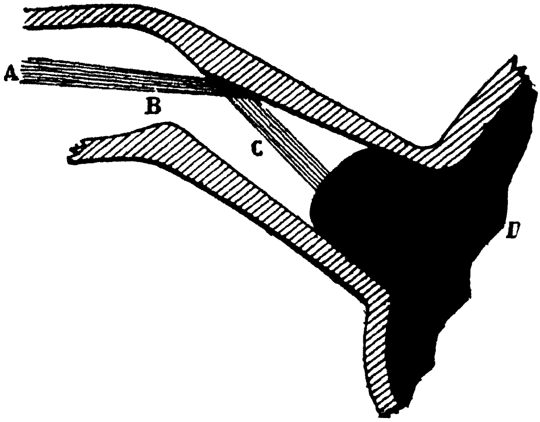


FIG. 2.17.—Maintaining Constant Levels of Electrodes in a Quartz-Mercury Vapour Lamp.

more mercury is vaporised, and the pressure and the P.D. of the burner increase. The steadying resistance in series with the arc must thus be high at first and decrease with a decrease in the current. Such a resistance is obtained with iron wire worked near red heat in hydrogen (similar to those used for the Nernst lamp) and marked *h* in fig. 2.18. *m* is a permanent ballast resistance which may be varied to suit the supply pressure.

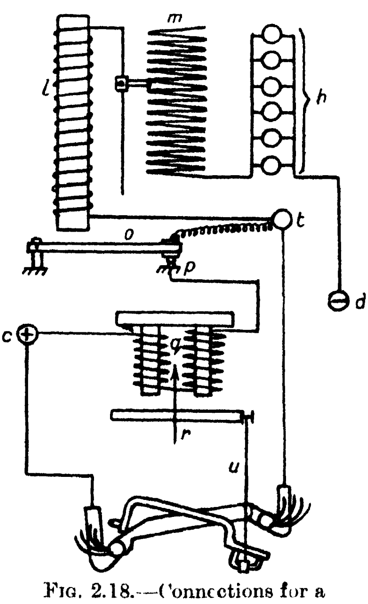


FIG. 2.18.—Connections for a Quartz D.C. Lamp.

On switching in, the electro-magnet, *q*, is energised, whereby the quartz tube is tilted so that a mercury thread brings the two electrodes into contact. This causes a large rush of current which passes through the magnet, *l*, causing the circuit of the tilting magnet to be interrupted at *p*, so that the tube tilts back. The mercury is interrupted in the tube, and the arc is struck.

At the instant of striking the arc there is only a low pressure in the tube, and hence the voltage is low. Most of the P.D. must thus be absorbed by the iron resistance. But as more and more mercury vaporises, the pressure and P.D. of the tube increase while the P.D. of the iron resistance decreases, and the current drops. Equilibrium and full light is obtained after about twelve minutes. Fig. 2.19 holds for a 3·5-ampere 220-volt lamp. It will be seen that at first the iron resistance has a value of about 12 ohms, and after fifteen minutes of only 4 ohms.

The values given in fig. 2.15 represent the specific consumption in watts per mean vertical candle (tube horizontal). The loss in the ballast resistance and in diffusing globes bring the efficiency down; a lamp in the author's laboratory, with an opal globe, showed an efficiency of 0·50 watt per mean spherical candle. On account of the passage of ultra-

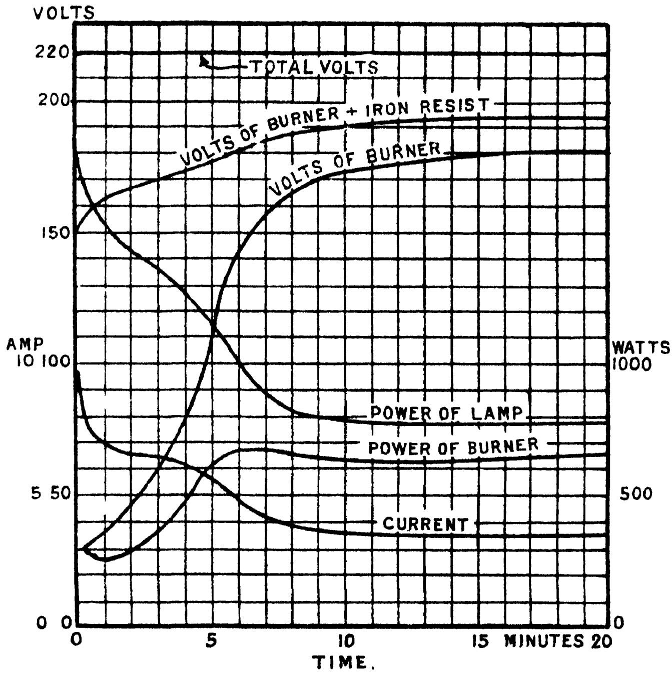


FIG. 2.19.—Characteristics of a Quartz D.C. Lamp.

violet rays through quartz, the lamp must not be lit without a glass globe.

Although the mercury arc is a direct current phenomena, a lamp for alternating current may be produced if care is taken that the arc is not interrupted. This is easily possible with a three-phase current by the employment of three anodes, joined to the three phases, while the cathode forms the neutral point. It is also possible with single-phase current by supplying the lamp with two anodes, which are joined to the ends of a transformer winding, while the cathode is connected to the middle. The connections for such a lamp are shown in fig. 2.20.* Between cathode and the middle of the transformer flows (after lighting) a pulsating direct current, whereas the anodes are alternately plus and minus and allow current to enter the burner only as long as they are

* *Elektrotechnische Zeitschrift*, 1912, p. 676.

positive The two anodes therefore exchange places continuously If the tube is ordinarily made for 180 volts (see fig 2 19) the pressure at the terminals of the secondary must show 360 volts It will be obvious that the lamp may not light in the first instance, and may have to be tilted several times No lighting occurs if at the instant, when the mercury thread is interrupted, the mercury of the cathode is plus or the current passes through zero The construction of the lamp is such that the tilting recurs until the lamp remains alight

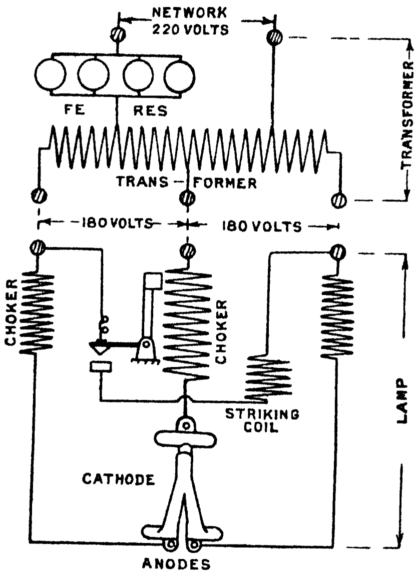


Fig 2 20 — Connections for an Alternate Current Mercury Vapour Lamp

To prevent a short circuit between the electrodes and the consequent extinguishing of the lamp, a separating wall of 6 millimetres height is placed at the bottom of the quartz tube from the cathode terminal to the place where the two anodes branch off When the tube tilts back, the mercury is thus divided into two parts

As the anodes are only half as fully loaded as the cathode, it follows from the curve of fig 2 15 that the efficiency must be somewhat less than that of the direct current lamp The alternating current lamp requires, however, less ballast resistance, and the specific consumption is practically the same as for the direct current lamp

A burner for an alternating current lamp, as manufactured by the

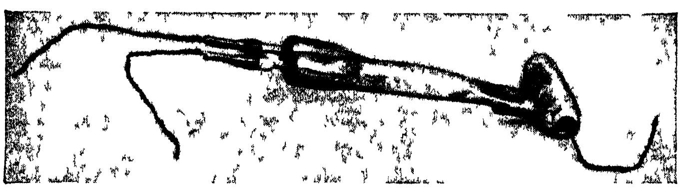


Fig 2 21 - Burner of an A C Mercury Lamp

General Electric Co , is illustrated in fig 2 21 * The anodes consist, however, no longer of mercury, but of tungsten The difficulty of tight joints with these anodes, which form at the same time the leading-in wires, has been overcome by the use of graded glass seals having gradually decreasing expansion coefficients Tungsten can be used for anodes

* *General Electric Review*, March 1914.

because it has high melting- and evaporation-points. The cathode consists of mercury, but as no balancing of the vaporisation of mercury of the two electrodes is needed, since no mercury is evolved at the anode, the conical shape of the cathode may be dispensed with, thereby still further reducing the vapour pressure. This means that for the same current a smaller mercury reservoir may be used, and no radiators are necessary unless the current exceeds more than 4 amperes. As the mercury reservoir is smaller than in the Heraeus lamp, the time taken to reach maximum brightness is less.

The cathode mercury reservoir is either horizontal (tube vertical) or vertical (tube horizontal). The graded seal with the tungsten leading-in wire is in the form of a drop seal on the cathode. The arc tube is shaped in the form of a sloping roof near the cathode, mainly for the purpose of steadying the arc.

The lamp is started by tilting the tube by means of a shunt magnet, or a series coil.

The lamp with solid anodes has the advantage that it may be burned in any position, a thing impossible with the Heraeus lamp, and no special separating walls are needed in alternating-current lamps in order to prevent short circuiting of the anodes.

The pressure inside the quartz tube should not exceed 1 atmosphere, to prevent mercury vapour, which is poisonous, from leaking out. The light of the quartz lamp is much whiter than that of the glass lamp, but still largely deficient in red rays. This disadvantage may be overcome by replacing the steadying resistance by a tungsten lamp. The mercury tube is then in the form of a ring, with the tungsten lamp in the centre. Another method consists of using a fluorescent reflector. Rhodamine and similar dyes fluoresce pink in the light of the mercury vapour lamp, converting some of the blue and green light into yellow or red.

A patent was granted to the late Dr C. P. Steinmetz for a method dealing with the introduction of red rays in mercury vapour lamps. If metals are included in the mercury for giving red rays they collect on one pole, and a pure mercury spectrum replaces the mixed one. Moreover, if sodium, potassium, lithium, rubidium, or thallium be added, the glass tube is attacked and gradually becomes black. This may be obviated by the use of an iodide or other salt of these metals. Well adapted is lithic meta-silicate, which causes a transparent deposit. The vessel is evacuated, and a little hydrogen let in. The substances to produce the red rays are given an excess of pure iodine or mercury iodide.

2.25. CADMIUM LAMP.*—According to Dr Wolke, pure cadmium with 3 to 10 per cent. of mercury, depending on the size of the lamp, may be employed in place of pure mercury to obtain a light containing the missing rays in the spectrum of a mercury lamp. Cadmium forms a deposit on the quartz tube, in the cold state, which disappears as soon as

* *Elektrotechnische Zeitschrift*, 1912, p. 917.

the tube heats up. The light is said to be similar to that of an arc lamp, and has an efficiency comparable with that of a quartz-mercury lamp. As the electrodes are solid, the starting of the lamp presents difficulties. One method consists in utilising the deposit formed on the cold tube. This metallic layer enables the lamp to conduct before the metal is vaporised, and the resultant ionisation leads to the complete starting up of the lamp. Experiments were also carried out with a graphite anode, the starting being caused by dipping the tube so that the anode slips down to the cathode, making contact, after which it slips back.

The writer is not aware how the lamp has developed further.

2.26. PROF. NERNST'S NEW LAMPS.—In one of these lamps an arc is formed between carbon electrodes in a mercury atmosphere, resulting in an efficiency similar to that of other mercury lamps. In another type salts are added, which fuse at the temperature of mercury vapour. This lamp is stated to yield 2700 candles (vertical) on 120 volts at 4 amperes, thus working at $\frac{480}{2700}=0{\cdot}178$ watt per candle.

2.27. INTERMITTENT OR DISRUPTIVE CONDUCTION.—In the Geissler tube the gas enclosed carries the current whereby it becomes luminous. Hence the spectrum depends on the nature of the gas, and has nothing to do with the electrodes, as long as these do not melt.

For intermittent conduction, it is necessary that a certain potential difference should be applied before any conduction takes place. We call this the "disruptive voltage."

2.28. MOORE TUBE.—The resistance of such a circuit is thus a variable quantity, being infinite for low voltages and low for voltages above the disruptive potential difference. This resistance, or rather impedance, varies with the temperature and pressure of the gas, so that for a constant terminal potential difference the current will vary inversely proportionally to it. This makes it necessary to provide mechanisms, which tend to keep the circuit in equilibrium. In the Moore tube lighting system, the efficiency is a maximum when the pressure of the gas enclosed is about 0·11 millimetre mercury. On the passage of the current through the gas (which is usually nitrogen) part of the latter is used up, whereby the impedance of the circuit is reduced, its value becoming a minimum when the pressure is about 0·08 millimetre. The flow of the current would then be a maximum. This increase in the vacuum is due to a solidification of the enclosed gas. A special valve must thus be supplied, which automatically feeds the tube with nitrogen when the pressure has dropped from 0·11 to 0·10 millimetre.

The system is illustrated in fig. 2.22.

The valve consists of a porous carbon plug, placed at the bottom of the glass tube (in communication with the main tube, into which dips a hollow glass plunger, which forces the mercury up to cover the plug and closes up the entrance to the vacuous tube). The inner glass tube carries a number of iron wires, and as the whole valve is surrounded by a solenoid in series with the primary of the transformer, which supplies the tube with current, it follows that the position of the plunger depends upon the load on the transformer. As the load increases, with a decrease in the vacuum, the plunger is drawn further into the solenoid, and as this causes the mercury to drop, part of the porous plug is exposed and gas or air can filter through the plug into the vacuous tube. Where nitrogen is the gas wanted, it is only necessary to place the valve in an air-tight box with a few holes, before which phosphorus is placed. The latter

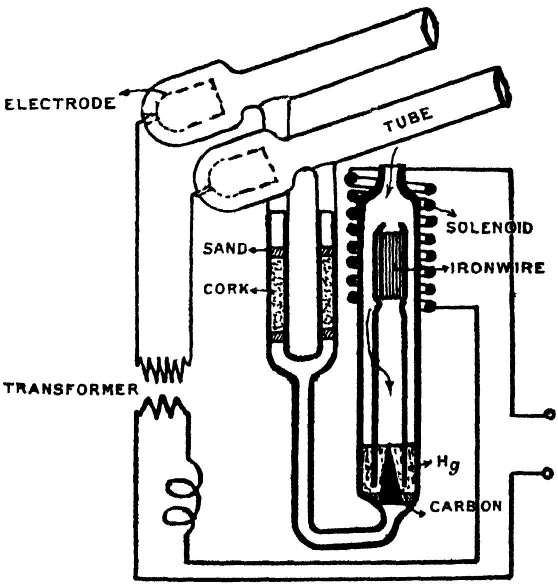


FIG. 2.22.—Moore's Tube Lighting.

absorbs the oxygen of the air, and an unlimited supply of nitrogen becomes available. The colour of the light depends on the gas enclosed; it is a golden colour for pure nitrogen, orange-pink for ordinary air, and a white when fed with carbon dioxide. For colour discrimination the latter is thus the most suitable, as it approaches the colour of daylight very closely. With a variation of the pressure of the enclosed gas not only does the rate of the flow of the current change, but also the visible part of the radiation, as one would naturally expect; hence the flow of current must be so regulated that the visible radiation becomes a maximum. Also, the potential difference depends on the gas pressure, to which it is approximately proportional.

Temperature has also some influence on the disruptive voltage, lowering the same when it is high.

The P.D. required for a Moore tube is approximately represented by the following table :—

TABLE 2.10.—P.D.'S REQUIRED FOR MOORE TUBE LIGHTING SYSTEMS.

Length in metres . .	7 5	15	22·5	30	45	60
R.M.S. volts . .	2100	4000	5500	7000	9500	12,000

The light of the Moore tube is well diffused on account of the great length of tube, especially as the diameter is also considerable, being about 4·5 centimetres. It flickers, however, in unison with the feeding alternating current, unless the frequency is higher than 50 cycles per second.

The consumption is about 2 watts per candle; the system is therefore less economical than lighting with tungsten lamps.

Voltage variations have little influence on the candle-power, since the latter is practically directly proportional to the voltage, whereas the candle-power of even a tungsten lamp varies as the fourth power of the supply pressure.

When moving objects are to be illuminated, a three-phase arrangement is superior to a single-phase one, as this obliterates any tendency to stroboscopic images caused by cyclic variations in the light. We then employ three tubes, with three or six electrodes. In the former case the three electrodes at the beginnings of the tubes are connected to the secondary of the three-phase star connected transformer, while the ends of the tubes are joined together; in the latter case the three tubes are quite separate, the electrodes at the beginnings being joined to the secondary of a three-phase transformer, the neutral point of which is connected to earth, while the electrodes at the ends of the tubes are also earthed. The earth thus carries current if one tube is disconnected.

As the Moore tube with nitrogen or carbon dioxide has a low efficiency, it is not generally employed, but for colour matching it is probably the best light, since a tube with carbon dioxide gives a light equal to that produced by daylight in a room having its windows facing the north. It is thus excellent for dye-works, photographic and painters' studios, drapers' shops, in fact everywhere where colour matching is of importance (see fig. 6.50).

2.29. THE NEON TUBE.—If the Moore tube is filled with neon gas in place of nitrogen or carbon dioxide, the efficiency of light production is considerably improved. According to M. Claude, such a tube uses only about 0·6 watt per maximum candle.* Neon is one of the rare gases of the atmosphere; but, nevertheless, it can be extracted with comparative ease. It is obtained as a bye-product in M. Claude's process for liquefying air, and producing from it pure nitrogen and oxygen. The separation is easily effected at hardly any increase in the cost of the main process. It is claimed that the tube requires no automatic valve of any kind, as the gas is only very slightly absorbed. If the electrodes are

* *Soc. Int. des Electriciens, Bull.*, November 1911, p. 505; *Illuminating Engineer*, October 1914, p. 478.

made sufficiently large the tube should have the life of an incandescent lamp without a refill.

Difficulties were at first encountered, of which one was the vivid red colour. This was overcome by the use of correcting tubes containing mercury, the mixed light of mercury and neon being approximately white.

Another difficulty was the fact that the slightest traces of foreign vapours given off by the electrodes destroyed the luminous power of the gas. According to the discovery of Dewar, at low temperatures carbon acts towards gases as a strong absorbent. With gas at low boiling-point the absorbing power is less. Hence it was found that, if the neon of a neon tube had to be purified, all that was necessary was to join the tube to the vessel containing carbon and immerse the vessel in liquid air. The impurities given off by the electrodes were gradually absorbed, while the neon was left behind.

Various installations of this type have been carried out for festival occasions, sign lighting, etc.

During the last two years neon discharge lamps of low wattage (about 5) have been put on the market. The lamp looks externally like an ordinary small incandescent lamp. The negative electrode in one particular type of lamp is a saucer-shaped, thin nickel cap about 1¼ inch in diameter and ⅜ inch high, while the positive electrode is similar but of about ⅞ inch diameter and height, fixed below the cathode. The light is given by the negative orange glow, which makes an excellent night light. The pressure of the neon gas is less than 1 millimetre mercury. At this pressure the gas is easily ionised and thus becomes conducting.

It is interesting to remark that a 5-watt lamp is in most cases unable to start the electricity meter.

2.30. CHARACTERISTICS OF ARCS.—An equation connecting

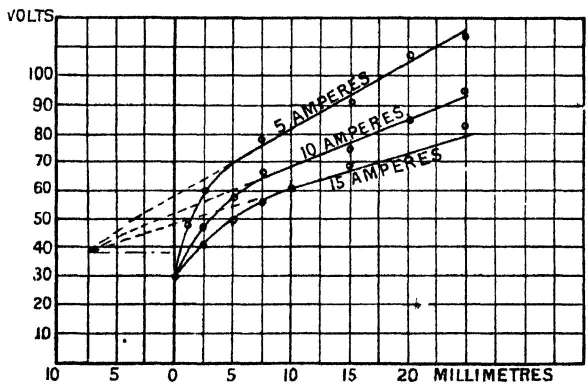


FIG. 2.23.—P.D.'s for Different Lengths of an Enclosed Arc (Current Constant).

length of arc, current, and P.D. required may be obtained by plotting two sets of curves. In the first set we keep the current constant and plot the volts as a function of the length of arc. The resulting curves are approximately straight lines, according to fig. 2.23, which holds for ordinary enclosed arc lamps. These lines intersect in a point for which $V_0=38$ volts and $l_0=-7{\cdot}5$ millimetres. This voltage is constant for all lengths of arc and for all currents. It represents the fall of potential from the negative carbon to the arc, and may be considered of the nature of a back E.M.F. The additional voltage is required for the vapour stream; it is directly proportional to the length of the latter. Expressing the curves by equations, we find

$$V=V_0+c_1(l+l_0) \quad . \quad . \quad . \quad . \quad 2.18$$

in which l=length of arc, l_0=additional length and is equal to 7·5 millimetres in the example of fig. 2.23, and c_1 is a constant.

In the second set of curves we plot for constant lengths of arc the P.D.'s

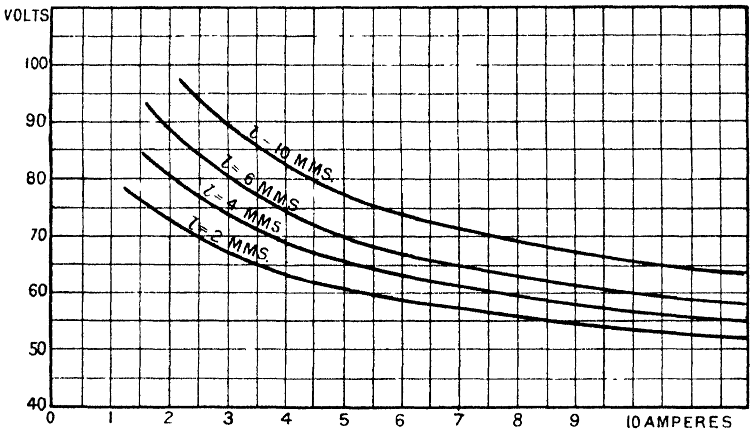


FIG. 2.24. P.D.'s for the Different Currents of an Enclosed Arc (Length of Arc Constant).

as functions of the currents and obtain curves having approximately the shape of cubic hyperbolas (see fig. 2.24), with the equations $(V-V_0)^2I_c=c_2^2$, in which I_c is the current and c_2 a constant. The actual voltage required is then

$$V=V_0+\frac{c_1}{2}(l+l_0)+\frac{c_2}{2\sqrt{I_c}},$$

which is very nearly equal to

$$V=V_0+c\frac{l+l_0}{\sqrt{I_c}}\,* \quad . \quad . \quad . \quad . \quad 2.19$$

This equation may be also found if we consider the physical conditions of the arc.

We have seen that the flow of the luminous arc is from the cathode, and that the nature of the arc depends on the material of this cathode. To cause this flow at all, a definite voltage V_0 must be applied. It is constant whatever the strength of the current and the length of the arc may be. When the current increases, so does the flow; hence the

* Steinmetz, *Proc. Amer. I.E.S.*, 1906.

resistance through which the current passes decreases, keeping the fall of potential from the negative carbon to the arc constant. The power wasted thereby is therefore equal to $P_1 = V_0 I_c$, where I_c is the current.

As regards the arc proper, we may assume that its temperature is approximately constant, so that the power absorbed by it is proportional to the surface of the arc, *i.e.* to $l_1 d$, in which $l_1 = l + l_0$ = length of arc plus the length l_0. The latter accounts for the heat carried off by the ends of the electrodes. As the diameter of the arc d is equal to $\sqrt{\frac{4S}{\pi}}$, *i.e.* proportional to the square root of the cross-section S of the vapour column, and as S is proportional to the current by which the vapour is produced, it follows that d is proportional to $\sqrt{I_c}$. We have therefore:

$$\text{Power absorbed by the arc proper} = P_2 = c_2 l_1 d$$
$$= c_2(l + l_0)d$$
$$= c_2 c_3 (l + l_0)\sqrt{I_c}$$
$$= c(l + l_0)\sqrt{I_c},$$

and the total power $= P = P_1 + P_2 = VI_c = V_0 I_c + c(l + l_0)\sqrt{I_c}$,

whence
$$V = V_0 + c\frac{l + l_0}{\sqrt{I_c}}.\text{*}$$

It will be noticed in fig. 2.23 that, if we reduce the length of the arc below 7 millimetres, the lines bend downwards, intersecting approximately at 30 volts in the ordinate axis. This does not occur with the mercury vapour and the magnetite lamps. In both these cases consumption of the positive pole does not take place, hence it would appear that the disturbing factor lies at the positive electrode of the ordinary arc lamp. It is feasible to assume that the constant voltage $V_0 = 38$ volts is not totally absorbed at the negative carbon, but only to the extent of 30 volts, and that the difference of 8 volts is necessary to overcome the layer of mist near the positive carbon caused by the evaporation of this electrode.

The constants in equation 2.19 vary with the nature of the arc. Approximate values are given in the accompanying table.

TABLE 2.11.—CONSTANTS FOR ARC LAMPS.

	Ordinary Carbon Arc.	Enclosed Carbon Arc.	Flame Arc.†	Magnetite Arc.	Vapour Arc.
V_0	$8_+ + 28_- = 36$	$8_+ + 30_- = 38$	12	31	$5{\cdot}7_+ + 5{\cdot}3_- = 11$
l_0	6 mms. (0·24 in.)	7·5 (0·3)	5 (0·2)	2 (0·08)	
c	5 (127)	5 (127)	4·9 (124·5)	4·8 (122)	

* The equation given by Mrs Ayrton of the P.D. for the electric arc in her well-known treatise on the electric arc is

$$V = V_0 + cl + \frac{c_1 + c_2 l}{I_c},$$

in which V_0, c, c_1, and c_2 are constants.

† The constants for this type of lamp vary considerably.

2.31. STEADINESS OF THE ARC.—From equation 2.19 it follows that an arc lamp cannot be worked on a voltage which is just sufficient for the current for which the lamp is built. As the electrodes are consumed, the length of the arc increases, hence for a constant P.D. at the terminals the current ought to increase (since V_0 is constant), keeping the second member of the equation constant. As, however, the resistance of the arc increases with its length, it follows that the current must decrease, *i.e.* the second member increases so that, as V is constant, this increase takes place at the expense of V_0, and the voltage is therefore insufficient for maintaining the arc stream, and thus the lamp is extinguished. On the other hand, a slight increase in the current reduces the fall of P.D. across the arc proper, so that a decrease in the resistance takes place on

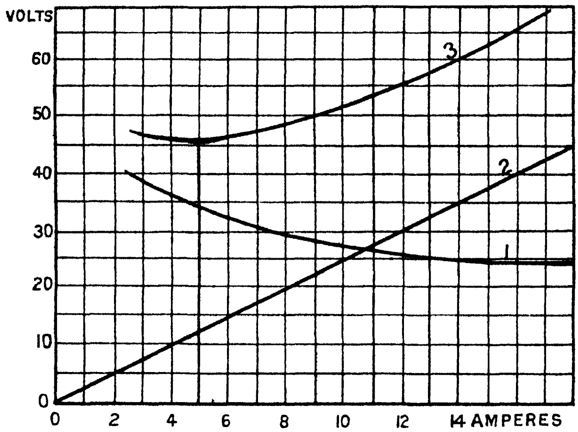


FIG. 2.25.—Flame Arc Lamp and Steadying Resistance.

account of increased production of vapour, thereby augmenting the rise in the current, which goes on until the lamp short-circuits. We require, therefore, ballast or steadying resistances which prevent these variations. Moreover, without steadying resistances arc lamp mechanisms would not work. On constant potential the current of the shunt coil would also be constant and the coil thus useless.

Consider a 10-ampere flame arc lamp (of which two are usually joined in series to a 100-volt circuit). For a 5-millimetre arc the lamp itself requires 27·5 volts (see curve 1 of fig. 2.25). If we join in series with it a resistance of 2·5 ohms, then the voltage absorbed by the latter will be represented by the straight line in fig. 2.25. By adding curves 1 and 2 we obtain curve 3. We see that below 5 amperes the voltage actually increases with a decrease of current, hence this part of curve 3 represents the unstable condition of the lamp. Where the curve is flat, small variations in the voltage cause comparatively large current fluctuations, and it is evident that the lamp should not be worked below 8 amperes. The fluctuations could be somewhat checked by winding the steadying resistance on an iron core; the inductive effect then opposes rapid variations of the current.

The steadying resistance has the disadvantage that it absorbs power. To reduce this waste, we join as many lamps in series as possible, say three flame lamps on a circuit of 110 volts. The lamps then absorb $3 \times 27{\cdot}5 = 82{\cdot}5$ volts, so that 27·5 volts are left for the resistance. With 10 amperes this means a ballast resistance of 2·75 ohms. The conditions are represented in fig. 2.26. The total voltage curve has now become extremely flat, and the stability limit has been shifted from 5 to 8·5 amperes. The mechanism of such lamps should be extremely sensitive,

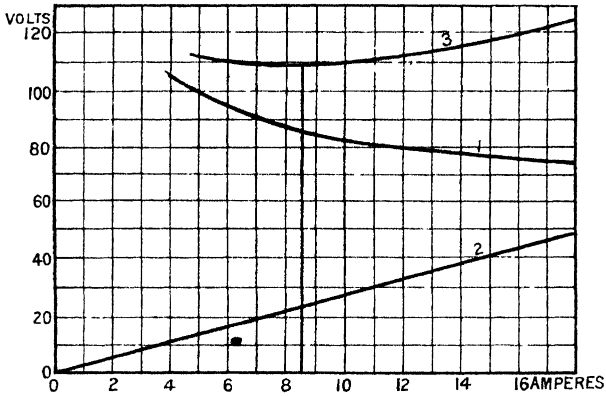


FIG. 2.26.—Three-Flame Arcs in Series on 110 Volts.

i.e. the lamps should feed for very slight variations in the current or voltage.

The minimum voltage required to reach the stability limit is equal to the total voltage required by the lamp plus half its variable part, *i.e.*

$$V_{min.} = V + \tfrac{1}{2}c\frac{l + l_0}{\sqrt{I_c}} \quad . \quad . \quad . \quad . \quad 2.20$$

Thus in fig. 2.25 we have

$$V = 33 = V_0 + c\frac{l + l_0}{\sqrt{I_c}} = 12 + 21 \text{ (for 5 amperes),}$$

and

$$V_{min.} = 33 + \tfrac{1}{2} \times 21 = 43{\cdot}5 \text{ volts.}$$

In fig. 2.26

$$V = 3 \times 12 + 3 \times 16 = 84 \text{ (for 8·5 amperes),}$$

and

$$V_{min.} = 84 + \tfrac{1}{2} \times 3 \times 16 = 108 \text{ volts.}$$

The lamps should therefore feed when the voltage variation is less than 2 volts, or $\frac{2}{3}$ of a volt per lamp. A better result would be obtained with 12-ampere lamps. In this case the minimum voltage would be $3 \times 12 + 3 \times 14 + \frac{1}{2} \times 3 \times 14 = 99$ volts, leaving a considerable margin.

It should be noted that the above deductions hold for an arc of 5 millimetres length. To change a lamp from 10 to 12 amperes would necessitate alterations in the mechanism of the lamp, especially if the same be supplied with a series solenoid. Also the carbons would have to be enlarged, as otherwise hissing might occur.

Formula 2.20 may be proved as follows: The slope of curve 3 is nil for 5·5 amperes. It is the resultant of the slopes of curves 1 and 2, which are equal and opposite for this point. We have

$$\frac{dV_{min.}}{dI_c}=\frac{dV}{dI_c}+\frac{dV_R}{dI_c}=0.$$

But
$$\frac{dV}{dI_c}=-\tfrac{1}{2}c\frac{l+l_0}{I_c^{\frac{3}{2}}}\ \text{(see equation 2.19)},$$

and
$$\frac{dV_R}{dI_c}=R=\text{resistance of steadier},$$

hence
$$R=\tfrac{1}{2}c\frac{l+l_0}{I_c^{\frac{3}{2}}}.$$

The total voltage required for the stability minimum is therefore

$$V_{min.}=V+I_cR=V+\tfrac{1}{2}c\frac{l+l_0}{\sqrt{I_c}}.$$

2.32. VARIATIONS OF THE CONSTANTS V_0, c, AND l_0 WITH THE PRESSURE.—The values of V_0, c, and l_0, as given in Table 2.11, are correct for atmospheric pressure. When this pressure is altered, the values of V_0, c, and l_0 are generally no longer constant. This is illus-

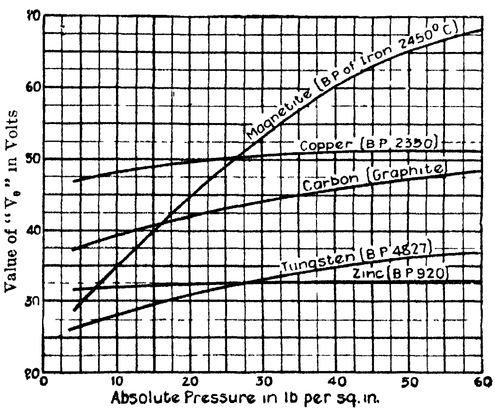


FIG. 2.27.—Variation of V_0 with Pressure.

trated for various materials in figs. 2.27, 2.28, and 2.29.* With these curves it will be easy to find for any given length of arc and current the voltage as function of the air pressure. For instance, for $l=2{\cdot}0$ centimetres, $I_c=4$ amperes, we have:

Pressure	5	10	20	30	40	50	60 lbs./inch.^{2}
Volts	96·5	96·5	99	104	110·5	117	124·5

(The values of c and l_0 (in the figures) are for centimetre units.)

* W. N. Eddy, *General Electric Review*, March 1922, p. 188.

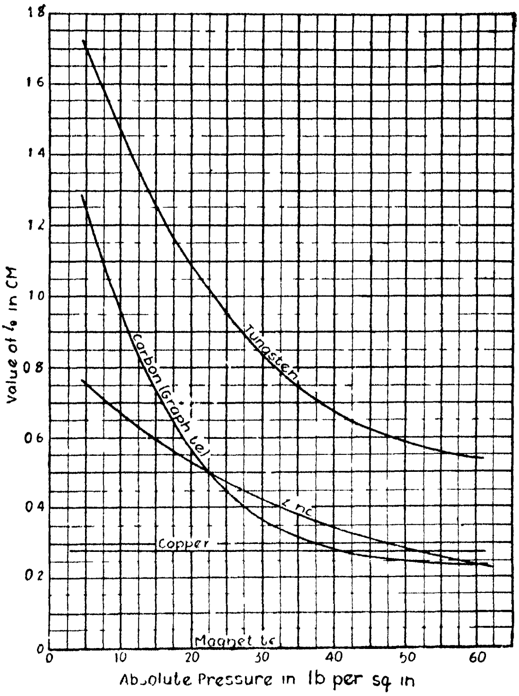


Fig 2 28 – Variation of l_0 with Pressure

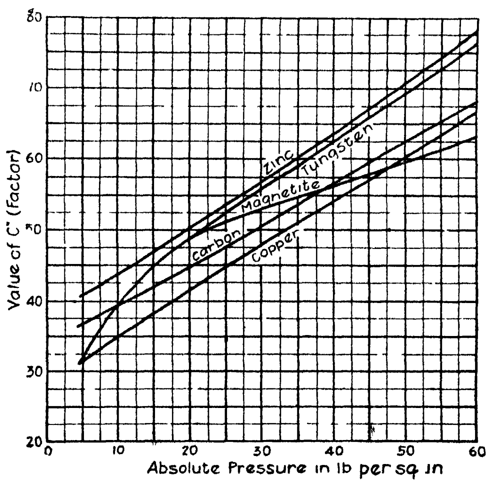


Fig 2 29 —Variation of c with Pressure

CHAPTER III.

THE EYE AND ILLUMINATION.*

3.01. CONSTRUCTION OF THE EYE. The eye consists essentially of six parts, as illustrated in *fig.* 3.01, viz.: (*a*) the cornea, shaped somewhat like a watch crystal, with a refractive index 1·37, (*b*) the anterior chamber, containing the aqueous humour, having a refractive index 1·34; (*c*) the iris, with the pupil capable of expanding and contracting in order to regulate the quantity of light entering the eye, a quality termed *adaptation*; (*d*) the crystalline lens, with a refractive index 1·437, an elastic transparent body controlled by a muscular ring, the ciliary muscles, by means of which the curvature of the lens is altered in order to bring the objects looked at into focus, a quality called *accommodation*; (*e*) the cavity, with the vitreous humour, having a refractive index 1·34; and (*f*) the retina, possessing great adaptation to various conditions. The whole construction of the eye thus resembles a modern camera. The phenomena which occur between the incidence of light on the cornea and the mental appreciation of the fact may be divided into three stages:

(1) The production of an image on the retina by means of the dioptric system of the eye enumerated above. This differs from the production of an image in the camera in that the actions of the adaptation of the iris and retina and of the accommodation of the crystalline lens are almost involuntary.

(2) When the light focussed on the retina reaches a layer of the latter, called rods and cones, it produces some photochemical or other change which acts upon the terminations of the optic nerve fibres and sends along these a series of disturbances called nerve impulses.

(3) In the brain these impulses are distributed to a complex system of centres composed of nerve cells, where processes occur associated with the conscious perception of light and lighted objects.

It seems to be generally agreed that the light-perceiving organs of the retina are the rods and cones. This is proved by the fact that the

* See also Dr J. Kerr, "The Effect on the Eye of Various Degrees of Brightness and Contrast," *Illuminating Engineer*, February 1917, p. 41; and Professor W. M. Bayliss, F.R.S., "Light and Vision," *Illuminating Engineer*, April 1918, p. 104.

spot of the retina which has no rods and cones, at the point of entrance of the optic nerve, is the blind spot. The rods and cones stand endwise on to the light, and consist of an inner swollen half and an outer thin transversely striated part, the extreme end of which abuts on a pigment layer. The latter prevents irregular dispersion and reflection, and acts as the chief agent in the light adaptation of the retina. From this layer fine prolongations of the pigment-containing cells reach up between the rods. When the eye has been rested in the dark, the pigment granules in the cells form a thin, dense black layer, just touching the outer end of the rods. If, however, the eye has been exposed to light so that the retina is adapted for it, the prolongations of the cells running up

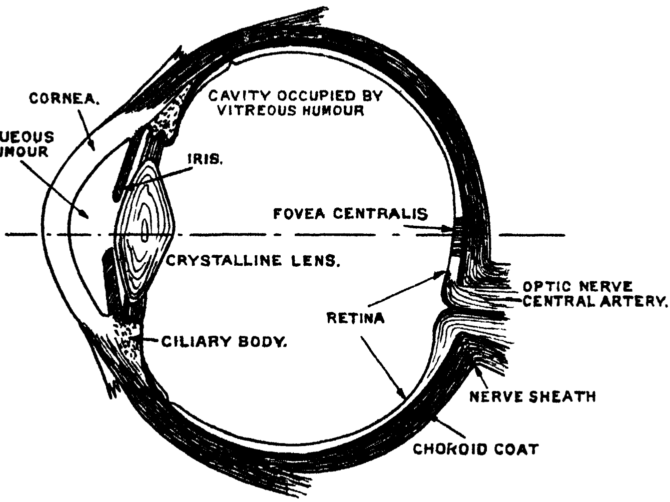


FIG. 3.01.—The Construction of the Eye.

between the rods are filled with the black pigment granules, which absorb light and probably help to replenish a photosensitive material called "visual purple."

The most sensitive part of the retina, the yellow spot, or "macula lutea," contains only cones, and its centre, with only big cones, is known as the "fovea centralis." (The yellow spot is somewhat less sensitive to green than to yellow light, whence the name.) In order to see an object well, we should therefore focus the image on the yellow spot, *i.e.* look straight at it, as it is practically in the centre of the retina. This part is the real eye which is used for exact knowledge, the rest of the retina giving indications or hints to orient the exact sensations at the macula. For this reason the other parts of the retina are sensitive to movements or to the merest flicker, but not to the form.

If one sees an object it means, of course, that the ether within the imaginary cone formed between the eye and the object looked at is in transverse vibration.

It is also the macula vision which is of greatest importance, and which reacts to fatigue and poison. For instance, with excessive tobacco-smoking the reds and greens disappear in the exact spot looked at.

The eye is most sensitive after it has been rested for a time in the dark. It is stated that such a rested eye is a million times more sensitive than in broad daylight. The centring of the eyes on the object looked at is accomplished so automatically that the image falls on the macula. In reading print held at a foot distance, and without moving the eye from a given fixation point, say the dot of an *i*, the number of letters clearly seen simultaneously is determined. In any exact vision the eyes are constantly being centred on little spots like this, and the rest of the retina merely gives orientation. This centring of the eyes means muscular adjustments and is termed "convergence."

In reading the eyes pass along a line in a series of little jumps, fixing a series of such spots in succession, not necessarily in contact, but sufficient to give hints of words for the brain, and if the light is poor, or the image confused, or the text strange, greater exactness of fixation is required, which is the beginning of strain.

3.02. QUANTITY OF LIGHT REQUIRED.—Of importance is the amount of light required. According to a number of investigators, such

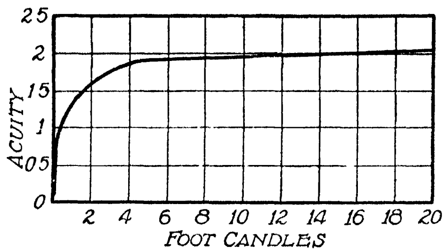


FIG. 3.02.—Visual Perception as Affected by Illumination.

as Uthoff, Laporte, and Broca, an illumination of 3 to 10 foot-candles is generally sufficient, and it is useless to increase the illumination beyond this, as it would simply mean waste of light. The eye may be considered saturated, and a further increase in illumination does not increase the acuteness of vision. Fechner has already pointed out that the relationship between the stimulus (illumination) and the sensation is given by a logarithmic curve, so that an increase in the illumination from 10 to 100 foot-candles increases the sensation from 1 to 2 only. This is known as *Fechner's Law.*

In fig. 3.02 the acuity or visual perception has been plotted as function of the illumination.* The curve practically confirms the previous remarks. On the other hand, the speed of perception is practically

* S. E. Doane, *General Electric Review*, February 1922, p. 98.

directly proportional to the illumination, as is proved by fig. 3.03.* People whose eyes are slightly astigmatic, or which have other slight errors in refraction, are benefited even more by increased illumination than workers with normal eyes. It will be obvious that this is of enormous importance as regards production, and that a low illumination in workrooms will not pay. For this reason modern factories employ very high illuminations where fine work has to be carried out.

A highly interesting article on the effects of brightness on the sensibility of contrast on vision appeared in the *Journal of the Franklin Institute*, No. 3, March 1917, by P. G. Nutting. The photometric sensibility, *i.e.* the brightness just noticeable in adjacent fields, rises

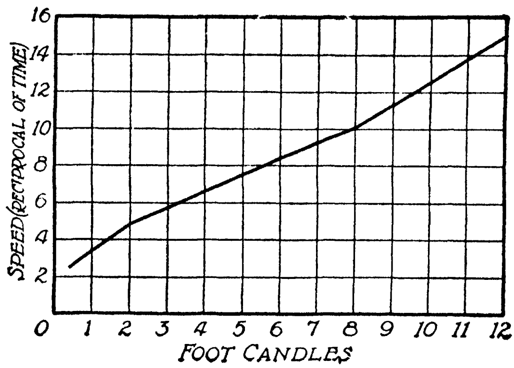


Fig. 3.03.—Speed of Perception as Affected by Illumination.

comparatively slowly from zero to about one-tenth metre-candle, then rapidly to about 100 metre-candles, beyond which point there is little gain if the brightness is increased to 1000 metre-candles. Exceeding this value, the sensibility actually decreases. From these figures one may judge that a higher illumination becomes necessary for fine work involving slight contrasts, while a relatively low illumination suffices for handling large objects, or in dealing with black and white.

We can also understand why, when black letters appear on dark paper, or when faded or coloured ink is used, the illumination needs to be increased, since the contrast is reduced, and contrast is essential for distinguishing fine details. The illumination must therefore vary for different industrial purposes (see also paragraphs 8.02 and 9.05).

Also vibrations, such as are experienced in a railway carriage, make an increase in the illumination essential.

In the author's opinion, the illumination required depends also upon the surroundings. In a room with dark walls and furniture the same comfort will not be obtained as in a room with light walls and furniture, even if the illumination is the same in both cases. The

* S. E. Doane, *General Electric Review*, February 1922, p. 98.

accompanying table shows results which give approximately the same comfort of reading ordinary text-book print in rooms of different colours.

TABLE 3.01.—MINIMUM AMOUNT OF LIGHT REQUIRED FOR ROOMS OF DIFFERENT COLOURS.

Colour of Room.	Illumination.	
	Metre-candles.	Foot-candles.
Black	35	3·28
Deep red	32	3·00
Dark green	30	2·80
Pale blue	28	2·62
Light yellow	25	2·34
Cream silvery	23	2·15
White	20	1·87
White (indirect light)	15	1·40

The divergency of the table may be explained as follows: In a dark room the eye feels the surrounding blackness instinctively, and the slightest roaming causes the eye to expand as it encounters the surrounding blackness, but looking at the brilliantly illuminated paper again, a strain is experienced, causing the eye to contract. This contraction makes the illumination now appear insufficient, and the eye has to expand again. This repeated expansion and contraction seems to make the higher illumination necessary. There is no doubt that the eye is affected more by contrast than by actual illumination.

The illuminations given in the above table may be considered minimum values for comfort. Where fine details have to be recognised the illumination should be considerably greater. Ability to see depends upon the perception of form, light and shade, and colour. Perception of form depends on the construction of the observer's optical system, *i.e.* on good focussing. The illumination must, of course, be sufficient. If the central part and the edges of the crystalline lens focus in different planes, we call this *spherical aberration*. The perception of light and shade varies with the individual. A normal person will notice the slightest change in tone. People who do not easily notice a change in tone have difficulties in finding their way about. The perception of colour also varies largely with the individual, and it depends upon the illumination too. In very poor light no colours are seen, only grey. In fading light the red disappears first, the greens and blues later.

The eye is, on the whole, a splendid organ for adapting itself to all sorts of conditions. These changes must, however, not be too abrupt, as then the iris, lens, and retina cannot adapt themselves to the changes, and a strain results. We must see that great successive contrasts are avoided. At the same time, too even an illumination appears monotonous. This would mean that we should install a general illumination for orientation and local light for the actual work. A good mixture consists of 40 per cent. of general and 60 per cent. of local lighting. The general illumination must certainly not be too low, as otherwise the eye, on roaming about, will experience excessive contrast and a strain. Worse still is simultaneous contrast, such as is given, for instance, by a bright metal filament bare lamp in front of a blackboard. Even with a low illumination *glare* will be experienced under such conditions.

3.03. GLARE.—An exact definition of glare is difficult to arrive at. Some people define it as the intrinsic brilliancy which, when it exceeds a certain value—a value which somewhat depends on the individual—causes dazzling and pain to the eyes. But this definition is not sufficient. If we look at the filament of an incandescent electric lamp with a rested eye in the evening we experience a dazzling sensation; if we look at it during the day, especially in the open, the glare is absent. As a matter of fact, a bright lamp in the sunshine is hardly noticeable. And yet the light is there all the same. Again, if we place a light in front of a white screen, even at night, little of a glare is experienced when looking at it, but when studied before a blackboard the glare appears strongly, as explained above. We see that contrast and illumination play important parts in what constitutes glare, which may be explained as follows: When looking at a lamp in front of a white screen, which makes the illumination appear high, or when studying the lamp in the road on a sunny day, the nerves of the eye are less sensitive, and as the pupil has contracted, the sensation is small; whereas in looking at a light in front of a blackboard the pupil extends to take in the dark background, and as the illumination is mostly small, the nerves of vision are rested and therefore more sensitive. Glare occurs thus chiefly when a rested or sensitive eye experiences simultaneously a high intrinsic brilliancy and sharp contrasts.

The remarks require, however, some discrimination. Nutting, in the above-mentioned paper, also gives curves for the so-called threshold sensibility, or the lowest perceptible brightness, and the glare sensibility, or the brightness which is just painfully bright. His curves show that as long as the intrinsic brightness does not exceed 10 metre-candles (about 1 foot-candle) glare occurs when the contrast ratio exceeds 1000 to 1. But when the brightness is raised to 10,000 metre-candles the ratio drops to 10 to 1. It would appear that if the brightness is further increased, the brightness itself is glaring.

As the evolution of the eye has been chiefly influenced by daylight, we should see that the type of illumination at night approaches as near as possible that at daylight. The illumination of a clear sky is about 0·4 to 0·5 candle per square centimetre ($2\frac{1}{2}$ to 3 candles per square inch), so that the intrinsic brightness of artificial lights should certainly not exceed this value. The majority of modern artificial illuminants have, however, intrinsic brilliancies far in excess of this value, which means that bare lights must be avoided and the illuminants must be surrounded with diffusing globes or shades. An ordinary tungsten filament lamp has an intrinsic brightness of about 150 candles per square centimetre (1000 candles per square inch), and the electric pure carbon arc about 13,000 (85,000). It will be obvious that lights of this nature must cause an excessive strain on the eye, and if the exposure is prolonged, the injury is lasting. When the eye is subjected to an excess of, say, green light, it becomes colour-blind to this radiation. If we look into an intense source and then away we see an after-image. This may change its colour and then disappear as the eye recuperates.

Besides intrinsic brightness, the total volume of light is of importance as regards glare. A 500-watt gas-filled lamp in a 10-inch opal globe, hung 7 or 8 feet above the floor and a similar distance ahead of the observer, is as glaring as a bare 50-watt incandescent filament in the same position.

Illuminants are nowadays rated as regards glare, as is indicated in Table 3.02.*

TABLE 3.02.—CLASSIFICATION OF LIGHT SOURCES FROM THE STANDPOINT OF GLARE.

Grade I indicates sources of maximum softness.
Grade X indicates sources of maximum harshness.

Maximum Visible Brightness.	Total Candle-power in Direction of Eye.				
(Apparent Candles per sq. in.)	Less than 20.	20 to 50.	50 to 150.	150 to 500.	500 to 2000.
	Grade.	Grade.	Grade.	Grade.	Grade.
Less than 2	I	I	II	II	III
2 to 5	II	II	III	IV	V
5 to 20	II	III	IV	VI	VII
20 to 100	IV	V	VI	VII	VIII
100 to 1000	V	VI	VII	VIII	IX
1000 and up	VI	VII	VIII	IX	X

The next table, 3.03, gives details of the glare quality of various electric lamps taken from the same source.

* *Code of Lighting*, prepared by Illuminating Engineers' Society (U.S.A.), 1922.

TABLE 3.03.

ARC LAMPS.

	Grade.
Enclosed arcs, clear globes	IX
Flame arc, clear globes	X
Flame arc, opal globes	VII–VIII

MERCURY VAPOUR TUBES	VI

CARBON AND METALLISED FILAMENT INCANDESCENT LAMPS.

	Grade.
8 candle-power	V
16 ,, ...	V
32 ,, ...	VI

TUNGSTEN FILAMENT INCANDESCENT LAMPS.

Watts.	10 25.	40 60.	75–100.	150–200.	300.	500 1000.
	Grade.	Grade.	Grade.	Grade.	Grade.	Grade.
Bare lamps . .	VI	VII	VIII	IX	IX	X
Frosted lamps or frosted globes . . .	II	III	VI	VII-	VIII	..
8-in. opal globes * .	I	I–II	II–IV	IV–VI	..	..
12-in. opal globes * .	..	..	II -III	II–V	IV–VI	VII-VIII
16-in. opal globes * .	..	..	..	II–V	IV–VI	V–VII
Flat reflectors—filament visible . . .	VI	VII	VIII	IX	IX	X
Dome reflectors —steel or dense glass :						
Filament visible from working position .	VI	VII	VIII	IX	IX	X
Filament not visible from working position . .	I	I	III	III	IV	VI
Bowl reflectors—steel or dense glass :						
Filament visible from working position .	VI	VII	VIII	IX	IX	X
Filament not visible from working position . .	II	II	III	IV	VI	VII
Dome reflectors—bowl-enamelled lamps .	..	..	IV	V	VI	VI
Semi-enclosing units * .	..	..	III–IV	IV–VI	IV–VII	VI–VIII
Totally indirect lighting*	..	..	I–II	I–II	II	III
Semi-indirect bowl * .	..	..	I III	II–III	II–IV	III–VI

* Where a range is given, the best grade, that is the lowest, applies to globes that are evenly luminous, and the poorest to globes which have a decidedly bright spot in the centre.

Of importance is also the distance of the light source from the eye and the angle of the line of vision. If the lamp is right above the head of the observer, glare is, of course, entirely absent unless the person lies on his back.

Table 3.04 gives the limiting grades of light sources permissible for various sources. Where the background and the surroundings are very dark in tone a light grade of one grade softer than that specified in the table may be required. Where the background and surroundings are very light in tone, one grade more harsh than that specified in the table may sometimes be permitted.

TABLE 3.04.—SHOWING LIMITING GRADES OF LIGHT SOURCES PERMISSIBLE FOR VARIOUS SOURCES.

Classification of Position.	Space or Work to be Lighted.			
	Roadways and Yard Thoroughfares.	Storage Spaces, Aisles, Stairways, handling coarse Material.	Ordinary Manufacturing Operations.	Offices and Drafting Work and certain Manufacturing Operations.
	Limiting Grade.	Limiting Grade.	Limiting Grade.	Limiting Grade.
A . .	VI	V	III	II
B . .	VII	VI	V	IV
C . .	VIII	VII	VI	V
D . .	IX	VIII	VII	VI
E . .	IX	IX	VIII	VII
F . .	X	X	IX	VIII
G . .	X	X	X	X

The classification of position is given in Table 3.05.

TABLE 3.05.—CHART OF THE FIELD OF VIEW.

Classification of position of light source which takes into account the distance from the eye and the angle of the line of vision.

Height above Floor in Feet.	Horizontal Distance of Light Source from Observer in Feet.															
	1.	2.	3.	4.	6.	8.	10.	12.	16.	20.	25.	30.	35.	40.	50.	60.
6·5 or less	A*	A*	A	A	A	A	A	A	A	A	A	A	B	B	B	B
6·5 to 7	G	E	D	C	C	B	B	B	B	B	B	B	B	B	B	C
7 ,, 8	G	G	F	E	D	D	C	C	C	C	C	C	C	C	C	C
8 to 9	G	G	G	F	F	E	D	D	C	C	C	C	C	C	C	D
9 ,, 10	G	G	G	G	F	F	E	E	E	D	D	D	D	D	D	D
10 ,, 11	G	G	G	G	G	F	F	F	E	E	D	D	D	D	D	D
11 to 12	G	G	G	G	G	F	F	F	F	F	E	E	D	D	D	D
12 ,, 13	G	G	G	G	G	G	F	F	F	F	E	E	E	E	E	E
13 ,, 14	G	G	G	G	G	G	G	G	F	F	F	F	E	E	E	E
14 to 15	G	G	G	G	G	G	G	G	G	F	F	F	F	E	E	E
15 ,, 16	G	G	G	G	G	G	G	G	G	F	F	F	F	E	E	E
16 ,, 17	G	G	G	G	G	G	G	G	G	G	F	F	F	F	E	E
17 to 18	G	G	G	G	G	G	G	G	G	G	G	G	F	F	F	F
18 ,, 19	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	F
19 ,, 20 and up	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G	G

*** Classified as A unless light source is so nearly above the head of the operator as to be quite outside of field of view, in which case classify as E.**

We should also avoid as far as possible working with different colours at the same time, as the eye cannot adapt itself to a variety of colours simultaneously. For red light the image may appear beyond, and for blue and violet lights before the retina, thus causing a strain and headache. When an eye is unable to focus all colours in the same plane, we refer to it as *chromatic aberration*. It sometimes happens that light which enters the eye is reflected within the eye over and over again, causing a blurred vision. This is also the case if ultra-violet rays produce fluorescence of the eye lens. Direct reflection—for instance, when reading from glazed paper—gives an excess illumination.

The image produced on the retina is the sharper the more the light becomes monochromatic, so that it frequently pays to blot out some colours of the light in order to produce a sharper image, in spite of the illumination being reduced thereby.

If we view a landscape on a clear day through a yellow glass, the view appears very sharp. The yellow glass cuts out the purple haze, and it eliminates the diffuse light skylight in all shadows because these shadows are lighted mainly by blue light. The amount of light is little affected, as the blue in it is but a small fraction of the total luminosity.

3.04. WAVE-LENGTH AND FREQUENCY. The sensitivity of the eye depends also upon the nature of the light, *i.e.* upon the wave-length

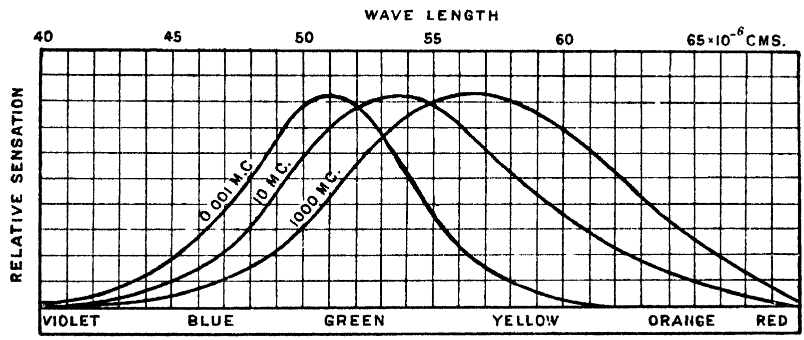


FIG. 3.04.—Sensation of Light.

and frequency. It begins with the red, then gradually increases, becoming a maximum between the yellow and green (see fig. 3.04).

The sensation depends, however, somewhat on the intensity. Its peak moves towards the red for high intensities and towards the blue for low ones. These curves will also explain why it is impossible to compare, with the ordinary equality photometer, lights of different colours, especially if they differ largely in intensity. For high intensities the sensitivity is highest for yellow light; in the case of low ones, for the green. But even if we produce on the two sides of a photometer screen equal illuminations, it will be obvious that it is impossible to compare a yellow light with a greenish-blue one—for instance, an incandescent carbon lamp with the mercury vapour lamp—since for the former the sensitivity of the eye is higher, *i.e.* the sensation on the eye is greater with less candle-power for yellow light than with blue light. The application of the Flicker photometer, however, overcomes this difficulty (see notes on Flicker photometer); or we can compare the lights by finding out the distances at which given colourless letters (black on white or *vice versa*), arranged out of order, can be read equally well by the two lights. This method of comparing lights is not used, because the distances differ so much for individuals. From the curves we see also that as for high intensities the sensation is a maximum for yellow light, for low intensities it is a maximum for greenish-blue light. Both lights, when of equal intensities, will look differently bright when viewed from different distances. Thus the mercury vapour lamp will appear much brighter from a great distance and less bright than the carbon lamp when studied close by. For search-lights, etc., we should therefore install lights of a greenish-blue colour, if it were not for the fact that they penetrate the fog less effectively than yellow lights.

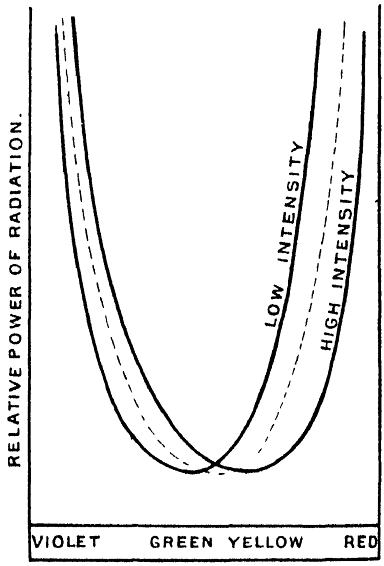


FIG. 3.05.—Power required for Radiations of different Frequencies.

We have seen that the average sensitivity of the eye is greater for the yellow-green part of the spectrum than for the red and the violet. It follows, therefore, that for a given sensation the maximum power is required for red and blue-violet radiations, as is approximately illustrated in fig. 3.05.

As the light enters the eye, its energy is changed, mostly into heat. If the rate of conversion becomes too great, the heating becomes excessive and the eyes give pain. Continued "overheating" causes inflammation. If the time of overheating is short, a few hours will see full recovery. Temporary blindness is also due to excess power absorption. Looking at the curve, it will be obvious that for red and violet lights the absorption of power for a given sensation will be much greater than for yellow-green lights; consequently the danger of overheating is also greater. Yellow-green lights are therefore preferable, especially where the intensities are great. At the same time, less harm is done by red radiation than by violet and ultra-violet. The latter is invisible, yet the radiations may be there all the same, and the invisibility makes it all the more difficult to guard against such rays. The harm done by ultra-violet rays is greater than that due to red and infra-red radiations, on account of the greater frequency and shorter wave-lengths. As long as the wave-length is great, the eye, or rather its constituent particles, are able to respond to, or resonate with, the impressed motions; but when the frequency becomes too high, as is the case with the ultra-violet rays, a response is no longer possible, and dissociation results. It is therefore absolutely essential that lights which produce largely ultra-violet rays, such as open arcs of all kinds, discharges across spark gaps, should be studied with protecting glasses.

Ordinary clear glass gives sufficient protection in some cases, as it is opaque to ultra-violet rays of higher frequencies. These rays can be completely shut off by special glasses of a yellowish tint, or by proper globes, and it is advisable to do this where direct light has to be employed.

The metal filament incandescent lamp, which produces ultra-violet rays, is not to be employed in positions where direct rays are liable to enter the eye.

The harm done by ultra-violet rays is effective and lasting. The author remembers taking a number of students over the Vickers-Maxim Works at Sheffield in 1905, where they were shown electric welding. Unfortunately, there were only two pairs of protecting glasses available, and as the author, who was interested in the mechanism of the machine, studied it without protection for several minutes, he received an overdose of ultra-violet rays. About twelve o'clock the following night he awoke with a maddening pain at the back of the eyes, which lasted for about an hour, and for weeks afterwards he had difficulty in keeping anything properly in focus. Experience has also proved that an open electric carbon arc alone is not nearly as dangerous as when used in connection with the welding of iron. The rays from metal arcs are extremely harmful, and those from the mercury vapour arc are the most dangerous of all modern illuminants.

Overheating is experienced instantaneously, and it is cured quickly. The harm done by ultra-violet rays is noticed ten to twenty hours afterwards, but it is lasting. It is therefore essential that for open arcs the necessary protection should be applied, that glasses should be used which prevent ultra-violet rays from entering the eyes above or below them. Once eyes are weakened by such radiation, they become very sensitive to it, and the least dose causes headache. This is also experienced in brilliant sunshine, especially in places where a large quantity of light is reflected. White sand and snow reflect a large part of ultra-violet radiations contained in sunlight, so that it is advisable to wear protecting glasses.

No ill-effects are caused by radiations above the blue, to which the organs of the eye can respond; but light which contains blue and violet radiations only cannot be tolerated for any length of time. The most sensitive part of the eye, the yellow spot, does not respond to them (it is blue-blind), and as a result these radiations are seen by the surrounding parts of the retina only, and when the latter endeavours to focus them on the yellow spot the light disappears altogether. A greatly irritating effect is the result.

Different eyes show different degrees of sensitiveness to ultra-violet rays If we place an arc lamp at the back of a screen consisting of a fine silver deposit on glass, no visible light will pass through, but for ultra-violet light the screen is transparent. Most people will therefore be unable to see the light at the back of the screen, but some persons are

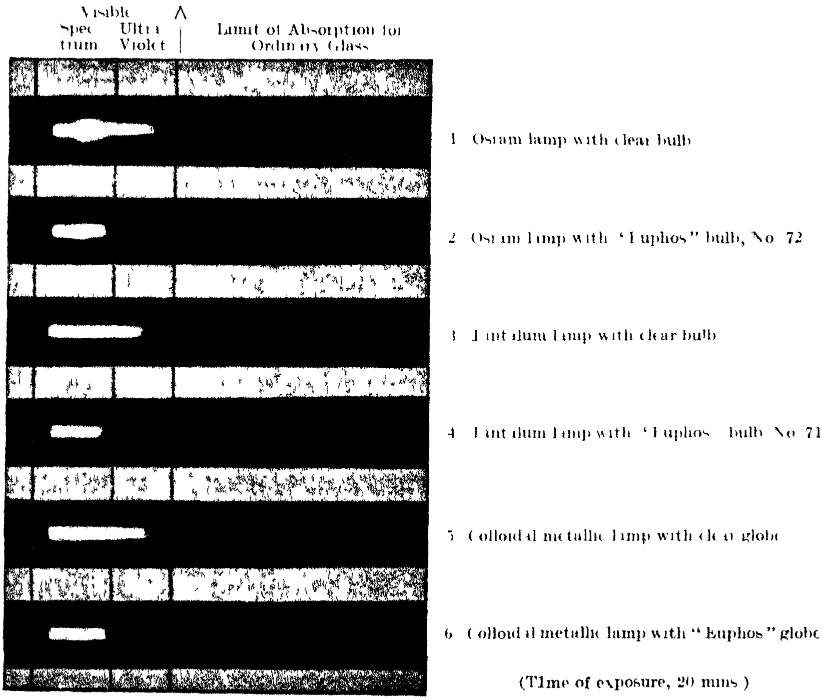


FIG. 3.06.—Effect of "Euphos" Glass on Ultra Violet Light

able to do so. This is especially the case with individuals who have been subjected to an operation for cataract, involving the removal of the crystalline lens of the eye. The inability of ordinary people to see ultra-violet light may therefore be partly due to the fact that the crystalline lens absorbs it.

The lens very often changes its colour during life, and this gradual coloration seems to afford protection, since little children appear to be more susceptible to ultra-violet light than older people.

Doctors Schanz and Stockhausen have invented a glass, which they call "Euphos." * It consists of a mixture of red and green glass, giving a yellowish tint, which cuts off most of the ultra-violet light, as is marked in the above fig. 3.06. They also claim that this glass does not absorb

* See *Illuminating Engineer*, vol. i., 1908, p. 772.

more than 2 to 3 per cent. of the visible light. This can be judged by means of fig. 3.07.

The reason why daylight is so much less harmful than artificial radiation is to be found in the fact that daylight is luminescent, or selectively radiant, so that the amount of power which enters the eye, even in sunshine, is comparatively small; moreover, the light is perfectly diffused. In artificial light, however, the percentage of visible radiation

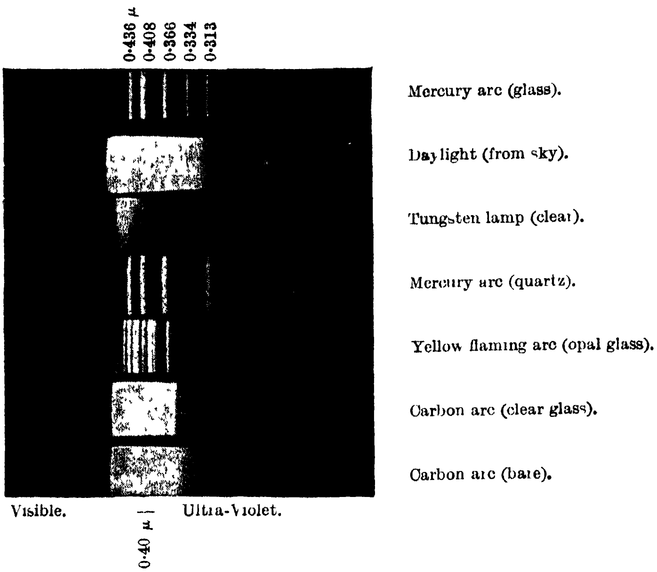


FIG. 3.07.—Short Wave Spectra of Common Illuminants for Equal Photometric Intensities and Equal Photographic Exposure.

is small, and, as it is caused by temperature radiation, the amount of power that enters the eye is large.

At the extreme end of the ultra-violet follow the X-rays, which are consequently of a very high frequency. The effect of X-rays is similar to that of ultra-violet rays, but in a greater degree. Excessive application will cause dissociation of the part treated. Care must therefore be taken when applying such light.

It should be pointed out here that opinions about the harmful nature of ultra-violet rays, or rays below a wave-length of 40×10^{-6} centimetres, do not agree. According to M. Luckiesh,* artificial light is less harmful in this respect than daylight, and he tries to prove this by means of a series of photographs, of which one is given in fig. 3.07. It shows undoubtedly that daylight contains far more ultra-violet light than most modern illuminants, but the fact that it is luminescent is not taken into account. The power which enters the eye from artificial sources of great intrinsic brightness is far greater than that during daylight.

* *Electrical World*, vol. lix. p. 1314, 1912.

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Dr C. R. Kindall, Surgeon of the Bureau of Mines, has issued a report in which it is stated that thirty men were recently viewing the demonstration of a new portable electric arc-welding outfit, and a few hours later seventeen of the thirty men reported to the doctor for treatment. They were suffering from traumatic conjunctivitis. In two cases the pain was very severe, and the symptoms were similar to those of iritis. Morphine had to be administered to afford relief from pain. Only two men of the thirty were not affected in some way from this exposure. These two men wore thick-lensed orange-coloured glasses. Several of the men wore orange-coloured glasses with thin lenses, but the latter were not heavy enough to afford protection against an exposure as long as took place. The distance of the eye from the arc also influences the possibility of injury.

Conjunctivitis is an inflammation of the conjunctiva; the conjunctiva is the mucous membrane covering the inside of the eyelids and part of the eyeball. Traumatic conjunctivitis is caused by foreign bodies in the eye, exposure of the eyes to high winds, dust, smoke, intense light from electric arc lamps, and from electric welding apparatus. In the instance mentioned above, the inflammation was due to the ultra-violet rays. In some cases the effect is so severe that, in addition to conjunctivitis, an inflammation of the skin similar to sunburn is produced.

The symptoms of conjunctivitis caused by intense light or by the ultra-violet rays are abnormal intolerance to light, excessive secretion of tears, intense smarting of the lid, contraction of the pupil, sometimes swelling of the lid, and small ulcers developing on the eyeball or cornea. Unless properly treated by a physician immediately, chronic inflammation of the conjunctiva, cornea, iris, or retina, and possibly blindness, may result.

Under proper treatment most cases get well in a few days. All treatments should be under the direction of a physician. He usually advises placing packs on the patient's eyes three or four times daily. The pack should be left on from fifteen minutes to an hour. The eyes should be irrigated with normal salt solution (a teaspoonful to a quart of sterile water) or a saturated solution of boric acid several times daily. If there is a discharge of pus, a few drops of a 25 per cent. solution of argyrol or a 5 per cent. solution of protargol should be placed in the eyes three to six times daily. The patient should be confined to a darkened room until his condition improves in order to avoid complications. These treatments will reduce the swelling, give the patient comfort, and prevent the development of chronic conjunctivitis. In severe cases it may be necessary to administer morphine to relieve the pain.

3.05. PROTECTION OF EYESIGHT.*—(*a*) **Against Heat.**—Various

* See also W. S. Andrews, *General Electric Review*, November 1917, p. 903, and December 1918, p. 961.

kinds of glasses are sold which will accomplish this. The following table gives substances which are good as heat absorbers :—

TABLE 3.06.—HEAT-ABSORBING GLASSES.

Material of Screen.	Thickness.		Percentage of Heat absorbed.
	Inches.	Millimetres.	
Clear white mica	0·004	0·102	19·0
Clear window glass	0·102	2·59	26·0
Flashed ruby glass	0·097	2·46	31·0
Blue glass	0·093	2·36	57·0
Emerald green glass	0·100	2·54	64·0
Dark mica	0·004	0·102	67·0
Corning G 124 glass	0·095	2·41	90·0
Dark Noviweld	0·096	2·44	96·0
Pfund gold-plated	0·114	2·90	99·2

The figures represent, of course, only average results. They are affected by the chemical constituents of the glass and by the thickness. Long-continued proximity of the eyes to sources of heat may produce cumulative action and cause cataract, which can be prevented by the use of these protective glasses.

(*b*) **Visible Light.**—Excessive brilliancy, glare, and flickering must be avoided. As the eye is more sensitive to yellow-green light than to other combinations, protecting glasses of this tint will give the best results. Against excessively bright light, such as produced in arc welding, a smoky effect is mostly introduced into the glass to aid the absorption.

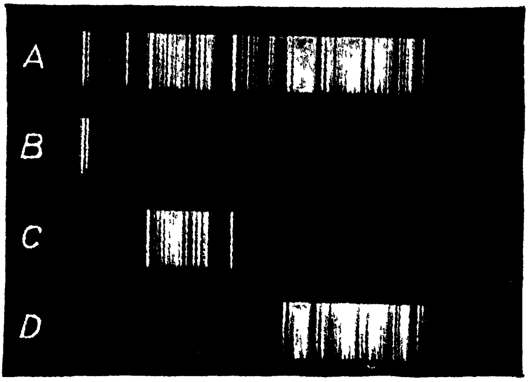
Certain tints of dark mica have been found excellent, especially as they are good heat absorbers.

In very heavy welding operation the whole face has to be protected, and masks of vulcanised card or fibre are used, with openings provided with a combination of ruby and green glass plates. Dark mica would even be better.

(*c*) **Ultra-Violet Rays.**—Waves having a length of less than 34×10^{-6} centimetres are absorbed by almost any kind of glass, so that even ordinary glasses provide good protection against this invisible radiation. Arcs between carbon and iron, iron and iron, in fact all metal arcs, and especially the mercury vapour arc, are extremely prolific in these rays.

It is not sufficient to protect the eye and face from direct radiations of this nature, but we must do so also against reflected rays. A mercury vapour lamp with a quartz tube should never be burned without a pro tecting glass globe.

Ultra-violet rays produce fluorescence in certain chemical substances, and when these are seen by a mixture of visible and ultra-violet light, such as is emitted by an iron arc, their apparent colour is changed. A high-tension disruptive discharge between iron electrodes is an excellent source of ultra-violet rays, which are far in excess of visible rays. A pebble (natural clear quartz) lens can readily be distinguished from one of



(A) Spectrum of Iron Spark.
(B) Spectrum through Ruby Glass.
(C) Spectrum through Green Glass.
(D) Spectrum through Blue Glass.

FIG. 3.08.—Spectra of an Iron Spark (Andrews).

plain glass, because, if the lens is placed between the iron spark discharge and a fluorescent substance, such as soda salicylate, the blue colour, caused by the ultra-violet rays, appears. With a clear glass lens the

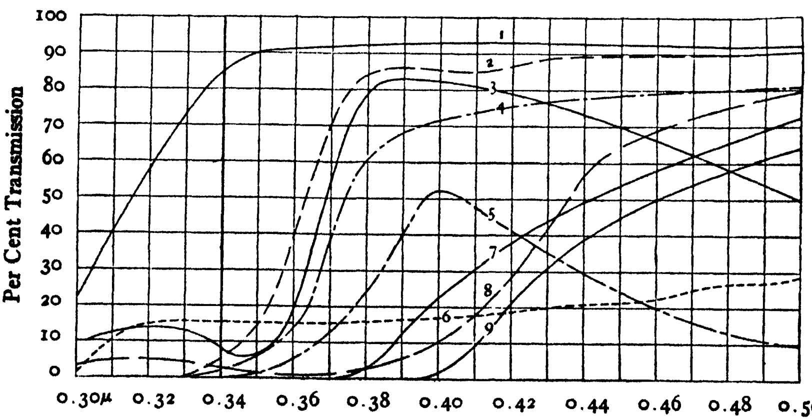


FIG. 3.09.—Transmission Curves for Various Glasses.

natural white remains. Fig. 3.08 illustrates the spectra of an iron spark under various conditions.

Transmission curves for a number of glasses are shown in fig. 3.09 for the ultra-violet region.* It will be seen that the transmission of the clear lead glass (1) remains unchanged to a wave-length of $0{\cdot}35 \times 10^{-6}$

* M. Luckiesh, *Trans. Illum. Eng. Soc.* (*U.S.A.*), vol. ix. p. 472, 1914.

centimetres, where it begins to absorb, becoming opaque to rays somewhat shorter than $0{\cdot}3 \times 10^{-6}$ centimetres. The smoke glasses were representative of many examined. They show that it will not do, in choosing protecting glasses, to judge simply by a mere visual observation. None of the glasses shown absorb all the ultra-violet radiation, so that the question arises as to the best colour in various processes. In general it has been found that a yellow-green glass of minimum colour, opaque to ultra-violet rays and supplemented by a neutral tint or smoke glasses in order to reduce the brightness encountered in welding, etc., gives satisfaction.

3.06. THEORY OF COLOUR PERCEPTION.—Various theories have been propounded as regards the perception of colour. Some express this perception as an effect having a chemical basis, and that the nerve system is stimulated by a small electric current flowing from the retina and depending on the intensity of the light striking the eye.

According to Young and Helmholtz, the retina of the eyes has three sets of cones sensitive to the three primary colours: red, green, and blue respectively. When the three sets of nerves are stimulated, the sensation of white light is realised. The sensations of intermediate colours occur as the curve representing a primary colour sensation extends beyond the point on the spectrum for which that set of cones is especially sensitive. This theory, however, does not suffice for many cases of colour-blindness, and not for very low illuminations when no colours are seen at all.

Hering assumes that the eye possesses three photochemical substances, of which the first one undergoes a constructive change in one direction when acted upon by red light, and the reversed destructive change when subjected to green. The second element undergoes similar changes for yellow and blue lights; and the third one responds to the sensations of light only, and undergoes similar changes corresponding with black and white. This would require three distinct pigments, which—like the three sets of cones in the Young-Helmholtz theory—have not yet been found experimentally.

It has already been pointed out that the yellow spot is less sensitive to the green end of the spectrum than the surrounding part. If, therefore, in a photometric test we alter the distance between the eye and the screen, different portions of the retina are affected, and the photometer may appear out of balance. This is especially the case when the screen is badly illuminated. The brighter the illumination the greater will be the accuracy obtained. In no case should the illumination be less than one foot-candle. This is, of course, easily obtained when dealing with laboratory measurements, but not in the case of testing street illumination, where the illumination is much less in nearly all cases.

Suppose, further, we have two similar pieces of red and green paper and illuminate them with white light. As long as the illumination is strong, the red one appears the brighter of the two. When, however, the illumination is gradually reduced, the papers finally change places with regard to apparent brightness. This is called the "*Purkinje effect*," by which is meant that with increasing light the luminous sensation produced by the red end of the spectrum increases more rapidly than that which would be produced by the green part (see also fig. 3.02). In the above experiment the surfaces should be placed at a great obliquity to the eye, for, if the angle is small, the Purkinje effect does not take place.

Von Kries explains these phenomena as follows: The light-perceiving organs of the retina consist of rods and cones, of which only the latter perceive the colours. The cones are also most sensitive to yellow light, and, while they do not respond to very much illumination, once they have commenced to act with increasing stimulus they keep on doing so long after the rods have ceased to do so.

The rods are unable to perceive colour, and all light appears to them white. They are sensitive to weak light, to which the cones do not respond at all, but when the stimulus is further increased the rods become saturated and respond no further.

When light is fairly strong we see by means of the cones, and hence we have a colour sensation. Very weak light is seen through the rods and the colour disappears, everything looking grey.

From the photometric standpoint it is of importance to find out when the struggle between the rods and cones begins. As the extreme central portion of the retina contains practically only cones, then, if the image of the illuminated surfaces falls within this region, the Purkinje effect is absent. But when the angle between the eye of the illuminated surfaces is great, and the cone region is largely affected, the Purkinje effect is pronounced. In properly constructed photometers the angle is usually small, and the Purkinje effect is of little importance as long as the illumination does not drop below 1 metre-candle.*

Also this theory of light and colour perception is not endorsed by all experts. Dr F. W. Edridge Green † suggests that the struggle between the rods and cones can be explained by the distribution of visual purple over the retina, and that the rods are merely concerned in the distribution of visual purple. Light falling on the eye causes the visual purple to retreat from the rods and spread over the other parts. The chemical change causes a corresponding sensation stimulus, which depends in quality and quantity on the nature of the light causing it, and this stimulus is communicated to and analysed in a special centre of the brain. Hence, according to this theory, it is in the brain and not in the eye where the sensations of light and of colour are analysed. The divergency in opinion shows that further investigations are needed.

3.07. PHYSIOLOGICAL EFFECTS OF COLOURED LIGHT.—Lights

* See J. S. Dow, *Illuminating Engineer*, 1908, p. 153.

† *Ibid.*, 1909, pp. 210, 741, 802.

of different colours have different effects upon human and plant life. Red light is cheering and stimulating, as long as not too much of it is supplied. An excess causes irritation and even hysterics. It is on account of the stimulating and pleasant effect that red light is called a warm light.

Blue and violet (cold) lights have a soothing effect, but an excess thereof produces depression and melancholy. The term "in the blues" is probably derived in this way. Coloured lights have been employed with success in the treatment of lunatics.

It has actually happened in film works in England that workmen, who worked under yellow light, complained of the heat. The owner then replaced the lamps by others with a bluish tint, when he was informed that the shop was much cooler. The temperature of the room was actually the same in both cases.

Experience has also shown that red, orange, and yellow light improve the growth of plants, whereas ultra-violet rays destroy. Plants are, of course, not alike in this respect; lettuce, for instance, can be kept going with artificial light at night, but tomatoes insist on sleeping and decline to grow in such conditions. On the whole, one hour of sunlight will cause more growth than several nights of artificial light.

An interesting article on this subject will be found in the *General Electric Review* of March 1918, by Hayden and Steinmetz, p. 232. It concludes as follows: "By intense artificial illumination, of the magnitude of 700 lumens per square foot, the rapidity of the growth and development of plants can be approximately doubled. Economically such use of light for raising plants may be justified where the electric current is generated as a bye-product of the heating plant; but at any cost of purchased power it would be economically justified only for temporary use with plants which have a market value only at a definite time."

Ultra-violet light is, however, not entirely useless; it may be employed as a germ-killer. Many pathological bacteria live in the dark, and light destroys them. The ultra-violet rays are the most effective as germicides.

Ultra-violet rays may even be employed for the purification of water, and their use in this direction is already applied on a commercial basis. The rays are produced by means of a mercury vapour lamp, enclosed in a vessel consisting of quartz. The water is so conducted that it passes at least three sides of the quartz lamp, and tests have shown that bacteria are completely destroyed in this way. The water should, however, be previously clarified in order to prevent an absorption of the ultra-violet rays.

CHAPTER IV.

LIGHT FLUX AND DISTRIBUTION.

4.01. SOURCES EMITTING LIGHT UNIFORMLY IN ALL DIRECTIONS. This class embraces point and spherical sources. For the former the intrinsic brilliancy is infinite, since the emitting area is nil.

For a sphere the intrinsic brilliancy is expressed by

$$i=\frac{\phi}{4\pi R^2} \quad . \quad . \quad . \quad . \quad . \quad 4.01$$

$$=\frac{4\pi I}{4\pi R^2}$$

$$=\frac{I}{R^2} \quad . \quad . \quad . \quad . \quad 4.02$$

i.e. it is inversely proportional to the square of the radius of the sphere.

4.02. CIRCULAR PLANE RADIATORS. Such a source is to be found in the tip of the carbon of an enclosed arc lamp. Let I_n be the normal intensity, then the intensity of the light under the angle θ is

$$I=I_n \cos\theta \quad . \quad . \quad 4.03$$

The figure of this equation is a circle as shown in fig. 4.01.

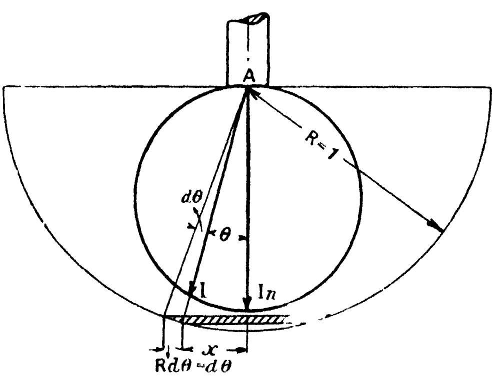


FIG. 4.01.—Light emitted by a Circular Plane.

The total light flux emitted by the radiator may be found as follows: With A as centre draw a circle with radius unity. The length of an elementary arc formed by the angle $d\theta$ is then $Rd\theta=d\theta$, and the area swept out by it when rotating it round the vertical axis is $2\pi x d\theta$, and since $x=R\sin\theta=\sin\theta$, the area becomes $2\pi\sin\theta d\theta$. The flux striking the area is

$$\frac{I}{R^2}2\pi\sin\theta d\theta=2\pi I\sin\theta d\theta,$$

since $R^2=1$; hence the total flux

$$\phi=\int_0^{\frac{\pi}{2}} 2\pi I \sin\theta d\theta$$

$$=\pi I_n\int_0^{\frac{\pi}{2}} 2\sin\theta\cos\theta d\theta$$

$$=\pi I_n\int_0^{\frac{\pi}{2}} \sin 2\theta d\theta,$$

and as

$$\int_0^{\frac{\pi}{2}} \sin 2\theta d\theta=1$$

$$\phi=\pi I_n \quad . \qquad 4.04$$

The flux emitted within the angle θ against the vertical is given by

$$\phi^\theta=\pi I_n\int_0^{\theta} \sin 2\theta d\theta$$

or

$$\phi^\theta=\frac{\pi}{2} I_n(1-\cos 2\theta) . \quad . \quad . \quad . \qquad 4.05$$

The mean hemispherical intensity of the light is given by

$$I_\sigma=\frac{\phi}{2\pi};$$

hence

$$I_\sigma=\frac{I_n}{2} \quad . \quad . \quad . \qquad 4.06$$

The intrinsic brilliancy of the source is expressed by the flux per unit area, so that, if the radius of the radiating plane is R_1,

$$i=\frac{\phi}{R_1^2\pi}$$

$$=\frac{\pi I_n}{R_1^2\pi}$$

$$=\frac{I_n}{R_1^2} \quad . \quad . \quad . \qquad 4.07$$

4.03. CURVED SURFACE RADIATORS.—The intensity I of an elementary area A B is equal to $I_n \cos\theta$; but $I_n=is_1$, where s_1 is the size of the small elementary area A B, whence $I=is_1\cos\theta$ (see fig. 4.02). $s_1\cos\theta$ is the projection of A B on the horizontal plane A C, hence the effect of the luminous curved surface A B C is the same as that of a plane surface A C with the same intrinsic brilliancy, and the intensity curve is a circle having the maximum intensity I_n as diameter.

The positive crater of a direct current arc with vertical carbons comes under this class of radiators. We see that the depth of the crater has no influence on the radiation, which depends solely on the intrinsic brilliancy and the diameter of the crater.

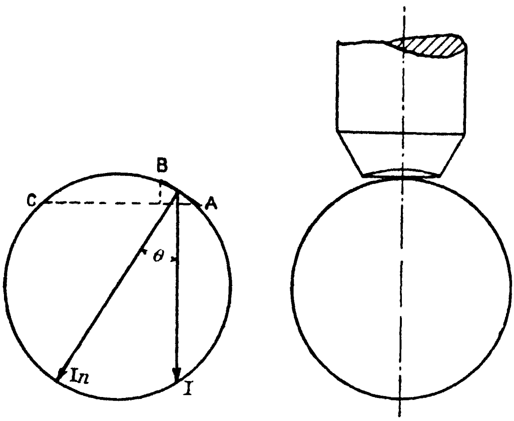


FIG. 4.02.—Light emitted by a Hollow Radiator.

4.04. CYLINDRICAL RADIATORS.—To these sources belong the luminous arcs of arc lamps, mercury vapour lamps, Moore's tube light, straight filaments of incandescent lamps, etc. We assume a uniform intrinsic brilliancy over the mantle surface of the cylinder, which is supposed to be of short length, so that the maximum intensity I_n will be in a direction perpendicular to the axis of the radiator. The intensity of a ray OI will then be expressed by $I_n \sin\theta$, being zero for $\theta = 0$ degrees. The intensity curves of such a cylindrical radiator are circles, with I_n as diameters, and having centres in an axis perpendicular to the axis of the radiator (see fig. 4.03).

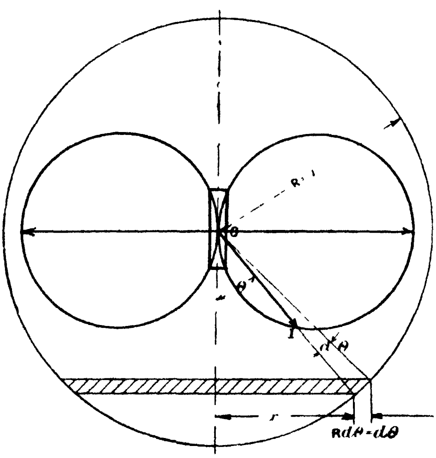


FIG. 4.03.—Light emitted by Cylindrical Radiators.

To find the total flux we proceed as under (4.02) and obtain:

$$\text{Length of elementary arc} = Rd\theta = d\theta, \quad \text{for} \quad R = 1.$$

The area swept out by it when rotating it round the vertical axis is

$$2\pi x d\theta = 2\pi R \sin\theta d\theta = 2\pi \sin\theta d\theta,$$

and hence the total flux is

$$\phi=\int_0^{\pi}2\pi \mathrm{I}\sin\theta d\theta$$

$$=2\pi \mathrm{I}_n\int_0^{\pi}\sin^2\theta d\theta$$

$$=2\pi \mathrm{I}_n\times\frac{\pi}{2}$$

$$=\pi^2\mathrm{I}_n \quad . \quad . \quad . \quad . \quad . \quad 4.08$$

For any angle θ against the vertical, we obtain

$$\phi^{\theta}=2\pi \mathrm{I}_n\int_0^{\theta}\sin^2\theta d\theta$$

$$=2\pi \mathrm{I}_n\left(\frac{\theta}{2}-\tfrac{1}{2}\sin\theta\cos\theta\right)$$

$$=\pi \mathrm{I}_n(\theta-\sin\theta\cos\theta)$$

$$=\pi \mathrm{I}_n(\theta-\tfrac{1}{2}\sin 2\theta) \quad . \quad . \quad . \quad . \quad . \quad 4.09$$

The mean spherical intensity is given by

$$\mathrm{I}_o=\frac{\phi}{4\pi}$$

$$=\frac{\pi^2\mathrm{I}_n}{4\pi}$$

$$=\frac{\pi}{4}\mathrm{I}_n \quad . \quad . \quad . \quad . \quad . \quad 4.10$$

The intrinsic brilliancy follows from

$$i=\frac{\phi}{\text{emitting surface}}$$

$$=\frac{\phi}{\pi dl}$$

$$=\frac{\pi^2\mathrm{I}_n}{\pi dl}$$

$$=\frac{\pi \mathrm{I}_n}{dl} \quad . \quad . \quad . \quad . \quad . \quad . \quad 4.11$$

where d is the diameter and l length of the radiator.

Also

$$\mathrm{I}_n=\frac{dli}{\pi}$$

and

$$\mathrm{I}_{n1}=\frac{di}{\pi}=\text{maximum intensity per unit length.}$$

When the radiator is of great length, as with Moore's tube lighting, the calculation of the total flux is somewhat more complicated. Assuming that the light is a luminous line concentrated in the axis of the tube, Dr J. Pole * found that the flux may be expressed by

$$\phi=\pi^2 I_n l \qquad 4.12$$

when the mean spherical intensity results in

$$I_0=\frac{\pi I_n l}{4} \qquad 4.13$$

4.05. HEMISPHERICAL RADIATOR.—In this case the intensity in a horizontal direction is not zero, but equal to $\frac{1}{2}I_n$, since the projection of the hemisphere upon a vertical plane is equal to a semicircle. For any position intermediate between I_n and $\frac{I_n}{2}$ the intensity is $\frac{I_n}{2}+\frac{I_n}{2}\cos\theta=\frac{I_n}{2}(1+\cos\theta)$. Fig. 4.04 also indicates that the light above the horizontal, *i.e.* for θ

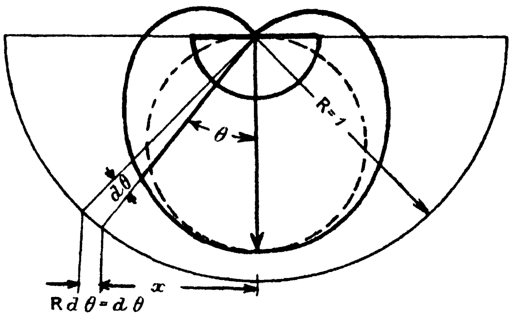


FIG. 4.04.—Light emitted by Hemispherical Radiators.

greater than 90 degrees, is not zero, since the projection of the luminous area is not zero and only when $\theta=180$ degrees, or $\cos\theta=-1$, does the light disappear completely. We obtain thus the intensity curve of fig. 4.04. To find the total flux we sweep out again an elementary area $2\pi x d\theta=2\pi\sin\theta d\theta$ by an elementary arc

$$Rd\theta=d\theta, \quad \text{for} \quad R=1,$$

whence

$$\phi=\int_0^\pi 2\pi I\sin\theta d\theta$$

$$=\frac{2\pi I_n}{2}\int_0^\pi \sin\theta(1+\cos\theta)d\theta$$

$$=2\pi I_n \qquad 4.14$$

If we integrate between the limits O and $\frac{\pi}{2}$, *i.e.* for the lower hemisphere only, we get

$$\phi=\tfrac{3}{2}\pi I_n.$$

The mean spherical intensity is given by

$$I_0=\frac{\phi}{4\pi}=\frac{2\pi I_n}{4\pi}=\frac{I_n}{2},$$

* *E.T.Z.*, 1911, p. 448.

and the mean lower hemispherical candle-power is

$$I_{\triangledown} = \frac{\frac{3}{2}\pi I_n}{2\pi} = \frac{3}{4} I_n.$$

Comparing the different sources we obtain the following table:—

TABLE 4.01.—FLUXES AND MAXIMUM INTENSITIES OF VARIOUS SOURCES.

	Spherical Radiator.	Plane and Hollow Radiator.	Cylindrical Radiator.	Hemispherical Radiator.
Flux emitted . . .	$4\pi I_n$	πI_n	$\pi^2 I_n$	$2\pi I_n$
Maximum intensity . .	$\frac{\phi}{4\pi}$	$\frac{\phi}{\pi}$	$\frac{\phi}{\pi^2}$	$\frac{\phi}{2\pi}$

From this follows that with the same total flux the intensities of the various sources must be in the following proportions:

Sphere.	Plane.	Cylinder.	Hemisphere.
1	4	1·28	2

4.06. INFLUENCE OF THE SCREENING EFFECT OF THE LOWER CARBON ON THE LIGHT DISTRIBUTION OF ARC LAMPS.—In the ordinary direct-current lamp it is the positive electrode which produces the maximum amount of light. Unfortunately, not all the light of the crater becomes available, since the lower carbon, the negative electrode, screens off a large part of it. The amount is the larger the closer we bring the carbons together. It would therefore appear that we could increase the efficiency by burning the lamp with an arc as long as possible. This is not the case, since with an increase in the length of the arc the P.D. and the power required to maintain the arc increase also. There is therefore a limit to the length of the arc. The best results are obtained when in the open type arc the length is about 3 millimetres ($\frac{1}{8}$ inch). That we can bring the carbons so closely together is due to the fact that the negative carbon burns to a conical shape, and thereby reduces the shadow which it throws. In the enclosed arc lamp both carbons remain flat, as the pressure inside the globe prevents the temperature from rising to the high value of the open arc, and thus combustion is reduced to a minimum by the partial absence of oxygen inside the inner globe. To obtain the maximum amount of light for a given expenditure of power, the length of the arc must be increased to about 10 millimetres ($\frac{3}{8}$ inch).

The amount of the obscuration may be calculated if it be assumed that the positive crater radiates as a circular disc emitting light according to the cosine law, and the negative may be regarded as a circular disc parallel with the positive and at a distance from it equal to the arc length. The first condition is very nearly true, but as regards the second it must be pointed out that the negative electrode soon becomes conical, whereby the obscuration is reduced, while the screening effect by the stem of the negative holder and the holder itself is neglected. Assuming that one effect counterbalances the other, the percentage of the light emitted from the positive crater of diameter D, which is obscured by a negative of diameter d, at an arc length L is given by the formula :

$$\text{Obscuration } \% = \frac{50}{D^2}\{(D^2 + d^2 + 4L^2) - \sqrt{[(D^2 + d^2 + 4L^2)^2 - 4d^2D^2]}\}.*$$

The screening effects of the lower carbons are illustrated in figs. 4.05 to 4.07. Fig. 4.05 represents the ordinary direct current arc; fig. 4.06, *a* and *b*, the enclosed type; fig. 4.07 the alternate current arc. From the

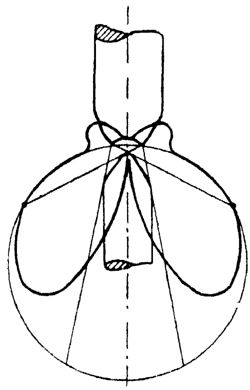


FIG. 4.05.—Screening Effect of the Lower Carbon in a D.C. Ordinary Arc Lamp.

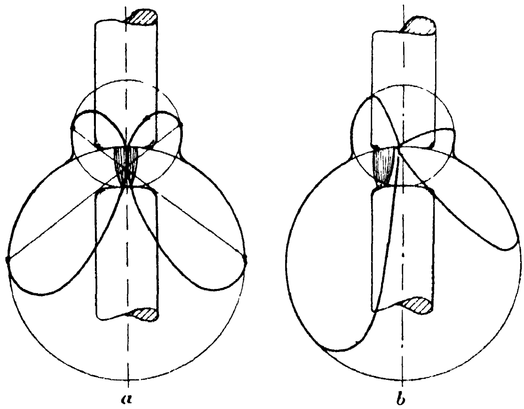


FIG. 4.06.—Screening Effect of the Lower Carbon in a D.C. Enclosed Arc Lamp.

latter we see that the light thrown upwards is as large as that emitted into the lower hemisphere and would therefore be wasted. A suitable reflector, however, directs it downwards, causing the resultant distribution as shown by the thick curve.

Fig. 4.06, *a*, is drawn with the arc in the centre of the carbons. In reality the arc travels round the electrodes so that the light distribution varies considerably, according to fig. 4.06, *b*, in which the arc happens to be near the left edge.

In modern flame and luminous arcs with vertical carbons the length of the arc is much greater than with pure carbon electrodes, up to one inch, so that the screening effect is not great, especially as most light comes from the arc itself. With inclined carbons there is no screening and the polar curve approaches the circle.

4.07. REFLECTION OF LIGHT.—Reflection of light is regular or irregular. Regular reflection is caused by mirrors, irregular by diffusing surfaces such as drawing-paper, whitewash, etc. In the former case the

* Paterson, Walsh, Taylor, and Barnett, *J.I.E.E.*, vol. lviii. p. 97.

impinging ray is reflected at the same angle as that at which it strikes the reflector, but with loss of intensity, the reflected ray being weaker than the impinging ray. We thus have $I_r = mI$, in which m is the reflection coefficient. If we surround a source of light with suitable reflectors, we can redistribute the light and direct it in any desired way. The subject will be considered fully in Chapter VII.

Of greater importance than regular, is irregular or diffuse reflection.

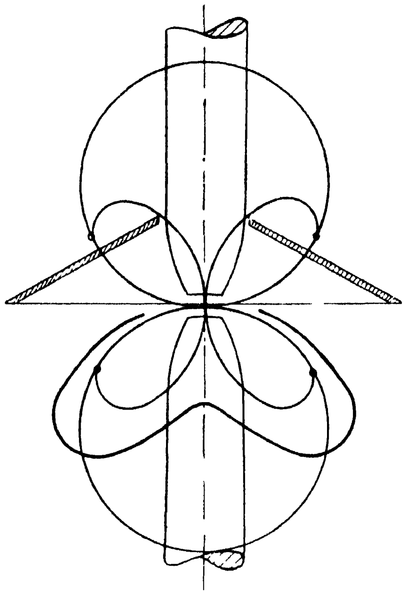


FIG. 4.07.—Screening Effect of the Lower Carbon in an Alternate Current Arc Lamp.

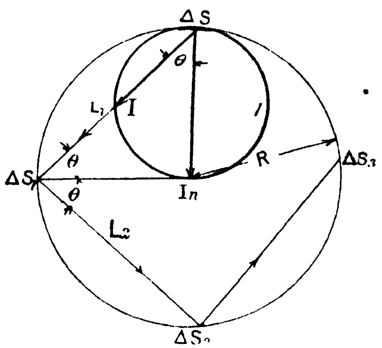


FIG. 4.08.—Reflection in a Sphere.

In this case the light is scattered, and, instead of dealing with intensities, we must now consider the fluxes. If a flux ϕ strikes a diffusing surface S, it is reflected in all directions, but not without loss.

We have

$$\phi_r = m\phi,$$

in which m represents now the diffuse reflection coefficient. The area S is a second radiator with the flux $m\phi$.

Reflection in a Sphere.—Consider the simplest case, a white diffusing hollow sphere with a radiating surface ΔS, for which the polar curve (1) is a circle (see fig. 4.08).

The impinging ray I has the intensity $I_n \cos\theta$, and as the angle of incidence on ΔS_1 is θ, we obtain for the illumination of ΔS_1, the value

$$E^1 = \frac{I_n}{L_1^2} \cos^2\theta.$$

But

$$\cos\theta=\frac{L_1}{2R},$$

where R is the radius of the sphere; hence

$$\cos^2\theta=\frac{{L_1}^2}{(2R)^2},$$

and

$$E^1=\frac{I_n}{{L_1}^2}\times\frac{{L_1}^2}{(2R)^2}=\frac{I_n}{(2R)^2} \qquad . \quad . \quad . \quad . \quad 4.15$$

The normal illumination is

$$\frac{I_n}{(2R)^2}=E,$$

whence it follows that the sphere is uniformly illuminated. The total flux is therefore given by

$$\phi=SE$$

where S is the area of the sphere.

So far we have neglected reflection altogether. The flux ϕ which strikes unit area of the sphere is reflected the first time as $m\phi$, and as this applies to all parts of the sphere the illumination is increased uniformly to the extent of $m\frac{\phi}{S}$. On emerging again the flux is reduced to $m^2\phi$, so that the second increase in the illumination of the sphere will be $m^2\frac{\phi}{S}$. This reflection goes on indefinitely, causing a total illumination of the sphere

$$E=\frac{\phi}{S}+m\frac{\phi}{S}+m^2\frac{\phi}{S}+\ .\ .\ .\ .\ .\ m^{\infty}\frac{\phi}{S}$$

$$=\frac{\phi}{S}\left(1+m+m^2+\ .\ .\ .\ .\ .\ m^{\infty}\right).$$

As m is less than unity,

$$1+m+m^2+\ .\ .\ .\ .\ m^{\infty}=\frac{1}{1-m},$$

whence

$$E=\frac{\phi}{S}\left(\frac{1}{1-m}\right) \qquad . \quad . \quad . \quad . \quad . \quad . \quad 4.16$$

Let $m=1-a$, where a is the absorption, then

$$\frac{1}{1-m}=\frac{1}{a},$$

and

$$E=\frac{\phi}{aS} \qquad . \quad . \quad . \quad . \quad . \quad 4.17$$

These equations apply of course to spherical chambers only, but they indicate that for all rooms we get considerable assistance from reflection if we employ surfaces with large reflection coefficients. In the following table, the values of a and $\frac{1}{a}$ have been calculated for various values of m.

TABLE 4.02.—REFLECTION OF LIGHT.

Reflection Coefficient, m.	Absorption Coefficient, a.	Factor of Increase, $\frac{1}{a}$.
1·0	0	
0·95	0·05	20 0
0·90	0 10	10 0
0·85	0·15	6·67
0·80	0·20	5 0
0·75	0·25	4 0
0 70	0 30	3·33
0·65	0·35	2·85
0 60	0 40	2·50
0·55	0·45	2·22
0 50	0·50	2·0
0·45	0·55	1·81
0·40	0 60	1 67
0·35	0 65	1·53
0 30	0·70	1·42
0 25	0·75	1·33
0·20	0·80	1·25
0 15	0·85	1·17
0·10	0·90	1·11
0·05	0·95	1·05
0	1·0	1·0

The next table shows a number of diffuse reflection and absorption coefficients for various colours, as given by Dr L. Bell, in the Convention issue of the American Illuminating Engineering Society.* The table holds chiefly for wall-papers illuminated by incandescent lamps.

On studying this table we see that the light cream and yellow colours are by far the best, that apparently *light colours* such as grey and green absorb the light in an astonishing fashion, which is due to the fact that grey colours usually contain a mixture of black and red. The table was compiled for different finishes, but there appears to be little difference for all except for silk finishes, which absorb the light strongly. A polished silver mirror has a reflection coefficient of 0·90 to 0·95. White blotting-paper absorbs 18 per cent. of light, white drawing-paper 20 per cent., polished brass 25 to 30 per cent., ordinary foolscap 30 per cent., plain clean deal wood 55 per cent.

4.08. ILLUMINATION—FUNDAMENTAL CONSIDERATION.—The illumination E of an elementary area by an intensity I is expressed by

$$E = \frac{I}{L^2} \cos \theta \text{ (see equations 1.03}a\text{ and 1.04)},$$

* See also the *Illuminating Engineer*, 1908, p. 72.

TABLE 4.03.– TABLE OF DIFFUSE REFLECTION. (BELL.)

Colour.	m.	a	$\frac{1}{a}$.
Very faint grey-cream	0·64	0·36	2·77
Deep cream	0·60	0·40	2·5
Deep buff	0·58	0·42	2·38
Deep cream silvery	0·57	0·43	2·32
Faint ecru	0·55	0·45	2·22
Faint greenish	0·53	0·47	2·12
Yellow medium	0·53	0·47	2·12
Light yellow	0·49	0·51	1·96
Light strawberry silvery	0·49	0·51	1 96
Light bluish	0·47	0·53	1·89
Light strawberry-pink	0·43	0·57	1·75
Light grey	0·38	0·62	1·61
Faint yellow-green-grey	0·33	0·67	1·49
Salmon-buff	0·33	0·67	1·49
Pale bluish white	0·31	0·69	1·45
Light green and gold	0·28	0 72	1·38
Pale grey	0·27	0·73	1·37
Light ecru	0·26	0·74	1·35
Light green (stripes)	0·26	0·74	1·35
Silvery light green	0·23	0·77	1·3
Light grey-green	0·23	0·77	1·3
Pale pink	0·19	0·81	1·24
Light green (cartridge)	0·18	0·82	1·22
Deep yellow-grey	0·15	0·85	1·18
Medium crimson	0·12	0 88	1·14
Light red	0·10	0·90	1·11
Medium red	0·08	0·92	1·09
Deep green	0·06	0·94	1·06
Full green	0·06	0·94	1·06
Deep red	0·05	0·95	1·05

in which θ is the angle of the incident ray with the normal to the illumin-

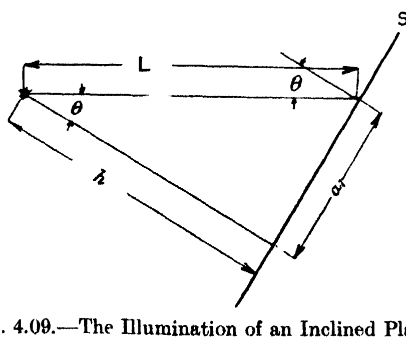


FIG. 4.09.—The Illumination of an Inclined Plane.

ated area, and L the distance of the source from this area. Consider the plane S in fig. 4.09. We see that

$$L^2 = a_1^2 + h^2,$$

and

$$\cos\theta = \frac{h}{\sqrt{a_1^2 + h^2}}.$$

whence

$$E = \frac{I}{a_1^2 + h^2} \cos\theta$$

$$= \frac{I}{h^2} \cos^3\theta \quad . \quad . \quad . \quad . \qquad 4.18$$

$$= \frac{Ih}{(a_1^2 + h^2)^{\frac{3}{2}}} \quad . \quad . \quad . \quad . \quad . \quad . \qquad 4.19$$

This holds for any plane, whether horizontal, vertical, or inclined.

4.09. HORIZONTAL ILLUMINATION. Consider a source L_0 fixed at a distance h above the area S to be illuminated. The illumination of any point P in this horizontal plane is then given by

$$E_h = \frac{I}{h^2} \cos^3\theta,$$

in which θ is the angle by which the ray is inclined to the vertical.

For the evaluation of E_h it is convenient to know the values of $\cos\theta$

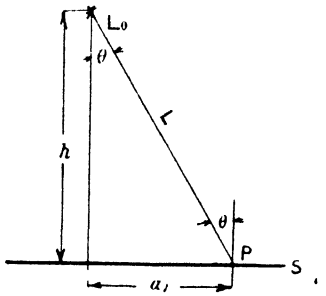


FIG. 4.10.- The Illumination of a Horizontal Plane.

and $\cos^3\theta$ for various values of θ, especially if we know the intensities of the illuminant under different angles against the vertical.

TABLE 4.04.—VALUES OF $\cos\theta$, $\cos^2\theta$, $\cos^3\theta$, AND $\cos^4\theta$.

Angles.	Cos θ.	Cos² θ.	Cos³ θ.	Cos⁴ θ.
0	1·0	1·0	1·0	1·0
5	0·996	0·991	0·988	0·982
10	0·985	0·970	0·956	0·939
15	0·966	0·933	0·901	0·870
20	0·940	0·883	0·830	0·780
25	0·906	0·822	0·745	0·676
30	0·866	0·750	0·649	0·563
35	0·819	0·671	0·550	0·450
40	0·766	0·587	0·450	0·345
45	0·707	0·500	0·354	0·250
50	0·643	0·413	0·266	0·171
55	0·574	0·329	0·189	0·108
60	0·500	0·250	0·125	0·0625
65	0·423	0·179	0·076	0·0320
70	0·342	0·117	0·040	0·013
75	0·259	0·067	0·0173	0·00449
80	0·174	0·0302	0·00524	0·000912
85	0·087	0·0076	0·00066	0·0000578
90	0·000	0·000	0·000	0·000

As an example take an arc lamp for which the intensities in the lower hemisphere are as follows:

Angle against the Vertical.	Intensity in Candles
0 degrees	2070
10 ,,	1980
20 ,,	2160
30 ,,	2700
40 ,,	3330
50 ,,	3420
60 ,,	3300
70 ,,	3000
80 ,,	2170
90 ,,	1820

If this lamp be fixed on poles 15 metres high, the ground illumination will be represented by fig. 4.11.

We see that the illumination is a maximum for $\theta = 0$ degrees. Suppose

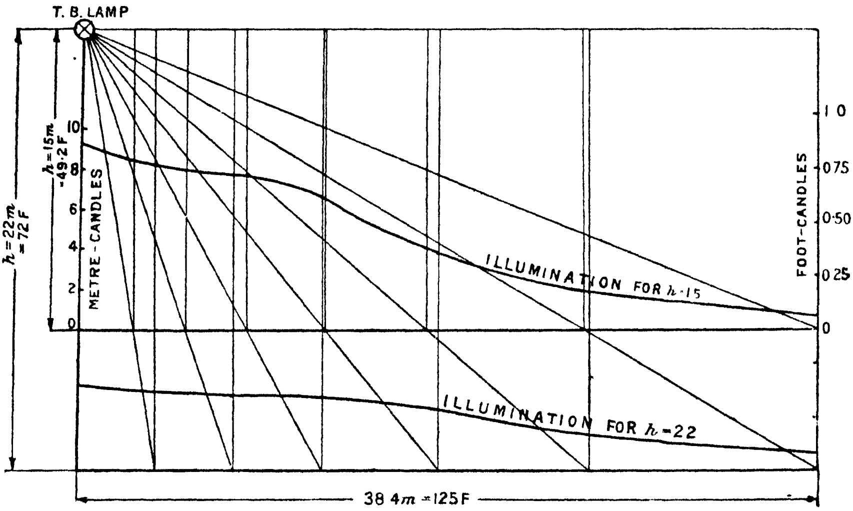


FIG. 4.11.—Illumination caused on the Road Surface by an Alba Lamp fixed on Poles 15 metres high.

that the lamp is to give a uniform illumination over a radius of 30 metres, what ought then to be the shape of the polar curve?

We obtain

$$I = E_h \frac{h^2}{\cos^3 \theta} \quad . \quad . \quad . \quad . \quad . \quad . \quad 4.20$$

$$= \overline{E}_h \frac{(a_1^2 + h^2)^{\frac{3}{2}}}{h} \quad . \quad . \quad . \quad . \quad . \quad 4.21$$

in which $\overline{E}_h$ represents now the uniform illumination. For $\overline{E}_h = 6$ metre-candles and $h = 15$ metres, the result is illustrated in fig. 4.12.

The two examples show that, if we wish to produce a uniform illumina-

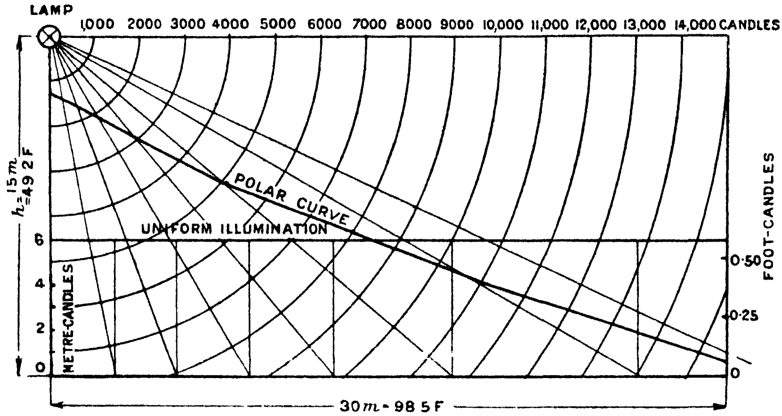


FIG. 4.12.—Polar Curve of an Arc Lamp for Uniform Illumination.

tion, the light flux must be chiefly directed towards the horizontal through the centre of the arc.

4.10. NUMBER OF LAMPS REQUIRED. In most cases the illumination by a single lamp is insufficient, and a number of lamps are required.

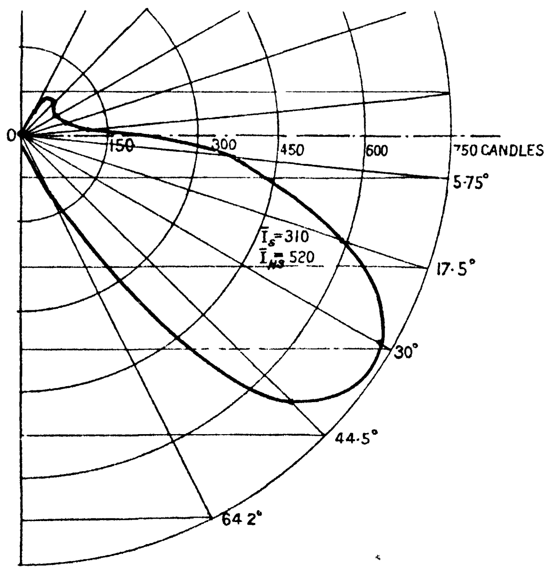


FIG. 4.13.—Polar Curve of an Ordinary Arc Lamp with Vertical Carbons.

The area which can be effectively illuminated by a single lamp depends upon the size of the lamp, the illumination required, the height of the lamp above the area, and the distribution of the light. When a number of lamps take part in the illumination, we must plot the illumination curve of each lamp and add the ordinates. For two lamps with polar curves as shown in fig. 4.13, we obtain the fig. 4.14.

If we have a single symmetrical source of light (with diffusing globes we may assume most sources to be symmetrical), the illumination will be the same for all points equidistant from the source. If we join all these

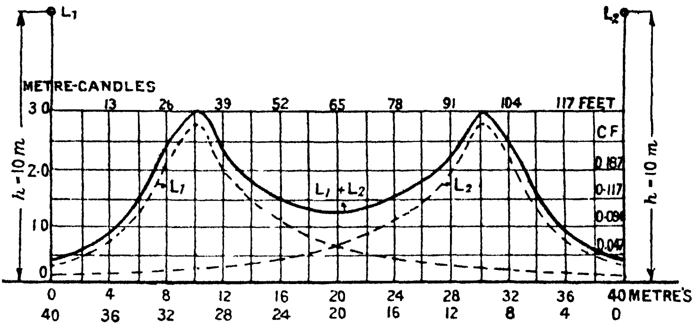


FIG. 4.14.—Illumination by Two Lamps.

points, we obtain the so-called contour or equipotential lines, which in this case are circles. Fig. 4.15 represents the contour lines obtained from an arc lamp with a polar curve as shown in fig. 4.13. Fig. 4.16 shows the

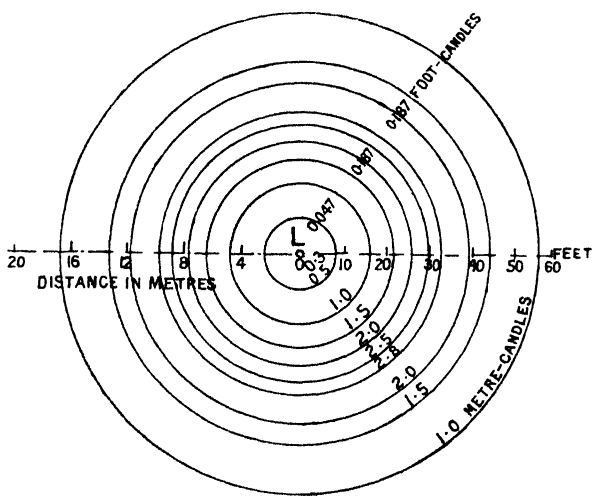


FIG. 4.15.—Contour Lines for Single Lamp.

contour lines for two arc lamps obtained by adding the values of two such figures as 4.15, and fig. 4.17 for three lamps placed at the corners of an equilateral triangle. The lamps are fixed in all cases 10 metres (32·8 feet) above the illuminated area.

The variation in the illumination for different heights of the illuminant is illustrated in fig. 4.11. We have

$$E_{h_1} = \frac{I}{h_1^2} \cos^3 \theta, \quad E_{h2} = \frac{I}{h_2^2} \cos^3 \theta,$$

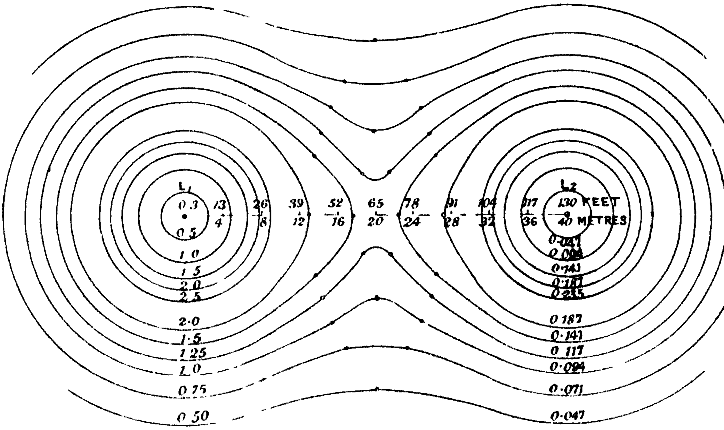


FIG. 4.16.—Contour Lines for Two Arc Lamps.

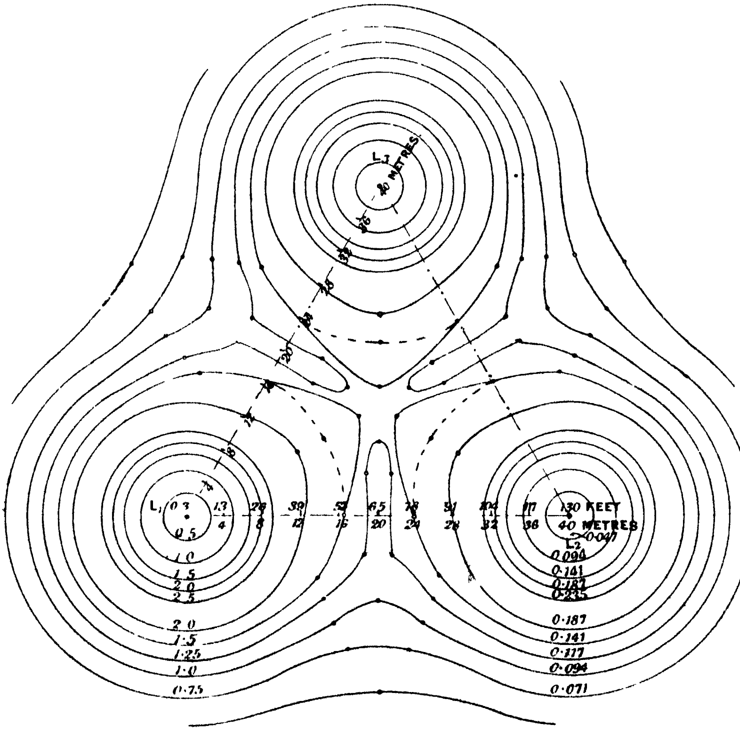


FIG. 4.17.—Contour Lines for Three Arc Lamps.

whence for the same ray

$$\frac{E_{h_1}}{E_{h_2}}=\frac{h_2^2}{h_1^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad 4.22$$

i.e. the horizontal illuminations vary inversely as the square of the heights of the lamps, so that we can easily find the illumination for a given height and type of lamp if the illumination is known for any other height. We have

$$E_{h_1}=E_{h_2}\frac{h_2^2}{h_1^2}.$$

It is also useful to know how the illumination varies if a lamp is replaced

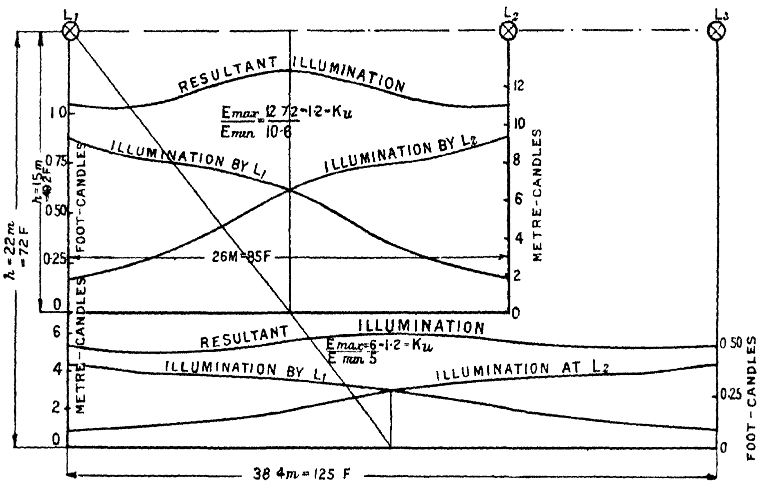


FIG. 4.18.—Uniformity of Illumination.

by another having the same distribution but a greater or smaller intensity.

$$E_{h_1}=\frac{I_1}{h^2}\cos^3\theta,$$

$$E_{h_2}=\frac{I_2}{h^2}\cos^3\theta,$$

whence

$$\frac{E_{h_1}}{E_{h_2}}=\frac{I_1}{I_2} \quad . \quad . \quad . \quad . \quad . \quad 4.23$$

i.e. the illuminations vary directly as the intensities.

If the illumination is to be given by two similar lamps, its uniformity is not altered if we alter the heights of the lamps as long as we vary the distance between them in a similar manner, *i.e.* as long as $\frac{h_1}{h_2}=\frac{a_1}{a_2}$ (see fig. 4.18). The degree of uniformity of the illumination may be expressed by the following ratio :—

$$K_u=\frac{E_{max.}}{E_{min.}} \quad . \quad . \quad . \quad . \quad . \quad 4.24$$

It is sometimes called the diversity factor. The nearer its value lies to unity, the greater is the uniformity of the illumination. In determining K_u, average maximum and minimum values should be taken, not freak values.

4.11. VERTICAL ILLUMINATION.—The illumination given by the source L_0 at any point P on the vertical plane S is expressed by (see fig. 4.19)

$$E_v = \frac{I}{L^2} \sin \theta,$$

and as

$$L^2 = h_1^2 + a_1^2 = \frac{a_1^2}{\sin^2 \theta},$$

we obtain

$$E_v = \frac{I}{a_1^2} \sin^3 \theta \quad . \quad . \quad . \quad . \quad . \quad . \quad 4.25$$

$$= \frac{I a_1}{(h_1^2 + a_1^2)} \quad . \quad . \quad . \quad . \quad . \quad . \quad 4.26$$

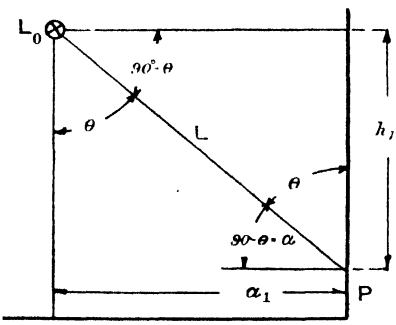


FIG. 4.19.—Illumination on a Vertical Plane.

The determination of the illumination of a vertical plane offers therefore nothing new. We may even use Table 4.01 if we call the angle $(90° - \theta) = \alpha$ and replace in the table θ by α.

4.12. INDIRECT ILLUMINATION.—The greatest degree of uniformity in the illumination is obtained when employing the indirect method. By means of a reflector below the radiator, light is directed upwards against another reflector, or against the ceiling, where it is scattered and reflected downwards more or less perfectly diffused.

4.13. ILLUMINATION BY A SMALL ILLUMINATED AREA.—Let an elementary area ΔS be struck by a flux $\Delta\phi$, then its own illumination is $\frac{\Delta\phi}{\Delta S}$, and the flux which it radiates again is $m\frac{\Delta\phi}{\Delta S}$, where m is the reflection coefficient. Suppose now this illuminant area illuminates another surface at a distance L (see fig. 4.20). The candle-power of the illuminant is $\Delta S i$, where i is the brightness, whence the illumination at

O in S_1 is

$$E_1 = \frac{\Delta S i}{L^2},$$

and since

$$\frac{\Delta S}{L^2} = \Delta\omega = \text{the spherical angle},$$

it follows that

$$E_1 = \Delta\omega i \quad . \quad . \quad . \quad . \quad . \quad 4.27$$

It will be noticed that in this nothing is altered if we replace ΔS by ΔS^1 (since the angle $\Delta\omega$ is unchanged) as long as the brightness remains constant.

Take next a larger area S illuminating an area S_1 at a distance L (see fig. 4.21). The question is, what will be the illumination of the point O in

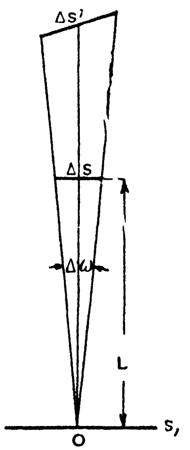


FIG. 4.20.—Illumination by a Small Illuminant Area.

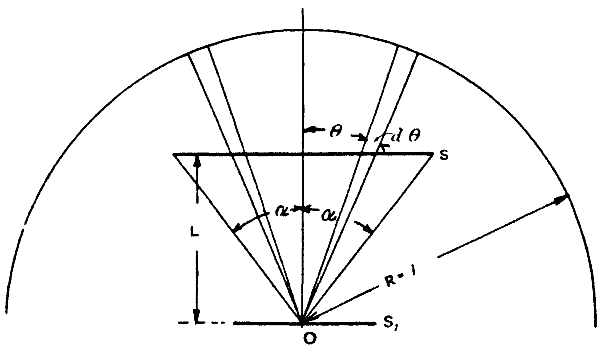


FIG. 4.21.—Illumination by an Illuminant Surface.

S_1? We determine the illumination as caused by an elementary circular *zone* ΔS which, as we have already seen, is expressed by i multiplied by the spherical angle multiplied by the cosine of the angle of incidence. The spherical angle is $2\pi \sin \theta R d\theta$, and for $R=1$ it is $2\pi \sin \theta d\theta$; hence the illumination is

$$dE = i 2\pi \sin \theta \cos \theta d\theta$$
$$= \pi i \sin 2\theta d\theta,$$

and

$$E = \int_{\theta=0}^{\theta=a} dE = \pi i \int_0^a \sin 2\theta d\theta$$
$$= \pi i \sin^2 a \quad . \quad . \quad . \quad . \quad . \quad . \quad 4.28$$

For $a = 90$ degrees,

$$E = \pi i \quad . \quad . \quad . \quad . \quad . \quad . \quad 4.29$$

This is the case when $L=0$, *i.e.* when S_1 coincides with S, or when S is infinitely large. It also holds approximately for rooms in which all walls and ceilings radiate uniformly with a brightness i, and also for the sky if the latter is uniformly clouded. The sky brightness on a cloudy day may thus be determined by measuring the illumination of the ground and dividing it by π.

Equations 4.27 and 4.28 hold for the point O only. As we move away from this point, the illumination decreases. If we consider the light concentrated on a small area, for which the distribution curve is a circle

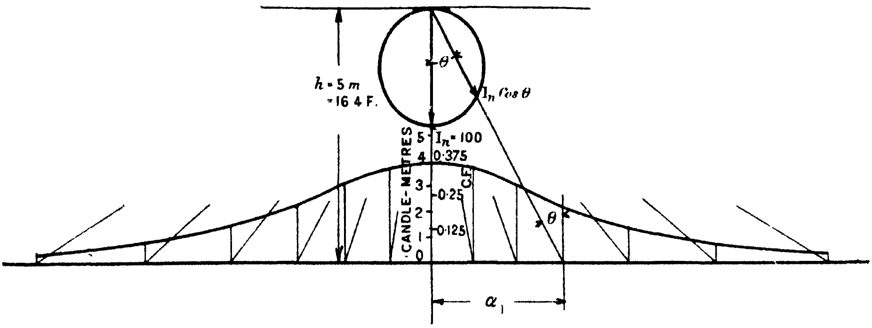


FIG. 4.22.

with I_n as the maximum intensity, then the illumination for any point P is expressed by

$$E=\frac{I_n \cos\theta \cos\theta}{L^2},$$

and as

$$L=\frac{h}{\cos\theta}=\sqrt{a_1^2+h^2}$$

$$E=\frac{I_n}{h^2}\cos^4\theta \quad . \quad . \quad . \quad . \quad . \quad . \quad 4.30$$

$$=\frac{I_n h^2}{(h^2+a_1^2)^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad 4.31$$

The results are plotted in fig. 4.22 for $I_n=100$ candles and $h=5$ metres (16·4 feet).

In most cases the radiating surface is of considerable extent, so that for the same total intensity the illumination will be smaller directly under the lamp, and greater as we move away from point O. This means that the illumination improves in uniformity. Its value under the lamp can be obtained with the aid of equation 4.28. Suppose the diameter of the radiating surface is 2 metres, then for $h=5$ metres,

$$\sin\alpha=\frac{1}{\sqrt{26}}.$$

For $I_n=100$, and $S=R^2\pi=1^2\pi=3{\cdot}14$, and $i=\frac{100}{3{\cdot}14}=31{\cdot}8$, we obtain directly under the lamp

$$E=\pi i \sin^2 a$$
$$=31\cdot 8\pi \times \frac{1}{26}$$
$$=3\cdot 85 \text{ metre-candles,}$$

whereas according to equation 4.29 it is 4 metre-candles. In this case the reduction is only about 4 per cent. With $R=h$ we should have found $E=2$ metre-candles, which means a reduction of 50 per cent. The degree of uniformity has, however, now greatly improved.

For any point on an area parallel to the radiating surface, *i.e.* for any radius R of the radiating surface, any h and any a, we obtain

$$E=\frac{\pi i}{2}\left[1-\frac{a_1^2+h^2-R^2}{\sqrt{a_1^4+2(h^2-R^2)a_1^2+(h^2+R^2)^2}}\right]^* \quad . \quad 4.32$$

which holds for any point except for $h=0$ when $a_1<R$.

If in equation 4.32 $a_1=0$, we obtain $E=\frac{\pi i}{2}\left[\frac{2R^2}{h^2+R^2}\right]=\pi i \sin^2 a$, which is equation 4.28. h is the same as L in fig. 4.21.

* P. D. Foote, *Bull. of Bureau of Standards*, No. 263, March 1916

CHAPTER V.

PHOTOMETRIC APPARATUS.

5.01. PHOTOMETERS. Photometers are usually classed as follows:

(1) Intensity photometers employed for comparing the candle-power of two sources of light.

(2) Illumination photometers, for measuring the illumination of streets, squares, halls, rooms, etc.

(3) Spectro-photometers, in which selected rays from the spectra of two sources are compared as regards their luminous intensity.

5.02. INTENSITY PHOTOMETERS. There is a very large variety of this class of photometer on the market. Only a few representative types will be discussed here.

The Bunsen Grease-Spot Photometer.—This is based on the equalisation of the illumination all over a screen, the greater part of which is opaque and the rest transparent. The transparent part, made so with grease (oil or paraffin wax), allows more light to pass than the rest of the screen, so that if a light be placed, say, on the left, the opaque part which reflects all the light will appear bright, the grease-spot darker. Viewed from the right-hand side, the grease-spot appears light, the rest of the screen dark. Suppose now we place here another light, then the distance of the screen from the two sources of light may be so adjusted that the grease-spot disappears on one side.

Next we adjust until it disappears now on the other side and take the mean of the two readings.

We then have

$$\frac{I_1}{I_2}=\frac{L_1^2}{L_2^2}.$$

If I_2 be the standard lamp, the candle-power of the test lamp is given by

$$I_1=I_2\frac{L_1^2}{L_2^2}=I_2\frac{L_1^2}{(L-L_1)^2} \qquad . \quad . \quad . \quad 5.01$$

in which L_1 and L_2 are the corresponding distances, and L their sum.

The accuracy to be expected lies within ± 3 per cent. This is due to the fact that the grease-spot is not perfectly transparent. Even the above accuracy can be expected only by the employment of mirrors, as shown in fig. 5.01, in order to be able to view both sides of the screen simultaneously. Moreover, the screen should be rotatable through 180 degrees, so as to neutralise any difference in the nature of the two illuminated surfaces. The distances L_1 and L_2 must not be too small, as equation 1.04 and the relationship $\frac{I_1}{I_2}=\frac{L_1^2}{L_2^2}$ hold for point sources only. Again, we should not look too long at the screen, as it tires the eyes and does not increase the accuracy. It is preferable rather to make a larger number of observations rapidly.

The difference in the nature of the two sides of the grease-spot screen may be determined as follows: Place the screen in the middle of the bench, and on the back of it a light. The direct rays of the latter are kept off the grease-spot screen by means of an opaque disc. On the right and on the left from the grease-spot disc and at equal distances place two

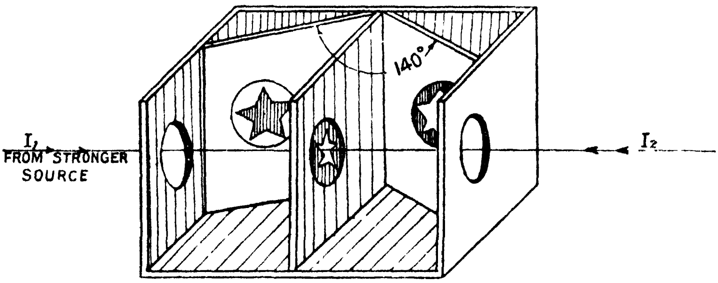


FIG. 5.01.—Bunsen Grease-Spot Photometer.

mirrors, cut from the same piece, which reflect the light on the photometer screen. If both sides of the latter are equal in nature, they will appear equally well illuminated; if not, the screen must be moved through a length L^1 one way or the other, until equality is obtained. If L be the distance between the mirrors, L_0 that of the light from the axis of the photometer, then, as may easily be proved, the measure of the inequality of the two sides of the screen, as regards whiteness, is given by

$$\frac{4L^1}{L+\frac{LL_0}{L^2}}.$$

When L_0 is small this changes into $\frac{4L^1}{L}$ (nearly).

5.03. RITCHIE'S WEDGE PHOTOMETER.—This instrument is shown in fig. 5.02. Two adjacent sides of a white prism (pressed magnesia or plaster of Paris), inclined at equal angles to the incident rays, serve as the two illuminated surfaces which are to be compared. When both are equally bright, the edge disappears. Care must be taken that the latter is not blunted, as this would compel the eye to travel from a bright surface over a less illuminated part to another bright area, whereby the accuracy is impaired.

For accurate tests it is essential that both surfaces of the wedge should be equally inclined. The best angle is about 70 degrees. If the angle is smaller, the surfaces are brighter, but less is seen of them; whereas if the angle is greater, the illumination decreases too much.

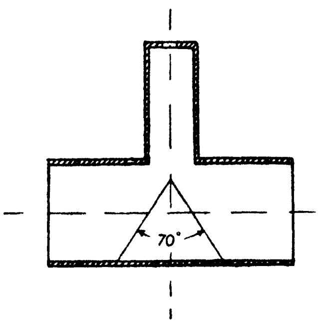


Fig. 5.02.—Ritchie's Wedge Photometer.

5.04. LUMMER-BRODHUN PHOTOMETER.—This is a superior kind of grease-spot photometer, the "grease-spot" of which is perfectly transparent. A diagrammatic sketch of this type is shown in fig. 5.03, a photograph in fig. 5.04.

A white magnesia slab S is illuminated on both sides by the lights to be compared (fig. 5.03). By means of two totally reflecting prisms, A and B, the diffused light is sent through a compound prism C D, which takes the place of the grease-spot in the Bunsen photometer. This compound prism consists of two right-angled prisms, placed base to base. One

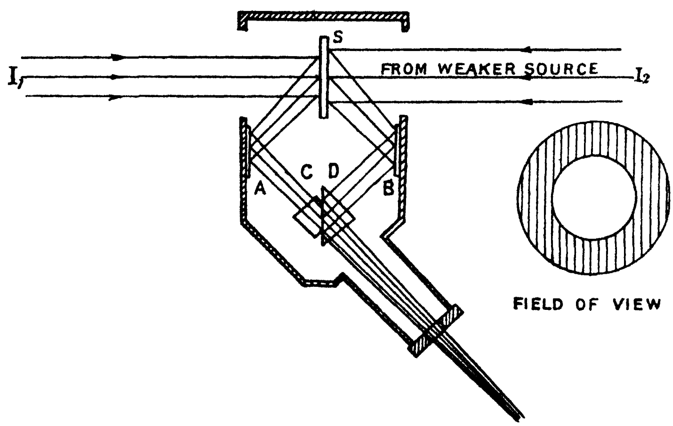


Fig. 5.03.—Arrangement of the Lummer-Brodhun Photometer.

of the prisms has parts of its hypotenuse surface taken off by sand-blasting, so as to be at a lower level than the rest. The hypotenuses of the two prisms are then put together, being faced to come into optical contact where they touch. When such a prism is viewed by means of a telescope and an eye-piece in the proper position, we see the field of view divided into two parts, one of which is illuminated by the diffused light scattered from one side of the magnesia slab, and the other part by light scattered from the other side of the screen. By adjusting the distances of the lights, the brightness of the two parts of the field of view may be equalised The accuracy obtainable with this type of photometer when comparing lights of similar colour lies within 1 0 per cent

The accuracy may be further increased by employing the contrast type of photometer In this, the hypotenuse of one part of the compound prism is shaped as shown in fig 5 05, the lower levels being obtained with

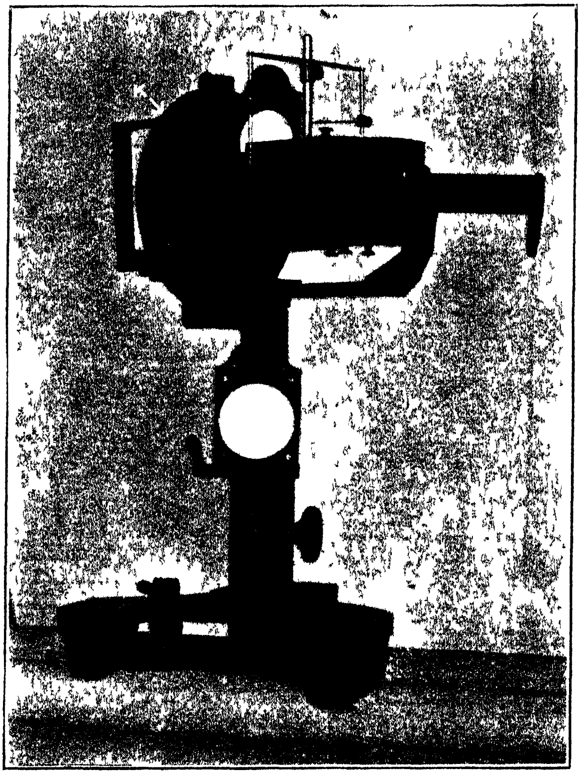


FIG 5 04 Lummer Brodhun Photometer

sand-blasting The raised parts allow all the light to pass, the lower parts reflect all, as shown The observer consequently sees the recessed parts illuminated from the right, the raised parts from the left of the screen

In order that the fields R and L may come into contrast, glass plates G_1 and G_2 are so arranged that the fields R_2 and L_2 remain uninfluenced, whereas R_1 and L_1 are somewhat darkened

The distance of the screen from the two sources of light has been adjusted properly when the fields R_1 and L_1 stand out equally prominently from the slightly brighter background.

The photometer shown in fig 5 04 is suitable for comparing lights under different angles, by the application of a divided circle K In order to be able to test whether the angles of incidence of the rays from the two sources are the same, a shadow-thrower S H is employed. A steel rod is screwed into the lid of the frame and carries by means of two vertical rods the horizontal rods *h*. The magnesia slab is replaced by a white carton disc, provided with black lines (it is placed at the foot of the

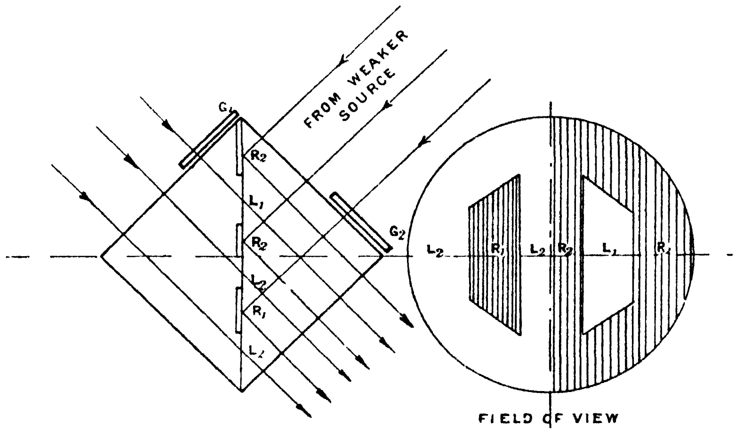


FIG. 5.05.—Contrast Type of Lummer-Brodhun Photometer.

photometer). By a simultaneous adjustment of the rods of the sleeve and by turning of the photometer, the shadows of the two rods may be made to fall on the horizontal black lines of the carton. The paper disc is afterwards again replaced by the magnesia slab, and the comparison takes place as before.

The Lummer-Brodhun contrast photometer is up to the present the

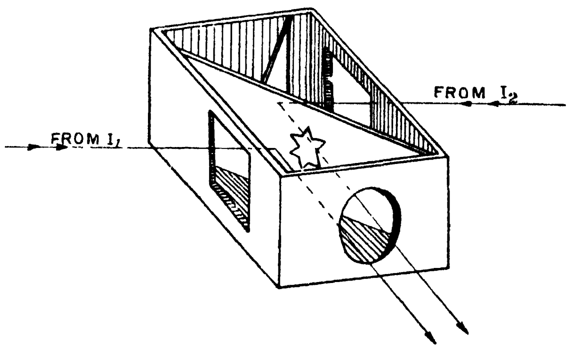


FIG. 5.06.—Trotter's Intensity Photometer.

most accurate intensity photometer invented, and is probably used more than any other type. It is, however, a somewhat expensive instrument.

5.05. TROTTER'S PHOTOMETER.—This apparatus is illustrated in fig. 5.06 and is based on the equalising of the illumination of two white surfaces inclined at equal angles (35 degrees). One screen has a hole or holes in it through which the observer looks at the other screen. The material of the screens is white cardboard. If one hole only is used in the nearer screen, it is best to have it star-shaped, with the star distorted so that when seen at an angle it appears symmetrical. The edges must be carefully bevelled. The screens are equally illuminated when the holes apparently vanish.

The apparatus is easily made, even by an amateur, and is quite as accurate as a more expensive grease-spot photometer.

5.06. POLARISATION PHOTOMETERS. - These instruments are based on the equalisation of two fields of light by weakening one of them by means of crossed polarising prisms. The theoretical range of such an instrument is infinite.

A ray of ordinary white light, either from the sun or from an artificial source, when passed through a crystal of Iceland spar is separated into two rays of practically equal intensities. These are called the ordinary and extraordinary rays. Let the two rays be received on the surface of a plate of glass held at a fairly high obliquity to the ray so as to reflect it through an angle greater than a right angle. It will be found that for most positions of the reflecting plate two rays on emerging will differ in intensity. Thus we see that the two doubly refracted rays have sides, or are unsymmetrical about the direction of propagation, and it is this sideness, or laterality, which is known as polarisation.

In unpolarised light the vibrations take place in all possible planes containing the ray, the sole condition being that they are perpendicular to it. When the light is passed through the doubly refracting crystal, every vibration is decomposed into two components at right angles to each other, the exact directions of which depend upon the position of the Iceland spar with respect to the ray. The complete separation of the two is usually effected by means of a Nicol prism, which is a suitable length of Iceland spar cut along the short diagonal and joined together again by a thin layer of Canada balsam. The refractive index of the latter for any light is between the refractive indices of the Iceland spar for the ordinary and extraordinary rays. It is therefore possible to get rid of what is known as the ordinary ray by total reflection, while the extraordinary ray passes on practically unaffected. The Nicol prism allows only one ray to pass; but this ray is polarised in a certain plane. To the ordinary untrained eye this ray does not differ from common unpolarised light. To prove that the light transmitted by the Nicol is in this peculiar condition, we take a second Nicol and view the light through it. When the two Nicols are placed so as to have the similar crystalline faces parallel to one another, the second Nicol will transmit the light which has passed through the first Nicol; but if the second Nicol is rotated through a right angle about the ray as axis, it will completely cut off the light. We may suppose the first Nicol to transmit light made up of vertical vibrations. The two together, being what is called crossed, cut the light off entirely. If either is rotated now, light will begin to appear.

The first Nicol is called the polariser, the second one the analyser, because by it the polarised condition of the ray after it has passed through the polariser is recognised.

5.07. DR MARTENS' POLARISATION PHOTOMETER.* The construction of this instrument will be seen from figs. 5.07 and 5.08. The column S carries at its upper end a sleeve M which supports the lamp-holder G for the comparison glow lamp g, and the polarisation photometer; also the rotatable tube T, the inclination of which is read from a divided circle A. The light from the source to be compared strikes the magnesia slab F, which scatters it on the reflecting prisms P and Q. It

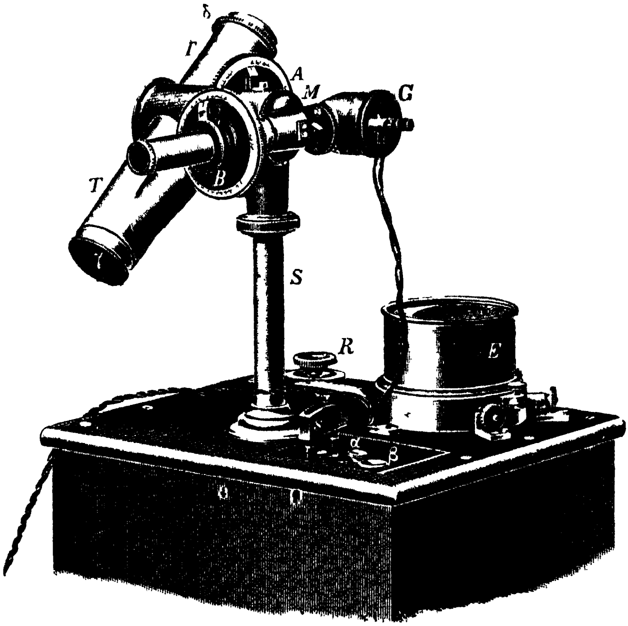


FIG 5.07 Martens' Polarisation Photometer (Elevation)

then passes through the blend and the lens o to the doubly refracting prism W on the polarising Nicol 2, and then through the analysing prism N, lenses L and H, into the eye of the observer. The light from the comparison lamp takes a similar course, except that it strikes surface 1 of the Nicol and vibrates in a direction perpendicular to that of the polarised rays from surface 2. Equality of the fields of view is obtained by rotating the Nicol prism N—its position with regard to the polarising prism being shown on the divided circle B—until the surfaces 1 and 2 appear equally illuminated, *i.e.* when the edge between them apparently disappears. The intensity of the source of light to be tested is then given by $I = CL^2 \tan^2 \theta$, where L is the distance of the light from the slab F, θ the angle read on the divided circle B, and C a constant of the instrument. The latter is found as follows:—

We place a standard lamp (say a 10-c.p. pentane lamp) instead of the

* *Verh. d. D. Phys. Ges.*, vol. v.

light to be compared at a distance L_1 from the slab F, then

$$C = \frac{10}{L_1^2 \tan^2 \theta_1},$$

where θ_1 is the angle now read on the circle B. For θ_1 we have two values, and hence we obtain also two constants. To avoid errors in

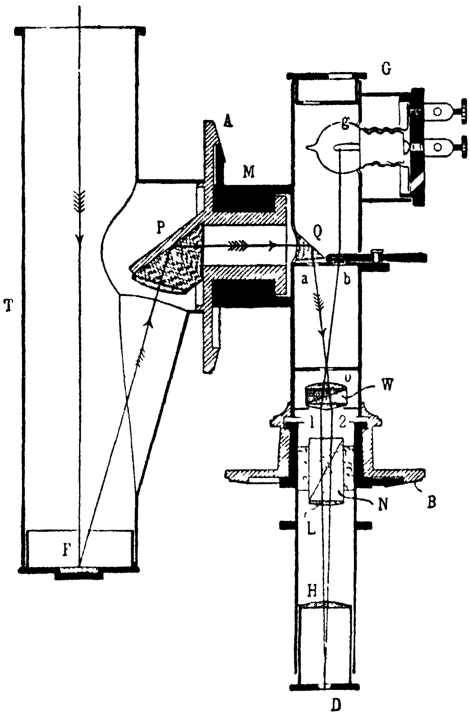


Fig. 508.—Martens' Polarisation Photometer (Sectional View).

readings and mechanical errors of the scale, it is advisable to proceed as is usual with geodetic instruments, as indicated below:

θ_1.	θ_2.	θ_3.	θ_4.
14·9	165·0	194·8	345·0
14·8	164·8	194·9	344·8
15·1	164·9	195·0	344·9
Mean 14·9	164·9	194·9	344·9
+180·0	..	180·0	..
			..
194·9		374·9	..
$-\theta_2$=164·9		θ_4=344·9	..
θ_5= 30·0		θ_6= 30·0	..

$$\theta = \frac{\theta_5 + \theta_6}{4} = \frac{30{\cdot}0 + 30{\cdot}0}{4} = 15{\cdot}0.$$

The above equations are easily proved when the fact is taken into consideration that the light which emerges from a pair of crossed Nicol prisms is proportional to the square of the cosine of the angles between the principal planes of the prisms, and that the vibration of the light from the comparison glow lamp is at right angles to that from the source to be compared.

5.08. GLASSES FOR REDUCING LIGHT. It has already been indicated in Chapter I. that the inverse square law holds for point sources only, but that this law could be applied for other sources as long as the distance of the source from the photometer were at least twenty times the greatest dimension of the light. When comparing an arc lamp of great candle-power with a standard glow lamp, this would involve a photometer bench of great length, 10 metres or more - since the glow lamp must not be brought too close to the photometer, which is rarely available. Endeavours were therefore made to manufacture glasses, by means of which the incident ray is reduced in a definite ratio. Such glasses, in order to be accurate, should be perfectly neutral, *i.e.* they should reduce all the radiations from the red to the violet in the same ratio. Unfortunately, it has been impossible to manufacture such a glass, and the best types available answer with fair accuracy for white light only, and are not reliable in studying coloured light.

The glass employed at present is mostly a mixture of cobalt blue and brownish smoke, or yellowish.

The polarisation photometer may also be used in such cases, as its range is theoretically infinite. These instruments are, however, extremely expensive, as large Nicols are essential for accurate work. They are inaccurate for very low illuminations (see paragraph 5.10).

Ives and Luckiesh * advocate opaque line gratings on clear glass, which are made by ruling through a layer of wax on glass, then etching the glass, and finally filling in the etched lines with opaque paste. The gratings may be made of varying fineness of spacing and of various ratios of opaque to clear spaces. By proper choice of the latter, transmission from 80 per cent. down to 10 per cent. may be secured.

The transmission may even be made variable by superposing two black-line gratings with their lines parallel, separated slightly, as, for instance, by a thickness of paper.† They are mounted so as to rotate about an axis parallel to the grating-lines. In consequence of the rotation, the lines, as seen from a distance, overlap more or less, thereby changing the transmission.

With two gratings of 60 lines to the inch, opaque and transparent spaces equal, and separated by a thickness of paper, a rotation of 40 degrees varied the transmission from a maximum to zero.

Krüss also proposes to employ two such screens, but to alter their

* *Physical Review*, vol. xxxii. p. 522, 1911.

† Ives, *Electrical World*, vol. lix. p. 598, 1912.

lateral position by means of a micrometer screw. The transmission becomes zero when the dark lines in one screen are superimposed over the clear spaces in the other. The micrometer screw may be calibrated in terms of the light transmitted.

The screens may easily be fitted to a Lummer-Brodhun photometer, and as the observer only sees the prisms illuminated by the white screen and not the screen itself, he does not notice inconvenient shadows in the field of view.

Experiments have shown that for all practical purposes such screens are almost perfectly neutral and may be employed for all kinds of illuminants.

Dispersion Lenses.—Light may also be reduced by means of dispersion lenses (concave). The principle involved is illustrated in fig. 5.09.

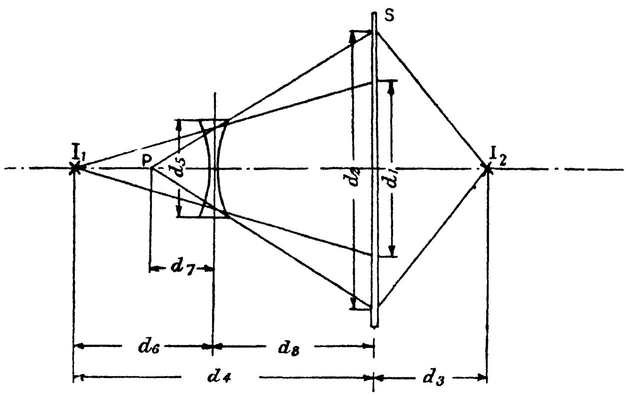


FIG. 5.09.—Principle of Dispersion Lenses.

Let us assume that in the first case the lens has been removed, then the illumination of an area with diameter d_1 is

$$E_1 = \frac{\phi_1}{d_1^2 \pi}.$$

If now the lens is inserted, the light is dispersed, so that the cone of light becomes shorter, but of a greater base—the rays appear to come from P—and the illumination now is

$$E_2 = \frac{\phi_1}{d_2^2 \pi} \quad . \quad . \quad . \quad . \quad . \quad . \quad 5.02$$

whence

$$\frac{E_1}{E_2} = \frac{d_2^2}{d_1^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad 5.03$$

The position of the screen is next so adjusted that equality of the optical fields is obtained; then

$$E_3 = \frac{I_2}{d_3^2} = E_2,$$

and

$$\frac{E_1}{E_2}=\frac{E_1}{E_3}=\frac{d_2^2}{d_1^2}=\frac{I_1}{I_2}\times\frac{d_3^2}{d_4^2} \qquad . \quad 5.04$$

We have further (see also fig. 5.09):

$$\frac{d_1}{d_5}=\frac{d_4}{d_6} \qquad 5.05$$

$$\frac{d_2}{d_5}=\frac{d_7+d_8}{d_7} \qquad . \quad 5.06$$

$$\frac{1}{d_7}=\frac{1}{d_6}+\frac{1}{l} \ . \qquad 5.07$$

where l is the focal length (negative) of the lens. We also have

$$\frac{d_2}{d_1}=\frac{d_7+d_8}{d_7}\times\frac{d_6}{d_4},$$

whence

$$\frac{d_2^2}{d_1^2}=\left(\frac{d_7+d_8}{d_7}\ \frac{d_6}{d_4}\right)^2,$$

and

$$\frac{E_1}{E_2}=\frac{d_2^2}{d_1^2}=\left(\frac{d_7+d_8}{d_7}\times\frac{d_6}{d_4}\right)^2,$$

$$=\frac{I_1}{I_2}\times\frac{d_3^2}{d_4^2},$$

and

$$I_1=I_2\frac{d_4^2}{d_3^2}\left(\frac{d_7+d_8}{d_7}\times\frac{d_6}{d_4}\right)^2 \qquad 5.08$$

From 5.07 it follows that

$$d_7=\frac{d_6\times l}{d_6+l}.$$

Substitution into 5.08 produces, after arranging,

$$I_1=\frac{I_2}{d_3^2}\left(d_6+d_8+\frac{d_6\times d_8}{l}\right)^2 \qquad 5.09$$

and, since

$$d_6+d_8=d_4,$$

$$I_1=\frac{I_2}{d_3^2}\left(d_4+\frac{d_6\times d_8}{l}\right)^2 \quad . \qquad . \qquad . \quad 5.10$$

The lens gives the greatest effect when $d_6=\frac{1}{2}d_4$.

Equation 5.10 would be correct if the lens did not absorb any light. To make up for this we place on the other side of the photometer in the rays of the second lamp a piece of plane glass the thickness of which is the same as that of the thinnest part of the lens.

The focal length l is found as follows: We employ two lamps of nearly equal intensity; place the one at zero of the photometer scale, the other at d' and the screen at d'' from zero, so as to obtain equality of the field of view. Next place the lens at $\frac{d''}{2}$ and again obtain equality by moving the second lamp further away from the screen, say to d''' from zero; the focal length is then expressed by

$$l=\frac{d''}{4}\times\frac{d_1}{d'''-d'} \qquad . \quad . \quad . \quad . \quad . \qquad 5.11$$

The employment of dispersion lenses is, of course, not nearly as convenient as that of neutral reduction glasses, especially if the latter are of the variable line-grating type. For every new position of the photometer screen new calculations have to be made, and for very accurate work it would also be necessary to see that the piece of glass used for finding the transmission of the lens comes from the same material from which the lens was manufactured, since not even all clear glasses transmit all radiations equally well. For these reasons dispersion lenses are but little used in photometry. Where no reliable glasses are available, the variable aperture disc is preferred.

5.09. VARIABLE APERTURE DISC PHOTOMETER. This is based upon the discovery that when a ray of light is obstructed by a rapidly rotating disc with a sectoral aperture, whereby the light is allowed to pass on at definite intervals, the intensity of the emerging ray is reduced in the ratio of $\frac{\theta}{360^\circ}$, where θ is the angle of the opening. The variable aperture disc may be kept stationary and the lenses of the instrument rotated.

5.10. PHOTOMETERS FOR LIGHTS OF DIFFERENT COLOURS.—With a Lummer-Brodhun contrast photometer on a bench 3 metres (10 feet) long, when comparing lights of similar colour, we may obtain accuracies within less than 1 per cent. If, however, the colours differ considerably, the accuracy is greatly impaired. The results usually vary for different observers. Broca, Jouast, and Laporte * report differences amounting to 100 per cent. when testing neon and mercury vapour lamps by different persons. The reasons for these results have already been explained in Chapter III., paragraph 3.04. The difficulties are the greater the smaller the illumination of the photometer screen. In very weak light red is not seen at all and appears black. The measurements are further affected by the distance of the eye of the observer from the photometric surfaces, the angle of inclination at which they are seen, and the size of the latter.† In the laboratory, the eye is, moreover, a rested one and possesses a somewhat different colour sensation to what it would experience in a position where the light is later installed. We should therefore see that the illumination of the photometer screen is about of the same magnitude as that which the lamp is expected to provide in practical use. From fig. 3.02 it follows that for an illumination above 10 metre-candles (1 foot-candle) the colour effects are of little importance.

* *Bull. Soc. Int. des Electriciens*, February 1913.

† Dow, *Phil. Mag.*, August 1906.

These considerations show that polarisation photometers, which are of the extinction class, should be employed with discretion, as the results are not at all reliable if the illumination is low, say, below 1 foot-candle, since the eye is then in an abnormal condition.

It must also be obvious that, if equality of brightness photometers are employed for comparing lamps differing widely in colour, the photometer screen should be well illuminated. The illumination should preferably be $2\frac{1}{2}$ foot-candles. The Lummer-Brodhun contrast instrument will then give fairly reliable results, which, in the author's opinion, are practically as satisfactory as those obtained with a Flicker photometer (see paragraph 5.13).

5.11. VISUAL ACUITY. Another system of testing lights of different colours might consist in determining the ability of the eye to distinguish

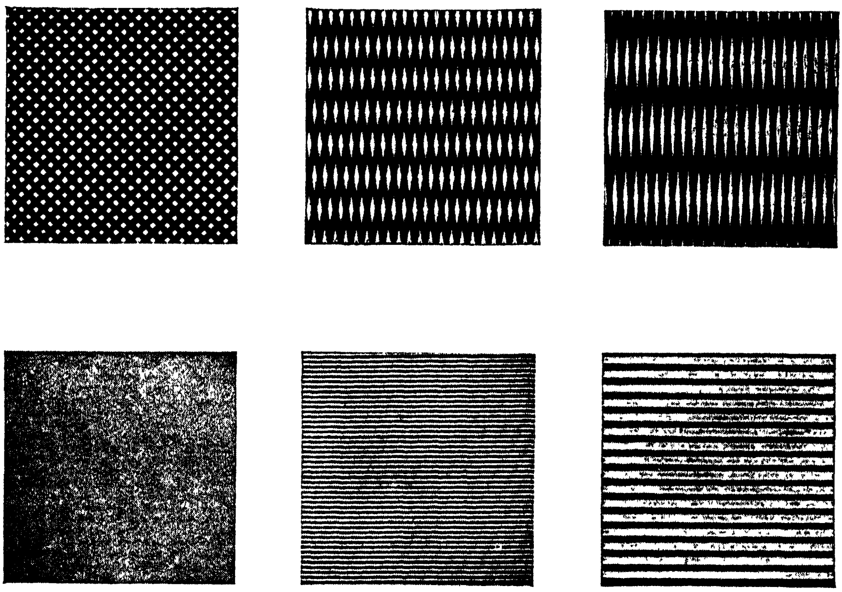


FIG. 5.10.—Test Gratings Superposed at Various Angles.

fine details, this being also a function of the illumination or brightness. As a matter of fact, this is really the most logical way of comparing lights, or rather illuminations, of different colours, as otherwise a red light can never be equal to, say, a green one, just as ebony is not equal to oak. Weber used black concentric lines composed of progressively diminishing thickness on a white background. Unfortunately, the results obtained in this way by different observers vary very greatly. This is largely due to the fact that different persons employed different illuminations. If the illumination is high, the acuteness of vision lies near a wave-length of 57×10^{-6} centimetres, while, when it is very low, the wave-length is 52×10^{-6} centimetres only. An apparatus based on this principle will therefore be altogether unreliable unless the illumination is of a definite value and wave-length. Even then the results of different observers will vary, as it is difficult to find the exact position in which the eye sees two equal black lines or small letters equally well, or in which such lines or letters will just disappear. In other words, apparatus based on this principle lacks sensitiveness.

A better test object than black lines or letters is a pair of opaque line gratings on glass,* with the lines so close as to be indistinguishable. These are superimposed and rotated about an axis perpendicular to their surfaces. The result is the production of dark bands on a grey field. The separation of these bands is altered continuously by the rotation of the gratings.

Fig. 5.10 shows in the upper set microphotographs of the crossed gratings set at three different angles. The lower set are photographs illustrating the corresponding appearance of the gratings when held at a sufficient distance.

The distance of the object and the flux of light entering the eye remains constant. Dark bands, whose visibility forms the test of acuity, may be varied continuously in their separation from invisibility to easy visibility.

5.12. USE OF COLOURED SCREENS.—With the Weber photometer described under paragraph 5.18, red and green glasses are usually supplied. Let the intensities found be G and R, then the ratio $\frac{G}{R}$ gives a value for which from a table (see Table 5.02) supplied with the instrument a factor K is taken, when the real intensity is K R.

It should be obvious, after what has been said previously and in Chapters II. and III., that such a method for testing coloured light will yield correct results only under certain conditions. The value K, which depends upon the absorption curve of the screens, will be accurate only for a particular type of illuminant burning under given conditions. The inaccuracies are the greater the more the spectra of the lights, which are compared, differ. A mercury vapour arc with a discontinuous spectrum could hardly be tested in this manner against an incandescent lamp with a continuous spectrum.

Crova advocated the employment of a yellowish screen capable of absorbing all radiations except those for a wave-length of $58{\cdot}2 \times 10^{-6}$ centimetre. Needless to say, the inaccuracies indicated above occur with this system also, and experiments have shown clearly that the wave-length of maximum sensibility ($58{\cdot}2 \times 10^{-6}$ according to Crova) has no direct connection with the wave-lengths representing the changes for the total light.†

At the same time the above system of comparing lights of different

* *Electrical World*, vol. lv. p. 939, 1910.

† H. E. Ives, *Physical Review*, vol. xxxii. p. 316, 1911.

colours may be improved by the application of three screens: red, green, and blue, corresponding to the three primary colours, with which any colour in lithography and colour photography may be obtained. These three screens are suitably fixed to a rotatable disc of the eye-piece of any large-range photometer (Bechstein or Brodhun, described in paragraphs 5.24 and 5.21 respectively). An eye-piece for this work is shown in fig. 5.11, and the transmission curves of the screens in fig. 5.11A.* We see from the latter that the curves overlap, so that all colour tones are measured.

Care should be taken during the measurements that the range of the

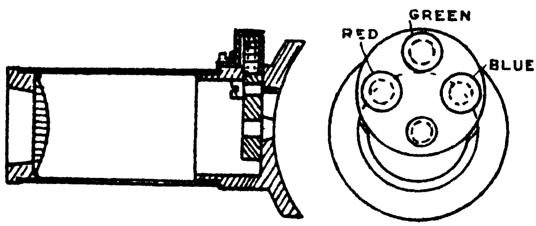


FIG. 5.11.—Eye-Piece for Colour Measurements.

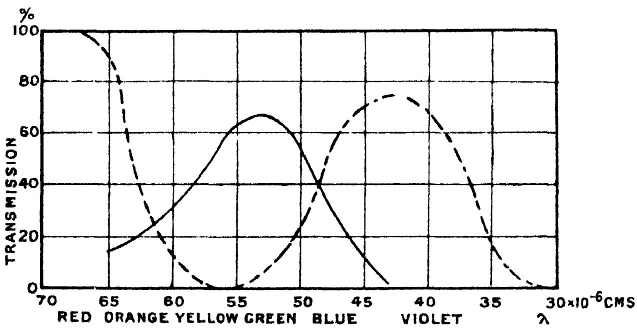


FIG. 5.11A.—Transmission Curves for Coloured Screens.

instrument is not altered, for instance, by the employment of reducing neutral glasses; or, if so, that the transmissions of the screen for the three radiations—red, green, and blue—are accurately known, so that the necessary corrections may be made.

The different illuminants are best compared with daylight under a covered sky, which may be taken as the standard. As this light may vary greatly during a test, a small tungsten lamp—for instance, the comparison lamp of the photometer—may be calibrated first with daylight and then used as a sub-standard. If the test light is not quite steady (arc lamps), the readings should be taken quickly and repeatedly, and a mean value taken. For a flame arc lamp such a test is indicated in Table 5.01.

* See also L. Bloch, *Elektrotechnische Zeitschrift*, 1913, p. 1306; W. Voege, *Illuminating Engineer*, August 1912, p. 375, who employed five screens.

TABLE 5.01.—COLOUR TEST OF A FLAME ARC LAMP FOR YELLOW LIGHT. (BLOCH.)

	Red	Green.	Blue.	Red/Green.	Blue/Green.
1st to 3rd readings	16·5	34·5	18·5	..	..
4th ,, 6th ,,	17·5	38·0	22·0	..	..
7th ,, 9th ,,	17·0	36·0	21·5	..	..
Sum	51·0	108·5	62·0	47·0 %	57·2 %
10th to 12th readings	9·5	20·5	11·5	..	..
13th ,, 15th ,,	9·5	20·5	12·5	..	..
16th ,, 18th ,,	9·5	21·5	11 5	.	..
Sum	28·5	62·5	35·5	45·5 %	56·8 %
Mean value	..	..	..	46·2 %	57·0 %
Daylight	48·0	103·0	199·0	46·5 %	193·0 %
Flame arc referred to daylight	..	..	..	99·5 %	29·5 %

We see from this table that the flame arc with yellow light is almost equal to daylight as regards red to green, but that it lacks largely in blue light.

In a similar manner all kinds of lamps may be compared. The results thus obtained give, of course, relative values only, but these are usually sufficient for the illuminating engineer (see also paragraph 6.27).

5.13. FLICKER PHOTOMETERS.—These were originally based on a discovery by Professor Rood that when two surfaces illuminated by lights of different colours are presented alternately to the eye, the latter requires a longer time to be influenced by a colour sensation than by one of brightness. Consequently, when two surfaces are equally illuminated and rapidly presented to the eye in turn, the surfaces appear stationary and to be of common tint. It would thus seem that a photometer based on this principle would be independent of the colours of the light. Experiments have, however, shown that this is not the case, although there seems little doubt that when a lamp with a discontinuous spectrum is compared with a standard incandescent lamp the flicker photometer gives the most reliable results. Ives and Luckiesh found that the Purkinje effect with the flicker photometer is actually reversed. We thus see that the problem is a very intricate one and complicated by the fact that different observers have different visions as regards colour. In other words, if we plotted the sensation curves as given in fig. 3.02 for different people, they would probably all be somewhat different. Ives obtained such a curve for the average eye, which is shown in fig. 5.12. All standard tests, such as inter-laboratory experiments, should be reduced to this curve.

During the last few years the flicker photometer has been very carefully investigated by H. E. Ives and E. T. Kingsbury,* and the conditions under which its readings may be relied upon are known fairly accurately.

The attainment of a high sensibility in a flicker photometer is dependent upon the following factors:

(1) The dividing line between the two fields which are alternated

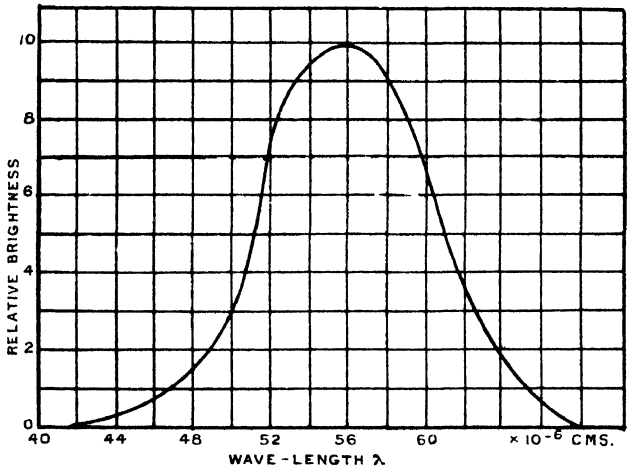


Fig. 5.12.—Sensation Curve for the Average Eye.

should be a line without breadth. A black line produces flicker of itself, necessitating a certain speed of alternation in order to make this mechanical imperfection disappear. But an unnecessary increase of speed reduces the sensibility.

(2) The speed of alternation must be accurately adjustable; as it determines the sensibility. The speed required in any particular case depends on the colour difference.

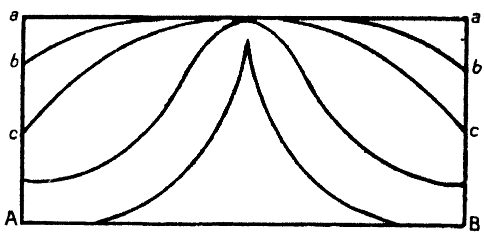


Fig. 5.13.—Flickering as Function of the Frequency.

In fig. 5.13, let A B be the photometer bar on which a flicker head is movable, with equal lights at A and B. If the speed is high enough, 70 or 80 alternations per second, the photometer head may be placed anywhere and no flicker is observable. This condition is represented by line *a*—*a*. If the speed is now reduced, flicker appears, but for a long space in the centre of the bar no flicker is perceived (line *b*—*b*). A further

* See also *Phil. Mag.*, November 1914, No. 167, p. 708; April 1916, No. 184, p. 290; Ives, *Physical Review*, 1914, p. 222; *Phil. Mag.*, April 1917, No. 196, p. 360; M. Luckiesh, *Physical Review*, 1914, p. 1.

lowering of the speed reduces the region of flicker and thus increases the sensibility.

If the two lights are different in colour, this decrease of speed may be carried only so far as no perception of colour flicker appears. The greater the colour difference, the higher must be the speed to prevent colour flicker.

It will be noticed from the figure that the lowest curve does not quite reach to the line *a a*, indicating that the position of match is that of minimum of flicker. To find this point, a series of oscillations about it is necessary, the oscillations constantly decreasing in amplitude until the least movement either way increases the flicker. A minimum of effort should thus be required for the movement of the photometer head. If a motion of body is necessary, the eye is apt to leave the eye-piece, and this movement itself causes flicker, just as a moving object reveals the fluctuating character of an otherwise steady light.

(3) The illumination of the fields of view should be high, say 25 metre-candles (about 2½ foot-candles), and this field should only subtend an angle of 2 degrees. Ives has selected this size of aperture and illumination, as for these values flicker and equality of brightness photometers give the same results (see also paragraph 5.17).

(4) For great accuracies the average eye must be used, *i.e.* a large number of observers should be employed, the mean result being taken.

5.14. CRITICAL OR VANISHING-FLICKER FREQUENCY.—We have seen that at certain frequencies the flickering in a flicker instrument disappears, no matter where the photometer is placed. We may even take away one light and alternate light with darkness, when at a certain frequency the flickering will again vanish. This critical or vanishing-flicker frequency is a function of the brightness of the target, so that the method may appear to be suitable for testing lights of different colours. Porter found that the critical frequency is expressed by $f = \mathrm{K} \log \mathrm{E} + p$, where E is the illumination, and K and p are constants. Further experiments by Luckiesh * show that this is correct, but when the illumination has dropped to somewhat low values the constant K varies, *i.e.* the straight lines which represent f as function of the logarithms of E have a bend in them.† Luckiesh's experiments proved that the frequency depends on the contour of the flicker, the maximum, minimum, and mean values of the illumination during the cycle.

For the testing of coloured lights, the method lacks sensibility, just like the acuity test, as an error of one or more cycles may easily be made, so that in the evaluation of candle-power or illumination errors of 20 and more per cent. may result.

5.15. IVES AND BRADY FLICKER PHOTOMETER. ‡—A flicker

* *Physical Review*, July 1914, p. 1.
† See also Ives, *Phil. Mag.*, vol. xxiv., 1912.
‡ *Physical Review*, 1914, p. 222.

photometer which fulfils the above conditions is illustrated in fig. 5.14. It is solely meant for the substitution method, *i.e.* we use in position L_2 first a standard lamp, and test it against the comparison tungsten lamp L_1, after which L_2 is replaced by the test lamp.

The light from the standard lamp L_2 falls upon a matt screen M, whence part of it is reflected through cube P and the small prism P_1 to the eye at E. The light from the comparison lamp passes through the lens and the variable neutral reducing screen V to the flashed opal

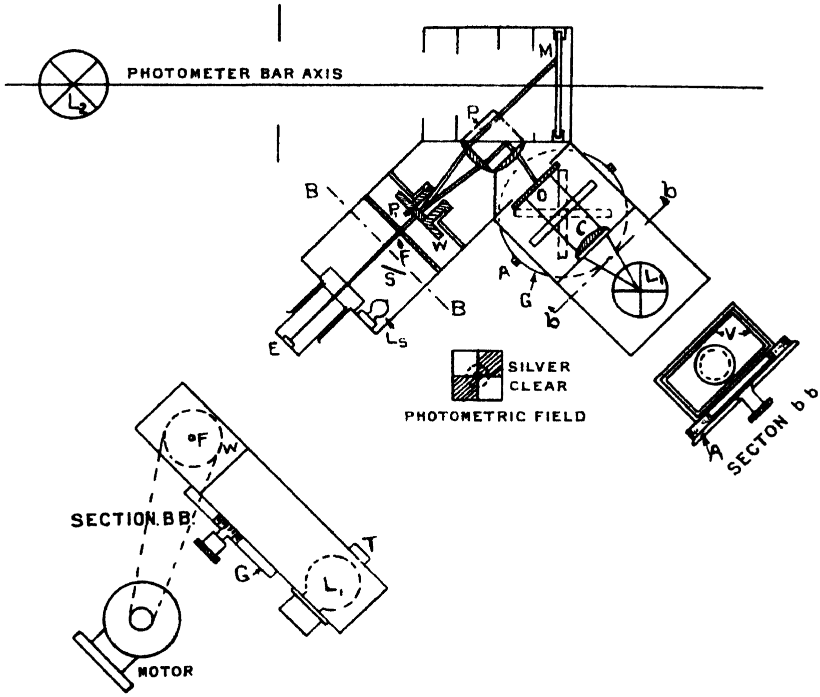


FIG. 5.14.—Ives and Brady Flicker Photometer.

(translucent) glass O. Part of the diffused light of the latter enters the cube P and is reflected through P_1 to E.

The mechanism for producing the alternation of the two fields is contained in P and P_1. P is a modified Lummer-Brodhun prism, of which one component is left untouched, while the other is silvered and the silvering cut away in the manner shown sepaıately. The silver is cut away by sand-blasting, after which the two prisms are cemented together with Canada balsam, which eliminates the diffusing roughness of its surface originally caused by the sand-blast. The slight selective colouring, due to the silver, is of no importance, as the substitution method is employed.

P_1 has an angle of 10 degrees, and is mounted in a collar W which is rotated by a motor. The plate F has a central opening of 2 degrees diameter viewed from E, and thus limits the actual area of the prism used. When the motor is running, the beam of light which reaches the eye is, as it were, whirled around the axis of the instrument, alternately passing over the clear and the silvered parts of the cube P. The successive appearance of the openings at F are seen from the separate sketch of the photometric field, where the small circle represents the section of the beam coming to the eye from E. The practically invisible dividing line between the silvered and the clear portion of the cube and the smooth and continuous motion of P_1 insures the first condition given above.

The second condition is fulfilled by using a small series-wound motor with a sliding variable resistance. The easy variation of the relative illumination is secured by the use of a variable neutral reducing screen V rotated by a milled head with a pointer A. The lens C helps to make the illumination of O uniform, and, as a further refinement, P is furnished with a curved lens focussed on one spot of the opal glass. The calibration curve of the screen is supplied with the instrument. It is very nearly a straight-line function.

The accuracy and comfort of reading are increased by illuminating the surroundings of the photometric field by the small lamp L, which throws its light on the white walls of the chamber facing F. S is a small translucent screen for securing a uniform illumination

The photometer has proved to be very sensitive, the variations from the mean of ten settings by two observers being 0·38 and 0·45 per cent. respectively for lights of slight colour difference, and 0·81 and 0·67 per cent. when the test lamp was a nearly monochromatic green light.

Another Flicker photometer, largely used in Great Britain, is the Simmance-Abady type, made by Messrs Alex. Wright & Co., Ltd., London, and illustrated in fig. 5.15.

It consists essentially of a diffusing rotating disc viewed edgewise. The alternate diffusing surfaces of this screen cause a flicker which moves from side to side until the illuminations are balanced. The change occurs twice in a revolution. The disc or screen is shown separately in fig. 5.15A. The instrument can be placed at any angle, and is therefore suitable for the determination of polar curves for arc lamps.

The sighting wheel may, of course, be so constructed that the change occurs four, six, and more times in every revolution. The instrument is not as accurate as the photometer of fig. 5.14, and, as it is spring-driven, the speed regulation is less sensitive.

H. F. Kingsbury succeeded in making the Lummer-Brodhun photometer into a Flicker instrument. The observer looks at the photometric field through a small aperture subtending 2 degrees at the eye. By means of a rotating prism in the observation tube the two illuminated surfaces in the photometric field are brought successively in front of the aperture, so that a flicker results. The combination is said to be a very sensitive

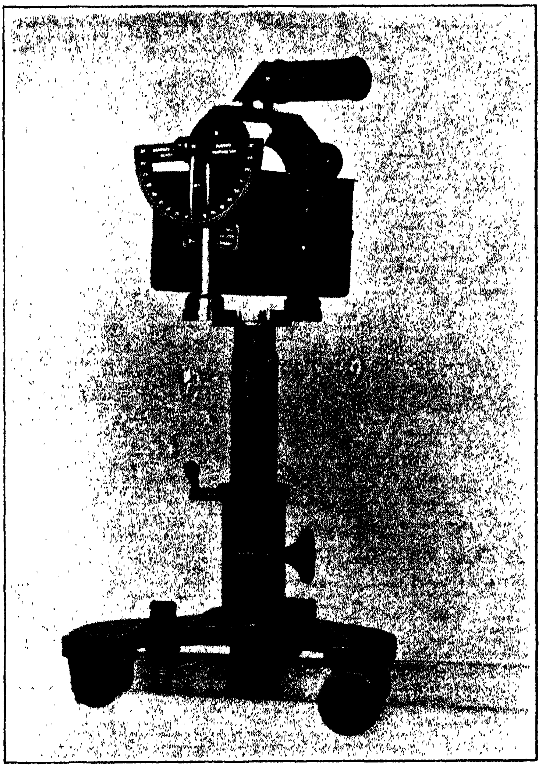


FIG. 5.15.—Simmance-Abady Flicker Photometer.

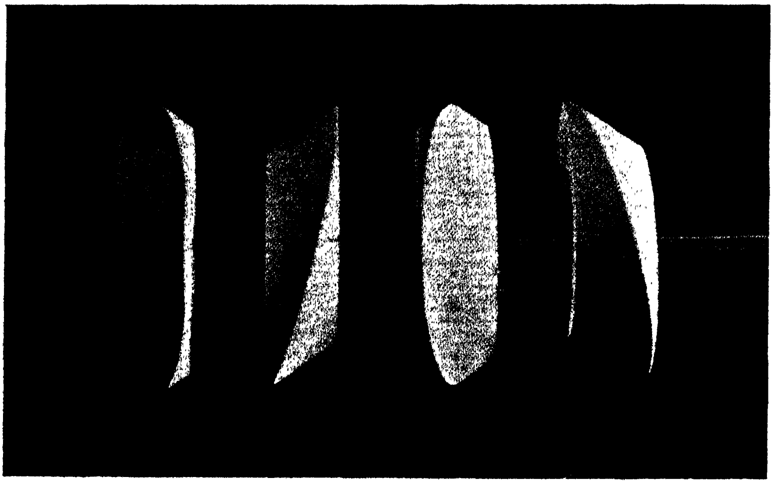


FIG. 5.15A.—Sighting Wheels of Simmance-Abady Flicker Photometer.

one. Kingsbury also illuminates the whitened eye-piece internally with a concealed glow lamp.*

Ives has also developed a polarisation flicker photometer, in which the alternate exhibition of two photometric fields is procured by means of a cop-rotated Nicol prism.† The light from the two surfaces is first polarised in two planes at right angles to each other. When the Nicol is rotated the two images wax and wane in quadrature, as explained in paragraph 5.06.

This photometer possesses the advantage that the transition from one field to the other is gradual and follows exactly the cosine curve which Ives assumed in his theoretical discussions of the flicker photometer. It is suitable for the measurement of the brightness and hue discrimination fractions for both steady and fluctuating impressions.

5.16. VON CZUDNOCHOWSKI'S PHOTOMETER.‡ - A somewhat different type of photometer for the comparison of light of different colours is suggested by W. B. von Czudnochowski. His instrument is based on the following principle :—

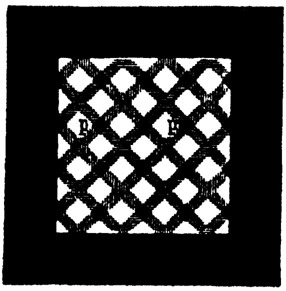


FIG. 5.16. Shadows caused by a Grating.

When the image of a solid object is projected on a semi-transparent screen, it appears sharply defined as long as the direction of vision is perpendicular to the screen, but it becomes indistinct when viewed obliquely, in consequence of the semi-transparency of the screen. Suppose now that we have a grating composed of parallel wires crossing at 45 degrees, those sloping to the right being illuminated by one light, those to the left by a second light; then the two shadows are formed on the screen, and the points of intersection, being illuminated by neither source, appear much darker than the rest, as shown in fig. 5.16. Let, further, the direction of the rays coming from the left-hand light coincide with the direction of vision of the right eye, and *vice versa*, then an image formed by the left-hand source appears sharp to the right eye, and, conversely, an image formed by the right-hand source appears distinct to the left eye. This gives rise to a stereoscopic effect, and one observes a system of apparently free black points, against a background caused by a grating. Certain conditions must, however, be fulfilled.

Let in fig. 5.17 A A represent two wires in the grating, L the diagonal distance between two such wires, B B be the transparent screen, L_1 the distance between the screen and the grating, θ the angle of incidence, I_1

* *Illuminating Engineer*, 1915, p. 462.

† *Philosophical Magazine*, April 1917.

‡ See *Illuminating Engineer*, 1908, p. 283.

and I_2 the two sources of light, then

$$\tan\theta = \frac{L}{L_1}.$$

The distance of the grating from the eye must be the smallest of distinct

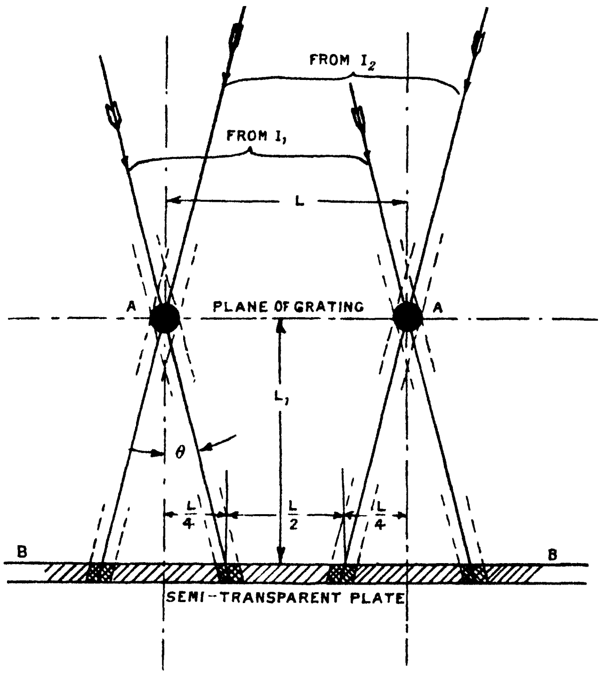


FIG. 5.17.—Principle of Czudnochowski's Photometer.

vision, about 250 millimetres (10 inches). Let this distance be called L_2 then

$$\tan\theta = \frac{\text{half the distance between the eyes}}{L_2},$$

$$= \frac{L_E}{2L_2}.$$

Combining these two equations we get

$$L = L_1 \frac{2L_E}{L_2}.$$

For a normal pair of eyes $L_E = 65$ millimetres, so that for $L_1 = 10$ millimetres, $L = 5{\cdot}2$ millimetres.

We have seen before that when the illumination drops below a certain value the colour effect disappears and everything looks a ghostly grey. With a photometer built on the above principle, a colourless field is obtained without employing a low order of illumination, by using two shadow patterns, which will appear grey on a white background with black intersections. If now one of the sources is moved sensibly out of balance, one of the patterns becomes coloured.

The general arrangement of the photometer is shown in fig. 5.18, in which I_1 and I_2 are the two sources to be compared, B B the diaphragm with the grating G, M the transparent screen, W W screens to divide the black box K K into two sections, and S a mirror for directing the light.

The grating is best stamped out of sheet metal, wire gauze being unsuitable, since by the crossing of the wires the grating becomes too thick.

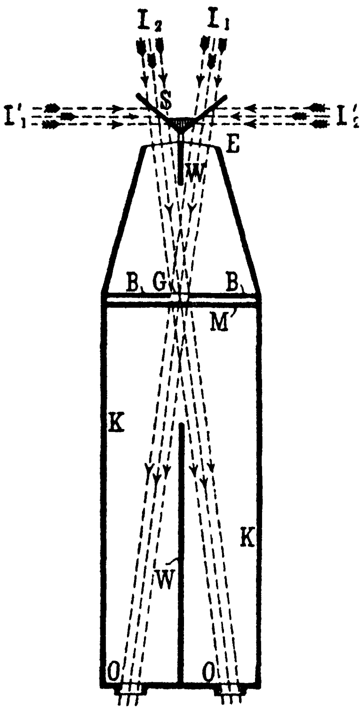


FIG. 5.18.—General Arrangement of Czudnochowski's Photometer.

It will be obvious that, as the balancing of the photometer consists in equalising the contrast of the "shadows" against a white background, colour plays no part in the accuracy of the adjustment.

5.17. SPECTROPHOTOMETERS.—Spectrophotometers are instruments used for the comparison of the brightness of the different parts of a spectrum (as far as this is at all permissible), and for finding the intensities of two light sources whose spectra have been resolved into their components, which are then compared. Work of this nature belongs more to the sphere of the physicist than to that of the illuminating engineer, and the elaborate instruments used for the purpose may be found described in every standard book on light, to which the reader is referred.

An apparatus due to Ives * is, however, described which is not only suitable for determining the relative spectral-luminosity curves of lights, but provides a ready means for comparing the sensitiveness of flicker and equality of brightness photometers. It is illustrated in fig. 5.19.

A Hilger constant deviation spectroscope forms a spectrum upon the eye slit, 1, of dimensions $\frac{1}{2}$ by 2 millimetres. The eye placed at the slit observes the prism face illuminated by monochromatic light. The size of the collimator slit, 3, is varied by screw 4. 9 is a ground-glass illuminated by the electric lamp 10 on track 11. At 6 is a thin metal disc of a shape shown separately in the figure, covered with magnesia and driven by a motor (not shown). The disc is illuminated by the lamp 8. The eye sees first the prism face illuminated by any desired monochromatic light (obtained by resolving the light from 10 into a spectrum by prism 2,

* *Phil. Mag.*, xxiv., 1912.

which is controlled by the micrometer screw 5), and then the disc which is illuminated by lamp 8. This is thus a flicker photometer. The apparatus may be converted into an equality of brightness instrument by turning the disc so that it bisects the photometric field. The size of the field may be altered by the blend 12.

The apparatus is thus so constructed that the measurements may be easily reproduced, and we may study the effects of changing the illumination in each method for each size of field, the relative positions of luminosity curves of the two methods, and the comparisons of luminosity curves obtained by different observers.

The tests carried out with the instrument showed clearly that for

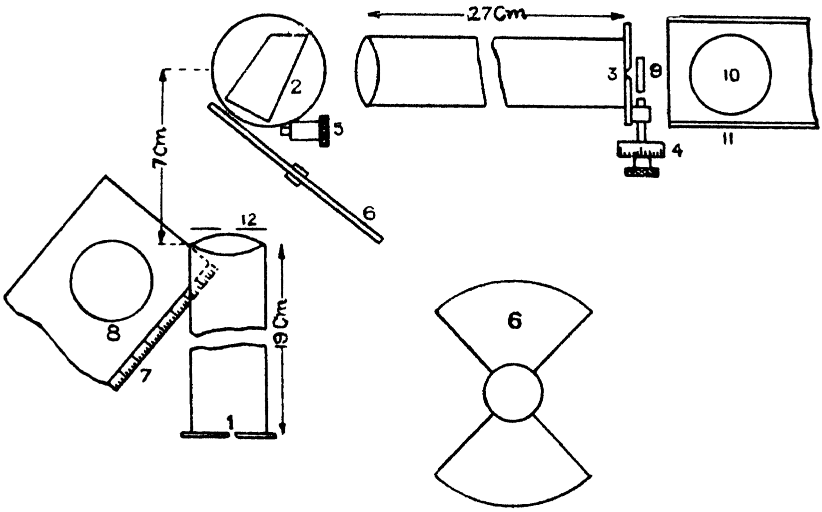


FIG. 5.19.—Ives Spectrophotometer.

studies in the photometry of lights of different colours the flicker instrument gives the more reliable and consistent results. A decrease of the illumination results in the Purkinje shift of the maximum of the luminosity curve towards the blue for the equality of brightness method, while a reversed shift is noted with the flicker method (as mentioned in paragraph 5.13). Decreasing the size of the field decreases the changes at low illuminations. The relative positions of the two kinds of spectral-luminosity curves differ with different individuals and with different intensities of illumination. The curves differ most at low illuminations with large fields. At high illuminations the mean of the equality of brightness curves and the mean of the flicker curves apparently agree, suggesting high illuminations as a standard condition for heterochromatic photometry.

The instrument may also be used for tests with the method of critical frequency, and for determining the distortions in spectral-luminosity curves produced by variations in the character of the comparison standard and of the surroundings of the photometric field. By the equality of brightness method a series of different luminosity curves were found, a different one for each colour of the comparison standard. The curves obtained with the flicker photometer showed no deviation from each other. A change in the illumination of the surroundings of the photometric field produced no effect when using the flicker instrument, but irregular changes occurred in the equality of brightness method. The flicker photometer thus measures true brightness. It was also through these tests that Ives arrived at an illumination of 25 metre-candles and a photometric field of 2 degrees diameter as best suited for flicker photometers.

5.18. ILLUMINATION PHOTOMETERS. These are employed to measure the illumination given by lights in regions such as rooms, halls, streets, etc., irrespective of the distance of the source away from this region. Photometers for this purpose are obtained by slight modifications of the intensity instruments. They should be portable and consequently of light weight.

Illumination photometers may be divided into two classes: diffused reflection and diffused transmission photometers. In the former the light is diffused by a screen and then reflected by mirrors to the photometer; in the latter it is diffused by a piece of ground glass and then transmitted to the photometer.

5.19. PROFESSOR WEBER'S PHOTOMETER.—A photograph of this instrument is shown in fig. 5.20, and the optical arrangement in fig. 5.20A. A standard benzine lamp *b* (or a standard electric lamp) is arranged in a box at one end of a horizontal tube A. In this tube, and capable of sliding in it, is a translucent screen of opal or ground glass. The light from *b* is reflected by means of a Lummer-Brodhun prism *p* into an eye-piece O. At the top of the vertical tube B, which can be placed at any angle, is another piece of translucent glass *g*, the light from which passes through the prism *p*. Both screens *f* and *g* are therefore viewed together. The distance *r* of the screen *f* from the comparison lamp *b* is shown on a millimetre divided scale. Equality of the field of view is obtained by altering the position of *f*.

The instrument may be used for intensity and illumination measurements. In the former case

$$I = C\frac{L^2}{r^2} \text{ candles,}$$

where L is the distance of the lamp to be compared from the glass plate *g*, and C a constant. The latter is found by means of a standard lamp, say a 10-c.p. pentane lamp, which gives

$$C = \frac{10 r_0^2}{L_0^2},$$

where r_0 and L_0 are now the distances indicated.

When using the apparatus as an illumination photometer, we place a white screen P at the desired angle in the region the illumination of

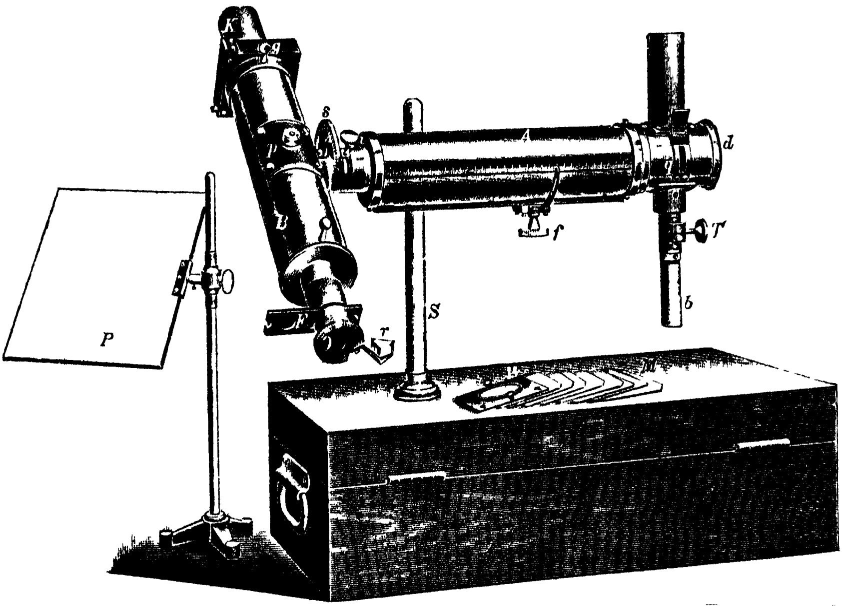


FIG. 5.20.—Weber's Illumination Photometer (Elevation).

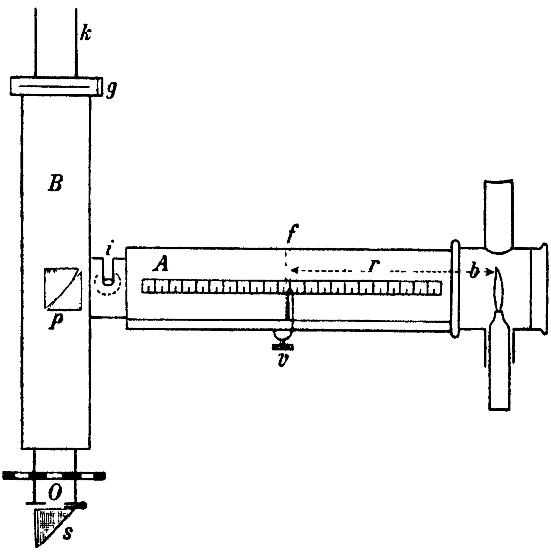


FIG. 5.20A.—Weber's Illumination Photometer (Sectional View).

which we desire to find, and direct the tube B towards the centre of this plate as perpendicularly as possible. The ground-glass plate *g* is taken out, and the illumination after equalising by moving f is given by

$$E=\frac{C^1}{r_1^2},$$

where C^1 is another constant and is found again with a standard lamp.

Suppose we use a 10-c.p. pentane lamp placed at a distance of 2 metres from a white screen, the illumination of the latter is given by

$$E=\frac{10}{2^2}=2{\cdot}5 \text{ lux}.$$

Suppose that with this illumination a balance be obtained with f at a distance of r_0 metres from b, then

$$C^1=2{\cdot}5r_0^2.\text{*}$$

The distance of the screen P from the photometer does not figure in the calculation.

The white screen must have a perfectly matt surface so that the reflection is perfectly diffused.

Instead of using a white screen P, the measurement may be accomplished by inserting frosted white glass plates μ at g, the illumination of which is found in an identical manner. The instrument then acts as a diffused transmission photometer. By placing the tube B at different angles, the illumination may be determined in any desired region and direction.

The instrument is usually supplied with green and red screens for the comparison of lights of different colours, expressing the intensities in red and green candles. Such tests have, however, any value only for lights with continuous spectra and under definite conditions (see paragraph 5.12). Table 5.02 holds for such tests.

The range of the Weber photometer is naturally small, on account of the short length of tube A. It may, however, be increased by the application of Nicol prisms or neutral screens of different degrees of transparency.

TABLE 5.02.—COLOUR COEFFICIENTS FOR WEBER'S PHOTOMETER.

$\frac{G}{R}$.	K.	$\frac{G}{R}$.	K.	$\frac{G}{R}$.	K.	$\frac{G}{R}$.	K.	$\frac{G}{R}$.	K.
0·3	0·50	1·4	1·28	2·5	1·84	3·6	2·20	4·7	2·52
0·4	0·56	1·5	1·34	2·6	1·88	3·7	2·24	4·8	2·55
0·5	0·64	1·6	1·40	2·7	1·92	3·8	2·27	4·9	2·57
0·6	0·72	1·7	1·46	2·8	1·96	3·9	2·30	5·0	2·60
0·7	0·80	1·8	1·50	2·9	1·99	4·0	2·33	5·1	2·62
0·8	0·87	1·9	1·55	3·0	2·02	4·1	2·36	5·2	2·64
0·9	0·94	2·0	1·60	3·1	2·05	4·2	2·39	5·3	2·67
1·0	1·00	2·1	1·65	3·2	2·08	4·3	2·41	5·4	2·69
1·1	1·08	2·2	1·70	3·3	2·11	4·4	2·44	5·5	2·71
1·2	1·15	2·3	1·75	3·4	2·15	4·5	2·47		
1·3	1·22	2·4	1·80	3·5	2·18	4·6	2·49		

* To be quite accurate, the screen should be spherical, so that the rays fall perpendicularly upon it. The accuracy is, however, sufficient if the flat screen is placed at a considerable distance from the illuminant.

5.20. TROTTER'S UNIVERSAL PHOTOMETER.* —A general view of the instrument is shown in fig. 5.21, and its optical arrangement in fig. 5.21A. The instrument is called universal, as it is claimed that illuminations and intensities can be accurately measured by it.

A small lamp (4 volts) throws a beam of light by means of a mirror M on the screen S_1. This is viewed through three small slits in the screen S_2, which receives the illumination to be measured. S_1 can be rotated about its axis by means of a cam, and the illumination thereby

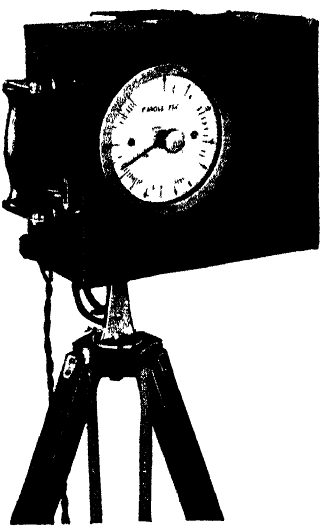


Fig. 5.21.—Trotter's Universal Photometer (Elevation).

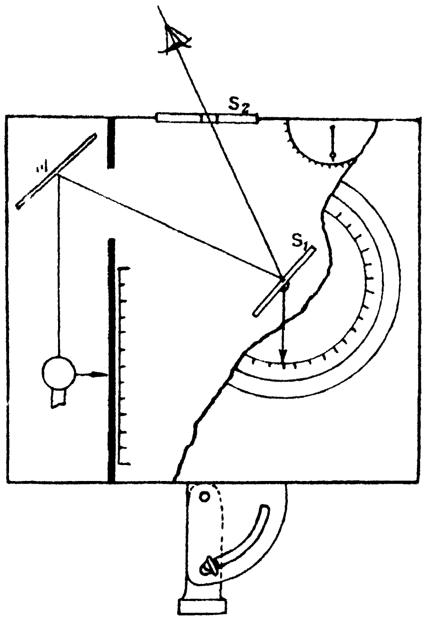


Fig. 5.21A. Trotter's Universal Photometer (Optical Arrangement).

varied until a balance of brightness between S_1 and S_2 is obtained. Calibration takes place with a standard lamp, which produces a known illumination at a given distance. The scale of the photometer may be made direct reading.

For candle-power measurements the perforated screen S_2 is set directly facing the lamp, and folding shutters or " blinkers " are provided to screen off other light. To set the screen in this position, the photometer is mounted on a tripod with a pivoted and hinged head, enabling the instrument to be turned in any direction and fixed at any angle. Since the screen faces the light, the direction of view must be other than perpendicular to it, and an angle of 20 degrees has been chosen.

The comparison lamp should be carefully aged and tested. It is fed

* Manufactured by Everett, Edgcumbe & Co. See also *Electrician*, 8th November 1907, and the *Illuminating Engineer*, 1909, p. 799.

from a 4-volt battery carried in a separate wooden case. Provision is made on the scale for a slight variation of voltage.

Screens S_1 and S_2 are interchangeable in order to test lamps of different tints.

The instrument is made suitable for colour photometry by the application of Crova's law. Crova found that if two lights, differing largely in colour, were each viewed through a yellow screen, whereby they are made practically monochromatic, the relative illumination remained unchanged.

The screen employed by Crova consisted of a solution of definite composition and thickness which only transmitted light of a certain wave-length. For practical purposes the method proved, however, unsuitable. In Trotter's photometer, the principle has been revived with success.

The weights and dimensions of the apparatus are as follows:

Photometer: 1·8 kilograms (4 lbs.), 23 × 19 × 11 centimetres (9″ × $7\frac{1}{2}$″ × $4\frac{1}{4}$″).

Battery: 2·27 kilograms (5 lbs.), 18 × 13 × $7\frac{1}{2}$ centimetres (7″ × 5″ × 3″).

Stand: 0·7 kilogram ($1\frac{1}{2}$ lbs.), 18 × $4\frac{1}{2}$ × 4 centimetres (19″ × $1\frac{3}{4}$″ × $1\frac{1}{2}$″).

These figures show that the instrument is exceedingly portable.

5.21. BRODHUN'S STREET PHOTOMETER. This is a variable aperture disc photometer and is illustrated in fig. 5.22. The comparison lamp at *g* illuminates an interchangeable frosted glass plate at *d*. A system of two lenses produces an enlarged field of this illumination on the compound Lummer-Brodhun prism W. The observer looks through the eye-piece *l* upon the separating surface of this prism and views there the rays from the two sources to be compared.

For the determination of the luminous intensity, the light is thrown on a magnesia slab S, here diffused and reflected as shown. Equality of the fields of view is obtained by reducing the light of the comparison lamp with a variable aperture disc. Two prisms *p p* are placed between *d* and W on a kind of drum which is rotated by means of a motor M and belt *c*. The rays between *p p* rotate, therefore, round the longitudinal axis of the apparatus and are screened off more or less by the variable aperture disc shown separately in fig. 5.22. The section consists of a fixed metal disc with two apertures of 90 degrees, which may be closed more or less by a second movable disc with an index.

The calibration of this apparatus is performed with a standard lamp. We have $I = C\theta L^2$, where L is the distance of the light to be tested from S, and

$$C = \frac{\text{candle-power of some standard}}{\theta_1 L_1^2},$$

θ_1 is the angle of the opening, and L_1 the distance when the standard lamp is used. When the instrument is to be used as an illumination photometer, the tube T is replaced by another tube, T_1, with a frosted glass plate, and S is replaced by a mirror to which the light is directed by a set of lenses fixed in T_1. The calibration is performed as before.

The glow lamp and the motor are fed from a six-cell portable

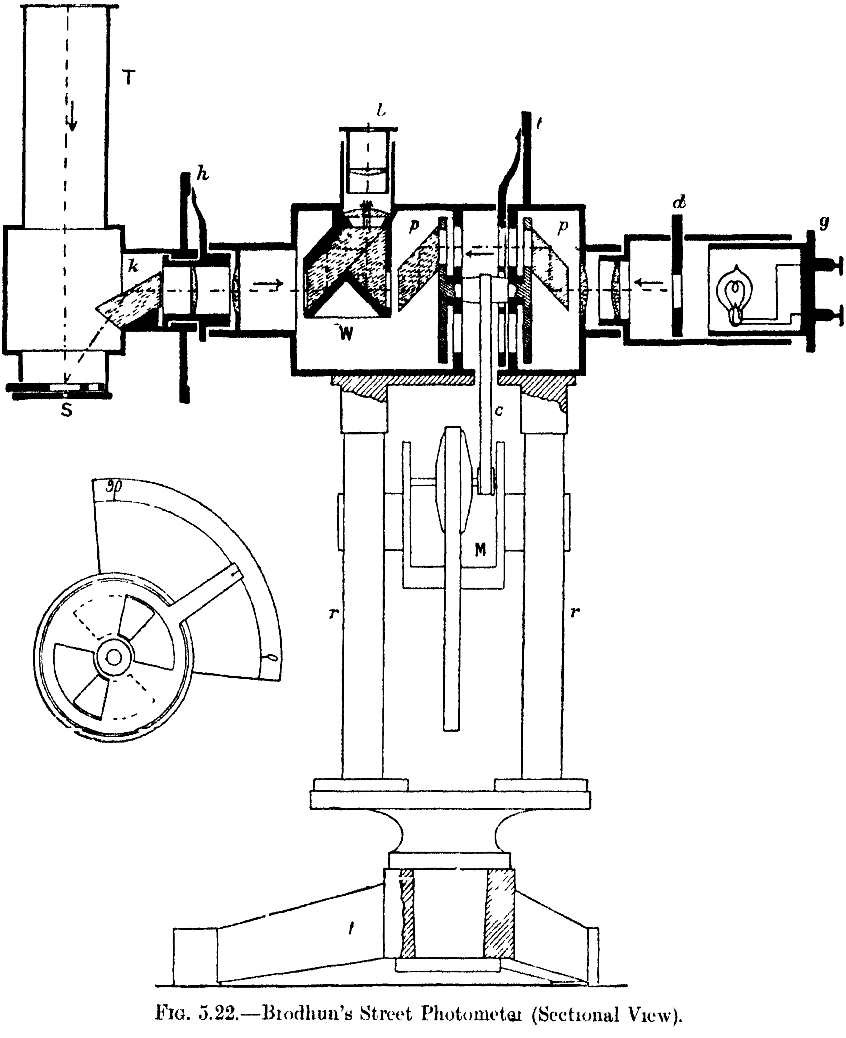


FIG. 5.22.—Brodhun's Street Photometer (Sectional View).

secondary battery. This and the use of a motor make the apparatus more bulky than Weber's or Trotter's photometers.

5.22. DR MARTENS' ILLUMINATION PHOTOMETER.—This instrument is illustrated in figs. 5.23, 5.24, and 5.25, and is of a very handy and portable construction. The screen F is brought into the region of the illumination which is to be found. The comparison lamp B (benzine or electric) illuminates the frosted glass *m* with the help of the reflecting mirrors S_1, S_2 and the prism *p*. By moving S_1 and S_2, the illumination of *m* is altered.

The rays from F and *m* pass through the openings *a* and *b* respectively

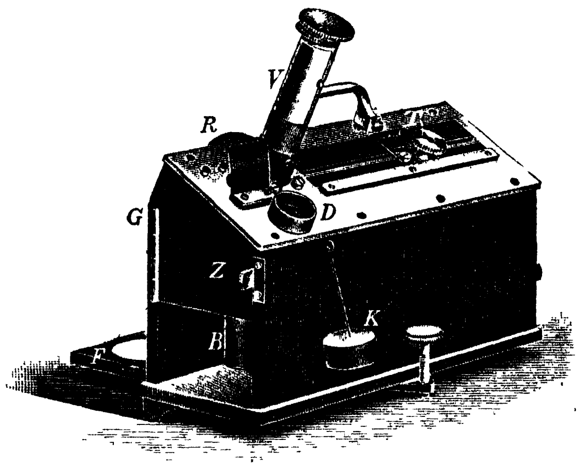


FIG. 5.23.– Martens' Illumination Photometer (Elevation).

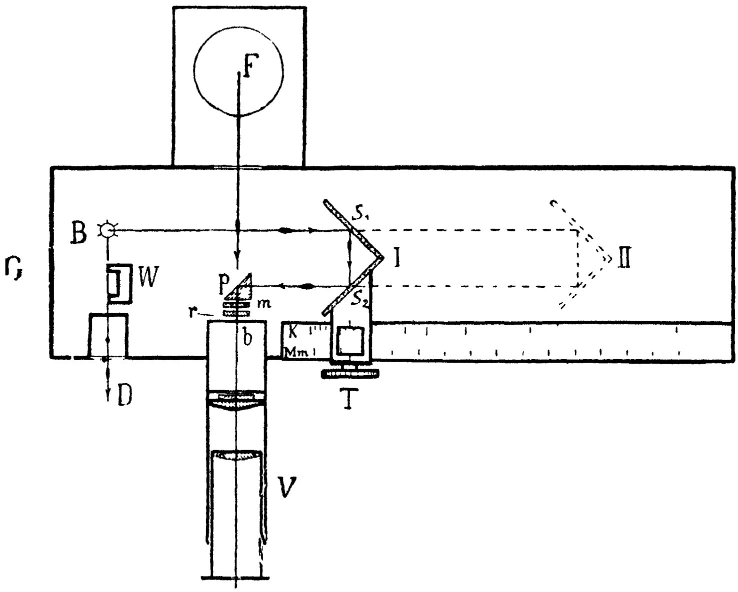


FIG. 5.24.—Martens' Illumination Photometer (Sectional View).

into the tube V, where they illuminate the surfaces 1 and 2 of the prism Z. Equality of the field of view is obtained by adjusting the position of the mirrors S_1 and S_2.

A revolving disc R, with opal glasses r of different degrees of transparency, increases the range of the instrument.

The illumination E is given by the apparatus as

$$E = \frac{K}{r^2},$$

where r is the distance read on the scale of the instrument. On a second scale K, the illumination is read directly in lux. When inserting the

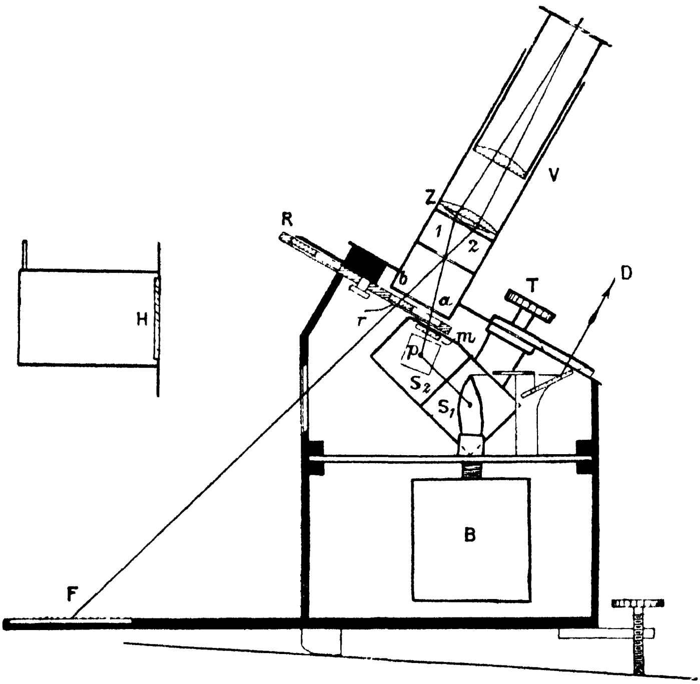


FIG. 5.25.—Martens' Illumination Photometer (Sectional Elevation).

revolving disc R with the constant K_3, the numbers read are correct; for K_4 the numbers must be multiplied by 10, for K_5 by 100, for K_2 by $\frac{1}{10}$, for K_1 by $\frac{1}{100}$.

5.23. SHARP-MILLAR PHOTOMETER.—The instrument is illustrated in fig. 5.26. A is the test plate of translucent glass, P a modified Lummer-Brodhun comparison prism, O the working standard (small tungsten lamp), E the scale, R a variable resistance, and S absorbing screens for increasing the range of the instrument.

The illumination on the photometric device is varied by moving the standard lamp O by means of a cord and pulley.

The complete outfit, with portable battery, regulators, and ammeter for the standard lamp, is shown in fig. 5.27.

The calibration is carried out as with the Weber photometer.

5.24. BECHSTEIN PHOTOMETER. This is shown in elevation in fig. 5.28 and in section in fig. 5.29. A (in the section) is again the test

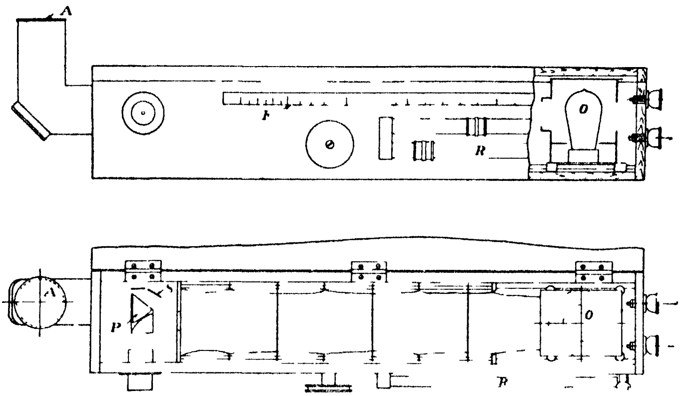


Fig. 5.26. Section of Sharp Millar Photometer.

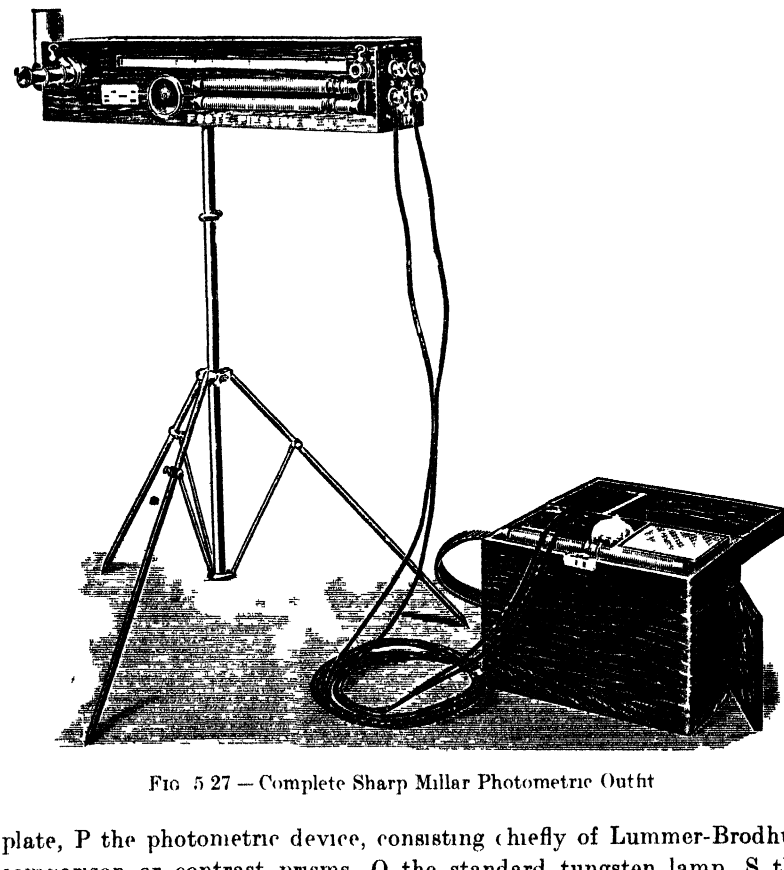


Fig. 5.27.—Complete Sharp Millar Photometric Outfit.

plate, P the photometric device, consisting chiefly of Lummer-Brodhun comparison or contrast prisms, O the standard tungsten lamp, S the stationary variable aperture, E the motor for rotating the lenses L, whilst R and M are screens for increasing the range of the instrument.

The calibration and use are similar to that of Brodhun's photometer.

5.25. CELL PHOTOMETER.—The instruments described so far are mostly expensive, and some of them are also cumbersome for outdoor use. Where only a somewhat rough estimate of the illumination is required, a photometer as illustrated in fig. 3.29 of the first edition usually suffices. This type of photometer has been much improved, as

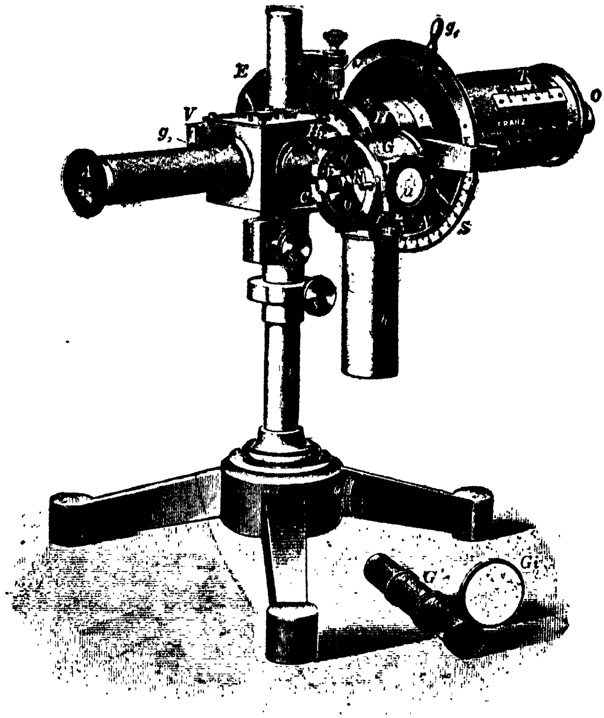


FIG. 5.28.—Elevation of Bechstein Photometer.

will be seen from fig. 5.30, which represents the apparatus made by the General Electric Co., U.S.A. A series of spots are lighted from a lamp in a fixed position which illuminates a box which forms the background of the series of spots.*

The screen consists of a piece of clear glass on which are two thicknesses of paper, one of which is punched with a series of round holes and is fairly opaque, and the other is highly translucent. This screen forms one side of the light box, which is so constructed that the screen is illuminated from within to a much higher extent at the right than at the left. The exposed side of this screen is very nearly uniformly lighted from the illumination which is to be tested; and, consequently, the round

* *General Electric Review*, December 1920, p. 964.

holes appear brighter than the screen surface at the right end and darker at the left. At the point where the spots change from lighter than the screen to darker, the illumination on both sides of the screen is approximately the same.

The instrument is calibrated with a standard lamp at a known distance. The internal lamp is always regulated to the same voltage by means of an internal regulating resistance in the circuit of the lamp.

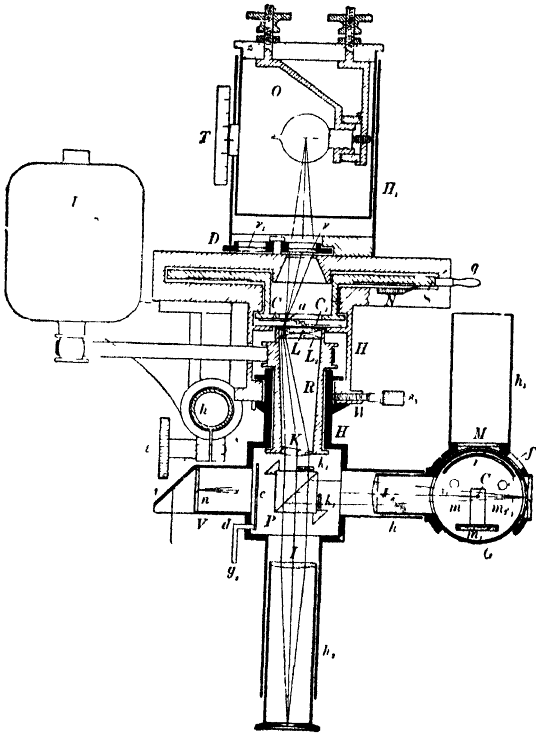


FIG. 5.29.—Section of Bechstein Photometer.

The current is supplied by a three-cell flash-light battery. The size of the whole equipment is 6 by 8 inches and weighs only 3 lbs.

Photometers of this type may also be made with a small sighting arrangement, so that the angle under which the screen is viewed is constant (see also paragraph 5.28).*

The same type of instrument has also been employed for measuring the illuminating value of fluctuating sources of high candle-power (flares).† The photometer by Clark consists of a tube 635 millimetres (25 inches) long and 75 millimetres (3 inches) in diameter. The interior is whitened and is illuminated by a small electric lamp placed at one end.

* See also *Illuminating Engineer*, August 1916, p. 262.

† See Trotter, *ibid.*, November 1918, p. 253.

A slot 50 millimetres (2 inches) wide extends nearly the whole length of the tube, and this is covered with a strip of thin metal having perforations

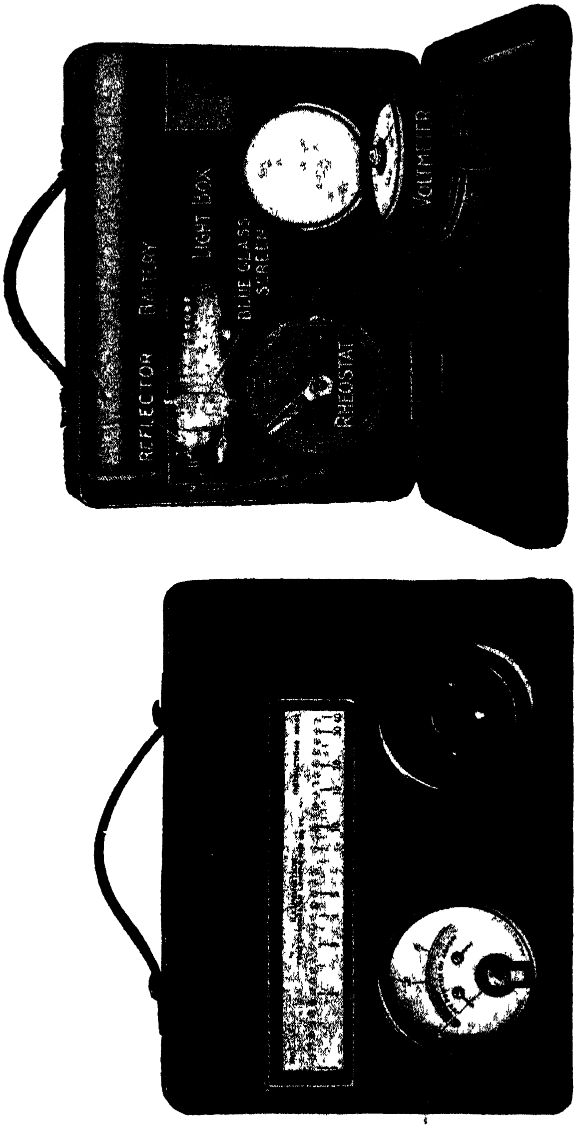


Fig 5 30 —Cell Photometer

in the form of letters The strip is painted white and receives the illumination to be measured The letters have the advantage of being noticed and dictated without having to look at any calibration on the photometer

Another apparatus used for the purpose and based on the same principle is the one by Dow, consisting of a lumeter in which a grid of 14 slots cut in white paper is illuminated by a small electric lamp and which is directed on a test screen, which may both be studied through an opening in one side of the box. The grid is again illuminated according to the cosine law. For increasing the range the test screen may consist of portions of different degrees of lightness, say, white and grey.

The disadvantage of the variation in the illumination according to the cosine law is the fact that near the lamp the illumination varies very rapidly, at the other end very slowly.

Various further modifications of the cell photometer have been suggested, which the reader will find in the March 1916 number of the *Illuminating Engineer.*

5.26. LUMETERS.—The ordinary illumination photometer is often

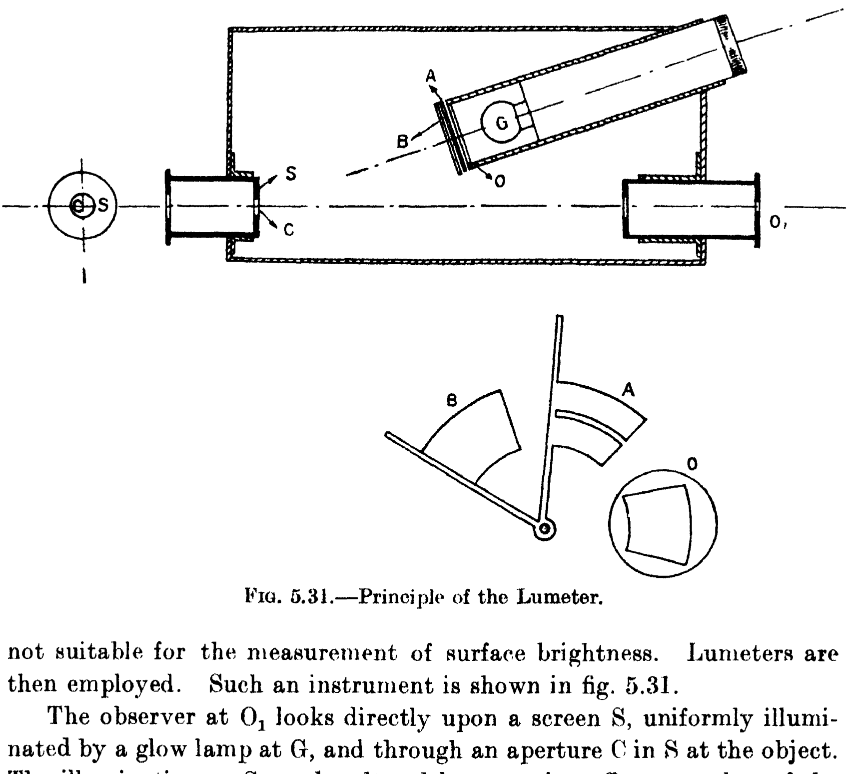


FIG. 5.31.—Principle of the Lumeter.

not suitable for the measurement of surface brightness. Lumeters are then employed. Such an instrument is shown in fig. 5.31.

The observer at O_1 looks directly upon a screen S, uniformly illuminated by a glow lamp at G, and through an aperture C in S at the object. The illumination on S can be altered by screening off more or less of the opal glass at O, as is indicated.

The opaque diaphragm *d* allows only a sector to be exposed, and the latter is more or less covered up by the screens A and B, and thus the quantity of the light transmitted to the screen S may be very finely adjusted. With A placed fully over O, the opening is exactly one-tenth of that of the whole sector, and this is further uniformly reduced to O with the aid of screen B. The screen S is made by depositing a matt white precipitate on thin glass, and scraping away a central disc. It is then covered with thin glass for protection. The instrument in reality measures intrinsic brilliancy or the number of candles per unit surface. It may, however, also be used for determining the illumination in foot-candles which a perfectly white surface would have to receive in order to have an equivalent brightness. It is for this purpose that the instrument is most useful. The calibration then is accomplished as follows:—

The position of the glow lamp, which illuminates the opal glass O, is adjusted until the brightness of the screen S is, say, 1 foot-candle, or 10 metre-candles, determined by comparing it with another similar white surface illuminated by a standard lamp. The lamp is then fixed in position, and we may regard the scale as registering foot-candles. The further calibration is made by closing the screens A and B by known

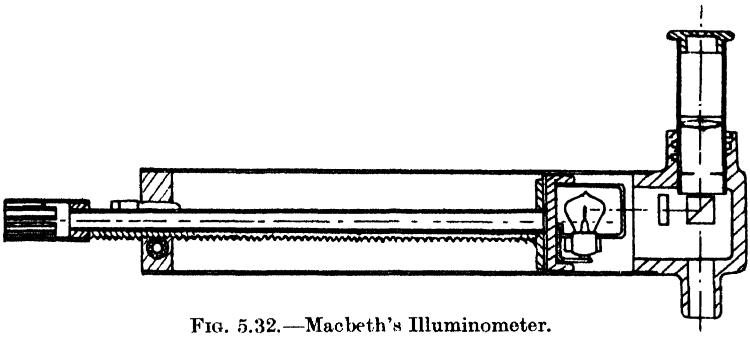


FIG. 5.32.—Macbeth's Illuminometer.

values. The range of the instrument is now from $\frac{1}{100}$ to 1 foot-candle, or from $\frac{1}{10}$ to 10 metre-candles.

By the insertion of reducing glasses the range may be increased to 100 foot-candles.

To ensure accuracy it is important that the glass should be uniformly illuminated, a result achieved by enclosing the lamp in a chamber with perfectly white walls.

The instrument can of course be used for rough candle-power and illumination measurements as well as for approximate determinations of surface brightness and diffuse reflection coefficients. For relative measurements the instrument is extremely handy. We first view a white screen placed in front of the object, and then the object itself, and compare the two.

5.27. MACBETH ILLUMINOMETER.—This is a kind of a universal instrument and is illustrated diagrammatically in fig. 5.32. A Lummer-Brodhun photometer is mounted in a rectangular box and viewed through a telescope. The aperture opposite the telescope is pointed toward a test plate or surface, whose brightness is to be measured. In a tube, 9 inches long, is mounted a small incandescent lamp which throws its light through a small aperture on the photometric apparatus. Balance of the fields of view is obtained by moving the lamp backwards or forwards by means of a rack and pinion.

The instrument is provided with a controller comprising the cells for the lamp, a Weston milliammeter, two close regulating rheostats, a double-pole change-over switch, and a reference standard. The apparatus is suitable for 2, 4, or 6 volts. A reference standard is added so that the apparatus may always be calibrated *in situ*. Its construction is shown in fig. 5.33; for calibration it is placed upon the test plate, so that the latter possesses a definite illumination. The sighting aperture of the illuminometer is then placed into the hole marked D and the calibration is made by adjusting the current of the working lamp, the scale showing the correct illumination.

The range of the instrument is increased by the use of neutral glasses placed on one side or the other of the Lummer-Brodhun cube.

For the measurement of illumination the test plate is placed into the position whose illumination is to be determined, and looked at through the telescope of the instrument, balance being obtained by moving the lamp inside. The test plate may also be done away with by the use of a rectangular horn provided with a translucent test plate placed over the sighting aperture of the lumeter.

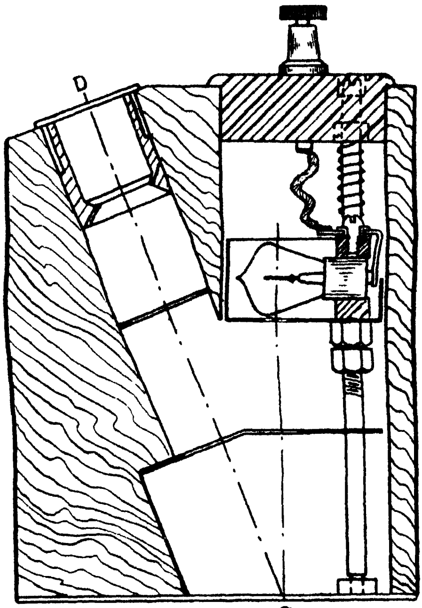


FIG. 5.33.—Standard Lamp for Macbeth's Lumeter.

For the measurement of surface brightness the sighting aperture (or horn) is pointed directly at the surface under test. The values secured must then be multiplied by the coefficient of reflection of the test plate with which the standardisation has been made, or a separate standardisation made, based on the apparent foot-candles emitted from the test plate in accordance with the value supplied with the apparatus.

If it is desired to reduce these readings to values in units of candle-power per square foot, divide by π.

It has already been pointed out that in all determinations with test plates the values obtained depend somewhat upon the angle at which the plate is viewed. In fig. 5.34 are given the errors which obtain with various materials. Curve A holds for plaster, curve B for magnesium carbonate, C for a special glass used in the Macbeth illuminometer, and D for an ordinary plate used for some time by the investigators.

A complete outfit of a Macbeth illuminometer is shown in fig. 5.35.

5.28. PHYSICAL PHOTOMETERS.—The complexities of the human

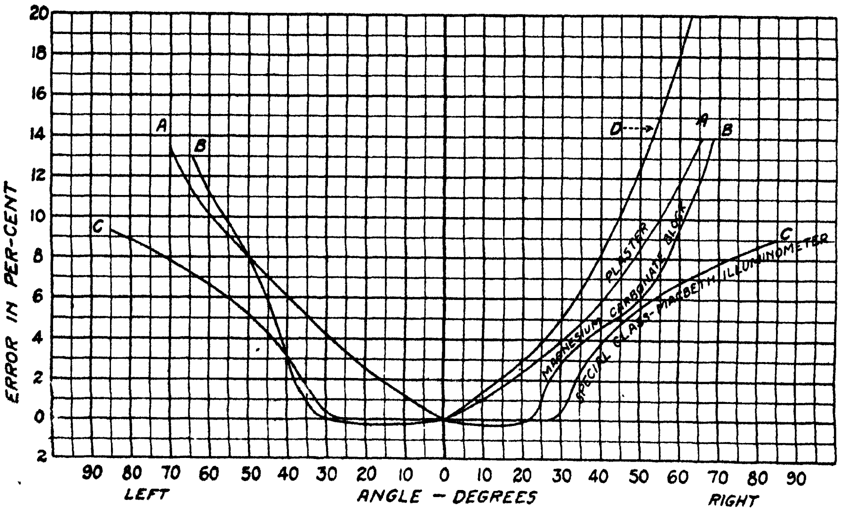


FIG. 5.34.—Errors of Standard Plates.

FIG. 5.35.—Complete Outfit of Macbeth's Illuminometer.

eye and the difficulties encountered in comparing lights of different colours suggested to a number of investigators the construction of a physical photometer, *i.e.* an instrument which will indicate the intensity of any light on a measuring instrument as an ammeter shows the current, being entirely independent of the eye. Unfortunately it has been impossible so far to produce a substance which will respond to radiant energy in the same manner as the human eye, or which will have a stimulus curve possessing the same shape as the curve of fig. 5.12.

One of the first instruments used was the thermopile, but as it is affected by heat rather than light rays, *i.e.* rays lying mainly near the red or infra-red part of the spectrum, glass, quartz, or any other suitable screen had to be interposed between the source and the thermopile in order to prevent pure heat rays from reaching the latter. As these substances possess various degrees of transmission for different radiations, it is obvious that the results obtained can be of a relative value only. For instance, it is possible to plot in this manner polar curves of a lamp (see paragraph 5.31), as the readings in different directions from a given source will all be affected in the same proportion. By means of a single measurement with an ordinary photometer, absolute values may then be obtained. An instrument of this type would also be suitable for recording the candle-power variations of an arc lamp in order to define the quality of the feeding mechanism, or to check the variations in the pressure of the supply.

Recently the thermopile has also been used for the absolute testing of illuminants, as a screen has been discovered whose transmission curve is similar in shape to the luminosity curve of the average eye (see paragraph 5.13). Such a screen or filter reduces the luminous rays in a manner that the effect upon the thermopile is relatively the same as it would be upon the eye. The degree of transmission of the filter having been determined, the absolute intensities will also be known. Care must, of course, again be taken in preventing pure heat rays from reaching the thermopile.

The setting up of such an apparatus and its use is, of course, far more troublesome than the employment of an ordinary photometer, but the principle has been used for finding the mechanical equivalent of light.

Another physical photometer is the bolometer, which changes light rays into heat. The Lummer-Kurlbaum instrument consists of a zigzag strip of platinum 30 millimetres long, 1 millimetre wide, and less than one-thousandth of a millimetre thick, such a thin strip being obtained by rolling a thin sheet of platinum together with a thicker sheet of silver, the latter being finally dissolved in nitric acid. The strip is then covered with platinum or lamp-black and made a branch of a Wheatstone bridge, which consists of four such arms. One of them is then subjected to a luminous flux which is absorbed and changed into heat, the latter causing a temperature rise and a consequent change in the resistance of this branch, bringing the bridge out of balance. The magnitude of the deflection of the galvanometer is a measure of the radiant energy and, if the heat rays have previously been absorbed, also of the radiant luminous energy. The remarks made about the thermopile as regards stray heat rays, etc., hold also for this instrument.

The chemical effects of light have also been tried for measuring the luminous intensity of light. Photographic paper has, however, a stimulous curve differing greatly from that of the eye, being chiefly affected by ultra-violet rays. We can, therefore, expect only relative results, and the method is inconvenient and therefore suitable for the laboratory only. It possesses the advantage that it records mean values during a test which is preferable when testing unsteady arc lamps.

In 1877 Werner von Siemens suggested that the selenium cell might be employed for testing luminous intensity. Selenium possesses the property of reducing its resistance with an increase in the illumination. Since then innumerable papers, dealing with the behaviour of selenium under the influence of light, have been published, but a perfectly satisfactory cell has not yet been produced. Its behaviour is irregular and its sensitiveness as regards lights of different colours depends upon the preparation. The maximum sensitiveness may lie near the red, green, or even the ultra-violet, and Pfund * states that the cell is affected by a phenomenon similar to the Purkinje effect, the position of maximum sensitiveness in the spectrum changing with the intensity of the illumination. The older cells showed deterioration after they had been in use only short periods.

Another disadvantage is the inertia of the cell, *i.e.* it takes a considerable time, after the cell has been placed in darkness, before it has regained its original resistance. This is especially the case for thick cells, as one would expect. During the last few years considerable progress has, however, been recorded in the manufacture of these cells, and F. Brown claims that his cell (U.S.A. Patent No. 1219432) possesses a sensitiveness a thousand times greater than those hitherto constructed, and that it may be exposed to an intense light for days in succession. This result is obtained by the production of the crystals by sublimation, the crystals being then permitted to absorb argon, helium, or neon gas at a temperature below that of the crystal formation.

Fournier d'Albe † uses in the construction of these cells a porcelain plate coated with graphite in which grooves are engraved by means of a diamond. The whole surface is then coated with selenium.

The principle of a selenium photometer is shown in fig. 5.36. I_1 and I_2 are the lights to be compared, A and D reflecting mirrors, S_e a selenium

* *Physical Review*, vol. xxxiv., May 1912.

† *Journal of the Röntgen Society*, April 1917. See also K. J. Dietrich, *Physical Review*, May 1916, p. 551 ; P. J. Nicholson, *ibid.*, January 1914, p. 1 ; E. H. Kennard and E. O. Dietrich, *ibid.*, January 1917, p. 58.

cell, B a battery, and M a milliammeter. The cell is rapidly moved backwards and forwards so that it is alternately illuminated by I_1 and I_2. When the illuminations from both sources are equal, the resistance of the battery circuit is stationary, but when this is not the case the pointer of instrument M vibrates.

During recent years alkali metal cells, made by Elster and Geitel, have been employed by Richtmyr * and Voege.† In such a cell we have two electrodes separated by air, with a certain P.D. between them. When the negative electrode is illuminated, electrons are emitted, and as a result a small measurable current flows. This " normal " effect occurs with all metals and increases with diminishing wave-length of light. With alkali metals there is, in addition, a selective action, for which the maximum sensitiveness lies in the visible region of the spectrum, viz. at 44×10^{-6} centimetres for potassium, 48×10^{-6} centimetres for rubidium. The

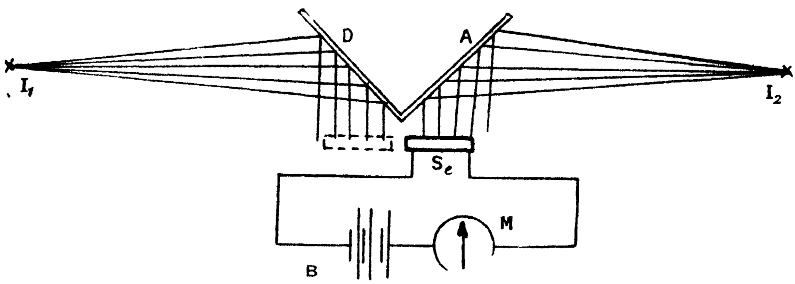


FIG. 5.36.—Selenium Cell Photometer.

selective effect may be made large enough so that the normal one is of little account.

The sensitiveness and constancy of the cell is greatly increased by allowing the discharge current to pass in an atmosphere of argon. It is claimed for these cells that they possess practically no inertia, that the photo-electric current is proportional to the intensity of illumination, and that they remain constant for a very long time. By the addition of a screen or filter it is possible to cause the maximum effect to occur at the same point in the spectrum as that of the eye. Voege uses a special type of gelatine filter, which he found very satisfactory.

The system is, of course, best again adapted for relative measurements. It possesses the advantage over the thermopile that no special care need be taken to guard against pure heat rays. By varying the voltage from about 60 to 150, the range of the instrument is increased beyond that possible by altering distances. At 200 volts a luminous discharge occurs between the electrodes of the cell, which must be prevented.

The arrangement employed for a test is shown in fig. 5.37. E is a

* *Trans. Ill. Eng. Soc. U.S.A.*, vol. viii., 1913, p. 459.

† *Elektrotechnische Zeitschrift*, 30th April 1914.

source of current joined in series with the cell C inside its filter F and a galvanometer G. A standard lamp is first placed at X at such a distance from the cell that the reading of the galvanometer is equal to the candle-power of the lamp (or a multiple thereof). (On account of the high resistance of the galvanometer a series resistance is usually not required.) The standard lamp is next replaced by the lamp under test, the galvanometer showing directly its candle-power. For correct results the standard and test lamps should be of the same type. R is a mirror to increase the illumination of the cell, since the filter reduces the sensibility. For rapid testing of glow lamps the method is extremely convenient.

There seems to be little doubt that one day a physical photometer will appear which will respond to light in the same way as the human eye, thereby reducing the work to the reading of a simple indicating instrument and greatly simplifying measurements, especially if the watt is adopted as the unit of luminous flux. The final judgment of an existing illumination will, of course, always rest with the eye.

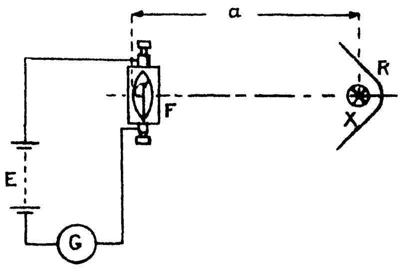


FIG. 5.37.—Alkali Cell Photometer.

5.29. CRITICISM OF PHOTOMETERS.—**Specifications.**—Since the first edition of this book was published, not many new types of equality of brightness photometers have been put on the market, and the Lummer-Brodhun type, or its modification, still holds the premier position as regards accuracy.

The flicker photometer has. however, been carefully investigated, especially by Ives and Kingsbury, its theory has been evolved, and the conditions of working under which this type of instrument may be relied upon are now known. The idea that photometers without eye-pieces are more satisfactory than those with them has been exploded, since the accuracy of work depends upon the angle at which a test plate is looked at. This is clearly proved by fig. 5.34. To this it must be added that with instruments without eye-pieces the eyes are too much influenced by the surroundings and are apt to roam about, which from its very nature reduces the sensitiveness.

Consequently, even the cell photometers, intended for rough work only, are being supplied with an eye-piece in order to view the test screen always at the same angle.

For reliable work the illumination of the photometer screen should be at least 1 foot-candle, and preferably 2½, a brightness not difficult to obtain in a laboratory, but rarely procurable in outdoor work. The accuracy obtainable in testing the illumination of streets is therefore much smaller than when determining luminous intensities in the laboratory. With the Lummer-Brodhun contrast photometer, when testing intensities of similar colour, the readings of an experienced observer may be expected to lie within 0·3 per cent., and the mean of a series of readings by a number of such observers may be repeated within one-tenth of 1 per cent. The general accuracy procurable in commercial work may be 2 per cent.* with excellent instruments under favourable conditions, but it will usually be very much less. It is questionable whether on outdoor work an accuracy within 5 per cent. can be guaranteed, 10 to 15 per cent. being the result more likely obtainable.

On the whole, it may be stated that at the present stage of the illuminating science the Lummer-Brodhun prisms give the most reliable results in laboratory and commercial work as long as the colours of the fields of view do not differ too much, while for the comparison of illuminants with greatly varying tints the properly constructed flicker instrument is preferable, as it gives the more consistent results. The readings of an experienced observer should lie within 0·75 per cent. Physical photometers are suitable for the laboratory only.

Speaking generally, the accuracy, or rather the precision, obtainable in photometric work depends largely upon the individual. A person used to a Bunsen grease-spot instrument will obtain better results with it than with a Lummer-Brodhun type, to which he is unaccustomed. As in everything, experience tells also in this class of work. Even the condition of the observer is of importance, and it will be quite obvious that a person out of health will be less reliable—under otherwise equal conditions—than a healthy individual. A large number of observations in succession causes fatigue, which means that the eye becomes less sensitive. This is probably due to the continuous observation of a highly illuminated surface, the photometer screen, which is in great contrast with the surrounding blackness of a photometer room, and it is therefore advisable to rest the eye by deviation to other work. Glare should be totally avoided, as it destroys the equilibrium of the eye completely.

Looking at the photometer screen for too short a time reduces the precision, but this happens also if the period is made too long. A time of about twenty seconds is suitable with a Lummer-Brodhun contrast pattern instrument. Instrumental errors, which are constant, can be determined and neutralised. They are chiefly due to stray rays, unsymmetrical photometer screens, and inadequate distances of the sources from the screen, so that the law of inverse square holds no longer. Care should also be taken that lamps burn under normal conditions.

Errors may be systematic, or accidental. The former are partly instrumental, and may be neutralised by calibration and by taking into account influences such as those of atmospheric conditions on flame standards. Errors are largely prevented by employing a number of equally skilled operators. As a matter of fact for accurate work the average eye is essential. Accidental errors can be determined mathe-

* C. H. Sharp, *Trans. Am. Inst. Electr. Eng.*, vol. xix. p. 1493.

matically by an application of the law of least squares. In photometric work it suffices to make a number of measurements under exactly similar conditions, and to take the mean result. To go further and find the probable error of a single observation and the mean error of the result, expressed by

$$0{\cdot}6745\sqrt{\frac{\Sigma R_0^2}{n-1}}=0{\cdot}6745M$$

and

$$\frac{M}{\sqrt{n}}$$

respectively, where R_0 is the residual, *i.e.* the difference between the mean and the single observations, and n the number of observations, would in many cases be waste of time.

The Committee appointed in 1913 to deal with street lighting made the following recommendations regarding the requirements for the testing and use of a street photometer :—

A. General Requirements for all Classes.

(1) *Division or Graduation.*—The instrument to be so made that it can be verified at any time for accuracy of graduation by direct test on a photometric bench with the light falling perpendicularly on the test plate. This verification to be made at not less than 5 points on the scale, the error under laboratory conditions not to exceed + or − 3 per cent. at readings above 0·05 foot-candle.

(2) *Range.*—The scale shall include, either directly or by means of adjustments for various grades, a range from 0·003 to 3 foot-candles.

(3) *Constant.*—Before and after making a series of outdoor tests, the constant of the scale shall be verified at least at one point on the scale between 0·05 and 1 foot-candle against a substandard. If an electric accumulator is used, it shall have been run, after charging, for not less than fifteen minutes.

(4) *The lamp* shall be tested (together with the electric battery, if any, and any controlling resistance or measuring instruments) at about mid-point on the range for fifteen minutes continuously without showing any appreciable change.

(5) *The angle of incidence* (that is, the angle between the direction of the ray of light to be measured and the vertical) shall be measured to 2 degrees by suitable means.

B. Requirements for a Candle-power Photometer.

(1) *Stray light* from neighbouring lamps, buildings, and sky shall be excluded.

(2) The height of the test screen from the ground is immaterial.

C. Requirements for an Illumination Photometer.

(1) The test plate, if forming part of the photometer, shall be so arranged that it may receive the sum of the illuminations of neighbouring lights without obstruction.

(2) The test plate shall be free from polish or glaze, and the photometer shall be tested in a laboratory for variation from the cosine law. Up to the angle of incidence of 60 degrees this total variation shall not, under working conditions, exceed 10 per cent.

(3) Provision shall be made for holding horizontally, and at a height of 3 feet 3 inches above the ground, the test plate which receives the light to be measured.

5.30. ABSORPTION OF LIGHT BY MIRRORS.—In a mirror the image appears as far behind the mirror as the light lies actually in front of it. We must therefore add to the distance between the mirror and the photometer that from the mirror to the lamp.

As light is absorbed by a mirror, the emerging ray is reduced in intensity. The reduction coefficient may be found as follows: Use two similar lamps and obtain equality of the optical fields without any mirrors, when

$$I_1 = I_2 \frac{L_1^2}{L_2^2}.$$

Next place I_1 at a distance L_3 from the axis of the photometer on the same level as before, and now conduct the same rays which previously reached the photometer by means of the mirror to be tested to the screen. The normal distance from the mirror to the light I_1 is L_3, that from the mirror to the screen L_4, and equality is obtained by making the distance from the photometer to the light I_2 equal to L_5; then, since part of the light is absorbed by the mirror,

$$I' = I_2 \frac{(L_3 + L_4)^2}{L_5^2},$$

whence

$$\frac{I'}{I_1} = K_r = \frac{L_2^2 (L_3 + L_4)^2}{L_1^2 \times L_5^2} = \text{reduction coefficient} \quad . \quad . \quad 5.12$$

If it is possible to make $L_3 + L_4 = L_1$, then

$$\frac{I'}{I_1} = K_r = \frac{L_2^2}{L_5^2} \quad . \quad . \quad . \quad . \quad 5.13$$

It is best to use polished silver or good glass mirrors for this class of work, as the reduction coefficient is then practically the same for all colours in the visible spectrum. The value of this coefficient for polished silver is about 0·93.

5.31. PHOTOMETER ROOM AND AUXILIARY APPARATUS.—A photometer room should not be too small. The space occupied by it should be not less than 50 cubic metres (1800 cubic feet) and preferably larger if possible, with a minimum length of 10 metres (32 feet). This is essential for the testing of arc lamps, since the bench must be of considerable length— at least twenty times the diameter of the globe – if the law of inverse squares is to be accurate. The ventilation of the room should be as thorough as possible, but draughts must be avoided. This is especially necessary when flame standards are used, the candle-power of which

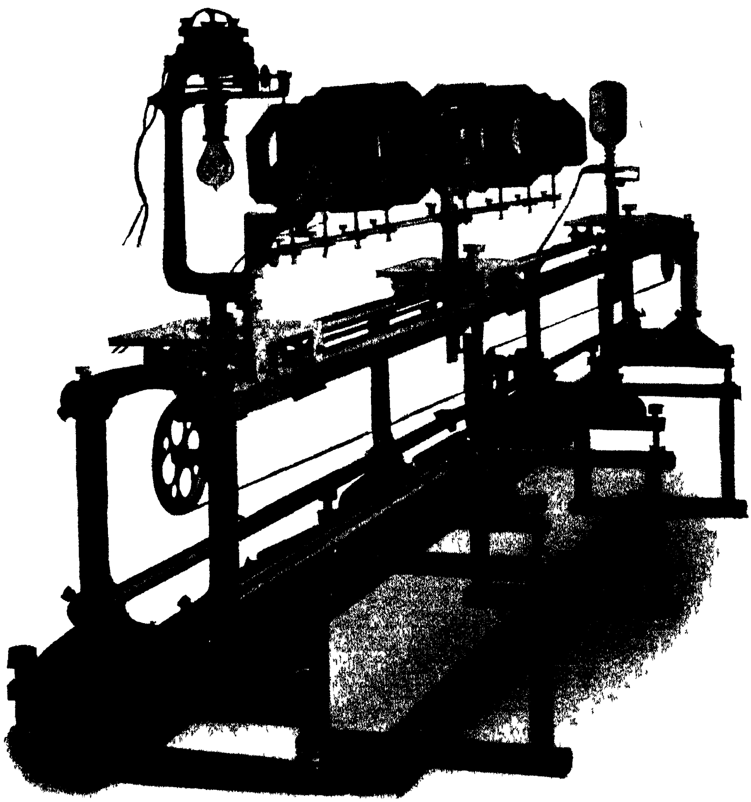


FIG. 5.38. Standard Photometer Bench.*

depends largely on the atmospheric conditions surrounding the lamp. The suitable size of a photometer room is 12 × 3 × 5 cubic metres (appr. 40 × 10 × 16 cubic feet).

Photometer rooms are usually painted a dead black; but this is not absolutely essential if only sufficient care is taken to prevent reflected light from reaching the photometer. A complete photometer bench for the testing of incandescent lamps is shown in fig. 5.38. Reflected light is kept from the photometer by means of aluminium screens covered with dead-black velvet. The direct light passes through holes in the screens.

* As manufactured by Alex. Wright & Co., Ltd., London, and used at the National Physical Laboratory, London.

These holes may be fitted with dispersion lenses or reducing glasses when lights of exceedingly unequal intensities are to be compared. The

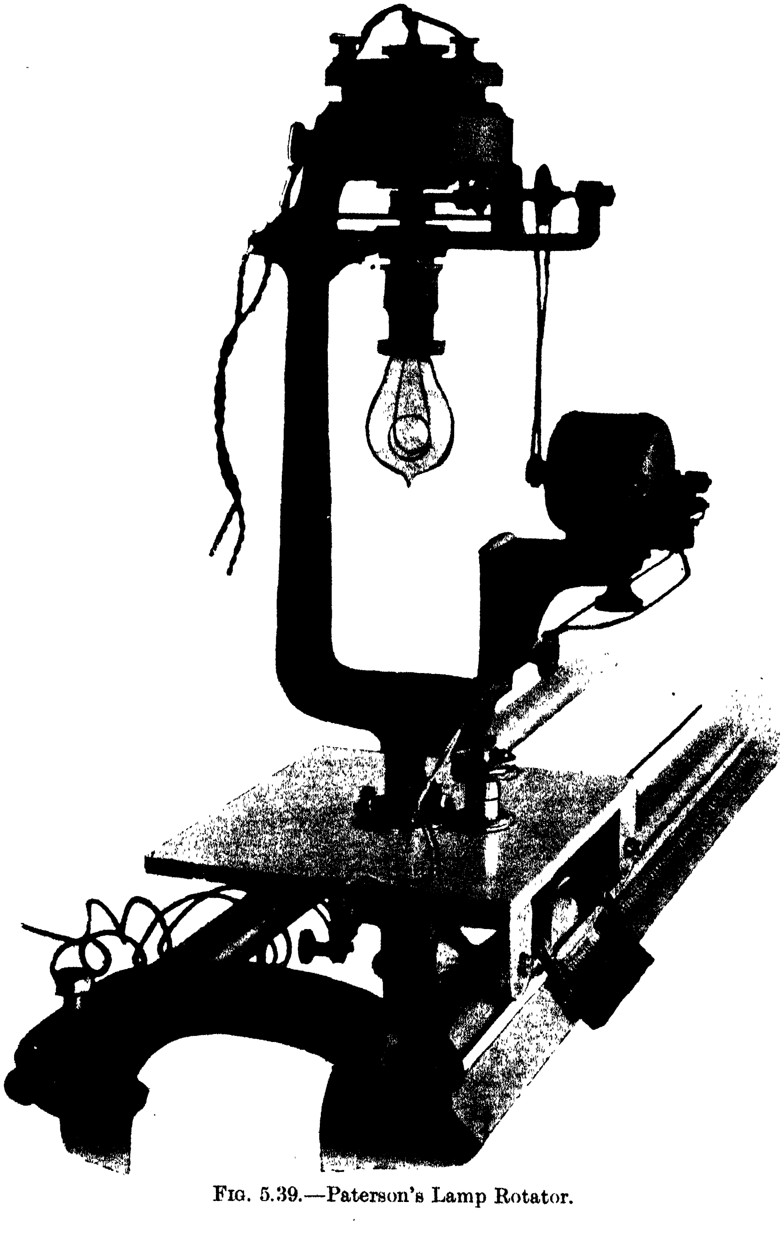


FIG. 5.39.—Paterson's Lamp Rotator.

carriage of the photometer is supplied with a small portable electric lamp in order to facilitate the reading of the scales. The error caused by the reflection of light from the screens is negligible when glow lamps are tested, and also—if sufficient care be exercised—when arc lamps are compared.

Photometer, standard lamp, and the lamp to be compared rest on carriages which slide on bars accurately turned and planished. Glow lamps are usually fixed on a universal joint, which allows the axis of the lamp to be placed in any direction.

The bench illustrated in fig. 5.38 is supplied with a lamp rotator, in order to enable mean horizontal candle-power tests to be rapidly carried out. This lamp rotator is shown in fig. 5.39, and is due to Mr C. C. Paterson. The scale of the bench, which consists of a strip of polished triangular brass, is provided with two graduations, one in centimetres and one for direct reading. The length of the bench is 3 metres.

The illumination of the photometer screen should be made at least 10 metre-candles (about 1 foot-candle). A 10 candle-power standard would then have to be placed at a distance of 1 metre from the photometer. Clamping the photometer to the working standard of this intensity, lamps up to 40 candles could be tested on a bench 3 metres long. The moving of the test lamp is on the whole to be preferred. As the test lamp may be at a considerable distance from the photometer, the moving of it is accomplished with rope and pulley.

For lamps larger than 40 candles the illumination on the photometer screen will be greater than 10 metre-candles. It may then be more convenient to place the standard lamp at 0 of the scale, the test lamp at 300 (centimetres). For the different positions of the photometer the accompanying table gives then the ratio of $\frac{\text{Test lamp}}{\text{Standard lamp}}$.

TABLE 5.03.—FOR A PHOTOMETER BENCH 300 CENTIMETRES LONG.

	0	1	2	3	4	5	6	7	8	9
50	25·0	23·8	22·7	21·7	20·8	19·8	19·0	18·2	17·4	16·7
60	16·0	15·4	14·7	14·2	13·6	13·1	12·6	12·1	11·6	11·2
70	10·8	10·4	10·0	9·7	9·3	9·00	8·69	8·39	8·10	7·83
80	7·56	7·31	7·07	6·84	6·61	6·40	6·19	5·99	5·80	5·62
90	5·44	5·27	5·11	4 95	4·80	4·66	4·52	4·38	4·25	4·12
100	4·00	3·88	3·77	3 66	3·55	3·45	3·35	3·25	3·16	3·07
110	2·98	2·90	2·82	2·74	2·66	2·59	2·52	2·45	2·38	2·31
120	2·25	2·19	2·13	2·07	2·01	1·96	1·91	1·85	1·80	1·76
130	1·71	1·66	1·62	1·58	1·53	1·49	1·45	1·42	1·38	1·34
140	1·306	1·271	1·238	1·205	1·173	1·142	1·113	1·083	1·055	1·027
150	1·000	0·974	0·948	0·923	0·899	0 875	0·852	0·830	0·808	0·787
160	0·765	0·745	0·726	0·706	0·688	0 669	0·652	0·634	0·617	0 601
170	0·585	0·569	0·554	0·539	0 524	0·510	0·496	0·483	0·470	0·457
180	0·444	0·432	0 420	0·409	0·397	0·386	0·376	0 365	0·355	0·345
190	0·335	0·326	0·316	0 307	0·289	0·290	0·282	0·273	0·265	0·258
200	0·250	0·243	0 235	0·228	0·221	0·215	0·208	0·202	0·196	0·190
210	0·184	0·178	0·172	0·167	0·161	0·156	0·151	0·146	0·141	0·137
220	0·132	0·128	0·123	0·119	0·115	0·111	0·107	0·104	0·100	0·096
230	0·093	0·089	0·086	0·083	0·080	0·076	0·074	0·071	0·068	0·065
240	0 063	0·060	0·057	0·055	0·053	0·050	0 048	0·046	0 044	0·042

In order to be able to plot the polar curves of incandescent lamps, *i.e.*

to measure the intensity of the rays in any part of a sphere surrounding a source, apparatus as illustrated in figs. 5.40 and 5.41 is suitable. The figures are self-explanatory.

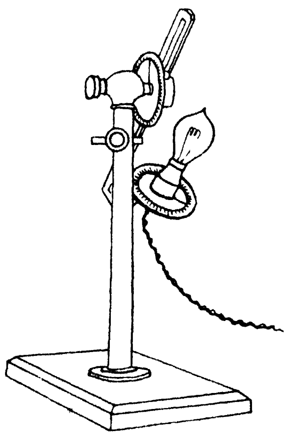


FIG. 5.40. Universal Lamp Holder.

The spherical candle-power of arc lamps may be determined by employing the system of mirrors shown in fig. 5.42. The reflecting mirrors A B may be placed at any angle, read on the scale K. G is a balance weight, and W the carriage which is placed on the rails of the photometer bench.

Another apparatus suitable for the determination of polar curves of arc lamps is described by Dr J. A. Fleming as follows *: On a suitable base is erected a wooden gallows about 9 feet high and 3 feet wide. From the top of this the arc lamp to be investigated is suspended. In the two uprights of the gallows are two openings

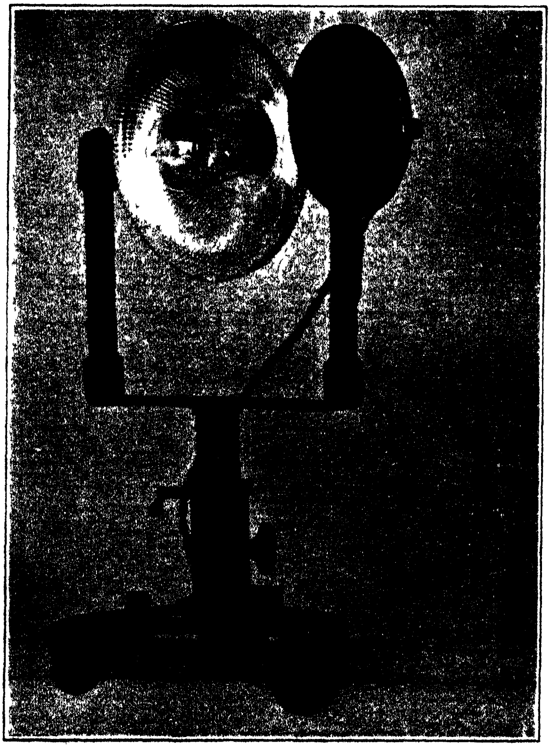


FIG. 5.41.—Lamp-Holder for Spherical Measurements.

* *J.I.E.E.*, vol. xxxii. p. 145.

through which pass brass tubes or hollow bearings to which is connected another rectangular swinging frame (see fig. 5.43). The lamp is placed so that the arc A is exactly in line with the axis of these hollow trunnions. On the outside of one of the uprights is a circular scale of degrees, and the swinging frame carries a pointer by means of which its angular position relatively to the horizon is determined. The swinging frame also carries three plane mirrors, I_1, I_2, I_3, which

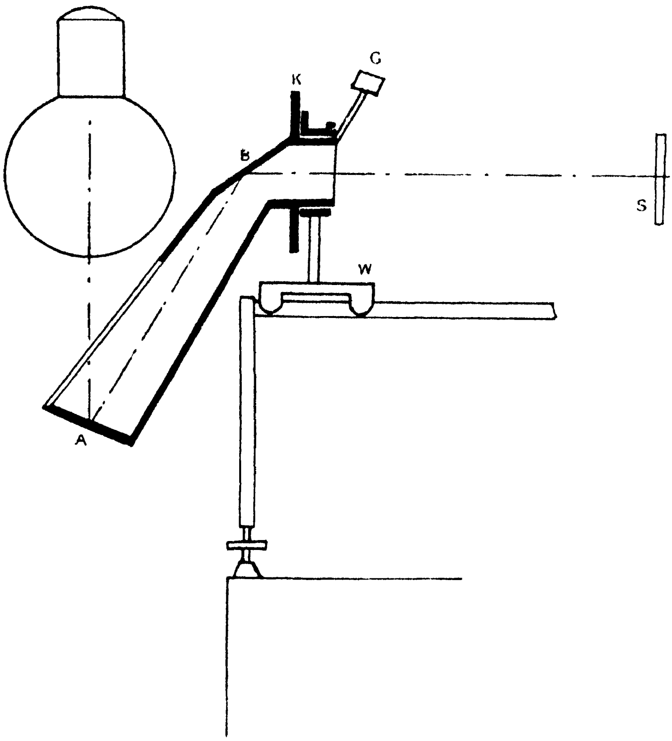


FIG. 5.42.—Lamp-Holder for Spherical Measurements.

are set at angles of 45 degrees and catch the ray from the arc lamp, and reflect it down one of the hollow trunnions. The ray therefore emerges in the same direction, no matter what may be the angular position of the swinging frame. This frame can be so set as to catch a ray coming from the arc at any angle above and below the horizon. It is quite possible, by means of a standard incandescent lamp, to determine the total and constant percentage loss of light by the three mirrors, at each of which the ray is reflected at an incidence of 45 degrees, and hence to apply the necessary correction to the intensity of the selected ray. By employing a photometer and a standard glow lamp, measurements can be made of the luminous intensity of the arc in any direction relatively to the horizontal plane through the arc. This direct measurement is often rendered difficult because the arc shifts its position continually, and there is, consequently, a periodic waxing and waning of the light in any direction. This difficulty may be overcome by testing the arc against itself—or, in other words, by comparing the luminous intensity of the ray coming from the arc in any direction with that of the

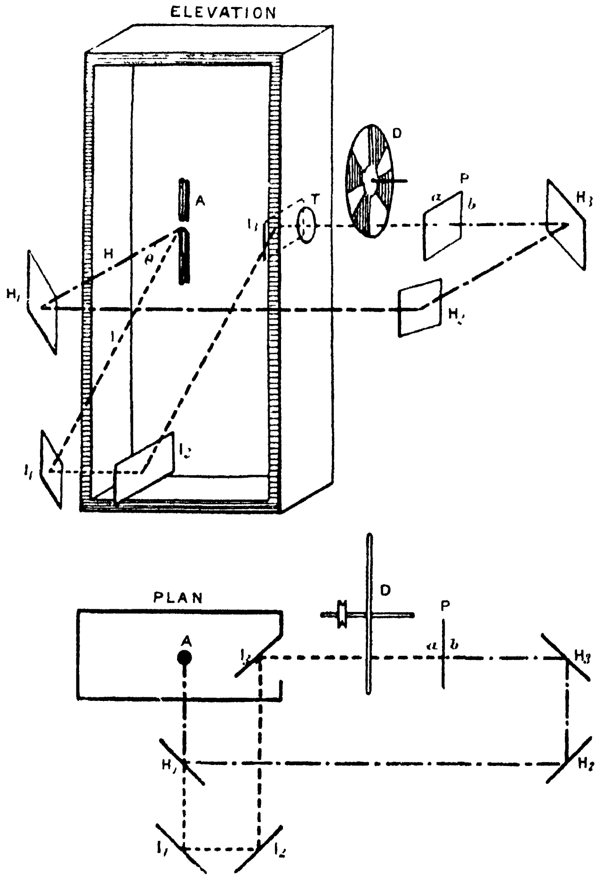


FIG. 5.43.—Fleming's Arc Lamp Testing Arrangement.

ray coming off in a horizontal direction. This is accomplished by fixing three mirrors, H_1, H_2, H_3, to reflect round the ray coming in a horizontal direction from the arc, and make it coincide in direction with the thrice-reflected ray coming from off the arc at any angle above or below the horizon. In each case the ray suffers reflection at three mirrors placed at angles of 45 degrees; hence there is no difference in the loss by reflection, and both the rays are weakened in the same ratio. We have then to determine the ratio of the intensities of these two rays; this may be done by, for instance, employing a variable aperture disc photometer, described under Brodhun's street photometer.

With the aid of a standard glow lamp, and a single direct observation (or, better still, the mean result of a number of observations), we are able to determine the mean absolute horizontal luminous intensity; and hence the polar curve of luminous intensity can be plotted, as will be shown further on.

A method somewhat similar to, but simpler than, Fleming's is the following: On a bracket is fixed a metal screen S, placed between the arc lamp I and the photometer P to keep from the latter all direct light (see fig. 5.44). To a shaft passing through the centre of S are pivoted two levers, each of which carries at its extremity a mirror M_1 and M_2. When the two arms are horizontal, the fields of view reflected by M_1 and M_2 should be equalised for equal distances. One lever, say 1, is now rotated, whereas the other one, 2, is kept horizontal, so that the light reflected from M_1 to P is emitted under different angles, seen on the metal screen.

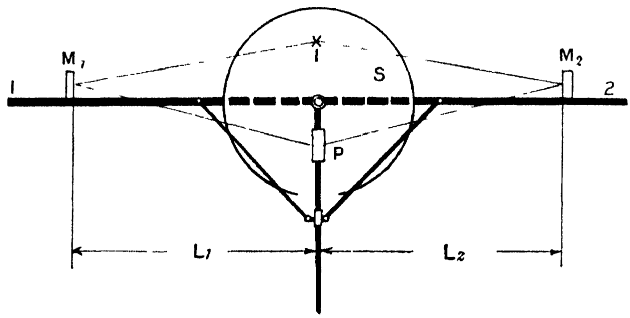


FIG. 5.44.—Arc Lamp Testing Arrangement.

By moving M_1, equality of the field of view is easily obtained, and the intensities of the rays inclined at these angles are given by

$$I_\theta = I_H \frac{L_1^2}{L_2^2},$$

in which L_1 and L_2 are the distances. I_H, the horizontal intensity, has been determined by a previous test. The photometer should be adjustable so that the angles of incidence of the rays on M_1 and M_2 are equal.

The absorption of light by the mirrors need not be considered, since both intensities are equally affected. The method gives correct results for symmetrical lights only, for which the horizontal intensity (along the same latitude) is practically uniform.

The previous methods possess the disadvantage that the lights must be symmetrical. Unfortunately, the position of the arc is not permanent, even for lamps with vertical carbons, and consequently the intensity of the ray under test varies. This difficulty is overcome by rotating the lamp round a vertical axis, as in the case of incandescent lamps. At the same time, the construction of the apparatus must be such that measurements can be made under any angle. Such a mechanism is shown in fig. 5.45, which has been employed by Dr Drysdale at the Northampton Institute. The illustration is self-explanatory.

In the test room of the General Electric Company the testing of arc lamps is carried out with the system illustrated in fig. 5.46. Two silvered mirrors are employed for reflecting light to the photometer screen, the beams being cut down in intensity by means of a rotating

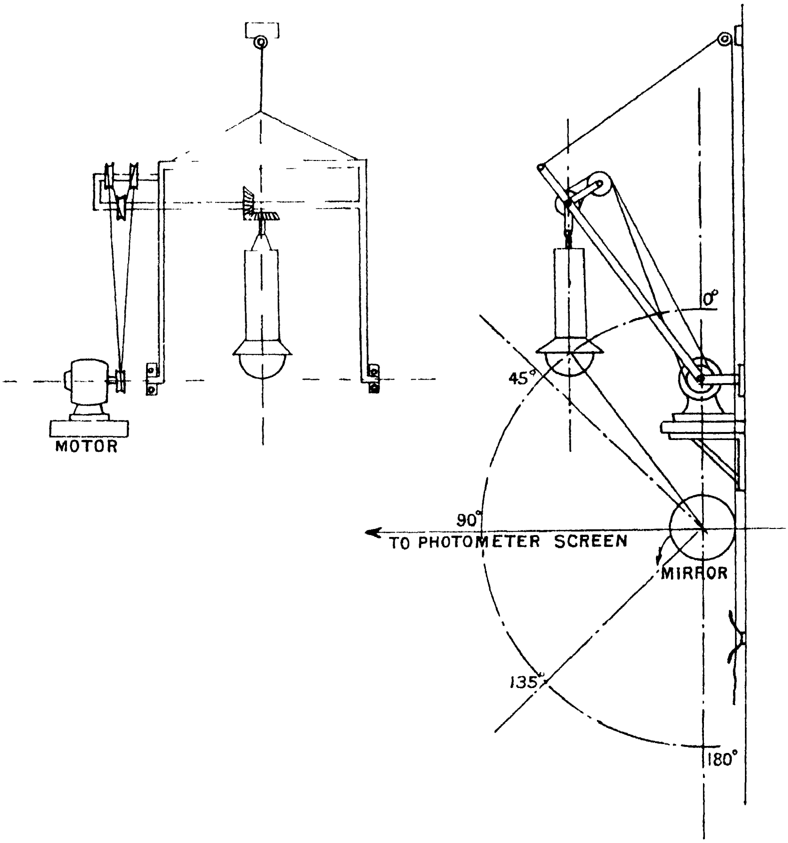


FIG. 5.45.—Drysdale's Apparatus for Testing Arc Lamps.

variable aperture disc. The mean of the readings in the two hemispheres is thus recorded, which is an advantage for unsteady lights. One screen can be used only in the vertical diameter. Balance is obtained by changing the position of the comparison lamp and the adjustment of the aperture of the rotating disc. The test lamp itself is stationary.

For very rapid work an alkali cell photometer is probably best adapted for plotting polar curves, as no adjustments have to be made. All that is necessary is to take the readings of a current-indicating instrument calibrated in candles, after the cell has been once compared with a good photometer. The system is indicated in fig. 5.47.

An arm *a*, carrying the alkali C, is rotated round the lamp L. Fixed to a is a disc S supplied with photo-sensitive paper inside a box K. The latter possesses a slit through which the light reflected by a mirror of the current-indicating instrument A enters. If a is slowly rotated round L,

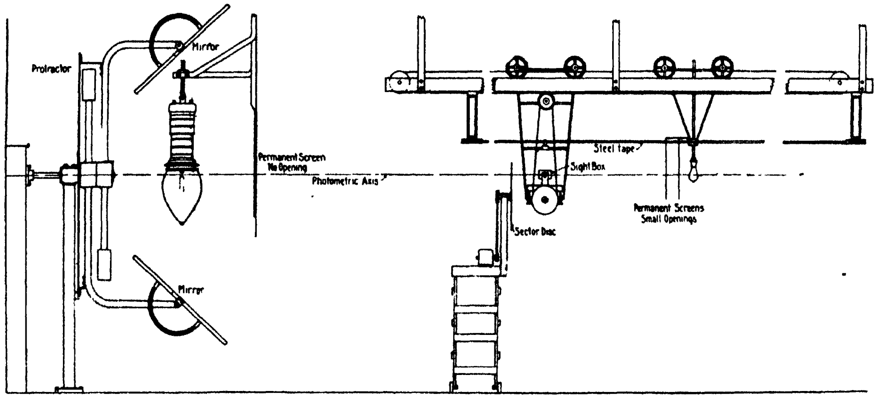


FIG. 5.46.—G.E.C. Apparatus for Testing Arc Lamps.

the beam of light from the mirror draws directly the polar curve of the lamp.

5.32. INTEGRATING PHOTOMETERS.- For the determination of

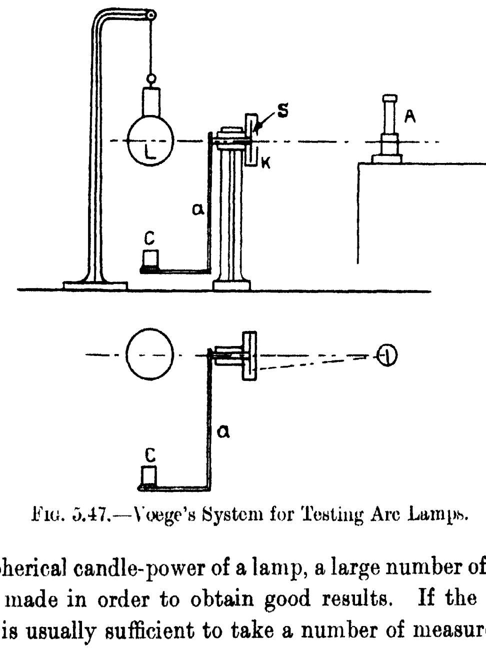


FIG. 5.47.—Voege's System for Testing Arc Lamps.

the mean spherical candle-power of a lamp, a large number of observations have to be made in order to obtain good results. If the light is symmetrical, it is usually sufficient to take a number of measurements along a meridian and to plot the Rousseau curve (see Chapter VI.), the mean ordinate of which gives the required result. In the case of non-symmetrical lights, the tests have to take place along several meridians, making the work very laborious. All this is avoided by employing integrating photometers.

5.33. MATTHEW'S PHOTOMETER. This instrument is shown diagrammatically in fig. 5.48, and gives reliable results for symmetrical lights only. But by rotating the lamp— for instance, by means of a small

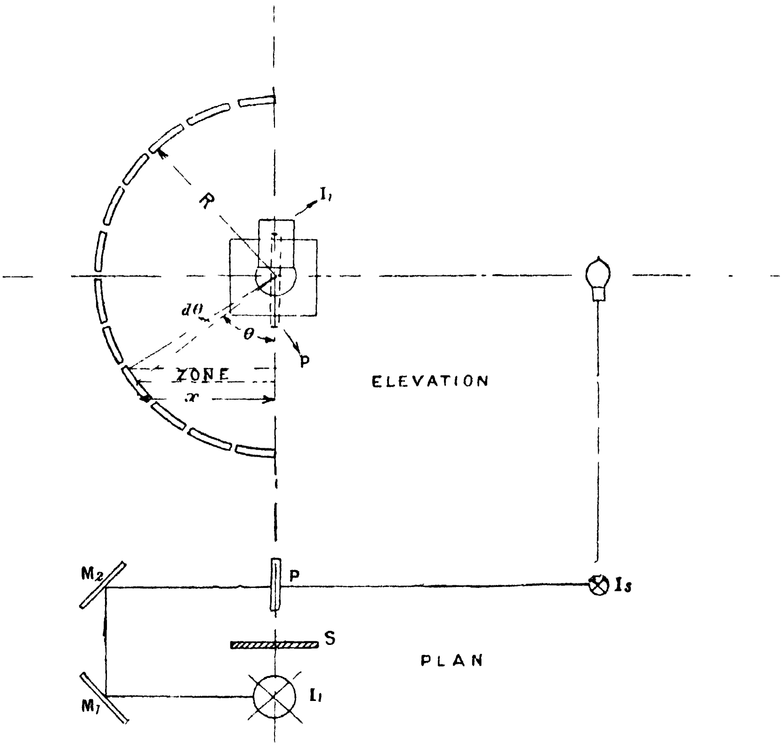


FIG. 5.48.—Matthew's Integrating Photometer.

motor,— or by making a number of observations along various meridians, any type of lamp may be tested in this manner.

The principle of the instrument will be clear from the figure.

The rays of the lamp are reflected by means of two mirrors, M_1 and M_2, to a photometer screen P illuminated on the other side by a standard lamp I_s. The calibration is made with a lamp of known mean spherical candle-power. For mean hemispherical measurements, the mirrors of the lower hemisphere only are employed, those of the upper ones being screened off.

The proof is as follows :—

The total flux from a point source of light is $\phi = 4R^2\pi\bar{E}$, where $\bar{E}$ is the uniform illumination on a surrounding hollow sphere. But

$$\bar{E} = \frac{I_0}{R^2};$$

hence

$$\phi = \frac{4R^2\pi I_0}{R^2} = 4\pi I_0,$$

where I_0 is the mean spherical candle-power (in this case the light is perfectly uniform all round). If this source is replaced by any other giving the same total flux, then we have

$$4R^2\pi E = 4\pi I_0 = \int E dS = \int \frac{I}{R^2} dS \quad . \quad . \quad . \quad 5.14$$

in which I_0 denotes now the mean spherical candle-power, and E is the illumination produced on any infinitesimal area dS caused by the candle-power I at a distance R. Suppose now that we have a symmetrical light, then the illumination of any *zone* dS along any given latitude will be uniform. If this zone lies at an angle θ inclined to the vertical (see fig. 5.48), then the area dS is equal to the circumference multiplied by the width, or,

$$dS = 2\pi x R d\theta,$$

and since

$$x = R \sin\theta, \quad dS = 2R\pi \sin\theta R d\theta,$$

whence

$$4\pi I_0 = \int \frac{I}{R^2} 2R\pi \sin\theta R d\theta$$

and

$$I_0 = \frac{1}{2}\int I \sin\theta d\theta \quad . \quad . \quad . \quad . \quad . \quad 5.15$$

The mean spherical candle-power may be found with the aid of this equation by dividing a polar curve (see also Chapter VI.) into small parts and adding up elementary products I sin θ.

If the number of parts be n for 180 degrees, then

$$\Delta\theta = \frac{\pi}{n}$$

and

$$I_0 = \frac{\pi}{2n}\sum_0^n I \sin\theta \quad . \quad . \quad . \quad . \quad 5.16$$

Take now in the Matthew integrator a ray of light inclined by an angle θ. According to equation 1.04, the illumination is proportional to the cosine of the angle of incidence; hence the illumination on the photometer screen as caused by a reflected ray is proportional to I cos $(90° - \theta)$ or to I sin θ, since the light from the mirror in question is incident on the photometer screen at $(90° - \theta)$ degrees, and the total amount from the mirror is proportional to

$$\sum^n I \sin\theta.$$

In place of mirrors J. Sahulka * employs small plaster of Paris matt surfaces, all inclined at 45 degrees to the axis of the circle, which are spaced at intervals round the circle surrounding the lamp tested. The angular intervals are so selected that the surfaces correspond with zones of equal area; hence the summation of the diffusely reflected light is a measure of mean spherical candle-power. The axis of the photometer bench passes through the centre of the circle, direct light from the lamp being screened, so that the photometer receives light only from the diffusing plates. The area of the source is thus of little importance, the distance of the photometer can be adjusted at will, and a small displacement of the lamp matters little. The constant is obtained by testing first a lamp of known mean spherical intensity.

It will be obvious that great accuracy can be expected only if calibrating and test lamps are of the same kind and the lights are symmetrical.

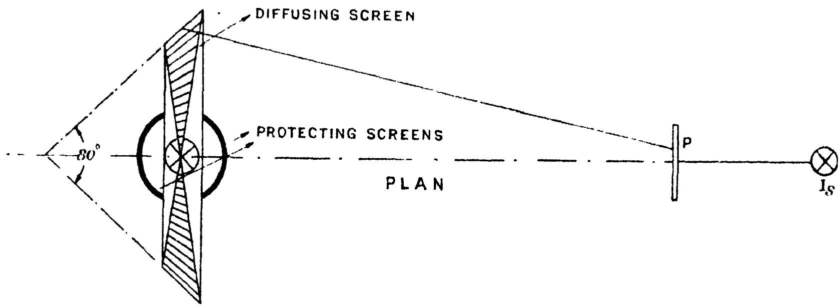


FIG. 5.49.—Blondel's Integrating Photometer.

If half-watt lamps are tested in this manner, the filaments must be similarly placed as regards the axis of the photometer bench.

5.34. BLONDEL'S INTEGRATING PHOTOMETER.—It is illustrated diagrammatically in fig. 5.49.

The light from the lamp under test is thrown on a diffusing screen which has the shape of a truncated cone. From here it is reflected on the photometer screen. The illumination on the latter is, of course, proportional to ΣI, where I is the intensity in any given direction. But the mean spherical candle-power is proportional to I sin θ. Blondel obtains this result by making the screen wide in the equatorial region of the lamp and narrow near the poles, as is indicated in the figure. The calibration is made with a lamp of known spherical intensity.

5.35. ULBRICHT'S INTEGRATING PHOTOMETER.†—This instrument, which was invented by Professor Ulbricht, consists of a large opaque sphere, painted white so as to give a smooth, well-diffusing surface. The size of the sphere should not be less than six times the diameter of the

* *Elektrotechnische Zeitschrift*, 27th June 1918, p. 253.

† See also *E.T.Z.*, 1900, pp. 512, 595; 1905, pp. 1047, 1074; 1906, pp. 50, 468, 669; 1907, p. 777; 1909, p. 322.

globe of the largest lamp tested. Smaller spheres are made of glass, which must be given an external coating. Larger ones are made of sheet metal and in two parts, for easy manipulation.

A light placed inside this sphere is diffused in such a manner that the resultant illumination is uniform over the whole surface; consequently the illumination of a window in the sphere is proportional to the mean spherical candle-power of the lamp inserted, as long as direct light is kept from the window. This is proved as follows * : –

Assume at first the light in the centre of the sphere, as shown in fig. 5.50. Consider any small area dS, the normal illumination of which is proportional to $\frac{I}{R^2}$, where I is the intensity of the ray in that direction and R the radius of the sphere. This area acts now as a source of light

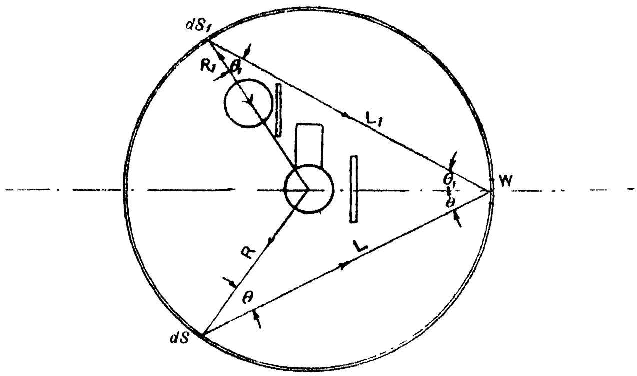


FIG. 5.50.—Principle of Ulbricht's Spherical Photometer.

to the window W, but the flux is emitted inclined at an angle θ. Its quantity to W is therefore proportional to

$$\frac{I}{R^2} dS \cos\theta,$$

according to the cosine law, and hence the normal illumination of W is proportional to

$$\frac{I}{R^2} dS \cos\theta \frac{\cos\theta}{L^2},$$

since the illumination is directly proportional to the angle of incidence and inversely to the square of the distance L. As

$$\cos\theta = \frac{L}{2R},$$

we get the illumination of W proportional to

$$\frac{I dS}{4R^4}.$$

* Ulbricht and Bloch give a more elaborate theory.

What applies to the area dS holds for the whole sphere; hence the normal illumination of W is proportional to

$$\frac{1}{4R^2}\int\frac{1}{R^2}dS,$$

or, according to equation 5.14, proportional to a constant multiplied by the mean spherical candle-power of the lamp.

It is not even necessary to place the lamp in the centre. Suppose it is anywhere between the centre and the circumference as indicated by the upper circle in fig. 5.50. We now have the normal illumination of dS_1 proportional to $\frac{I_1}{R_1^2}$, or to E_1, and the quantity of light emitted to the window proportional to

$$E_1 dS_1 \cos\theta_1,$$

while the normal illumination of W is proportional to

$$E_1 dS_1 \cos\theta_1 \frac{\cos\theta_1}{L_1^2}.$$

But

$$\cos\theta_1 = \frac{L_1}{2R},$$

whence the normal illumination of W becomes proportional to

$$E_1 dS_1 \frac{L_1^2}{4R^2L_1^2} = \frac{E_1 dS_1}{4R^2},$$

and the total illumination proportional to

$$\frac{1}{4R^2}\int E_1 dS_1,$$

or to a constant multiplied by the mean spherical candle-power (see equation 5.14). This result is not changed by any absorption of light as long as the coating is perfectly uniform. Neither is it affected by the fact that the light is reflected a number of times before it reaches the window, since this can only influence the constant of the sphere, which must be determined experimentally.

The results derived here are correct as long as the surface diffuses the light uniformly and no foreign bodies are included.

As regards the inclusion of foreign bodies, Professor Ulbricht has shown that the error caused by reflection of light from these bodies is negligible, as long as the sphere is made sufficiently large.*

The following precautions must, however, be taken. No direct light should reach the window, and the calibration of the sphere, which is usually accomplished with a large incandescent electric lamp (say a 200 watt metal filament lamp), must take place with the arc lamp already in position. We thus require three screens B and B_1 (see fig. 5.51)

* See *E.T.Z.*, December 1910, p. 1295.

and a screen b, which is employed to prevent any bright parts of the lamp from reflecting light from the standardising lamp to the window W.

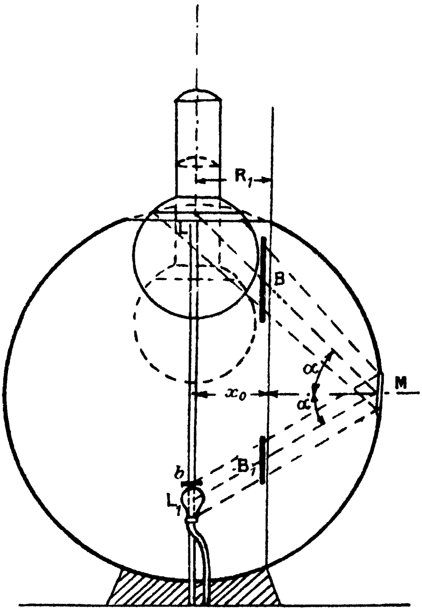


FIG. 5.51.—Arrangements of Screens in Ulbricht's Sphere.

5.36. APPROXIMATE ERRORS.—The approximate errors caused by the screens have been evaluated by Ulbricht, and are given as follows * :—

For spherical measurements,

$$\text{Error} = \frac{80S - 100S_1}{R^2\pi} \text{ per cent.} \qquad 5.17$$

which is to be added to the result.

For hemispherical determinations,

$$\text{Error} = \frac{50S - 100S_1}{R^2\pi} \text{ per cent.} \qquad 5.18$$

in which S = one-sided area of screen B in square centimetres,

S_1 = ,, ,, B_1 ,, ,,

R = radius of sphere in centimetres.

The screen B should not be larger than one-twentieth of the central cross-sectional area of the sphere and must screen off—

(*a*) For measurements without globes: the whole source of light and the reflector.

(*b*) For determinations with clear glass globes: the whole source, the reflector, and any image of the source.

(*c*) For tests with diffusing globes: the whole globe.

* See *E.T.Z.*, 1907, p. 777.

If the screens are comparatively large, the errors may be more accurately determined with the following equations (see also fig. 5.52) : –

$$\text{Error} = \frac{Sa}{R^2\pi}\left(i_B + 4i_C\right) - \frac{S_1 a}{R^2\pi}\left(5{\cdot}5 - \frac{2}{3}i_{c1}\right) \quad . \quad . \quad 5.19$$

and for hemispherical tests

$$\text{Error} = \frac{a}{R^2\pi}\left[S(i_B + 4i_C) - 5{\cdot}5S_1\right] \quad . \quad . \quad . \quad 5.20$$

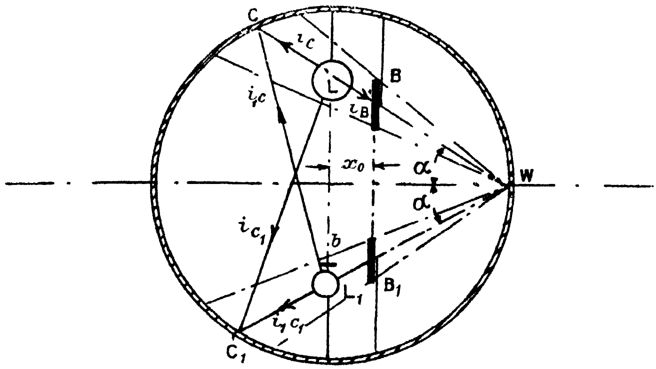


FIG. 5.52.— Determination of Errors for Ulbricht's Sphere, due to Screens.

in which a represents the absorption of the diffusing surface,

$$i_B = \frac{I_B}{I_0},$$

where I_B is the candle-power of the arc lamp in the direction of the screen B,

$$i_C = \frac{I_C}{I_0},$$

where I_C is the candle-power in opposite directions to I_B and

$$i_{c1} = \frac{I_{c1}}{I_0},$$

in which I_{c1} is the candle-power of the lamp in the direction of C_1, and screened off by B_1. I_0 is the mean spherical candle-power of the lamp.

Example. –Direct-current lamp in clear glass globe.

$$i_B = 3, \quad i_C = 0{\cdot}5, \quad i_{c1} = 0{\cdot}1,$$

$$S = \frac{R^2\pi}{25}, \quad S_1 = \frac{R^2\pi}{100}, \quad a = 0{\cdot}2.$$

Error (for spherical tests) $= 2{\cdot}9$ per cent.

The screen B_1 has usually an area equal to $0{\cdot}8$ of that of B, when, according to equation 5.17, the error is nil.

All screens must, of course, possess white diffusing surfaces.

For hemispherical tests, the test lamp must be placed in such a position that only the light of the lower hemisphere enters the globe. For this purpose it is necessary to cover up part of the globe which lies above the radiant centre of the arc, the radius of the black covering being R_1 (see fig. 5.51).

The radiant centre is found with a special grease-spot finder. The latter is illustrated in fig. 5.53, and consists of a blackened tube containing the grease-spot G, the mirrors M_1 and M_2, and the prisms P_1 and P_2. By means of the mirrors the observer at O views the upper and lower sides of G simultaneously. The images are brought into juxtaposition by the prisms P_1 and P_2, when the lamp is at a distance of $R_1\sqrt{3}$ from the grease-spot. A slight variation of this distance matters, however, little. The lamp is then raised or lowered until the illuminations of the upper

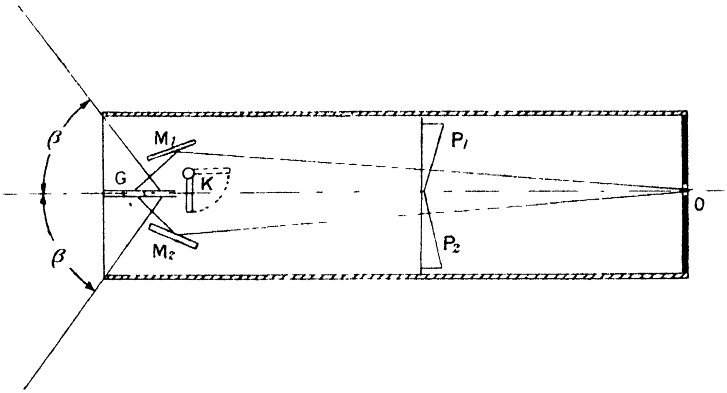


FIG. 5.53.—Ulbricht's Grease-Spot Finder.

and lower surfaces of the screen are the same. The observer is now able to determine that point in the source of the light which coincides with the plane of G, and to this point the globe must be raised so as to make the plane of the section of the globe coincide with it. Only light of the lower hemisphere is then considered in the measurement; K is a screen to guard the eye against direct light.

Care must be taken that all foreign light is carefully screened off G. This result is obtained by employing the arrangement of fig. 5.54 in which T is a large black tube and S a screen.

Further experiments were carried out in order to determine the influence of the colour of the diffusing surface of the globe on the accuracy of the test results.* The results of these investigations show that, with proper care in carrying out the tests, a perfectly white surface is not essential as long as the surface shows uniformity. A few dark spots make little difference in the ultimate result; but should, for instance, the lower half of the globe be darker than the upper one, the error is appreciable and a new coating is required. Care must also be taken that, if flame

* See *E.T.Z.*, 1910, p. 1295.

arcs are tested, the globe is sufficiently ventilated, as otherwise the light-absorbing gases affect the test result considerably. This is a very important point, especially if the lamp is surrounded with a globe (and without globes the tests are of little importance), and it may be found that the candle-power of the lamp varies considerably during a test if the ventilation is poor. It is impossible to obtain a surface which diffuses the light perfectly, but the tests carried out by Ulbricht (see last footnote) show that the results are not much affected if the diffused reflection is somewhat mixed with regular reflection. Tests were also carried out to determine the influence of an imperfectly diffusing window: they showed that the errors caused were within the range of observation errors, as long as direct light did not reach the window. As regards the nature of the coating, satisfactory results are obtained by coating the vessel first with a white oil paint, serving as a basis, and then with white zinc paint made with lime-water, the latter acting as binding material. Such a coating can easily be washed off and renewed. Good results are also obtained if the lime-water is replaced by unboiled milk. Sulphate of barium has also been employed successfully.

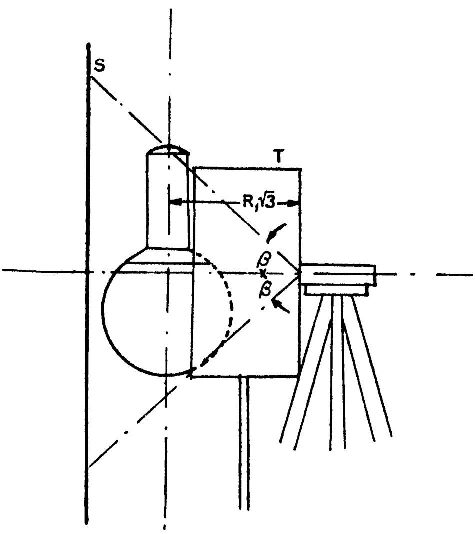


FIG. 5.54.—Determination of the Radiant Centre.

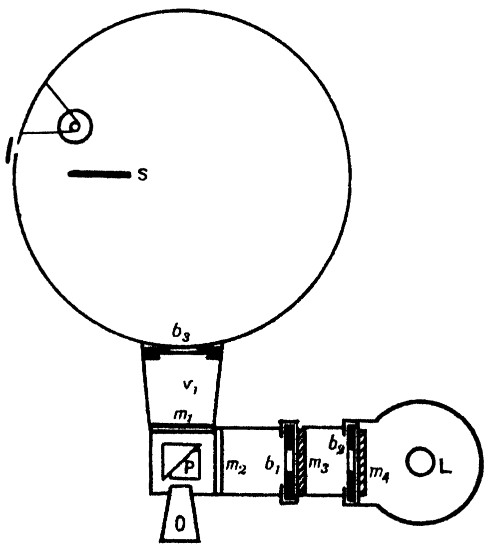


FIG. 5.55.—Modified Ulbricht's Sphere.

The nature of the glass used for the window is of importance. Whatever kind of milk glass is employed, care should be taken that it does not alter the colour of the light.

A modified Ulbricht's sphere is illustrated in fig. 5.55, in which the letters *b* represent variable apertures, letters *m* opal glasses. By these means the range of the instrument is greatly increased. The comparison lamp L is placed in a small chamber on the right, both fields of view being compared by means of a Lummer-Brodhun prism P through the eye-piece O.

For repetition work, and especially for the testing of large incandescent lamps, the modified sphere is extremely useful.*

5.37. CUBE INTEGRATING PHOTOMETER.– The sphere, especially when of large size, is an expensive article. Dr Sumpner expressed the view † that a perfectly white cubical box would give sufficiently accurate results, which might replace the more expensive globe, which also requires some skill in its manufacture on account of its size.

Since then elaborate tests have been carried out at the National Physical Laboratory,‡ and Dr Sumpner's contention has been largely proved to be correct. A synopsis of the results of these tests is as follows:

The cube gives quite accurate results with sources having similar distributions.

For sources which differ much in their distributions, the necessary corrections for each particular cube can be determined experimentally, so that the apparatus can be made an instrument of precision just as a globe photometer.

For further information the reader is referred to the original article.

5.38. MISCELLANEOUS APPARATUS.– **Candles per Watt Meter for Incandescent Lamps.**—The central idea is the use of a wattmeter, which indicates the power consumed in the test lamp by means of the quantity of light allowed to fall on one side of a photometer. One side of the photometer is then illuminated in proportion to the watts consumed by the lamp, while the illumination on the other side is proportional to the candle-power of the lamp. This may be made clearer by referring to fig. 5.56.§ The ordinates represent illuminations on the photometer screen, the abscissæ the voltages of the test lamp. The arrangement may be such that at a low voltage the illumination due to watts is greater than that due to candle-power. As the voltage of the test lamp is increased, both watts and candle-power increase, but the latter more rapidly than the former. At some voltage there will be a photometric balance.

The equality point corresponds to a certain definite ratio of candle-power to watts. If the distance between test lamp and photometer is changed, the candle-power illumination is changed as shown by the curve CP′, and the equality point is shifted to another voltage and

* R. von Vos, *Elektrotechnische Zeitschrift*, No. 52, 1917.

† *Illuminating Engineer*, May 1910.

‡ Buckley, *J.I.E.E.*, No. 297, vol. lix. p. 143.

§ H. E. Ives, *Electrical World*, vol. lix. p. 1268, 1912.

efficiency. In the instrument constructed, the illumination proportional to watts was obtained by having a vane fastened to a wattmeter needle which swung over an illuminated milk glass, perforated by a properly

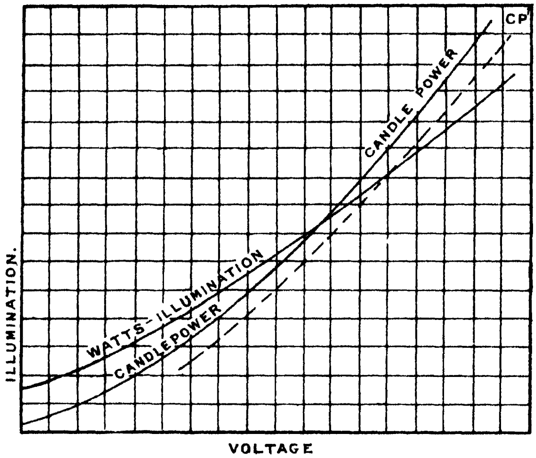


FIG. 5.56.—Candle per Watt Determinations.

calibrated opening. The light from this milk glass was admitted to one side of the photometer, constituting the illumination proportional to watts. The light from the test lamp fell directly upon the other side of the photometer.

A great advantage of this instrument is its entire independence of

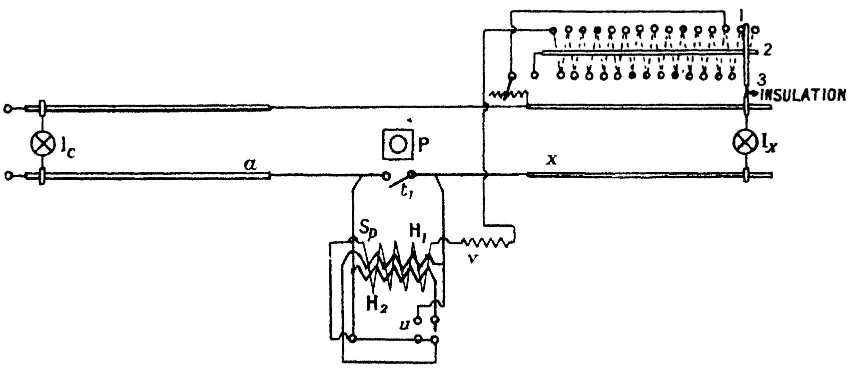


FIG. 5.57.—Candle per Watt Meter (Everett, Edgcumbe & Co.).

the kind of lamp or filament under test. Carbon or tungsten lamps may be measured with the same setting of the instrument.

Another candle per watt meter, made by Everett, Edgcumbe & Co., is illustrated in fig. 5.57.*

It consists of a portable photometer bench with wattmeter complete,

* Paulus, *Elektrotechnische Zeitschrift*, 1908, p. 166.

the photometer being fixed, while the test lamp may be moved along over a scale divided in candles. The operation is as follows:—

A standard lamp of known candle-power is placed in the socket of the test lamp and placed over the scale division corresponding to its candle-power. The comparison lamp is then moved until equality of the fields of view is obtained on the fixed photometer. The standard lamp is then replaced by the test lamp, and the latter is moved until another balance is obtained. Under the position of the test lamp its proper candle-power is then read.

Let I_s, I_c, and I_x be the intensities of standard, comparison, and test lamps respectively, b the distance of the standard, a that of the comparison, and x that of the test lamps, from the photometer, then

$$I_c = I_s\left(\frac{a}{b}\right)^2$$

and

$$I_x = I_c\left(\frac{x}{a}\right)^2 = I_s\left(\frac{x}{b}\right)^2 \quad . \quad . \quad . \quad 5.21$$

For a second test lamp

$$I'_x = I_s\left(\frac{x'}{b}\right)^2$$

when

$$I_x = I'_x\left(\frac{x}{x'}\right)^2 \quad . \quad . \quad . \quad . \quad . \quad 5.22$$

This determines the division of the scale of the photometer bench. Further

$$\frac{I_x}{x^2} = \frac{I'_x}{x'^2} = E \quad . \quad . \quad . \quad . \quad . \quad 5.23$$

which shows that the illumination of the photometer is constant and depends only on the choice of two corresponding values I'_x and x'.

In order to read on the wattmeter not only the power absorbed by the test lamp, but also the specific consumption in watts per candle, it is necessary that, with the movement of the test lamp which is required to obtain a photometric balance, the resistance R of the thin wire or volt coil of the wattmeter is so altered that the deflection of the instrument is directly proportional to the watts per candle. Let this change in the resistance be y, the unit of the power P indicated on the instrument be m, that of the specific power p be n divisions, then we have

$$p = \frac{P}{I_x}, \text{ and as } I_x = Ex^2,$$

$$p = \frac{P}{Ex^2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad 5.24$$

If now the specific consumption is to be registered, R must be altered to R + y, the relationship between the two being given by

$$\frac{mP}{np} = \frac{R+y}{R}$$

whence

$$y=R\left(\frac{m}{n}Ex^2-1\right) \quad . \quad . \quad . \quad . \quad 5.25$$

For a second test lamp

$$y'=R\left(\frac{m}{n}Ex'^2-1\right)$$

whence

$$y-y'=R\frac{m}{n}\left(I_x-I'_x\right) \quad . \quad . \quad . \quad . \quad 5.26$$

which determines the construction of the additional resistance and which says that for equal intervals of the intensities the differences in the auxiliary resistance are equal. The sign of y depends on the choice of the ratio $\frac{m}{n}$. For $m=1$, $n=20$, and $Ex^2=I_x=20$, $y=0$, which says that the wattmeter reads simultaneously the power and specific consumption. For lamps less than 20 candles y is negative, for larger ones, positive; *i.e.* R is increased.

The instrument complete is a rectangular closed box weighing 15 kilograms and having a length of 148 centimetres when opened out for use, 74 when closed, being hinged in the middle. Its height is 27 and its width 23 centimetres. The left-hand side contains the wattmeter, photometer head, and comparison lamp, the right-hand box the auxiliary resistance and test lamp. The instrument is completely closed and may be used in daylight.

CHAPTER VI.

TESTING OF ELECTRIC LAMPS AND ILLUMINATION.

6.01. LUMINOUS FLUX.—The quality of an illuminant is judged by its efficiency, the colour of its light, the size of unit, the distribution of the luminous flux, the glare or absence of glare, the steadiness of light, the cost of maintenance, and the characteristic of the electric circuit required for operation. First and foremost is the efficiency.

In order to be able to determine the efficiency of any illuminant, we must know the luminous flux which it produces. Direct-reading luminous flux meters have not yet been discovered, but some day a specially constructed instrument may appear which, in one way or another, will allow the luminous flux to be measured directly. At present it is necessary to find first the mean spherical candle-power (M.S.C.P.) and multiply this figure with $4\pi = 12 \cdot 57$.

6.02. SYMMETRICAL LIGHTS.—Rousseau Curve.—If we surround the source by an imaginary hollow sphere with the source as centre, and find that the illumination is of equal intensity as far as points on the same latitude are concerned, we call the light symmetrical. For a source of this nature we can find the M.S.C.P. by plotting first the polar curve, and from this the Rousseau curve. The mean ordinate of the latter gives the M.S.C.P.

The polar curve is obtained by determining the intensities of a symmetrical source along a meridian of the imaginary hollow sphere. Fig. 6.01 shows such a curve for a tungsten lamp. Curves of this nature are, however, misleading as regards the total flux, since their areas do not determine its magnitude. For instance, if we have two curves of similar shapes, but of which the first one has radii equal to half of those of the second curve, then the area of the latter is four times that of the former, whereas the candle-power is only double.

Again, if we consider two polar curves as shown in fig. 6.02, which are identical in shape and size except that the one is more inclined to the vertical axis than the other, we might expect the same intensity in both cases, but in reality this is not so. Curve 2 has a horizontal axis, consequently the intensity deals with an area of the circumference $2R\pi$, whereas for an inclination θ the area is only of the circumference $2R\pi \sin \theta$.

Hence the lamp with the horizontal polar curve will give a greater flux

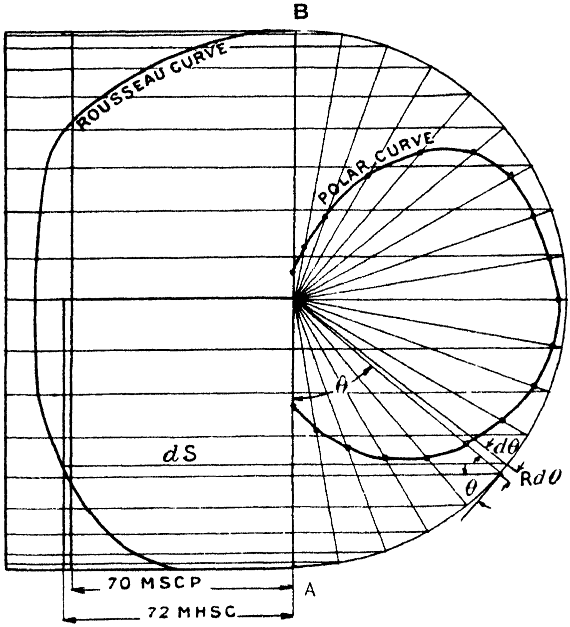


FIG. 6.01.—Polar Curve of a Tungsten Lamp.

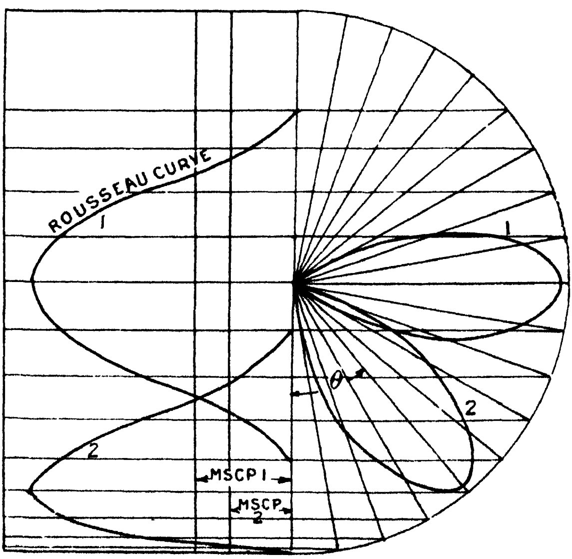


FIG. 6.02.—Polar Curves of Different Inclinations.

than the other lamp. This is strikingly illustrated when the Rousseau curve is drawn, the construction of which is as follows :—

Draw a suitable semicircle, and through each point in which the radii intersect the semicircle draw horizontal lines; then plot along these from A B the corresponding lengths of the radii, as cut off by the polar curve. The new curve thus obtained is the Rousseau curve (see also fig. 6.01). The proof of this has already been given under Matthew's integrator, where we found that

$$I_0 = \tfrac{1}{2}\int_0^\pi I \sin\theta d\theta.$$

But the area of the Rousseau curve is

$$R\int_0^\pi I \sin\theta d\theta;$$

so that the M.S.C.P. is found by dividing this area by 2R, *i.e.* by the diameter of the semicircle, and the total luminous flux $\phi = 4\pi I_0$.

It is, however, not even necessary to draw the Rousseau curve. Suppose we plot the polar curves by taking measurements under the angles of 0, 15, and 30 degrees, etc., against the horizontal and imagine the Rousseau curve drawn as before, but the various points joined by straight lines. The area of the curve may then be considered to consist of a number of trapezia, the area of which may easily be calculated. For symmetrical glow lamps it will be sufficient to take measurements under angles 0, 30, 60, and 90 degrees. The area between the ordinates (of the imaginary Rousseau curve) for the angles 15 and 45 degrees is very nearly equal to the intensity at 30 degrees multiplied by (sin 45 degrees − sin 15 degrees). If the length of line A B (fig. 6.01) is to be unity, we must multiply by the factor $\frac{1}{2}$. In this manner we obtain for all areas *—

	Intensity at	Intensity at
Above horizontal	$90^\circ \times \frac{1}{2}(\sin 90^\circ - \sin 75^\circ)$	$= 90^\circ \times 0{\cdot}017$
	$60^\circ \times \frac{1}{2}(\sin 75^\circ - \sin 45^\circ)$	$= 60^\circ \times 0{\cdot}1295$
	$30^\circ \times \frac{1}{2}(\sin 45^\circ - \sin 15^\circ)$	$= 30^\circ \times 0{\cdot}224$
Horizontal	$0^\circ \times \frac{1}{2}(\sin 15^\circ + \sin 15^\circ)$	$= 0^\circ \times 0{\cdot}259$
Below horizontal	$30^\circ \times \frac{1}{2}(\sin 45^\circ \quad \sin 15^\circ)$	$= 30^\circ \times 0{\cdot}224$
	$60^\circ \times \frac{1}{2}(\sin 75^\circ - \sin 45^\circ)$	$= 60^\circ \times 0{\cdot}1295$
	$90^\circ \times \frac{1}{2}(\sin 90^\circ - \sin 75^\circ)$	$= 90^\circ \times 0{\cdot}017$
		Sum 1·000

The sum gives the mean spherical candle-power.

For 90 degrees we should really measure the intensity under 82·5 degrees, but as these sections influence the result but little, measurements under the above given angles are usually sufficient.

For the polar curve of fig. 6.06 the measurements were as follows:—

* L. W. Wild, *Electrician*, 29th September 1905, p. 936.

Above horizontal	$I_{90^\circ} = 22$	$22 \times 0{\cdot}017 = 0{\cdot}4$
	$I_{60^\circ} = 117$	$117 \times 0{\cdot}1295 = 15{\cdot}1$
	$I_{30^\circ} = 176$	$176 \times 0{\cdot}224 = 39{\cdot}4$
Horizontal	$I_{0^\circ} = 198$	$198 \times 0{\cdot}259 = 51{\cdot}3$
Below horizontal	$I_{30^\circ} = 180$	$180 \times 0{\cdot}224 = 40{\cdot}3$
	$I_{60^\circ} = 128$	$128 \times 0{\cdot}1295 = 16{\cdot}6$
	$I_{90^\circ} = 48$	$48 \times 0{\cdot}017 = 0{\cdot}8$
	M.S.C.P.	$= 163{\cdot}9$

This result differs little from the one obtained by Kennelly's method, and the difference will probably be due to draughtsmanship.

The accuracy of this measurement may be improved by taking measurements under 0, 15, 30 degrees, etc., employing then the corresponding factors.

6.03. MEAN HEMISPHERICAL CANDLE-POWER (M.H.S.C.P.).—The spherical distribution of an incandescent lamp may be converted into a hemisphérical one by supplying the lamp with a suitable shade. This is frequently done in street lighting. The M.H.S.C.P. is found in exactly the same way as the spherical, except that we plot the lower half of the polar and the corresponding part of the Rousseau curves only. The area of the latter, divided by R, then gives the M.H.S.C.P. Where light is reflected from ceilings, directly or indirectly, the term M.H.S.C.P. is misleading and gives no true indication of the quantity of the flux emitted.

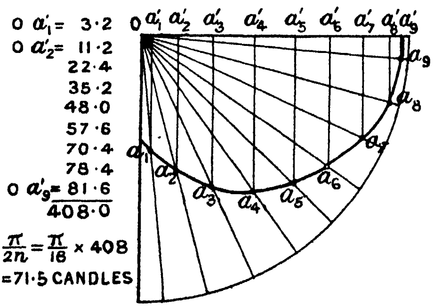


FIG. 6.03.—Determination of the M.H.S.C.P.

The construction of the Rousseau curve has the disadvantage that its area has to be estimated, either with a planimeter or in some other way. It has, however, been shown under Matthew's integrator that the determination of I_0 and I_σ can be accomplished by measuring the lengths $I \sin \theta$. We divide the polar curve into a number of parts, as shown in fig. 6.03, and project the points a_1, a_2, a_3, etc., on to the horizontal, then the mean hemispherical candle-power is expressed by

$$I_\sigma = \frac{\pi}{2n} \sum_0^n Oa' \qquad . \quad . \quad . \quad . \quad . \qquad 6.01$$

where n is the number of divisions.

This holds also for spherical measurements, except that the construction is made for both the hemispheres.

6.04. BLOCH'S METHOD.—This requires no planimeter and is as follows:—

After plotting the polar curve, we draw a quadrant with a radius unity (say, 1 decimetre). For each angle θ we obtain then on the vertical the corresponding cosine θ if we project the point of the intersection of each ray with the quadrant upon the vertical, since the triangle is a right-angled one. For instance, O B $=\cos\theta$, since the radius R is unity (see fig. 6.04). If, moreover, we divide O A into ten parts, then each part is equal to $0{\cdot}1=\Delta(\cos\theta)$. To each middle point of these divisions

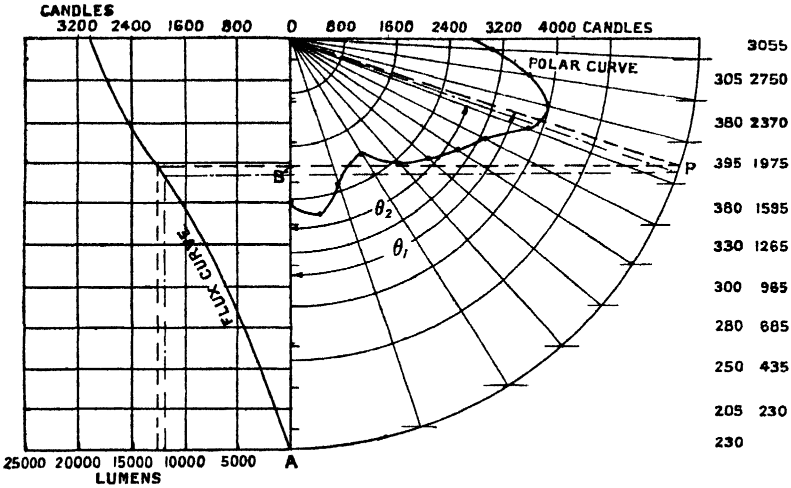


FIG. 6.04.—Determination of M.H.S.C.P.

correspond the various luminous intensities as seen from the polar curve. If now we multiply $\Delta(\cos\theta)$ by I, we get

$$I\Delta(\cos\theta)=I\times 0{\cdot}1$$

for each of the ten sections. By adding up the resulting values from below upwards, we get

$$\Sigma I\Delta(\cos\theta).$$

Previously we found that

$$\text{M.S.C.P.}=I_o=\tfrac{1}{2}\int_0^\pi I\sin\theta d\theta$$

$$=\tfrac{1}{2}\int_0^\pi I d(\cos\theta)$$

$$=\tfrac{1}{2}\sum_0^n I\Delta(\cos\theta) \quad . \quad . \quad . \quad 6.02$$

If therefore we make this construction for both hemispheres of the polar curves and take the mean result, we have the M.S.C.P.

The mean hemispherical intensity is expressed by

$$I_{\triangledown} = \sum_{0}^{n_1} I\Delta \cos \theta, \quad . \quad . \quad . \quad . \quad 6.03$$

found for the lower hemisphere only.

Weinbeer * has constructed a special slide rule for these determinations, based on the previous considerations, with trigonometrical instead of exponential functions (see fig. 6.05).

He determines the intensities under the following angles: 85 degrees, 75 degrees, 65 degrees, down to 5 degrees against the vertical, and then adds the quantities $I\Delta(\cos\theta)$ for the zones lying between these, *i.e.* from

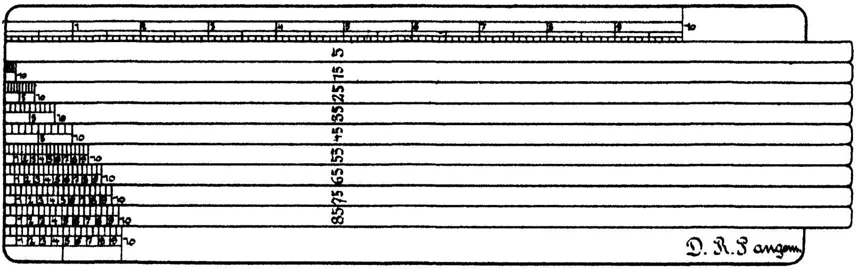


FIG. 6.05.—Weinbeer's Slide Rule for Spherical Determinations.

90 to 80 degrees, 80 to 70 degrees, etc., for which $\Delta(\cos\theta)$ is expressed in the following table: -

TABLE 6.01.—COSINES.

$\Delta(\cos\theta_1) = (\cos 80° - \cos 90°) = 0{\cdot}1736$
$\Delta(\cos\theta_2) = (\cos 70° - \cos 80°) = 0{\cdot}1684$
$\Delta(\cos\theta_3) = (\cos 60° - \cos 70°) = 0{\cdot}1580$
$\Delta(\cos\theta_4) = (\cos 50° - \cos 60°) = 0{\cdot}1428$
$\Delta(\cos\theta_5) = (\cos 40° - \cos 50°) = 0{\cdot}1232$
$\Delta(\cos\theta_6) = (\cos 30° - \cos 40°) = 0{\cdot}1000$
$\Delta(\cos\theta_7) = (\cos 20° - \cos 30°) = 0{\cdot}0737$
$\Delta(\cos\theta_8) = (\cos 10° - \cos 20°) = 0{\cdot}0451$
$\Delta(\cos\theta_9) = (\cos 0° - \cos 10°) = 0{\cdot}0152$

which sums up to unity.

The rule possesses two fixed scales, each divided into 10 (or 100) divisions, but the lower one is reduced in the ratio 0·1736 to 1. In addition to these there are 9 movable rules, of which the first has no scale; the second one, the same scale as the upper fixed one but reduced in the ratio 0·0152 to 1; the third one, a similar scale reduced in the ratio 0·0451 to 1, and so on. To find the M.H.S.C.P., we proceed as follows: Place the zero of the lowest movable scale (85) opposite the value of $I_{85°}$ on the scale below it; the zero of the second movable scale (from below, marked 75) opposite the value of $I_{75°}$ on the lowest movable scale; the zero of the third movable scale from below opposite the value of $I_{65°}$ on scale

* *The Illuminating Engineer*, 1908, p. 559.

(75), and so on, until eventually the last movable scale shows on the upper fixed scale the result.

For spherical measurements the determination is repeated for the upper half, and the mean of the two results is taken.

The method illustrated in fig. 6.04 possesses the advantage that it gives us the flux for any region below the horizontal. Take, for instance, any angle θ, then if we project the point of intersection P of the ray OP with the quadrant upon the curve on the left in fig. 6.04, which represents the values tabulated on the right, we cut off the value

$$\int_0^\theta \mathrm{I}d(\cos\theta)=\phi^1,$$

which, when multiplied by 2π, will give us the flux. If we multiply the ordinates by 2π and plot a new curve or alter the scale, we obtain this value directly. The figure also indicates a method for finding the average illumination, as given by a single lamp, for any given circular area lying within a given angular region 2θ, viz.

$$\overline{\mathrm{E}}=\frac{2\pi}{\mathrm{S}}\int_0^\theta \mathrm{I}d(\cos\theta) \quad . \quad . \quad . \quad . \quad 6.04$$

$$=\frac{2\pi}{\mathrm{S}}\phi^1 \quad . \quad . \quad . \quad . \quad . \quad . \quad 6.05$$

$$=\frac{\phi^\theta}{\mathrm{S}} \quad . \quad . \quad . \quad . \quad . \quad . \quad 6.05a$$

In *Elecktrotechnik und Maschinenbau*, 11th August 1918, Gerhardt describes a method for showing graphically the total light-flux from a lamp in the form of a curve giving an approximate representation of the polar distribution. The flux within a cone of total apex angle α is $2\pi\mathrm{I}_\alpha(1-\cos\alpha)$, where I_α is the mean intensity over the cone. Now the area of a sector of a circle of apex angle $\eta°$ is $\pi\mathrm{R}^2\eta/180$, where R is the radius of the circle. Hence if a polar diagram be drawn in which at an angle η given by $\eta=90(1-\cos\alpha)$ the radius vector R is given by $\mathrm{R}=2\sqrt{\mathrm{I}_\alpha}$, the area of the polar diagram is proportional to the total flux from the lamp, and the diagram exhibits the polar distribution to the extent that $\alpha/90$ approximates to $(1-\cos\alpha)$.*

6.05. KENNELLY'S METHOD.†—Let O″ A H B O′ represent the polar curve of a tungsten lamp, assumed to be symmetrical, with the horizontal candle-power O H. Divide the whole curve into regions of 30 degrees and determine the mid-radii of these zones, the radii thus being under angles of 75, 45, and 15 degrees. They are indicated by rays *ot, os, or, or′, os′, ot′*. Describe now in the upper hemisphere a circle with radius *or* round O, from *h* to *a*, draw ray 0–30 degrees—*a* and make (from *a*) *ab*=*os*. Next describe round *b* as centre with radius *os* an arc through

* *Science Abstracts*, B, vol. xxi., pt. 10, p. 384.

† *Electrical World*, vol. li., 1908, p. 645.

the second 30-degree zone thus that $b-c$ forms with the horizontal an angle of 60 degrees. On bc plot from c the mean radius ot of the third zone, $=cd$, and about d as centre with ot as radius an arc ce until de makes an angle of 90 degrees $(=3\times 30)$ with the horizontal. In a similar

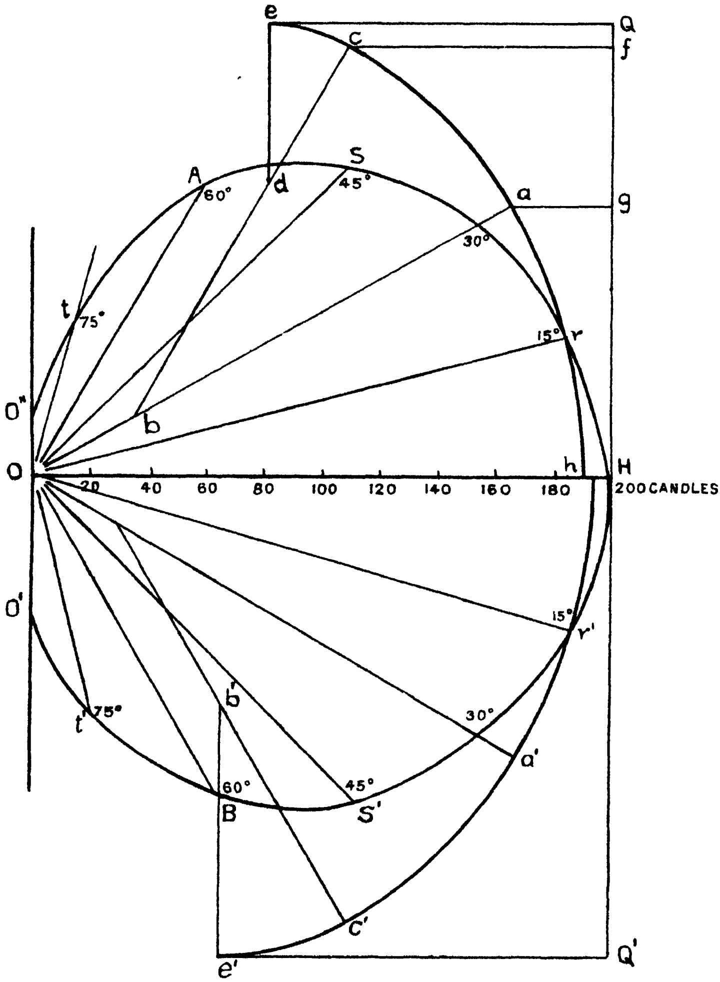


FIG. 6.06.—Kennelly's Method for Determining M.S.C.P.

manner we proceed in the lower hemisphere until the whole curve $e\,c\,a\,r\,h\,r'\,a'\,c'\,e'$ is completed. In H erect a perpendicular Q Q′ upon O H and project thereupon points e and e', giving Q and Q′ respectively, when $\frac{1}{2}$Q Q′=163 is the mean spherical candle-power, H Q=159 the upper and H Q′=167 the lower mean hemispherical candle-powers. The luminous flux in any region may also be found, for instance, in the zone Aoa by multiplying fg in candles by 2π.

The smaller the zones into which the curve is divided, the greater is the accuracy. On the whole, zones of 20 degrees give sufficiently accurate results unless the polar curve is greatly distorted. The proof will be found in the original article.

The connections when testing incandescent lamps are usually made according to fig. 6.07, the voltage being best regulated by means of a volt slide.

6.06. RUSSELL'S METHOD.*—This depends on the selection of rays at certain specified angles, experiments having determined that the integral effect of these gives a measure of the total flux. The vertical diameter of a circle is divided into ten equal parts, and from the middle point of each part horizontal lines are drawn until they intersect at the circle. The points of intersection are then joined to the centre of the circle, and under the angles of these lines we determine the intensities of the lamps. The mean spherical candle-power is given by the mean

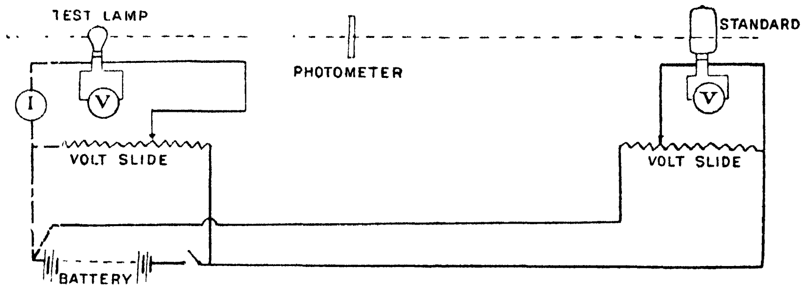


FIG. 6.07.—Connections for Testing Incandescent Lamps.

result of all ten determinations, the mean hemispherical candle-power by the mean of the lower five determinations only. The work may be facilitated by placing mirrors at these angles, all of which direct the light to the photometer so that the action is that of an integrator similar to Matthew's.

6.07. UNSYMMETRICAL FLAME ARC LAMPS.—Dr Bloch's Method. —When the lamp is unsymmetrical we must rotate the lamp and plot the polar curve and the resulting Rousseau curve, as Drysdale has suggested. When this cannot be done we must either make a large number of determinations in all directions, or employ Dr Bloch's method, which is as follows: First plot the polar curve along any meridian and then make three additional measurements under the angles of 90, 180, and 270 degrees against the meridian in each of two latitudes, one of which coincides with the equator or lies 10 degrees below it, and one of which lies 45 degrees lower down. Next divide the mean value of these four intensities as found on each latitude by the mean value along the meridian, which gives us two factors, of which we again take the mean, and with this we multiply the mean value along the meridian, the result being the M.H.S.C.P.

* *J.I.E.E.*, vol. xxxii. p. 631.

All these methods are laborious and consequently expensive, especially where lamps have to be tested in large numbers. Moreover, the accuracy attainable is by no means great, since the light of an arc is never steady on account of the burning away of the carbon and the consequent feeding of the lamp and the travelling of the arc from one side to another. Ulbricht's globe photometer is therefore to be preferred, and when lamps of similar type and size are to be tested, a simple calibration suffices.

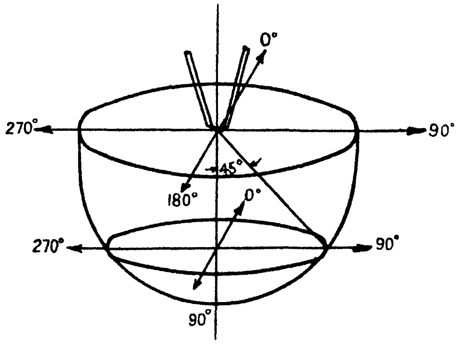


FIG. 6.08.—Dr Bloch's Method for determining the M.H.S.C.P. of Unsymmetrical Arc Lamps. (Inclined Carbons.)

USE OF ULBRICHT'S INTEGRATOR.—The calibration of Ulbricht's sphere, which has already been indicated under photometric apparatus, may be summarised as follows :—

Suspend the lamp to be tested conveniently near the centre of the sphere and the glow lamp with known spherical candle-power I_o in any convenient position, behind screens as shown in fig. 5.52. Compare the intensity I_{w1} of the window of the sphere, due to I_o, with a comparison lamp of intensity C, then for a photometric balance

$$\frac{I_{w1}}{C}=\frac{L_2^2}{L_1^2}, \text{ or } I_{w1}=C\frac{L_2^2}{L_1^2}=\frac{I_o}{K},$$

where L_1 and L_2 are the distances of the comparison lamp and window from the photometer respectively, and K is a constant.

Next switch off I_o and switch in the test lamp I'_o, when the intensity of the window is I_{w2}, and we have

$$I_{w2}=C\frac{L'^2_2}{L'^2_1}=\frac{I'_o}{K},$$

whence

$$I'_o=I_o\times\frac{L'^2_2}{L'^2_1}\times\frac{L_1^2}{L_2^2},$$

and

$$\phi=4\pi I'_o.$$

Example.—The M.S.C.P. of a gas-filled lamp is to be determined. The lamp absorbs 4·9 amperes at 220 volts, or 1075 watts. The mean spherical candle-power of a symmetrical tungsten lamp was found to be 163. In the test

$$L_1=150,\ L_2=170,\ L'_1=76, \text{ and } L'_2=244,$$

whence

$$I'_o=1285 \text{ M.S.C.P.},$$

and the specific consumption is

$$\frac{1075}{1285}=0{\cdot}835 \text{ w.p. M.S.C.P.}$$

$$\phi=4\pi I'_0=4\pi\times 1285=16150.$$

The mean horizontal candle-power of this lamp was 1585, so that the reduction factor is $\frac{1285}{1585}=0{\cdot}81$. This factor varies a good deal with the arrangement of the filament.

Carbon lamp 0·86 (average).
Tungsten lamp 0·82 (average).

For gas-filled lamps the following data are given * :—

TABLE 6.02.—DATA ON INCANDESCENT LAMPS.

DATA ON NEW MAZDA LAMPS FOR 110-VOLT (NOMINAL) CIRCUITS.

Rated Life of Lamp, 1000 Hours.

Watts.	Watt per C.-P.*	C.-P.* per Watt.	C.-P.*	Spherical Reduction Factor.	Mean Spherical C.-P. per Watt.	Total Lumens.	Style Bulb.	Maximum Diameter Bulb. (In.)	Length overall. (In.)
1000	0·55	1·82	1820	0·83	1·51	19,000	S-52	6½	13⅜
750	0·60	1·67	1250	0·83	1·38	13,000	S-46	5¾	13
500	0·70	1·43	715	0·83	1·19	7,440	S-40	5	10
400	0·75	1·33	530	0·83	1·11	5,560	S-40	5	10
† 300	0·78	1·28	385	0·83	1·06	4,000	S-35	4⅜	8¾
† 200	0·80	1·25	250	0·83	1·04	2,600	S-30	3¾	7⅞

* Mean horizontal candle-power.
† Medium screw base.

DATA ON MAZDA SERIES LAMPS FOR 6·6 AMPERES.†

Rated Life of Lamp, 1350 Hours.

Mean Horizontal C.-P.	Average Volts.	Watts per C.-P.*	C.-P.* per Watt.	Watts.	Spherical Reduction Factor.	Mean Spherical C.-P. per Watt.	Total Lumens.	Style Bulb.	Maximum Diameter Bulb. (In.)	Length overall. (In.)
600	55·5	0·61	1·64	366	0·80	1·31	7060	S-40	5	10
400	37·0	0·61	1·64	244	0·80	1·31	4020	S-40	5	10
250	23·9	0·63	1·59	157	0·80	1·27	2520	S-35	4⅜	9¾
100	9·8	0·65	1·54	65	0·76	1·17	955	S-24½	3 1/16	7¼
80	8·0	0·66	1·51	53	0·76	1·15	763	S-24½	3 1/16	7¼
60	6·1	0·67	1·49	40	0·76	1·13	574	S-24½	3 1/16	7¼

* Mean horizontal candle-power.
† Lamps are also made for 7·5, 5·5, and 4 amperes.

* *General Electric Review*, May 1915, p. 377.

TABLE 6.02.—DATA ON INCANDESCENT LAMPS—*continued.*

DATA ON SERIES LAMPS FOR USE WITH COMPENSATORS ON A-C. SERIES CIRCUITS.

Rated Life of Lamp, 1300 Hours.

Mean Horizontal C.-P.	Average Volts.	Watts per C.-P.*	C.-P.* per Watt.	Watts.	Spherical Reduction Factor.	Mean Spherical C.-P. per Watt.	Total Lumens.	Style Bulb.	Maximum Diameter Bulb. (In.)	Length overall. (In.)
1000	25·0	0·5	2·00	500	0·78	1·56	9800	S-40	5	12½
600	15·0	0·5	2 00	300	0·78	1·56	6800	S-40	5	12½
400	14 4	0·54	1·85	216	0·78	1·44	3920	S-40	5	12½

* Mean horizontal candle-power.

Current at lamp for 1000 and 600 candle-power, 20 amperes; 400 candle-power, 15 amperes.

Compensators are wound for 6 6- and 7·5-ampere circuits.

DATA ON PEAR-SHAPE TYPE 220 250 VOLT MULTIPLE LAMPS.

Watts.	Watts per Spherical Candle.	Spherical Candles per Watt.	Lumens per Watt.	Total Lumens.	Reduction Factor
200	1·00	1·00	12·57	2,514	0·80 1·10
300	0·92	1·09	13·66	4,100	0·80–0·90
400	0·90	1·11	13·97	5,590	0·80 0·90
500	0·85	1·18	14·79	7,395	0·80–0·90
750	0·82	1·22	15·33	11,500	0·80–0·90
1000	0·78	1·28	16·12	16,120	0·80–0·90

DATA ON STRAIGHT-SIDE TYPE TUNGSTEN (VACUUM) LAMPS ARE AS FOLLOWS:—

105–125 Volt Multiple Type.

Watts.	Watts per Spherical Candle.	Spherical Candles per Watt.	Lumens per Watt.	Total Lumens.	Reduction Factor.
10	1·67	0·60	7·54	75	0·78
15	1·47	0·68	8·52	128	0·78
20	1·41	0·71	8·91	178	0·78
25	1·35	0·74	9·34	234	0·78
40	1·32	0·76	9·52	381	0·78
60	1·28	0·78	9·80	588	0·78
100	1·22	0·82	10·32	1032	0·78
220–250 Volt Multiple Type.					
25	1·52	0·66	8·27	207	0·79
40	1·42	0·71	8·86	354	0·79
60	1·39	0·72	9·02	541	0·79
100	1·27	0·79	9·93	993	0·79
150	1·27	0·79	9·93	1490	0·79
200	1·20	0·83	10·45	2613	0·79

TESTING OF GAS-FILLED LAMPS.—This lamp shows a peculiar behaviour when rotated. This has been fully investigated by Middlekauff and Skogland.* In their summary on the tests they make the following remarks :—

On account of the comparative broadness of the filament spiral and the dissymmetry of the filament mounting, there is considerable irregularity in the distribution of the light about the vertical axis. Consequently, when the lamp is rotated, as is commonly done in rating lamps at the factory, the light as seen in the photometer flickers so excessively as to render accurate measurements of candle-power practically impossible without the use of auxiliary apparatus. However, as is sometimes done, if two mirrors inclined to each other be placed back of the lamp,† the flickering is so much reduced as to permit accurate candle-power measurements even at very low speeds of rotation.

But this expedient does not eliminate the most serious trouble caused by rotation. It was found that at constant voltage both the current consumed and the candle power are different when the lamp is rotating from that when it is stationary, the current changing in one direction and the candle-power always in the opposite direction; that is, there is a change in the operating efficiency of the lamp. Furthermore, this change in efficiency may be either positive or negative, depending upon the speed, and it is about twice as great when the lamp is rotating tip up as when it is rotating tip down.

Fortunately, from the standpoint of photometry, there is for each lamp in either position a particular speed at which the current and the candle-power have the same values, respectively, as when the lamp is stationary. Hence, with the lamp rotating at this speed its candle-power can be measured with accuracy in spite of its rotation. The speed for the above condition is practically the same for all lamps having the same number of loops in the filament; but for lamps having different forms of filament mounting it varies from lamp to lamp, being greatest for those having the smallest number of loops in the filament.

If the above precaution as to speed adjustment is not observed and lamps are rated while rotating at speeds ordinarily used in testing vacuum lamps, the errors which enter may amount to as much as 1 to 2 per cent. in current, or watts, in one direction, and as much as 15 to 20 per cent. in candle-power in the opposite direction. Hence, the voltage found for a desired operating efficiency may be so much in error as to give a lamp on test at this rated voltage a fictitious life value three or four times as large as the lamp would give if it were operated stationary at a voltage corresponding to that efficiency which during the rating was only apparent. That is, the lamp may be given credit for a much longer life than it really deserves. On the other hand, the speed may be such as to

* Bureau of Standards, *Bulletin* No. 264, 1916.

† Paragraph 6.08.

cause errors in the opposite direction resulting in a lamp life much shorter than would be expected from the apparent efficiency rating.

Another peculiarity of the gas-filled lamp is that while it burns the blackening occurs, not all over the bulb in approximate proportion to the light distribution as in the vacuum lamp, but principally at the top of the bulb, because the volatilised material is carried upward by the gas. Hence, in making a life test a true measure of the reduction in total light during the life of the lamp cannot be obtained, in the usual manner, by mean horizontal candle-power measurements, but by determinations of the total flux or mean spherical candle-power. This is accomplished most rapidly and conveniently by means of an integrating photometer, such as the Ulbricht sphere, in which the lamp is measured stationary, and thus all the complications arising from rotation are entirely avoided.

As to the cause of the variations observed in candle-power and efficiency when the lamp is rotated, it is concluded from the results of a number of special tests that the whole effect is produced by a change in the convection currents of the gas, a consequent variation in the temperature distribution in the bulb, resulting in a change in the resistance, and therefore a variation in the current and the candle-power of the lamp.

The lamps tested in this manner were chiefly of the heavy type, 200 watts and more. Even when stationary, both current and candle-power have higher values when the lamp is mounted tip up than when it is mounted tip down. The experiments prove conclusively that in the testing of these lamps the conditions should be similar to those under which the lamp is to burn afterwards.

6.08. MEAN HORIZONTAL CANDLES.—The mean horizontal candle-power is obtained by placing the lamp in a universal joint and testing it under different angles in a horizontal plane, taking finally the mean results of tests through 360 degrees. It can be achieved with one measurement if the lamp be rotated. The best speed is about 180 to 230 revolutions per minute. If the speed is too slow, results are unreliable, since a flickering takes place; and if it is too high, the filament expands by centrifugal force, and for long suspensions may extend to the wall of the globe. This causes a new distribution; moreover, brittle filaments are liable to break.

Another method frequently employed for determining the mean horizontal candle-power consists in the arrangement of two mirrors at the back of the test lamp, 9 centimetres away from the axis of the lamp and forming an angle of 120 degrees. The lamp with which the test lamp I_1 is compared should be one of the same type and size, carefully aged by burning it for 50 to 100 hours. An actual calibration is not required. Equality of the fields of view is now obtained, the distances from the photometer screens to the lamps being L_1 and L_2 respectively (see fig. 6.09). Next we replace I_1 by another lamp, the mean horizontal candle-power $\bar{I}_H$ of which is accurately known, and obtain equality of the fields of view by adjusting the distance of this lamp from the photometer screen

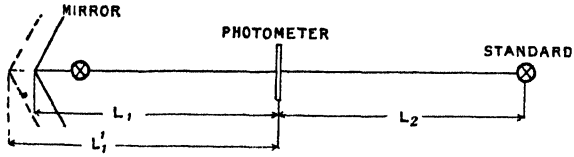


FIG. 6·09.—Testing Lamps for Mean Horizontal Candles.

to L^1_1, without, however, altering the distance L_2. The mean horizontal candle-power of the first lamp is then given by

$$\bar{I}_{1H} = \bar{I}_H \times \frac{L_1^2}{L'^2_1} \quad . \quad . \quad . \quad . \quad 6.06$$

This substitution method of testing is greatly favoured at present.

Testing in this manner makes it unnecessary to take into account the absorption of light by mirrors. The method gives sufficiently accurate results as long as the lamps which are compared are of exactly the same type and differ little in size. It would be useless to test in this manner a

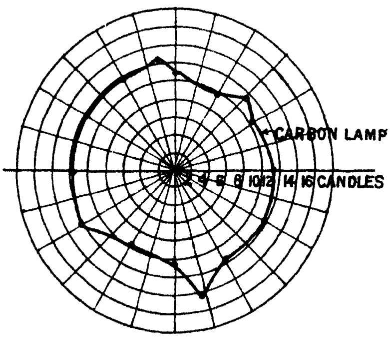


FIG. 6.10.—Horizontal Distribution of a Carbon Filament Lamp.

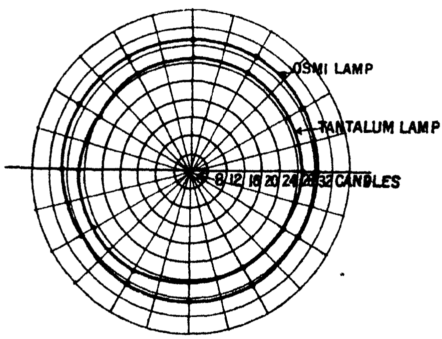


FIG. 6.11.—Horizontal Distributions of Metal Filament Lamps.

lamp with a straight filament against one with a loop in it, or a carbon lamp against one having a metal filament of different shape. For lamps of similar type, candle-power, and distribution, the method is to be recommended on account of its simplicity and the rapidity with which measurements can be carried out.

As will be seen from fig. 6.11, the horizontal distribution of tantalum and osmium lamps are practically circles, and we make on the whole little of an error by assuming this to be the case for all lamps whose filaments are arranged around an imaginary cylinder. The peaks in the distribution of the carbon lamp are due to images of the filament in the glass.

6.09. INITIAL RATING.—After the lamps have been finished in the factory they are brought into the test-room, where they are rated for candle-power and consumption. Work of this nature is usually performed by girls, of whom one manipulates the photometer, another notes the consumption, and a third inserts the lamps. The lamps are tested for mean horizontal candle-power, the determination taking place either by means of the method illustrated in fig. 6.09, or by revolving the lamp in a holder such as is shown in fig. 5.40. With a direct-reading scale, a large number of lamps can be dealt with in a short time, as the testing of a lamp does not exceed half a minute. All lamps, the consumption and candle-power of which at a constant normal voltage lie outside prescribed limits, are placed separately. If the values of the candle-power-watts are plotted according to fig. 6.12, we get the so-called target or shot-gun diagram. Fig. 6.12 holds for a normal 16 candle-power 3·25 watt per candle carbon lamp. All the lamps outside the rectangle or target are unsuitable for the given voltage, and should be re-sorted for other voltages so as to bring them within the target. A target diagram for tungsten lamps is shown in fig. 6.13.

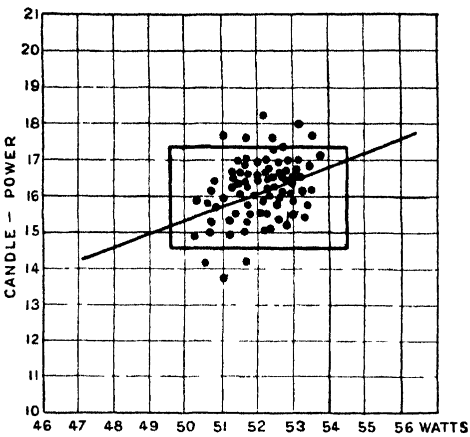


FIG. 6.12.—Target Diagram for a 16 Candle-Power Carbon Lamp.

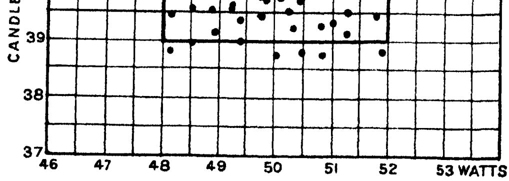


FIG. 6.13.—Target Diagram for a 50-watt Tungsten Lamp.

A more accurate sorting of lamps is as follows: We plot the candle-power-volts, and specific consumption-volt curves as shown for a tungsten lamp in fig. 6.14. This may be facilitated with the aid of Table 2.06, from which we get

$$\eta = \frac{C}{V^{2\cdot 26}}.$$

The exponents in these equations do not vary with the size of the lamps (or very little), so that the constants may be found by a single test.

In the example the value of the constant C is 245,000. Suppose, then, that we are given a batch of lamps to sort, the lamps being nominally for thirty candles at 220 volts and absorbing 1·25 watts per candle. We know that the correct voltage will be somewhere between 200 and 240, hence we test all lamps for 220 volts. The standard lamp should be conveniently of the same voltage and type, so that both lamps may be regulated simultaneously. Assume now that in the test one lamp absorbs 42 watts at 220 volts and gives 39 candles, thus 1·08 watts per candle. We require, however, a lamp using 1·25 watts per candle, *i.e.* we must find an ordinate which is $\frac{1\cdot 25}{1\cdot 08}$ or 1·158 times larger than the correct ordinate in the figure. This ordinate is indicated by point P; the corresponding abscissa gives the correct voltage equal to 203. To find the candle-power

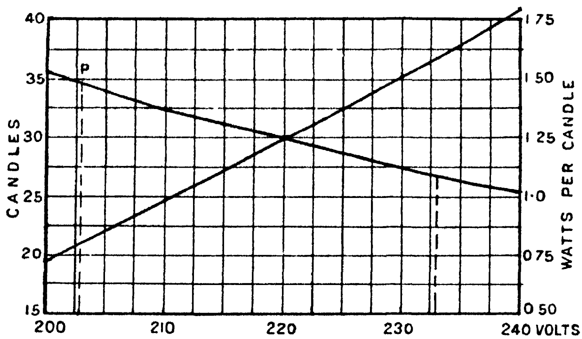


FIG. 6.14.—Sorting Incandescent Lamps.

of the lamp, we divide the candle-power ordinate corresponding to 203 volts by the ordinate for 220 volts and multiply the ratio by 39. We have $I = \frac{21}{30} \times 39 = 27\cdot 4$ candles. The method is both accurate and rapid when the experimentalist has become used to it.

Another method of rating lamps consists in the employment of a candles per watt meter. The photometer is set for a given normal specific consumption, say 1·25 watts per candle, and the voltage of the lamp under test is altered until a photometric balance is obtained. If the actual voltage differs from the normal by more than a certain value the lamp is unsuitable for that voltage. The voltage for which the lamp is suitable is now, of course, also known.

At the Bureau of Standards * the system of rating lamps has been greatly developed in order to facilitate the work. Special computers, operating on the principle of the slide rule and consisting of ampere- and watts per candle scales, are added. There is also a recording device for stamping the results on cards. By means of resistances in the circuit of the comparison lamp, which consists of a 100-watt tungsten lamp placed in a mirror-backed box illuminating a ground glass whose area is altered

* Bureau of Standards, *Bulletin* No. 265, 1916.

with a variable aperture screen, the colour of carbon lamps may also be obtained, so that all photometric balances occur at a colour match. For a detailed description the reader is referred to the original article.

6.10. LIFE TESTS.—All incandescent lamps age, *i.e.* their candle-power decreases with age except during the first fifty or a hundred hours. During this time the filament is not yet stable in its electrical characteristics.

Ageing is due to vaporisation of the filament. When the intensity has been reduced to 80 per cent., the lamp is usually considered useless. The interval is called the life of the lamp (in burning hours).

Life tests are chiefly carried out on groups of lamps to see whether they fulfil specified conditions, or to compare lamps from different manufacturers. This necessitates care in the initial rating and constancy of voltage at which lamps are operated. The time of a test may be considerably reduced by choosing test efficiencies higher than the normal, but within a range through which factors for life corrections have been fully established (see figs. 6.18 and 6.21).

The quantity of lamps selected for initial tests is specified as 5 per cent.* of the total of a lot including only lamps of the same class, size, and voltage range, and not less than ten lamps from any one lot. The number of lamps to be included in a lot is left to the judgment of the inspector.

The lamps must conform to certain specified requirements as regards bulbs, filaments, bases, and vacuum. Lamps which pass these requirements are then run on the photometer, and in determining their acceptability tables of allowable limits of watts and candle-power, or of watts per candle, as given in the specifications, are applied. In calibrating the photometer for these tests the inspector uses standards which have been certified by the Bureau for candle-power and current. A lot of lamps is accepted if the number of defective lamps on either test is below the specified percentage of the total.

The next step is to compute from the records of the photometric test the mean values of individual groups of test lamps representing not more than 250 lamps from any one lot. The lamp nearest the mean value of each group is selected, labelled, and sent to the Bureau to represent the group on life test.

During life tests lamps are run and photometered on the voltage corresponding to the rated specific consumption within the specified limits. This "rack voltage" need not necessarily be the same as the rated voltage.† The equipment must therefore be such that very fine voltage regulation is possible. The equipment at the Bureau of Standards is shown in fig. 6.15. By means of auto- and regulation transformers the voltage of the racks R_1 and R_2 may be varied to within 0·1 volt. The

* Bureau of Standards, *Bulletin* No. 265, 1916.

† In some laboratories lamps are tested at the rated voltage.

bus-bar voltage is kept constant by means of a fast Tirrell regulator. For further information see the above *Bulletin*, No. 265.

Lamps for life tests are usually joined to a rack with two stout copper leads, to which are soldered sockets carrying from one to four dozen lamps. A single row is preferable to a number of rows above one another, to

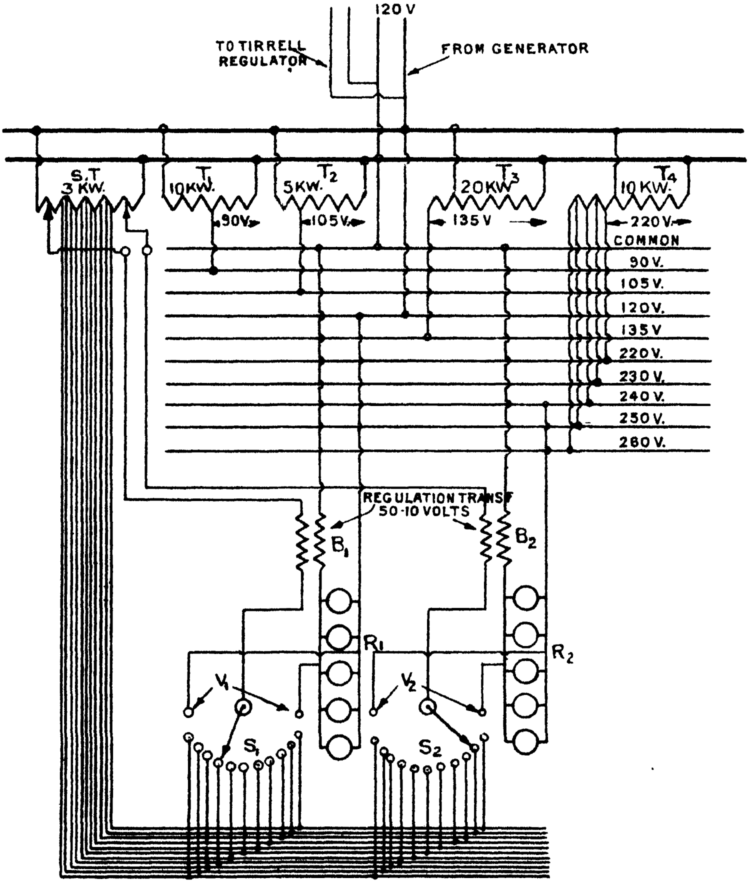


FIG. 6.15.—Wiring Diagram for Life Tests (Bureau of Standards).

prevent abnormal heating of the upper lamps. During the first hundred hours, tests should be made every ten hours, as the candle-power changes considerably during this time (usually increases); afterwards observations at intervals of from fifty to a hundred hours suffice. In the following figures the life curves of metal filament lamps are represented; they are self-explanatory.

As regards the tungsten lamp, it will be found that little blackening of the globes takes place so long as the vacuum of the lamp is maintained. The increase in the specific consumption is consequently also small.

The economical or commercial life of a lamp may be approximately predetermined for a given amount of light if we know the curve (watts per candle-time). Assume, for instance, that this curve is a straight line (which is often the case) and shows an increase of 0·5 watt per candle for 350 burning hours (curve 36B in fig. 6.16), so that the rate of increase is

$$p=\frac{b}{t}=\frac{0{\cdot}5}{350},$$

then the area enclosed by this curve and the horizontal represents the increased consumption, and is equal to

$$\tfrac{1}{2}bt=\tfrac{1}{2}pt^2,$$

and when the cost of this consumption amounts to the price of the lamp

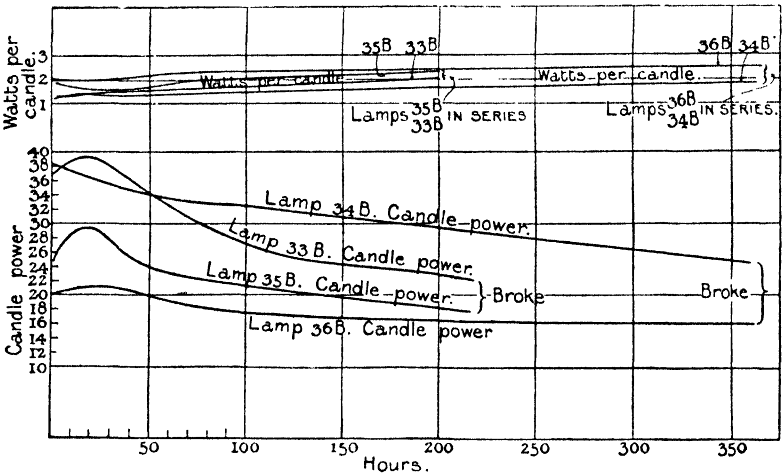


FIG. 6.16.—Life Curves of Tantalum Lamps.

per candle, the lamp should be thrown away. If $£_0$ be the cost per candle and £ the price per kilowatt hour, $\frac{£}{1000}$ per watt hour, then we have

$$\tfrac{1}{2}pt^2\times\frac{£}{1000}=£_0,$$

whence

$$t=\sqrt{\frac{2000£_0}{p\times £}} \quad . \quad . \quad . \quad . \quad . \quad 6.07$$

Let $£_0=1$ penny, £=fourpence, then

$$t=\sqrt{\frac{2000\times 1\times 350}{0{\cdot}5\times 4}}=594 \text{ hours.}$$

This, of course, is only approximate and assumes that a given amount of light is asked for. In domestic lighting, as the light decreases, this is usually accepted without troubling much about it. Where light, however, is installed on a scientific basis, the original illumination should be exactly what is required, plus the decrease which would take place in the time *t*. At the end of this time, the proper amount of light is still available, but a further decrease would bring it below the requirements, so that new lamps are now essential.*

It must here be added that the external temperature in which a lamp burns influences the life of lamps. Lamps in the open usually last longer than those in enclosing fittings within doors. Sunden † found that a lamp run at 200 degrees C. external temperature soon burns out, this being probably due to expansion of the glass and a reduction in the quality of the vacuum, and an increase in the temperature of the filament.

6.11. ECONOMICAL EFFICIENCY.—Another question arises: Do we run our lamps at the most economical efficiency? To determine this

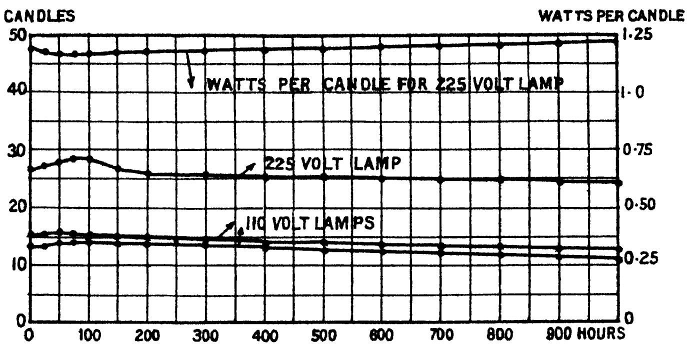


FIG. 6.17.—Life Curves of Tungsten Lamps.

we must find the relationship between the watts per candle and the useful life of a lamp. A curve connecting the two for a carbon lamp is represented in fig. 6.18. If, then, we know the economical life of the lamps and the increase in the candle-power of the same lamps with a reduction in the specific consumption (due to voltage increase), the initial cost of the lamp per candle-power, and the price per kilowatt hour, we can easily determine the most economical specific consumption. Take, for example, fig. 6.18, which illustrates the relationship between watts per mean horizontal candle and the useful life of a carbon lamp, normally manufactured for 4 watts per candle. The useful life of this lamp is about 1000 hours, but this is reduced in the manner indicated when the voltage is increased. Suppose we have an installation of forty-two 220-volt 25-c.p. lamps at 4 watts per candle, giving a total light of 1050 candles. Let the price per lamp be one twenty-fifth of a shilling per candle, or one shilling per lamp, then during 1000 burning hours we have the following results :—

* See also a paper by F. H. Reakes Lavender, M.Sc., *J.I.E.E.*, 1909, vol. xliv. p. 181.

† *E.T.Z.*, 1913, p. 992.

(1) The voltage must be increased according to curve 1 of fig. 6.19.

(2) The candle-power increases according to curve 2.

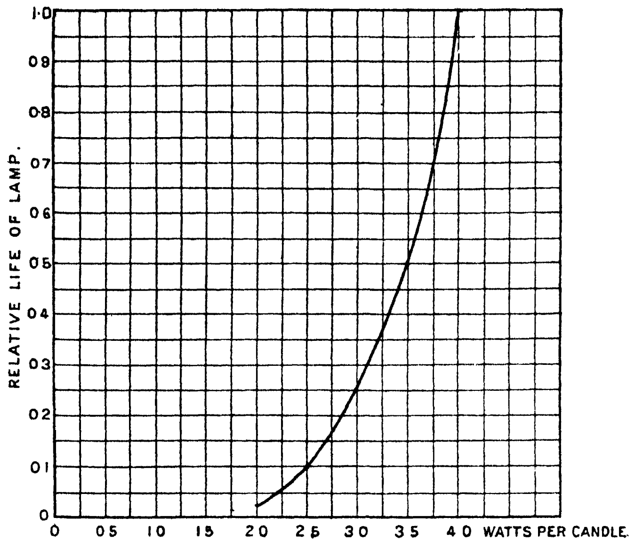


Fig. 6.18.—Relative Life of a Carbon Lamp for Different Specific Consumptions.

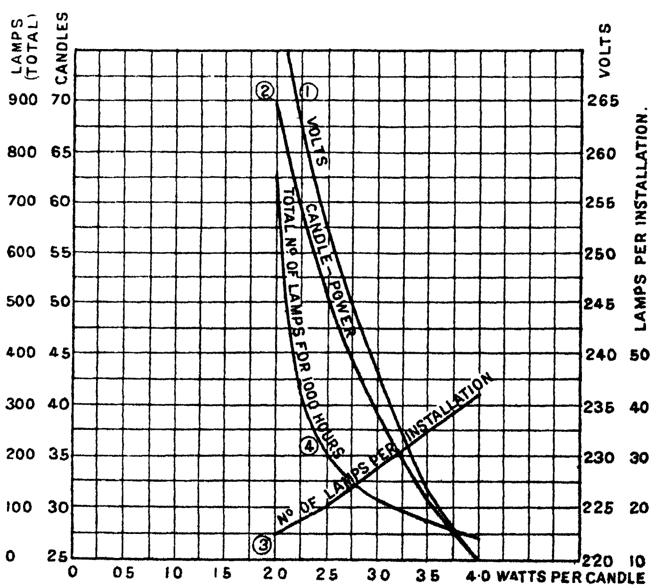


Fig. 6.19.—Voltage, Number of Lamps, and Candle-Power as Function of the Specific Consumption.

(3) The number of lamps required per installation decreases according to curve 3, and the total number of lamps wanted during the 1000 hours increases according to curve 4.

If we reckon 6, 5, 4, and 3 pence per unit of current consumption, we obtain fig. 6.20 as the total cost results.

We see that the carbon lamp has not been worked at its most economical specific consumption, and that commercially a better result would be obtained if on a 220-volt circuit we used a lamp normally made for 200 volts. The lamps would then have to be renewed every 100 hours, but this would still effect a saving of about 30 per cent.

The expense for labour required to exchange the lamps has been disregarded.

It is somewhat surprising to find the curves of fig. 6.20 with their

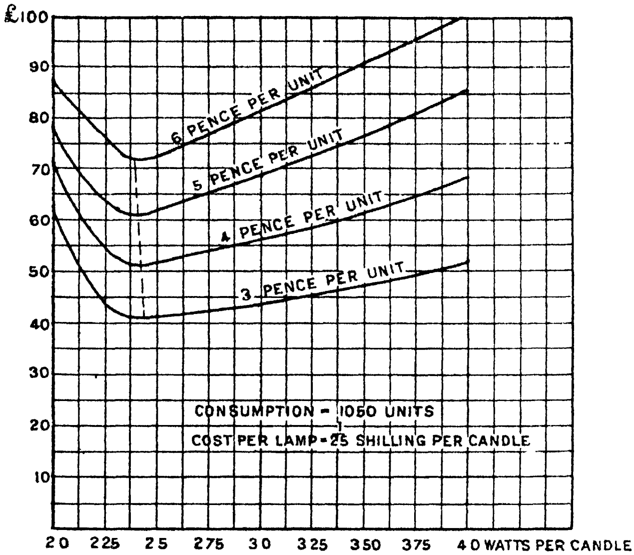


FIG. 6.20.—Cost of a 1050-candle Lamp Installation during 1000 Hours of the Specific Consumption.

minimum values practically on the same ordinate. This is due to the high price of the current compared with the low price per lamp, and does not hold for tungsten lamps, for which curves similar to those in figs. 6.18 to 6.20 have been plotted in figs. 6.21 to 6.23. It will be noticed that in this case the minimum value moves very much to the right as the price per kilowatt-hour is reduced. The installation is the same as in the example for the carbon lamp except that the time of burning is 10,000 hours and the price 2s. 6d. for a 50-candle lamp. The average life of the lamp has been taken as 1000 hours. We see that at fourpence per unit we should burn the lamps approximately at the normal specific consumption, *i.e.* at 1·2 watts per mean horizontal candle. At sixpence it would pay to reduce the consumption to about 1·03 watts per candle, which would mean that we should run a 200-volt lamp on a 220-volt circuit, and at twopence we should increase the consumption to 1·35 watts per candle, *i.e.* run 227-volt lamps on 220-volt circuits. In the latter case, the saving in wages for not having to renew the lamps so frequently would be an additional advantage.

The useful life of a tantalum lamp is about 700 to 800 hours, *i.e.* in

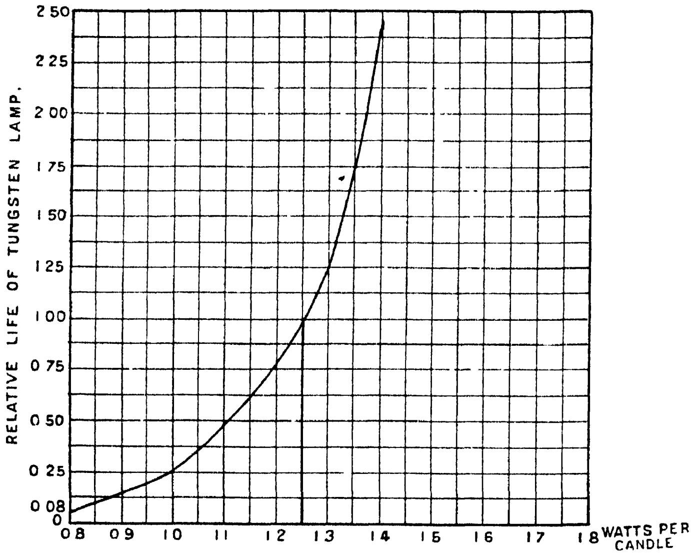


FIG. 6.21.—Relative Life of a Tungsten Lamp for Different Specific Consumptions.

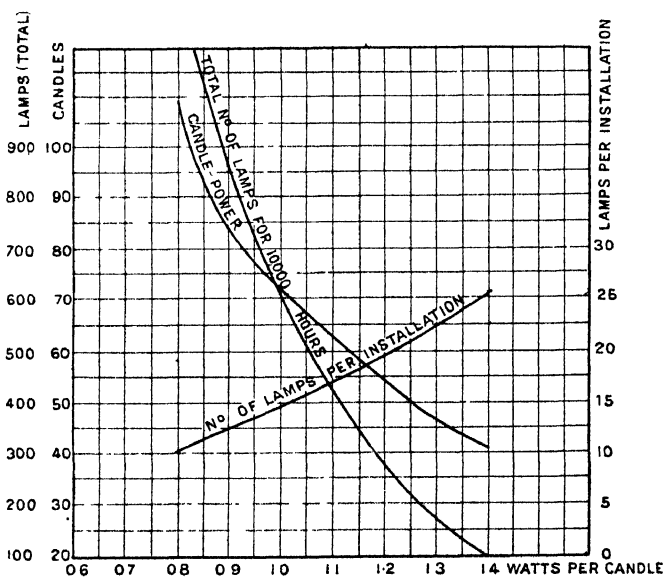


FIG. 6.22.—Voltage, Number of Lamps, and Candle-Power as Function of the Specific Consumption.

this time the candle-power has decreased so much that it pays to insert fresh lamps. The useful life of a tungsten lamp is in most cases greater than the actual life.

Lamps which are fixed to rising and falling pendants, or which have to be moved in any way, have a shorter life than fixed lamps. In no case should a tungsten lamp be taken from its socket before it has cooled down, as a contracting filament is so fragile that it breaks almost every

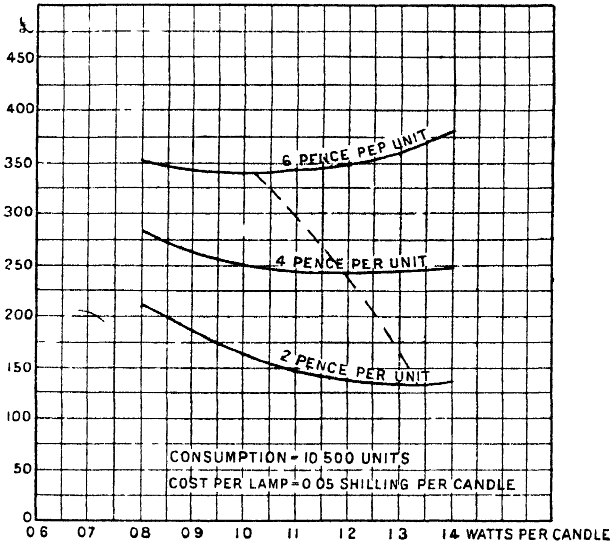


FIG. 6.23.—Cost of a 1050-Candle Tungsten Lamp Installation during 10,000 Hours as Function of the Specific Consumption.

time the lamp is handled. Otherwise a hot filament is less fragile than a cold one.

Speaking generally, we should replace carbon and tantalum lamps when they become dim and tungsten lamps when they break.

6.12. MEASUREMENT OF INTRINSIC BRIGHTNESS.*- The apparatus consists of an optical system similar in principle to that of the

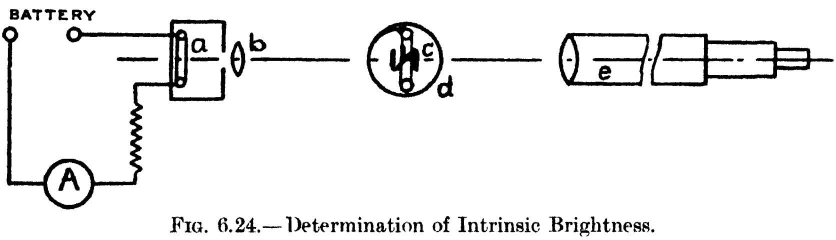


FIG. 6.24.—Determination of Intrinsic Brightness.

Holborn-Kurlbaum optical pyrometer. It is illustrated in fig. 6.24. The bright object under test is viewed against a background of known brightness, and the one or the other is varied until the object disappears against the background. Both are then of the same brightness.

* See Ives and Luckiesh, *Electrical World*, vol. lvii. p. 438, 1911.

For the testing of incandescent lamp filaments a suitable background is furnished by a Nernst glower. In order to have the background of sufficient size, an image of the glower is formed in space by means of a lens. The brightness of the background is changed by varying the current through the glower. The intrinsic brightness of the latter is determined by candle-power and area measurements.

In the figure *a* is a Nernst glower, *b* a lens, A an ammeter, *c* the enlarged image of the glower, *d* the incandescent lamp to be studied, and *e* the observing telescope.

Intrinsic brilliancies as determined by Ives and Luckiesh are as follows:—

Crater of pure carbon arc, 86,000 candles per square inch (130 per

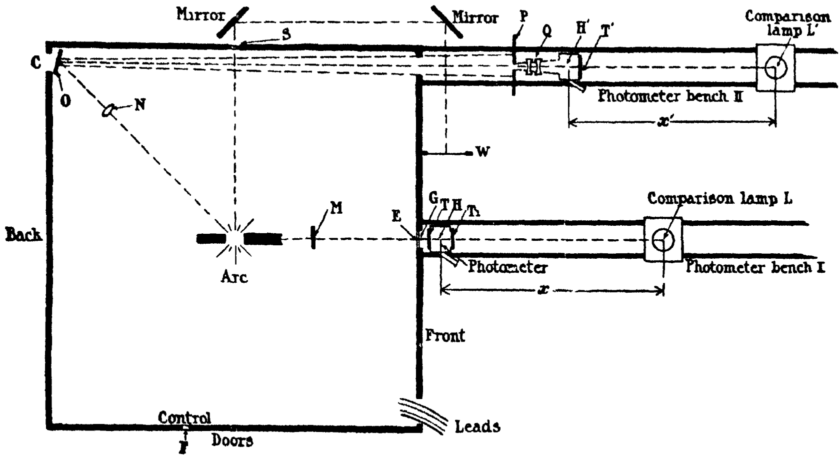


FIG. 6.24A.—Determination of Intrinsic Brilliancies of Arcs.

square millimetre); magnetite arc, 4000 (6·2); Nernst glower (115 volts, 6 amperes d.c.), 3010 (4·7); tungsten at 1·25 watts per candle, 1060 (1·64); graphitised carbon filament at 2·5 watts per candle, 750 (1·2); tantalum at 2 watts per candle, 580 (0·9); carbon filament at 3·5 watts per candle, 400 (0·63); glass mercury vapour lamp, 14·9 (0·023).

In the most modern high-intensity search-light the intrinsic brilliancy is as high as 1100 candles per square millimetre (700,000 per square inch).

Another method of measuring intrinsic brightness, evolved in connection with the testing of carbon electrodes for search-lights, is illustrated in fig. 6.24A.* The arc under test is placed into a large integrating cube and an image of the arc is reflected by means of a lens N, a mirror O, a xylonite screen P with an aperture, a negative system of lenses Q to a photometer H′, which has on its other side a comparison lamp L′. To overcome colour differences, a bluish filter T′ is placed over the photometer on the side of the comparison lamp L′.

* Paterson, Walsh, Taylor, and Barnett, *J.I.E.E.*, 1920, vol. lviii. p. 83.

Let r = radius of positive lens,

a = distance of N from the crater,

n = transmission of N,

m = reflection coefficient of mirror O,

t' = transmission coefficient of the colour filter T′,

x_1 = distance of N *via* O to P,

C' = candle-power of the comparison lamp at distance x' from the photometer,

i = normal brightness of the crater in candles per square millimetre, then the lumens incident on the positive lens from the crater is expressed by $\frac{i(\text{area of crater})r^2\pi}{a^2}$, and hence the lumens transmitted by $\frac{i(\text{area of crater})r^2\pi n}{a^2}$. Consequently, the illumination at the image on the screen at P is

$$\frac{i(\text{area of crater})r^2\pi nm}{a^2(\text{area of image})}.$$

But

$$\frac{\text{area of crater}}{\text{area of image}}=\frac{a^2}{x_1^{\,2}},$$

so that the illumination at P is

$$\frac{ir^2\pi nm}{x_1^{\,2}} \text{ millimetre-candles,}$$

and the illumination at H′ is

$$\frac{ir^2\pi nm}{x_1^{\,2}\text{R}} \text{ millimetre-candles,}$$

where R = illumination at P ÷ illumination at H′, determined by actual measurement, using a portable brightness photometer, or by the substitution of a source by means of an illuminant of known intrinsic brightness.

We have for the illumination on the other side of photometer H′ the value $\frac{c't'}{(x')^2}$, whence

$$\frac{ir^2\pi nm}{(x_1)^2\text{R}}=\frac{c't'}{(x')^2}$$

and

$$i=\frac{c't'(x_1)^2\text{R}}{r^2\pi nm}\times\frac{1}{(x')^2}.$$

The figure also illustrates the arrangement for the determination of the total flux from an arc. The values of intrinsic brilliancies obtained by the investigators varied from 152 to 163 candles per square millimetre for a current density of 0·2 ampere per square millimetre, for seven specimens; and from 164 to 184 at 0·3 ampere per square millimetre for four specimens tested, all carbons being pure and uncoppered. For coppered carbons the figures were 130 to 174 and 174 to 187 candles per square millimetre crater area (projection) for 0·2 and 0·3 ampere per square millimetre respectively.

A third simple system of intrinsic brightness measurements is given by J. A. Orange.* Two hand-camera lenses equipped with iris diaphragms are employed, each of 5-inch equivalent focus, of which one is set up opposite the light source at about 7½ inches distance. The other lens is deprived of its back compound and then mounted in line with the first lens, at a distance of about 15 inches (see fig. 6.24B). A portable photometer is arranged at 30 inches from the second lens.

The action is as follows: The first lens casts an image of the source at the position of the diaphragm in the second lens; the second one casts an image of the diaphragm of the first lens into the plane of the photometer disc. The diaphragm in the first lens gives a certain amount of control of the definition of the source image, and that in the second lens

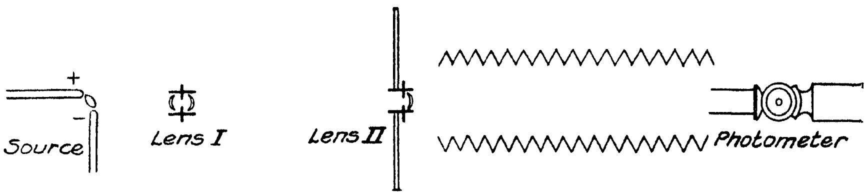


FIG. 6.24B.—Determination of Intrinsic Brilliancies.

enables one to vary the extents of the source image and to select different parts thereof.

In general the mean brilliancy is given by the relation

$$i=\frac{Ex^2}{St\ 10{,}000}\text{ candles per sq. mm.,}$$

where E is the photometer reading in metre-candles, x the distance from the second lens to the photometer in centimetres, S the area of the opening of the second lens in square millimetres, and t the transmission of the system (about 70 per cent.).

i may also be obtained by a substitution method, replacing the test lamp by one of known brilliancy, the readings on the photometer being a measure of the relative brilliancies.

6.13. LIGHT FLUCTUATIONS ON A GRADUALLY VARYING SUPPLY PRESSURE.—The relationship between voltage and candle-power is of great importance, and we shall see that in this respect metal filament lamps are the best, as long as the pressure varies gradually.

In fig. 6.25 is shown a voltage curve of a supply network, in fig. 6.26 the resulting candle-power variation for various lamps, and in fig. 6.27 the percentage candle-power variation. In analysing the latter, we find that the percentage candle-power variation is equal to $2px$, where p is the

* *General Electric Review*, May 1916, p. 403.

percentage voltage variation on either side of the normal and x the exponent in the candle-power-voltage equation. This may also be proved as follows:—

We have

$$\text{candle-power equals } I = cV^x \qquad 6.08$$

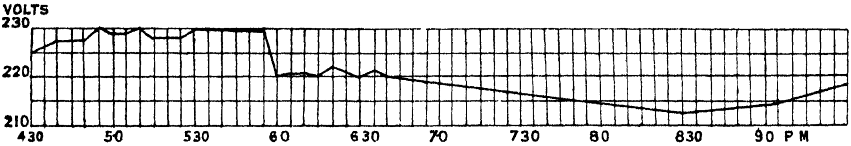


FIG. 6.25.– Voltage Fluctuation of a Supply Network.

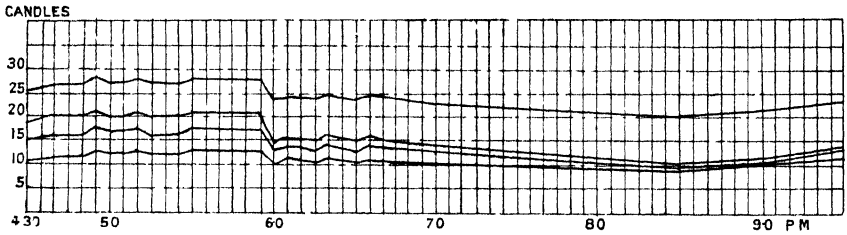


FIG 6 26 —Candle-Power Variation Resulting from Voltage of fig. 5.05.

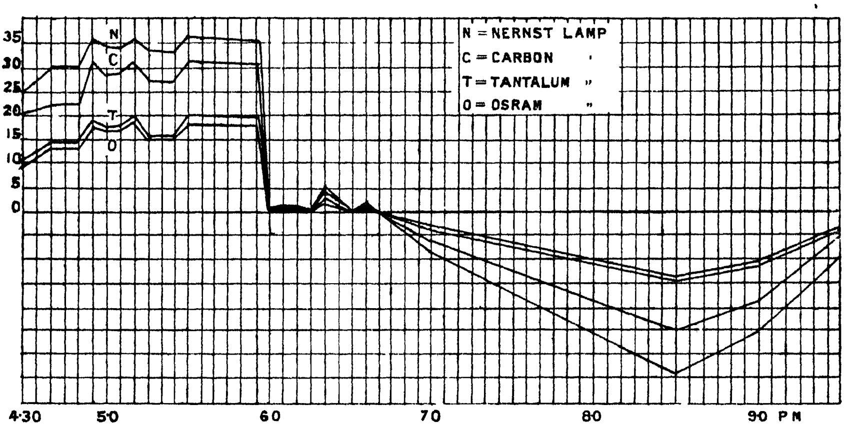


FIG. 6.27.—Percentage Candle-Power Variation Resulting from Voltage of fig. 5.05.

Suppose now the voltage is increased or decreased by p per cent., then

$$I_1 = c\left(V + V\frac{p}{100}\right)^x \text{ for an increase,}$$

$$I_2 = c\left(V - V\frac{p}{100}\right)^x \text{ for a decrease.}$$

The total variation in candle-power is then expressed by

$$I_1 - I_2 = cV^x\left\{\left(1 + \frac{p}{100}\right)^x - \left(1 - \frac{p}{100}\right)^x\right\}.$$

According to the binomial theorem,

$$\left(1+\frac{p}{100}\right)^x=1+x\frac{p}{100}+\frac{x(x-1)}{2\,!}\left(\frac{p}{100}\right)^2+\frac{x(x-1)(x-2)}{3\,!}\left(\frac{p}{100}\right)^3+\ldots\ldots,$$

$$\left(1-\frac{p}{100}\right)^x=1-x\frac{p}{100}+\frac{x(x-1)}{2\,!}\left(\frac{p}{100}\right)^2-\frac{x(x-1)(x-2)}{3\,!}\left(\frac{p}{100}\right)^3+\ldots\ldots,$$

whence

$$\left(1+\frac{p}{100}\right)^x-\left(1-\frac{p}{100}\right)^x=2x\frac{p}{100}+2\frac{x(x-1)(x-2)}{3\,!}\left(\frac{p}{100}\right)^3+\ldots\ldots$$

This series converges rapidly, so that even the second member may be neglected, since for $x=9{\cdot}35$ the result is affected by less than 1 per cent. We get therefore –

$$I_1-I_2=cV^x2x\frac{p}{100},$$

and for the percentage candle-power variation,

$$100\frac{I_1-I_2}{I}=100\frac{cV^x2x\frac{p}{100}}{cV^x}$$
$$=2xp \quad . \quad . \quad . \quad . \quad 6.09$$

Thus, with a $2\frac{1}{2}$ per cent. voltage variation to either side of the normal, the candle-powers vary as follows :—

Carbon Lamp.	Nernst Lamp.	Tantalum Lamp.	Osram Lamp.
35	46·75	22	20 per cent.

The difference in the behaviour of the lamps is due to the nature of the material of the filament. Those with positive temperature coefficients, such as the metal filament lamps, are naturally superior to lamps with negative coefficients. On the whole, the gradual intensity variation of a lamp should not be more than 15 per cent., as the eye will adapt itself to such a change without trouble. Rapid changes in the intensity of less than 5 per cent. cause flickering, and must be avoided. Moreover, where a voltage *drop* occurs, care must be taken that the light is sufficient at the lower voltage. With a 15 per cent. light variation we obtain the following percentage voltage fluctuations :—

Carbon lamp . .	1·07 on either side, or	2·14 total.
Nernst lamp . .	0·8 ,, ,, ,,	1·6 ,,
Tantalum lamp . .	1·7 ,, ,, ,,	3·4 ,,
Osram lamp . .	1·87 ,, ,, ,,	3·74 ,,

Where the supply pressure is 220 volts, the regulation must be within—

Carbon lamp	217·65 to 222·35 volts.
Nernst lamp	218·24 ,, 221·76 ,,
Tantalum lamp	216·26 ,, 223·74 ,,
Osram lamp	215·89 ,, 224·11 ,,

The consumption of power for the different lamps varies considerably. In Chapter II. it was shown on what conditions the consumption depends. On an average, we may reckon about 3·5 watts per mean horizontal candle for the ordinary carbon, 2·0 for the Nernst, 1·7 for the tantalum, and 1·0 for the tungsten lamps. For equal light intensities this would require an expenditure of power in the proportions of 1·0, 0·57, 0·49, and 0·29 respectively, and for the above given voltage drops the cross-sections of the mains would be in the ratios: 1·0÷0·77÷0·308÷0·188. This shows why the tungsten lamps are ousting all others from the market. The gas-filled lamp is even superior to the vacuum type, and in spite of its higher price is coming more and more into use.

6.14.—EFFECT OF FREQUENCY ON THE VARIATION OF CANDLE-POWER OF INCANDESCENT LAMPS.*—In order to determine the

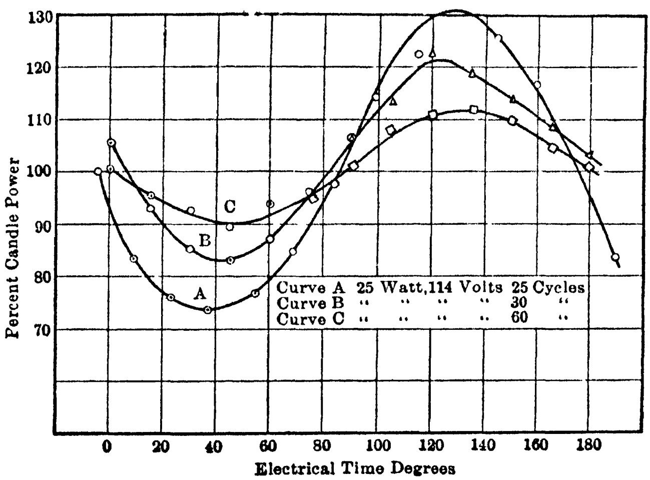


FIG. 6.28.—Curves showing Per Cent. Cyclic Variation in Candle-Power for Tungsten Lamps.

variation of candle-power of a lamp during the cycle of an alternate current, Messrs Kiely and Wasserboehr measured the intensity of light in a single horizontal direction at successive and regular electrical time-intervals throughout the cycle. A small single-phase synchronous motor was arranged to rotate a sectored disc in front of the lamp. This occluding disc had slots equal in number to that of the poles of the motor, and each slot had an opening of eight degrees. The disc was adjustable about the motor shaft to provide for admitting light to a Lummer-Brodhun photometer at any desired point of the cycle. The field of light was reduced by a second fixed screen having a $\frac{1}{4}$-inch slot. Owing to a difference in ratio of energy input and output at any instant, a lag is introduced into the candle-power curve. To investigate this, to determine the zero current point, and to provide a means of detecting any angular oscilla-

* See Kiely and Wasserboehr, *Electrical World*, 1911, p. 430.

tions in the synchronous motor (hunting), the oscillograph had to be employed. The vibrator of the latter was connected in the lamp circuit

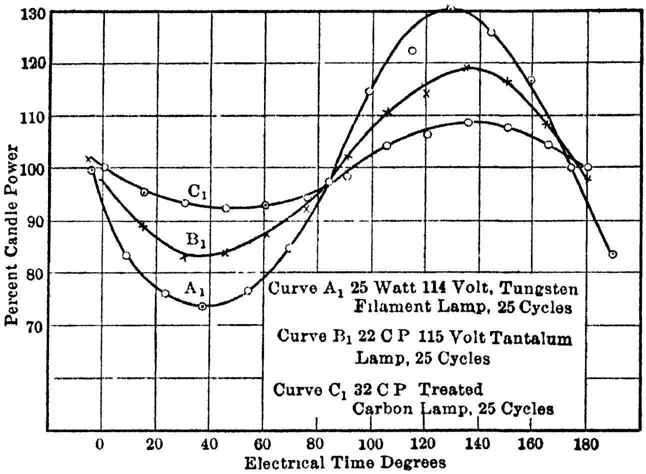


FIG. 6.29 —Curves showing Per Cent. Cyclic Variation in Candle-Power

and a direct-current carbon lamp was placed before the revolving disc. The intense beam of light from the arc was reflected by means of a train of mirrors and totally reflecting prisms to the vibrating mirror, and thence

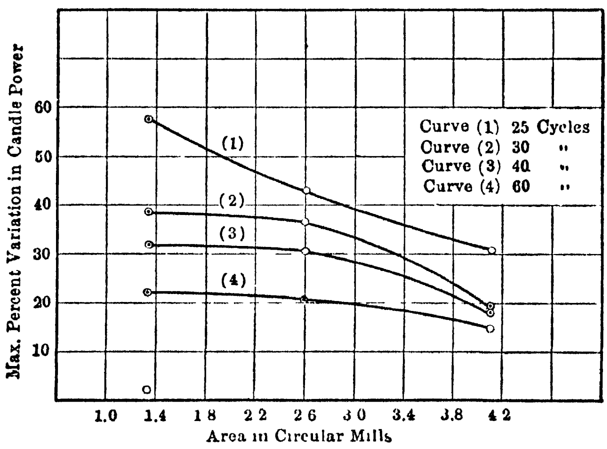


FIG 6.30.—Maximum Per Cent. Candle-Power Variation for Different Cross Sections of Tungsten Filaments.

to the ground-glass screen. When the cylindrical mirrors were at rest, by observing the two images on the screen—because of the two slots per pair of poles—the angular position of the occluding disc was easily adjusted for the zero point. Any hunting of the motor was seen by the surging of the images.

The results of the tests are shown in the accompanying figs. 6.28 to

6.31. We see that the variation increases with a decrease in the frequency of the alternate current and in the thickness of the filament, as one would expect, since on a low frequency the filament is given more time to cool down than on a high one, and since a thin filament has a smaller heat

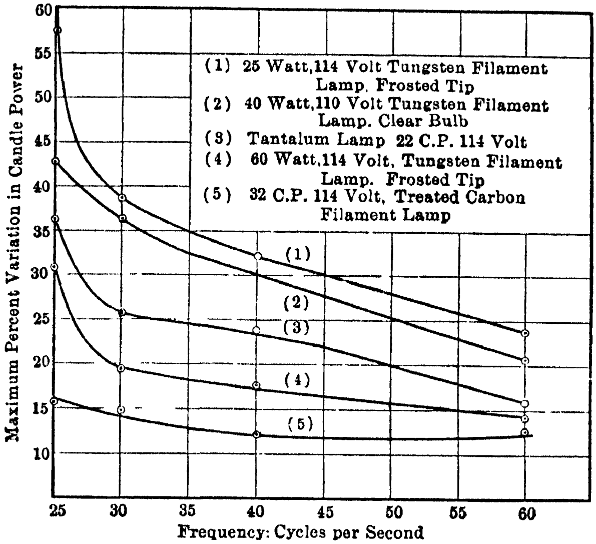


FIG. 6.31.—Curves showing Maximum Per Cent. Variation in Candle-Power with Frequency.

capacity than a thick one. The voltage wave applied in the test had a sine shape. The curves of the candle-power variation are approximately also sine curves.

Experience fully bears out these results. A 10-watt high-voltage tungsten lamp shows considerable flickering even at 25 cycles. The remedy is a lamp of higher candle-power which possesses a thicker filament. Langmuir * has connected the relationship between flicker F and frequency f, power consumption p_0, mass m of filament, and absolute temperature t by a formula, viz.

$$F = 20{,}000 \frac{p_0}{fmt} \qquad . \quad . \quad . \quad . \quad . \quad 6.10$$

The fluctuation is thus inversely proportional to the frequency and directly proportional to the power consumption. The presence of gas in the bulb thus increases the candle-power variation, as for a given mass m and equal temperatures the power consumption p_0 is greater on account of convection losses. On the other hand, as a filament in gas is usually wound in a tight helix, this decreases the fluctuation, as the ratio of power to mass is decreased, since the radiating surface is reduced.

Assuming for tungsten lamps a consumption of 1·0 watt per mean

* *General Electric Review*, March 1914, p. 294.

horizontal candle, that the power consumption is approximately proportional to the 4·7th power of the absolute temperature, the candle-power fluctuation thus to the 2·7th power of the absolute temperature, and taking the temperature of the filament for 1 watt per candle at 2400 degrees absolute, the power consumption is 0·54 watt per centimetre of a filament 1 mil in diameter. The mass of the thread is 0·098 milligram per centimetre length.

Substituting these values in equation 6.10, we obtain

$$F=\frac{19{\cdot}2}{f\times d}.$$

For such a lamp the current

$$I_c=0{\cdot}197d^{\frac{3}{2}};$$

$$p_0=0{\cdot}54dl,$$

$$m=98\times10^{-6}d^2l \text{ grams},$$

whence

$$\frac{p_0}{m}=\frac{5500}{d}=\frac{1860}{I_c^{\frac{2}{3}}}.$$

This, substituted in equation 6.10, produces (placing $t=2400°$)

$$F=\frac{6{\cdot}48}{fI_c^{\frac{2}{3}}}.$$

Speaking generally

$$F=\frac{A}{fI_c^{\frac{2}{3}}} \quad . \quad . \quad . \quad . \quad . \quad 6.11$$

where A may be taken from the following table :—

TABLE 6.03.—VALUES FOR A. (LANGMUIR.)

Watts per Candle.	Temperature.	A.
3·0	2050°K (absolute)	3·64
2·0	2160	4·22
1·5	2250	5·05
1·25	2315	5·62
1·00	2400	6·48
0·80	2490	7·40
0·50	2730	10·56
0 30	3050	15·60

By winding the filament in a helix, the fluctuation is approximately reduced in the ratio of 1·4 to 1 in vacuum. In a gas, the effect of helical winding is much greater, for not only the radiated energy, but also the heat carried from the filament by convection is decreased by concentrating the filament in a smaller space.

The following tables give the candle-power fluctuations of various tungsten lamps, as calculated by Langmuir. These figures agree well with experimental results.

TABLE 6.04.—CANDLE-POWER FLUCTUATIONS (F) FOR 110-VOLT TUNGSTEN LAMPS WITH EXHAUSTED BULBS. (LANGMUIR.)

Watts.	Amperes.	Watts per Candle.	F.		
			25 Cycles.	40 Cycles.	60 Cycles.
10	0·091	1·30	1·08	0·68	0·45
15	0·136	1·25	0·87	0·54	0·36
20	0·182	1·17	0·72	0·45	0·30
25	0·228	1·14	0·64	0·40	0·27
40	0·363	1·10	0·48	0·30	0·20
60	0·545	1·07	0·37	0·23	0·15
100	0·91	1·02	0·27	0·17	0·11
150	1·36	0·90	0·22	0·14	0·09
250	2·27	0·90	0·16	0·10	0·07
500	4·55	0·90	0·13	0·06	0·04

TABLE 6.05.—CANDLE-POWER FLUCTUATIONS (F) FOR NITROGEN-FILLED TUNGSTEN LAMPS WITH HELICAL FILAMENTS. (LANGMUIR.)

Amperes.	Watts per Candle.	F.		
		25 Cycles.	40 Cycles.	60 Cycles.
3·0	0·9	0·25	0·15	0·10
5·0	0·7	0·14	0·08	0·06
6·6	0·6	0·11	0·07	0·05
10·0	0·55	0·08	0·05	0·04
20·0	0·40	0·05	0·03	0·02

If the values of F given in these tables be multiplied by 100, the result will express the candle-power fluctuation directly in per cent.

It is seen at a glance from these tables that the candle-power fluctuations in the nitrogen-filled lamps are negligible. Thus a 5·0-ampere nitrogen-filled lamp on 25 cycles shows a total fluctuation of candle-power of only 14 per cent., an amount too small to be observable, being less than that of a 250-watt vacuum lamp.

6.15.—RELATIVE EFFICIENCY OF LIGHT PRODUCTION BY CONSTANT TEMPERATURE AND VARIABLE TEMPERATURE INCANDESCENT LAMP FILAMENTS.* —A lamp filament may be considered as a receiver, a holder, and a deliverer of energy. When operated at constant temperature it receives energy at a certain rate, depending on the current applied, *i.e.* on the P.D. and the resistance; the energy which it holds depends on the temperature, dimensions of the filament, and the specific heat; and the rate at which energy is delivered (chiefly by radiation) depends on the temperature and is equal to the rate at which it is received.

* From an article by E. J. Edwards, *Electrical World*, 1911, p. 421.

When a filament is worked on alternating current, it receives energy at a certain rate at any instant of time depending on the P.D. applied and the resistance of the filament at that instant; it holds a certain amount of energy which depends on the difference between the total input and output of energy up to that time; it delivers energy at a rate which depends upon the temperature at that instant. The amount delivered during a cycle is exactly equal to the amount received during that time.

Assume now, in order to compare the efficiency of light production under conditions of variable temperature with that obtained under conditions of constant temperature, that the same average luminous intensity (taken as unity for simplicity) is to be obtained with the same lamp in each of the two ways. Let the power required in the case of constant temperature be unity (output and input). Then the power output at any instant for variable conditions is

$$P_t = I_t^n,$$

where I_t is the candle-power (see fig. 6.28) and n a constant. Hence the total mean output (or input) per cycle is expressed by

$$P = \frac{1}{2\pi}\int_0^{2\pi} I_t^n d\theta$$

(assuming the candle-power curve to be a sine curve), so that—since for constant temperature conditions the output is assumed to be equal to unity—the ratio

$$\frac{\text{Variable power}}{\text{Constant power}} = \frac{1}{2\pi}\int_0^{2\pi} I_t^n d\theta \qquad . \quad . \quad . \quad 6.12$$

The exponent n is not entirely constant and increases a little with the candle-power. From 0·7 to 1·3 of normal candle-power (the maximum experienced in practice) it decreases 1·6 per cent. for tungsten, 2·16 per cent. for tantalum lamps. In Table 2.06 we had found for an Osram lamp I proportional to $P^{2 \cdot 32}$, when P is proportional to $I^{0 \cdot 432}$.

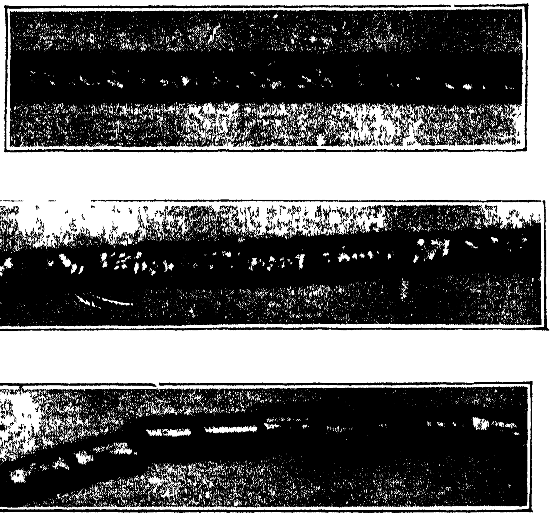
If, then, we insert for n the value 0·432 and integrate equation 6.12 for a maximum variation in the candle-power (above or below the average) of 30 per cent., we get,

$$\frac{\text{Variable power}}{\text{Constant power}} = \frac{1}{2\pi}\int_0^{2\pi} (1 + 0 \cdot 3 \sin\theta)^{0 \cdot 432} d\theta$$
$$= 0 \cdot 9943.$$

We see that for all practical purposes this ratio is unity, since observation errors in a test may easily account for more than the difference between this value and unity.

6.16.—BEHAVIOUR OF METAL FILAMENT LAMPS ON DIRECT AND ALTERNATING CURRENTS—EFFECTS ON SWITCHING-IN.—Incandescent lamps do not behave in the same way on direct as on alternate current circuits. The life of tantalum lamps on alternate current circuits is shorter than on direct current networks, this being probably due to crystallisation caused by repeated heating and cooling. As these lamps will withstand on a direct current circuit a temperature much higher than that occurring when the alternate current wave is at its maximum, the fault is only partly to be found in excessive temperature. This is also proved by the fact that with an increase in the frequency the life is reduced, showing that the *frequency* of heating and cooling is the disturbing factor.

The accompanying photographs * show how drawn filaments appear before and after use. Fig. 6.32 represents a new tantalum filament,



FIGS. 6.32 to 6.34 —Deterioration of a Tantalum Lamp on Alternate Currents of Different Frequencies.

fig. 6.33 one which has been running on a direct current circuit, and fig. 6.34 a filament joined to an 83-cycle network. The greater the frequency, the shorter are the sections † in which these filaments separate. These sections join themselves again, but only imperfectly so.

If the filament of a metal lamp breaks, it is often possible to weld it together again by carefully shaking the lamp. This usually reduces the length of the filament, hence its resistance, and thus causes an increase in the candle-power. Considerable additional life may in this way be obtained out of the lamps.

As metal filaments possess positive temperature coefficients it follows that on switching them on the full voltage, the current rises to several times its normal value, until the metal has had time to heat up. Fuses must thus be liberally dimensioned. The behaviour of various lamps on

* H. M. Sayers, *J.I.E.E.*, vol. xxxviii. p. 260.
† See also Dr C. Sharp, *Electrical World*, 1907.

switching them on is represented in the accompanying fig. 6.35,* which is self-explanatory.

Although there is considerable overshooting of the current, the candle power of a tungsten lamp overshoots very little.

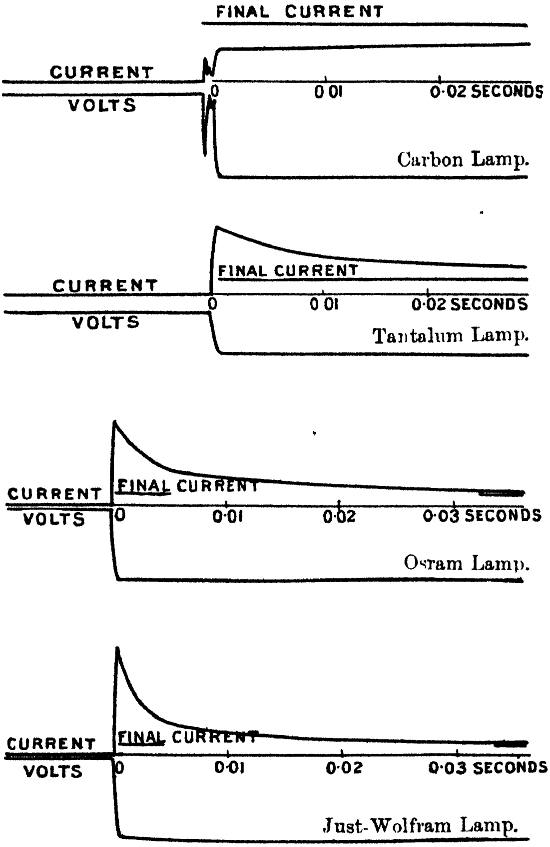


FIG. 6.35.—Behaviour of Lamps on Switching them into Circuit.

6.17. MECHANICAL LAMP TESTER.—When lamps are employed for the lighting of railway trains, or trams, they are subjected to frequent jerks and shocks. To get an idea of how lamps will last under these conditions, special mechanical testers are used with which the working conditions are imitated as nearly as possible. Such a lamp tester is shown in fig. 6.36, together with the connections employed in the tests.† The arrangement needs little explanation. A cam is rotated, and once in each rotation the lamp drops a small distance, thereby receiving a definite shock. The cam, which is driven by a small motor, carries at one end a counter on which the number of revolutions is read.

* J. T. Morris, *J.I.E.E.*, vol. xxxviii. p. 254.

† See *Electrician*, 22nd September 1911.

For testing the filament when glowing, the arrangement on the right in fig. 6.36 is employed (hot test). By means of an automatic switch the motor driving the cam is stopped as soon as the filament fails. To test the lamp when cold, the arrangement in the lower part of the figure is used. The current passes through the lamp only for an instant in each revolution, the time being too short to heat the filament to incandescence Should the lamp fail, the current through the automatic switch is for an instant interrupted and the circuit is broken. We see that the apparatus needs no attention whatsoever.

6.18. TESTING OF ARC LAMP CARBONS.* The test on arc lamp carbons includes the *range*, the *resistance*, and the *life*. The range is determined by supplying the lamp with the carbons to be tested, burning

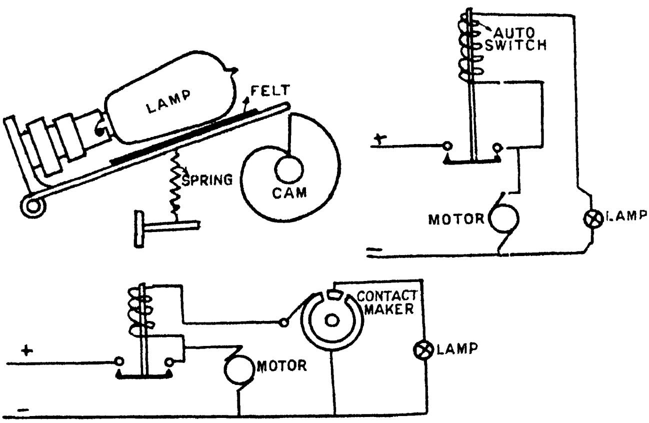


Fig. 6.36.—Mechanical Lamp Tester.

them until the tips are properly shaped and the lamp is thoroughly heated (half an hour). We then connect a voltmeter to the carbons and very carefully depress the upper electrode until the lamp commences to "hiss." The voltmeter will then show a sudden drop. We call this voltage the "hissing"-point; it varies with the quality of the carbons. For an ordinary arc lamp it lies somewhat near 40 to 45 volts. The test is then repeated, but this time the carbons are more and more separated until the arc commences to "jump," and may even leave the crater. The voltmeter then indicates the jumping-point, which should lie over 60 volts. If the length of the arc be further increased, the arc will commence to flame, and the voltmeter indicates the flaming-point, which should not lie below 65 volts.

Generally speaking, the hissing-point of carbon arcs should be at least 5 volts below the normal voltage of the lamp, where steadiness of light is required. Hissing-, jumping-, and flaming-points are entirely dependent on the quality of the carbon, and slight impurities greatly

* See also the article on "Carbon Arcs for Searchlights," by Paterson, Walsh, Taylor, and Barnett, *J.I.E.E.*, 1920, vol. lviii. p. 83.

reduce the steadiness of burning. Soft carbons contain a great deal of soot, while harder ones contain more retort carbon. The softer the carbon, the greater the amount of dust which is deposited by the carbons, but the greater the quantity of the light usually emitted. The quantity of dust should be less than 4 per cent. of the weight of the upper carbon. A smaller amount will show a long life, but will probably also indicate a poor light. The deposit of dust may be almost entirely eliminated by coating the carbon with copper. This also reduces the resistance of the electrodes. The latter is measured best by a Kelvin double bridge. A carbon 11 millimetres in diameter (seven-sixteenths of an inch), about 30 centimetres long (1 foot), has usually a resistance of 0·16 to 0·23 ohm, and carbons 12·5 millimetres (or $\frac{1}{2}$ inch) thick a resistance from 0·14 to 0·18 ohm. This resistance is reduced for 11-millimetre carbons to about 0·05 ohm if for 1000 30-centimetre carbons we employ about 1·23 kilograms (3 lbs.) of copper.

The life of the carbon is best tested by consuming it completely in the lamp at the normal voltage. The time of the test may be reduced by burning the lamp, say, for half an hour, so that the tips have assumed the proper shape, then weighing the carbons, and burning them again for an hour, after which the weighing is repeated. The amount consumed shows the rate of consumption. A rough idea of the life of the lamp would also be obtained by measuring the length of the carbons before and after the test. The one-hour test is best carried out at the average point of burning, so that a 30-centimetre carbon (12-inch) should be broken off to a length of about 16 centimetres. The carbons are, of course, not completely consumed, *i.e.* they must be renewed before the carbon-holders are brought into contact; stops have therefore to be provided, which prevent further feeding of the carbons when the length of 30-centimetre carbon has been reduced to about 5 centimetres. The weight of carbon 30 centimetres long consumed in a complete life test is about 63 per cent. for the ordinary open arc, so that, if we divide 63 per cent. of the weight of both carbons when new by the rate as determined in the one-hour test, we also get the life approximately.

As has already been pointed out, the ordinary arc is a thing of the past except for special purposes, as only flame and luminous arcs (magnetite and titanium) can compete with modern incandescent lamps. The testing of such lamps requires a good deal of care. The satisfactory burning depends largely upon the mechanism of the lamp, especially if the electrodes are inclined to each other. If one extends beyond the other, it will burn in an atmosphere containing more oxygen and thus consume more rapidly, the difference exceeding sometimes 10 per cent. Also the colour of the light will greatly vary as the relative consumptions of carbon and chemicals are altered. It is even possible that a certain set of carbons may burn well in one lamp and yet be unsatisfactory in others. The homogeneous flame carbons arranged vertically are on the whole superior to the inclined ones, independently of the light distribution, as long as there is no excess of chemicals, which would be deposited in a non-conducting layer on the lower electrode.

The quantity of the deposit is little of a criterion in these lamps, as it depends chiefly upon the ventilation. With metal cores it is especially high, and a small receptacle is often placed at the bottom of the globe where the heavier particles can collect and do little harm as regards the absorption of light. With zinc wire cores the deposit is large but white, while a brass wire gives less deposit, but it is of a brown colour and thus more absorbing. On account of the large deposits from flame and luminous arcs, good ventilation is thus one of the principal requirements of a satisfactory arc lamp.

Lamps used for series burning should be tested under such condition, as single lamp tests may give totally erroneous results. This is, of course, unnecessary when the tests are solely meant for the comparisons of electrodes of different makers, unless the electrodes have been built for a particular type of lamp. To obtain accurate results a number of tests should be carried out with at least two lamps in series and the average results taken. Variations in the life of electrodes due to differences in the diameters are then also detected.

The consumption of inclined flame electrodes in lamps of the open type varies from about 60 to 90 millimetres per hour, so that retrimming is necessary every day, at least in winter. It is for this reason that magazine lamps were constructed in which five or six pairs of electrodes could be consumed in succession. The mechanism of such lamps is, however, complicated and easily liable to get out of order. The lamp is therefore not favoured to-day. The difficulties of ventilation in flame or luminous lamps having been overcome, the enclosed long burning type with vertical homogeneous electrodes has become very popular, especially in the United States.

6.19. ABSORPTION OF LIGHT BY ARC LAMP GLOBES.—It would appear that the easiest method for determining the absorption of a globe would consist in finding the M.S.C.P. of the lamp (*a*) without the globe, (*b*) with the globe. This procedure possesses, however, serious objections. When a lamp burns without a globe the consumption of carbon is usually materially increased, since the supply of oxygen is unlimited, whereas most globes partly limit the passage of air. Again, for enclosed lamps such tests would be completely unreliable, as at least one globe is essential for such lamps. It will also be found that a lamp may flicker badly if burnt without a globe. Tests which are otherwise entirely satisfactory become in these circumstances almost impossible, since the absorption depends also somewhat upon the nature of the light and its distribution. The absorption of light depends largely upon the wave-length, so that it would be obvious that if we carry out the absorption test with, say, a standard glow lamp, the results obtained in this way might be altogether wrong when directly applied to arc lamps.

In all cases we obtain a higher mean spherical candle-power when testing without a globe, on account of the unlimited supply of oxygen, than would be the case if we could test the lamp without the globe, but limit the supply of oxygen to that of a lamp when burning with a globe. As arc lamps are always employed with globes, and mostly with reflectors, the results of a test should be stated for the lamp under working conditions.

Although absorption tests do not yield very reliable results, it is still possible to carry out tests in such a manner as to obtain some idea of how much the light is obscured by the globe. For this purpose we employ a large metal filament incandescent lamp, which, since the lamp burns in a vacuum, is independent of the supply of oxygen, and test the glow lamp first without the globe and then when placed centrally within it. The results obtained in this way will not be so very far out, since the light of a metal filament lamp does not differ very much from that of an ordinary arc lamp, although it differs materially from that of a flame arc. Some error will probably also be introduced by the fact that the distribution of the light of the incandescent lamp differs from that of an arc lamp. Tests carried out in this way by Professor J. T. Morris * are illustrated in the accompanying Table 6.06.

The first column shows the name and the size of the lamp; the second column, the dates of the tests on which they were carried out; the third column, the angle below the horizontal under which the maximum candle-power occurred; the next two columns show the mean spherical and hemispherical candle-powers; column seven represents the mean volt ×amperes; column eight, the mean watts; columns nine and ten, the mean spherical and hemispherical candle-powers per watt respectively. In column eleven is given the percentage of the light emitted; and in column twelve, the corrected M.S.C.P. per watt, which takes into account the absorption of light by the globes.

We see from this table that the absorption of light for the different lamps varies considerably. It should also be pointed out that the values hold for perfectly clean globes, and that the slightest deposit on the inside from the carbons materially reduces the light emitted. In fact, in some cases the light obscured might amount to 80 or 90 per cent. of the total amount.

From this it will be obvious that the efficiency of even a flame lamp will not be much greater than that of an incandescent metal filament lamp unless the globes are kept perfectly clean. On the whole, we may reckon that the following amount of light is absorbed :—

	Per cent.
Clear glass	10
Alabaster glass	15
Opalescent glass	20 to 40
Ground glass	25 ,, 30
Opal glass	25 ,, 60
Milky glass	30 ,, 60

* See *Illuminating Engineer*, 1908, p. 719.

TABLE 6.06.—EFFICIENCIES AND CONSUMPTIONS OF ARC LAMPS. (MORRIS.)

Name of Lamp.	Date.	Maximum C.P.	Angle of Maximum C.P.	M.S.C.P.	M.H.S.C.P.	Mean. V. A.	Mean Watts	M.S.C.P. per Watt.		M.H.S.C.P. per Watt.		Light Emitted.	Corrected M.S.C.P. per Watt.
			Degrees.										
New Century D.C. open,	9/6/08	930	43	600	810	51 × 15	765	0·78	0·75	1·06	1·0	75%	1·0
15 amp. . . .	6/7/08	1100	50	570	790	54 × 15	810	0·71		0·98			
Jandus enclosed ordinary,	25/5/08	570	42	250	340	80 × 5·8	465	0·54	0·55	0·73	0·75	91%	0·6
5 amp. . .	27/5/08	560	39	230	350	80 × 5·7	455	0·55		0·77			
Crompton-Blondel, 10	29/5/08	1080	10	720	910	40 × 10	400	1·80	1·95	2·27	2·5	60%	3·25
amp. . . .	10/7/08	1380	14	845	1110	40 × 10	400	2·11		2·77			
Excello, 10 amp. . .	1/6/08	1720	60	900	1400	47 × 10	470	1·92	2·25	2·98	3·55	74%	3·05
	6/7/08	2550	70	1130	1830	44 × 10	440	2·57		4·16			
Gilbert D.C., 10 amp. .	16/6/08	2450	60	1240	2000	48 × 10	480	2·58	2·25	4·17	3·65	78%	2·9
	10/7/08	2140	61	915	1490	47 × 10	470	1·95		3·17			
Oriflamme D.C., 9 amp.	12/6/08	1020	47	495	825	38 × 10	380	1·30	1·55	2·17	2·55	67%	2·3
	6/7/08	1140	52	540	880	34 × 9	306	1·77		2·89			
Westinghouse, 9 amp.	13/6/08	960	36	550	790	54 × 9	486	1·13	0·9	1·63	1·4	58%	1·55
	10/7/08	750	59	340	585	55 × 9	495	0·69		1·18			
Gilbert A.C., 12 amp.	19/6/08	1520	56	695	1130	55 × 11·5	630	1·10	1·05	1·79	1·65	73%	1·45
	15/7/08	1500	60	640	1000	55 × 11·8	650	0·98		1·54			
Oriflamme . . .	13/7/08	820	45	430	690	44·2 × 10	440	0·98	1·0	1·57	1·55	65%	1·55
		880	90										
Jandus enclosed flame,	24/6/08	1700	15–30	885	1425	58 × 6·1	355	2·49	2·65	4·01	3·9	84%	3·15
5½ amp. . . .	26/6/08	1820	0–10	1045	1400	59 × 6·3	370	2·82		3·78			

Globes usually alter the distribution of the light, especially if the lamp is provided with a reflector. In some cases, especially for flame arcs with inclined carbons, we place a special prismatic reflector near the bottom of the globe; the effect of this is to direct the light, which is chiefly emitted in a downward direction, towards the horizontal, whereby a great uniformity in the illumination is obtained. For further information see Chapter VII. on Shades and Reflectors, and paragraph 8.13.

Globes used with arc lamps often become discoloured in a short time. This is partly due to the deposition of fumes and to the influence of ultra-violet rays, especially in magnetite lamps. The glass develops a purple coloration, caused by the chemical effect of ultra-violet light on the manganese constituent. It is removed by treating the interior of the globe with hydrochloric acid, after which the globe is washed and dried (cold). The glass is then heated uniformly in an oven to about 500 degrees C., a temperature reached in four or five hours, kept thereat about one hour, and is then gradually cooled down in approximately fifteen hours, to prevent cracking. The globes thus treated remain clear for at least 75 per cent. of the time required to discolour new globes to the same extent.

6.20. THE CONTROL OF ARC LAMPS.—It is not intended to deal exhaustively with arc lamp mechanisms in this paragraph, as a whole book could easily be filled with this subject alone, because every manufacturer possesses his own methods.* The underlying principles are, however, the same for all.

The control embodies usually four elements: (*a*) a starting device; (*b*) a feeding mechanism; (*c*) a steadying resistance or impedance; (*d*) a compensating device.

(*a, b*) The principles of starting and feeding an arc are best seen from the accompanying fig. 6.37, which illustrates a differential lamp. The carbons are normally together, so that at the instant of switching-in a heavy current passes through the series coil S, which attracts its armature, thereby tilting the clutch C and raising the upper electrode, thus striking the arc. The carbons are now consumed and the P.D. across the shunt coil N increases until by the action of this coil—which is differential to that of S—the clutch C is brought again into a horizontal position and allows the upper carbon to feed. The system of control is thus a floating one, because the upper electrode is held in position by the balance of two forces, due to current and voltage respectively. The upper carbon is in consequence always on the move, but this does not matter much as long as the arc itself does not produce the maximum light, especially if the lamp regulates closely and quickly for constant voltage. This system is therefore used in most plain carbon arc lamps.

(*c*) It has been explained in Chapter II., paragraph 2.31, that arc

* The reader will find full descriptions in the book on *Electric Arc Lamps*, by Zeidler and Lustgarten (Harper Bros.).

lamps must be run in series with steadying devices. If a number of lamps are joined in series on a constant P.D. a single steadying resistance (or impedance for alternating current circuits) is the usual practice, although a resistance may be given to each lamp. When arc lamps are joined in series on a constant current system (Brush arc lighting machine or constant current transformer with or without mercury rectifiers) no steadying resistances are required, as the current is kept constant by the source.

In fig. 6.37 the steadying resistance is marked R_s.

(*d*) If the upper carbon in fig. 6.37 sticks and does not feed, contact K is closed by the action of the shunt coil N, and the current passes through the compensating resistance R_c. In alternating current circuits this would be an impedance, and, as the voltages of lamps and impedance are out of phase, the voltage across the impedance must be larger than that of a single lamp. On the whole impedances are more economical than resistances, but they possess the disadvantage of lowering the power factor of the system.* The advantage would be chiefly to the consumer, and the disadvantage to the supply company.

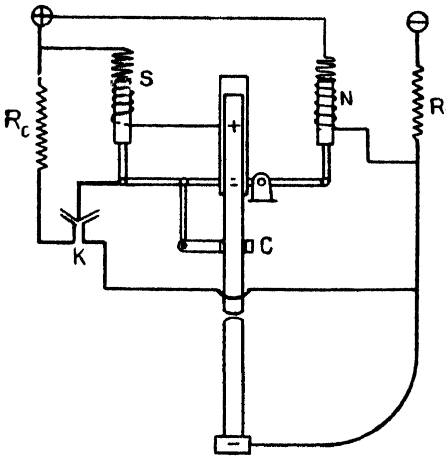


Fig. 6.37.—Principle of Differential Lamp.

Continuity of circuit in alternating current systems may also be obtained by joining choking coils in parallel to the lamps. On the extinction of the lamp the choker must carry the whole current, with a consequent rise in volts between its terminals and a drop in the current. For a constant current the supply pressure therefrom must be raised as lamps are extinguished, a constant current regulator thus being essential. This being the case, it is better to provide the lamp with a switch which automatically short-circuits the lamp when it fails.

If a lamp is to be operated singly on a constant potential circuit, the shunt coil may be left out. The lamp then feeds as soon as the series coil is unable to keep the clutch C tilted. A steadying resistance or impedance is now, of course, essential. Such lamps cannot be operated in series, as the feeding of one lamp would set the others moving too, since it regulates by the alteration in the current.

Lamps with shunt coils are also employed. Before switching-in the carbons are separated. When the switch is closed, the shunt coil brings

* See *Transformers*, by Bohle and Robertson, p. 304.

the carbons together. At that instant the lamp is practically short-circuited and the shunt coil releases one electrode, whereby the arc is struck. With a consumption of the electrodes the shunt coil becomes stronger and feeds the arc.

It is possible to run a limited number of such lamps in series.

The fixing of one electrode has the disadvantage that the position of the arc varies with the consumption of the electrodes, thereby changing the distribution of the light. As this is on the whole undesirable, it is better to connect the two electrodes mechanically by a cord or chain passing over a wheel and to let the clutch engage with the latter.

The control of flame arcs is on the whole based on similar principles. The employment of an economiser and blow magnets have already been explained in paragraph 2.22. The modern tendency in lamps with inclined carbons has been to simplify the mechanism as much as possible and to rely on gravity feeding. For a description of such lamps the reader is referred to the bulletins of arc lamp manufacturers.

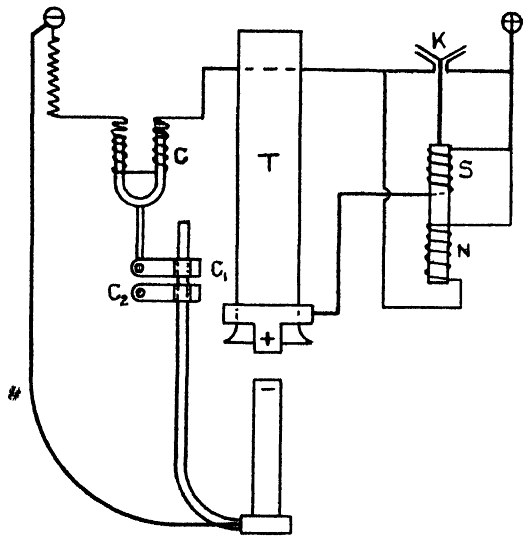


FIG. 6.38.—Principle of Luminous Arc Lamp Mechanism.

In luminous (magnetite) arc lamps the floating system of control, which regulates for constant voltage by varying the length of arc in accordance with the resistance of the circuit, is not a suitable one. In these lamps the light is proportional to the length of the arc, so that the control should be such as to keep this length constant within certain limits. The consumption in these lamps is very low, and it is sufficient if the feeding occurs about every twenty minutes.

The principle of such a lamp is given in fig. 6.38. The upper electrode is of copper, and the lower one consists of magnetite. Both must remain apart when the current is switched off, as otherwise the melted pool formed on the surface of the lower electrode would weld them together. We require thus a special starting coil C which, on switching-in the lamp, tilts the clutch C_1 and lifts the lower electrode. As the length of the arc in these lamps is great, $\frac{5}{8}$ to 1 inch according to the P.D., the stroke of the starting coil must be long. As soon as the electrodes touch, the series coil S is inserted; it draws up its core and thereby disconnects the starting coil C at K, so that the lower electrode drops again, but only as far as clutch C_2 allows. The arc is now struck. As the electrode is consumed the P.D. across the shunt coil N increases until this coil overpowers S and reinserts the starting coil C, which then feeds the arc.

It is obvious that with an ordinary arc lamp the arc would have to lengthen considerably before the shunt coil overcame the series one. This would be unsatisfactory. Fortunately, the resistance of the luminous arc at constant length varies continuously all the time, the voltage pulsations becoming larger and larger. In a lamp with a normal P.D. of 75 volts the shunt coil is so arranged that it overcomes the series coil when a sudden peak of 105 volts is reached; which occurs about every twenty minutes. It is thus the character of the arc as a resistance which is the basis for the controlling system. The latter fixes the position of the electrodes for a period of about twenty minutes by means of a shunt magnet which is set for a voltage about 45 per cent. above the normal.

In fig. 6.38 the tube T is a chimney which carries away the fumes of iron oxide from the arc. The upper electrode is always the copper anode, so that it is impossible for hot particles from the cathode to drop on the anode and cause trouble. The life of the composition cathode is from 120 to 200 hours, while the anode lasts from 1500 to 4000 hours, depending upon the current. The lamps of the General Electric Company are made in 4, 5, and 6·6 ampere sizes.

Flame arcs are worked singly (usually enclosed), or two or three in series of 110 to 130 volts. Care must, of course, be taken that the supply voltage is not too close to the stability limit. For higher voltages, such as 220 to 250 and 400 to 500 volts, the number of lamps which may be joined in series is proportionally greater. A single lamp on a 110-volt circuit is, of course, uneconomical, as a great part of the voltage is absorbed by the steadying resistance or impedance.

For a luminous (magnetite) arc 110 volts may even be insufficient for a single lamp. Take a 4-ampere lamp with an arc 20 millimetres long. The minimum voltage required is

$$V_{\text{min.}} = V + \tfrac{1}{2}c\frac{l+l_0}{\sqrt{I_c}} \text{ where } V = V_0 + c\frac{l+l_0}{\sqrt{I_c}} = 31 + 4{\cdot}8\frac{20+2}{\sqrt{4}} = 84,$$

whence

$$V_{\text{min.}} = 84 + \tfrac{1}{2} \times 48 \times \frac{20+2}{\sqrt{4}} \doteq 110{\cdot}5 \text{ volts.}$$

110 volts would thus be too near the limit. Generally, the luminous arc, which is almost exclusively used in America, is mainly employed on the series constant current system, the general practice being to join from fifty to a hundred such lamps in series. Seventy-five lamps is the most common figure. For 4-ampere lamps with a length of arc of 18 milli-

metres the voltage required would be

$$75 \times 31 + 75 \times 4{\cdot}8 \times \frac{18+2}{\sqrt{4}} = 5925, \text{ say about 6000 volts.}$$

The control of these lamps is at the source, and no steadying resistances are necessary.

The constant current required may be obtained from a Brush arc-lighting machine (old method). This is a kind of two-phase (4-coil) alternator with a four-part commutator, possessing a high armature reaction and a low field. An increase in the current causes increased

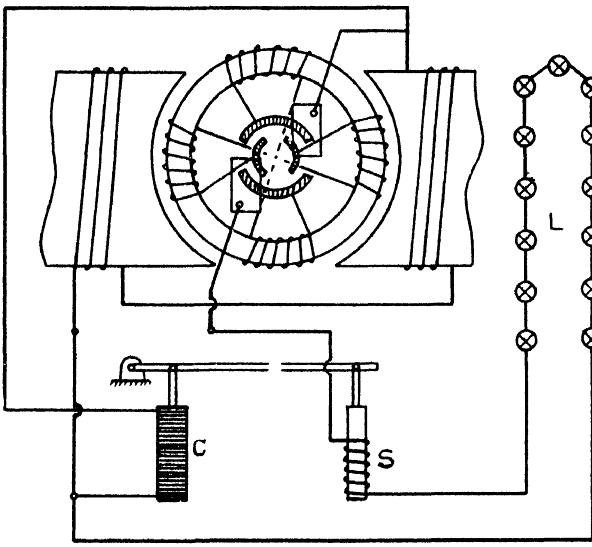


FIG. 6.39.—Principle of Brush Arc-Lighting System.

reaction, thereby reducing the resultant flux and bringing the current back to its former value. A shunt C across the field, of the compressible carbon pile type and manipulated by an electro-magnet S in the machine circuit, improves the inherent regulation. With an increase in the current the carbon pile is more compressed and more current is shunted from the main field, thereby reducing the flux and thus the voltage and current. The system is illustrated in fig. 6.39.*

In recent years the arc-lighting machine has largely been replaced by the mercury arc rectifier. The principle of this apparatus has already been explained in paragraph 2.18 when dealing with luminescence. We are here chiefly concerned with the constant current rectifier. It is shown diagrammatically in fig. 6.40. The secondary S of a constant current transformer T is tapped in the middle, this tapping forming

* For a theory of the phenomena, see Steinmetz, *Transient Electric Phenomena and Oscillations.*

one terminal for the arc-lighting circuit. The ends of the secondary are brought to two graphite anodes a and a' of the rectifier after passing through reactances r, which are used for the purpose of an overlap between the arcs a–c and a' c, where c is the cathode of mercury. The current of the first half-wave must be maintained beyond the zero value of its propelling E.M.F., and must not die out until the current in the next arc is well on its way. Another reactance is placed between the cathode and the arc circuit in order to reduce the fluctuation of the rectified current. The rectified voltage is somewhat less than one-half of the alternating voltage, and the current somewhat more than double the alternating current of the secondary of the transformer.*

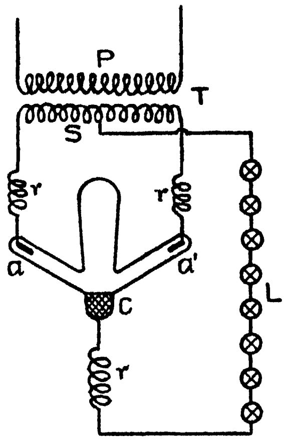
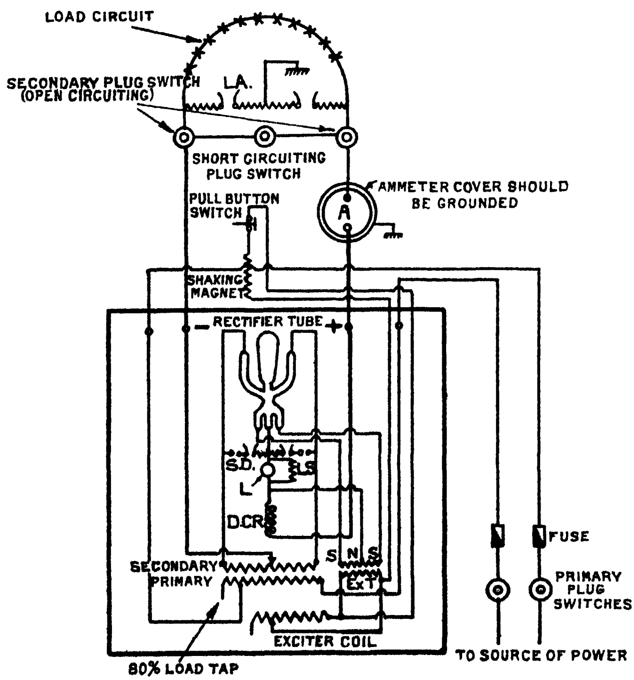


FIG. 6.40.—Principle of Mercury Arc Rectifier.

The rectifier has two additional small



Ex.T. Exciter Transformer; S.D. Static Discharger; D.C.R. D. C. Resistance; L.A. Lighting Arrester; S. Exciter Secondary; N. Exciter Neutral; L. Indicating Lamp; L.S. Indicating Lamp Shunt.

FIG. 6.41.—Connections for Mercury Arc Rectifiers.

* For a theory of the phenomena, see Steinmetz, *Transient Electric Phenomena and Oscillations.*

anodes near the cathode for starting purposes (see fig. 6.41), for producing from a small low voltage constant potential transformer auxiliary rectifying arcs when the tube is shaken. The shaking is done automatically by a shaking magnet energised by a push button. The complete connections are given in fig. 6.41. They include lighting arresters L A and static dischargers S D, the latter to protect the tubes from excessive electrical strains.

A tube of the General Electric Company is shown in fig. 6.42.* It is usually submerged in oil cooled by circulation of water by means of cooling coils inside the tank. An indicating lamp L shows whether the outfit is working normally or otherwise.

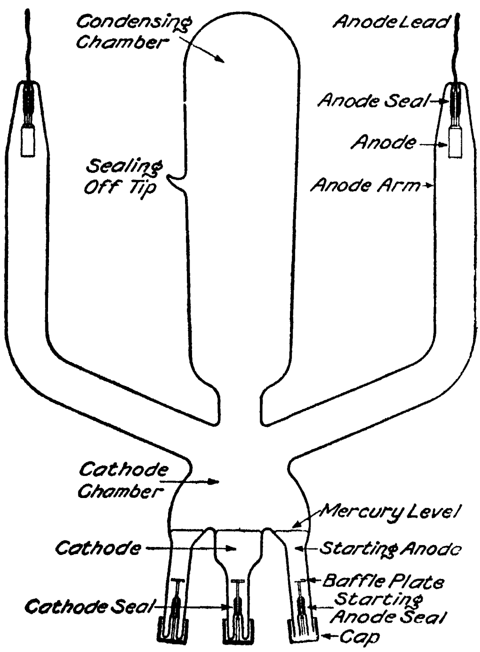


FIG. 6.42.—G.E.C. Mercury Rectifying Tube.

The constant alternating current is obtained by means of a constant current transformer which possesses a high magnetic leakage and regulates- as all apparatus with great reaction does—for constant current.†

In some cases of street lighting it may be inconvenient to use arc lamps. A smaller unit may then be sufficient, for instance, for side streets. Incandescent lamps of the correct current and low voltage may then be joined in series to luminous arcs. They must, of course, be supplied with compensating or short-circuiting devices in case of failure.

If the number of arc lamps exceeds fifty or seventy-five, two tubes are usually joined in series.

Polyphase rectifiers have also been placed on the market.

The efficiency of a mercury rectifier lies in the neighbourhood of 80 per cent. average, and may be as high as 88 per cent.

6.21. POLYPHASE LAMPS.—From time to time patents have been taken out for three-phase arc lamps, chiefly on account of such lamps yielding a greater luminous flux than single-phase lamps with the same expenditure of power. The difficulties encountered lay all in the controlling mechanism. Besides sure striking of the arcs between three

* *G.E.C. Bulletin*, No. 43,900, March 1915.

† See *Transformers*, by Bohle and Robertson, p. 316.

inclined carbons, it is necessary that the consumption of each electrode is so influenced by the consumption of each of the other electrodes that the currents and P.D.'s between the electrodes remain approximately equal and constant. As further inequalities in the material and composition of the electrodes cannot be avoided, these must also be neutralised, so that the tips of the electrodes remain in a horizontal plane. The more rapid burning of one electrode must always be neutralised if satisfactory action is to be expected.

These various simultaneous demands on the controlling mechanism were the stumbling-block to a successful three-phase lamp.

The difficulties seem, however, to have been overcome in a lamp by Schäffer,* which has been carefully tested under various conditions by Professor Wedding, and which has shown a satisfactory system of control. The lamp is probably the most efficient illuminant on the market. With a clear glass globe it is claimed that its specific consumption is only about 0·11 watt per international mean hemispherical candle. The source of the lamp yields a symmetrical light, as the three craters supplement one another. The mean hemispherical candle-power of a 10-ampere lamp with 9-millimetre flame electrodes is about 12,000. The lamp is therefore suitable for the illumination of very large squares. The specific consumption of 0·11 watt per M.H.S.C.P. includes losses in a clear globe, windings, and transformer, but not in a dioptric refractor, which would be necessary as the intensity is largely in a downward direction.

The author is not aware of how far the lamp has proved a commercial success.

6.22. MOORE TUBE LIGHTING.† In order to determine the light emitted by the Moore tube system, it is necessary to screen off the whole tube except a narrow strip, the intensity of which is to be determined. In the tests carried out by Professor Wedding, the tube was 44 millimetres in diameter, with a glass thickness of 2 millimetres. The whole tube was covered with black paper, leaving free only a strip of 1 square centimetre, which on testing gave an intensity of 0·202 candle. Increasing this area to 1×2; 1×3; and 1×4 square centimetres, in the direction of the axis of the tube, it was found that proportionality existed, *i.e.* the light increased directly with the length of the tube exposed.

The same thing applied to cylindrical exposed surfaces, the intensity of a ring surface of 1 centimetre length being 0·47 candle. On testing the tube for absorption of light by the gas enclosed, by placing two tubes side by side so that one screened off the other as far as the photometer screen was concerned, it was found that for all practical purposes the absorption was negligible. We may therefore judge the system by the amount of light emitted by a ring surface of 1 centimetre length.

The connections for the test are shown in the accompanying fig. 6.43,

* *Elektrotechnische Zeitschrift*, 1912, p. 579.

† See also "Das Moore Licht," by W. Wedding, *E.T.Z.*, 1910, p. 501.

in which A_1 and A_2 represent ammeters, V_1 and V_2 voltmeters, T the transformer, C the choker, S the solenoid for operating the valve, P_1 and P_2 wattmeters, and F the frequency indicator. The voltmeter V_2 is joined to a special volt transformer, which reduces the P.D. in the ratio 15,000 to 110. One pole of the high potential secondary circuit is joined to earth.

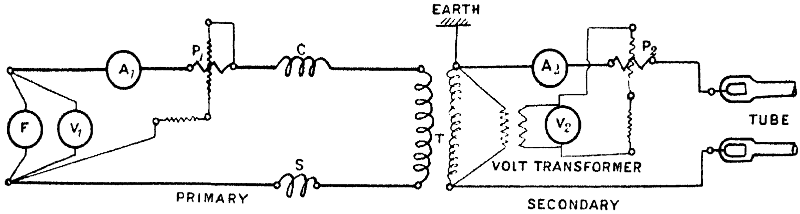


FIG. 6 43. - Connections for Testing Moore's Tube System.

The results of the tests are shown in the accompanying Table 6.07. The average value of candle-power is 0·485 for a surface of 1 centimetre width. As the length of the tube was 37½ metres, and the primary power 3333 watts, we have per metre length of tube 89 watts and 48·5 candles measured perpendicularly to the axis of the tube. Hence for one candle we must expend 1·87 watts.

TABLE 6.07.—BEHAVIOUR OF THE MOORE TUBE SYSTEM UNDER NORMAL CONDITIONS. (WEDDING.)

Frequency. f	Primary Volts. E_1.	Primary Current. I_{c1}.	Primary Power. P_1.	Power Factor $\cos\phi_1$.	Secondary Volts. E_2	Secondary Current. I_{c2}	Secondary Power. P_2	Efficiency. η.	Candles per Centimetre Length of Tube. i.
50	220·6	23 1	3348	0·658	12,800	0·279	2850	0·853	0·551
50	221·3	23·0	3356	0·658	12,860	0·279	2850	0·85	0·444
50	221·5	23·2	3356	0·658	12,870	0·279	2870	0·856	0·435
50·4	220·1	23·0	3272	0·645	12,780	0·273	2880	0·882	0·508
50·1	220·9	23·075	3333	0·655	12,827	0·277	2862	0·86	0·485

6.23. INFLUENCE OF THE PERIODICITY.—The behaviour of the system on different frequencies is represented in the accompanying Table 6.08. During the test it was impossible to maintain the secondary P.D. constant, as will be seen from the table. It will also be seen that, with increasing periodicity, constant primary P.D., and constant current, the secondary pressure drops on account of increasing losses in the circuits. Moreover, when the secondary P.D. falls too much, the light commences to flicker. It was also noticed that the luminous gas possessed considerable inertia, which prevented rapid variations in the light due to rapid changes in the supply P.D.

TABLE 6.08.—BEHAVIOUR OF THE MOORE TUBE SYSTEM FOR DIFFERENT FREQUENCIES. (WEDDING.)

f	E_1.	I_{c1}.	P_1.	cos ϕ_1.	E_2.	I_{c2}.	P_2.	η.	i.
36	153·0	23·0	2272	0·645	8680	0·272	1655	0 729	0·218
40	153·0	22·8	2272	0·652	8500	0·273	1655	0·729	0·23
43	153·7	23·1	2236	0·630	7860	0·275	1655	0·742	0·228
46	153·5	22·9	2184	0·622	7760	0·276	1655	0 757	0·216
49	153·0	22·9	2052	0·586	7180	0·271	1615	0·788	0·20
50	153·2	22·9	2024	0·578	6935	0·279	1665	0·848	0·189
53	153·7	22·9	1868	0·531	6320	0·279	1512	0·811	0·111
56	153·9	22·9	1684	0·478	5660	0·279	1258	0·748	0·072
60	156·0	22·7	1552	0·438	5160	0·274	1165	0·752	0·047

6.24. INFLUENCE OF INDUCTANCE IN THE CIRCUIT ON THE LIGHT.—The steadying resistance of arc lamps is replaced in the Moore system by a choking coil. The choker was provided with five tappings, allowing a fair variation in the number of the turns. The next table, 6.09, shows the results. When the choking effect is small, the secondary

TABLE 6.09.—EFFECT OF INDUCTANCE ON MOORE'S TUBE SYSTEM. (WEDDING.)

Tapping of Choker.	E_1.	I_{c1}.	P_1.	cos ϕ_1.	E_2.	I_{c2}.	P_2.	η.	i.
1	200·0	22·8	3220	0·706	14,150	0·261	2665	0·828	0·504
2	200·5	23·6	3152	0·677	12,295	0·278	2645	0·845	0·455
3	200·1	23·0	3068	0·666	11,325	0·277	2560	0·840	0·421
4	200·5	22·9	2902	0·632	10,360	0·277	2080	0·718	0·424
5	200·7	22·8	2592	0·567	9,020	0·279	2190	0·844	0·277
2	220·3	23·0	3400	0·670	13,800	0·274	3045	0·897	0·596
3	220·1	23·0	3272	0·645	12,780	0·273	2880	0·882	0·515
4	219·5	23·0	3176	0·628	11,900	0·272	2780	0·878	0·520
5	220·1	23·0	3024	0·598	10,840	0·278	2640	0·874	0·420

current and E.M.F. are very irregular, whereas, with an increase in the number of turns on the choker, the light decreases, due to a decrease in the secondary P.D. and power.

Again, when the number of turns in the choker is small, the light flickers considerably, and when the choker was short-circuited, the light was too irregular for testing; moreover, the valve commenced to pump and the equilibrium of the tube was destroyed. The choking effect should be such that the light is steady and the decrease in the intensity a minimum. The energy absorbed by the choker is represented in Table 6.10. For normal working, when tapping 3 was employed, the loss was 140 watts, or about 4 per cent. of the input.

TABLE 6.10.—POWER LOST IN THE CHOKER. (WEDDING.)

Frequency.	Current.	Tappings.	Volts.	Power.
50·5	22·9	1	39·5	77
50·5	23·1	2	86·8	120
50·5	23·1	3	111·0	140
50·	23·0	4	128·7	156
49·75	23·0	5	147·5	167·5

6.25. POTENTIAL AND CURRENT CURVES.—The behaviour of Moore's tube system is best studied by means of oscillograms. The con-

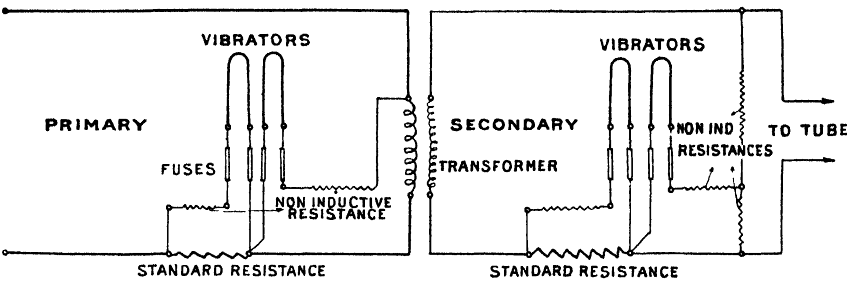
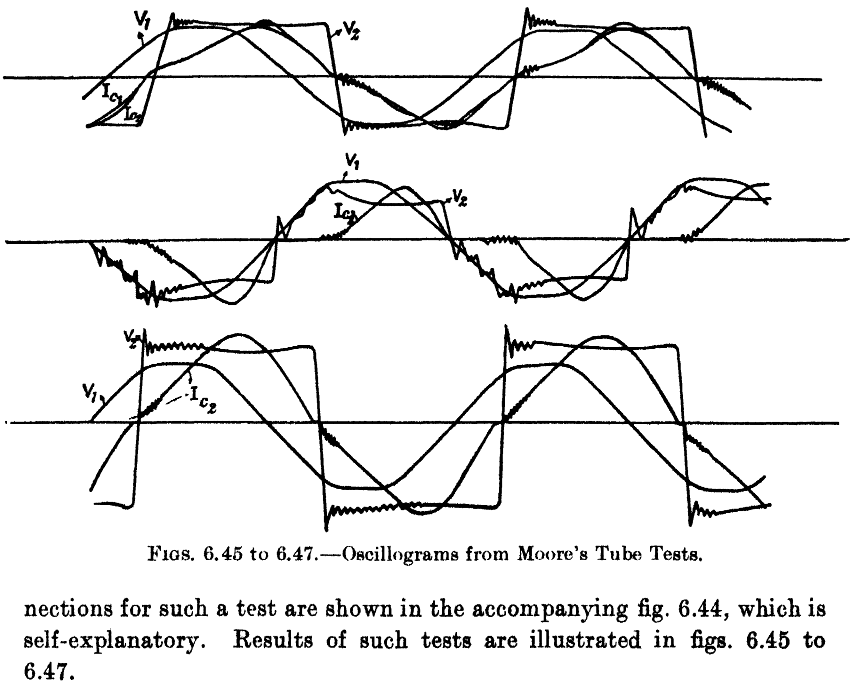


FIG. 6.44.—Connections for Moore's Tube Test.



FIGS. 6.45 to 6.47.—Oscillograms from Moore's Tube Tests.

nections for such a test are shown in the accompanying fig. 6.44, which is self-explanatory. Results of such tests are illustrated in figs. 6.45 to 6.47.

It will be seen from these figures that secondary P.D. and secondary current are in phase; but, if we look at Table 6.09, we find that there is an apparent phase displacement i.e. if we divide the secondary true power by the secondary volt-amperes the ratio is not unity, but lies between 0·7 and 0·8. This is due to the peculiar shape of the secondary P.D. curve. As secondary volts and currents are in phase, it follows that the gas column offers no capacity or inductive effects to the current, but acts as a pure resistance. The figures also illustrate the behaviour of the tube for different inductances in the primary circuit. When the choker is joined to the first tapping, the secondary current takes considerable time before it commences to change its direction (see fig. 6.46), whereas in fig. 6.47, which was plotted with the choker joined to tapping 5, the change of the current takes place almost instantaneously. The experiments show that the gas column itself chooses the most favourable conditions irrespective of the shape of the volt-curve which is impressed upon the transformer. The following table, 6.11, shows in a convenient form the behaviour of the tube for different inductances, as obtained for the various contacts of the choker. The apparent power-factor of the secondary circuit is included therein. The actual phase displacement is of course *nil.*

Moore's tube system with a neon filling is largely used for sign-lighting.

TABLE 6.11.--BEHAVIOUR OF MOORE'S TUBE SYSTEM FOR DIFFERENT INDUCTANCES. (WEDDING.)

Tapping of Choker.	Ratio of Wave-Length to Length of Zero Current (see figs. 6.46 and 6.47).	Cos ϕ_1.	Cos ϕ_2 (Apparent)
1	1 : 3		
2	1 : 6	0·670	0·806
3	1 : 11	0·645	0·826
4	1 : 14	0·628	0·859
5	1 : 18	0·598	0·876

6.26. RECORDING THE FLUCTUATIONS IN THE CANDLE-POWER OF LAMPS.—The testing of the fluctuations in the candle-power of a lamp when carried out in the laboratory is extremely laborious. The work may, however, be considerably reduced by the application of a selenium cell placed in a suitable position where the light of the lamp can easily fall upon it. The cell is joined in series with a recording milliameter of the permanent magnet-moving coil type, and also with a secondary battery of constant voltage. As we have seen in Chapter V., the selenium cell is not suitable for absolute measurements, but by making the cell extremely thin it is possible to reduce its inertia almost to vanishing point, and for relative measurements it is then quite suitable. According to the increase or decrease in the illumination, the resistance of the selenium cell decreases or increases correspondingly, and hence the current varies approximately as the illumination. Actual tests carried out in this manner have shown that the slightest variations in the intensities of illuminants are indicated by the recording instrument, so that the method is to be recommended where on a somewhat irregular supply P.D. a steady illumination is required, and where it is necessary to study the steadiness of light as given by different illuminants.*

In place of a selenium cell, an alkali cell as illustrated in fig. 5.48,

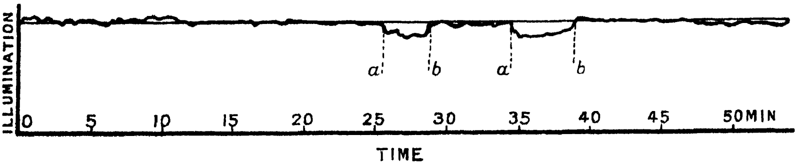


FIG. 6.48. - Candle-Power Variation of an Incandescent Lamp.

paragraph 5.31, may be employed. The method is especially suitable for recording the quality of the feeding mechanism of arc lamps. The light from the galvanometer mirror falls through a slit upon photo-sensitive paper fixed on a revolving drum. If the intensity of the lamp is constant the beam of light--with the arm *a* (fig. 5.47) in a fixed position- will describe a straight line.

Also the thermopile may be employed for this class of work as long as the necessary precautions are taken, and Voege obtained very satisfactory curves in this manner. The candle-power variation of a glow lamp is

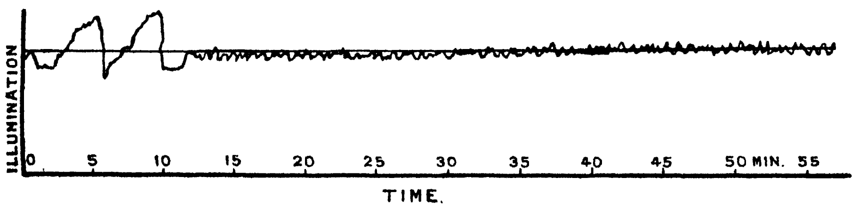


FIG. 6.49. - Candle-Power Variation of an Arc Lamp.

shown in fig. 6.48. At *a* additional loads were switched in, off at *b*. The figure gives also a good idea of the pressure regulation of the system.

Fig. 6.49 illustrates the candle-power variation of an arc lamp on a constant supply pressure (battery). At the beginning the lamp regulated, or rather pumped, twice.

Arm *a* is conveniently placed in a position in which it registers the maximum candle-power, which for street-lighting arc lamps is at an angle of about 10 degrees below the horizontal.

6.27. COLOUR OF LAMPS.—The methods for determining the colours of illuminants have been indicated in paragraphs 5.12 and 5.17. As for illuminating engineers relative values are of greatest importance, the system of using coloured glasses is the more convenient. The

* See E. Presser, *Elektrotechnische Zeitschrift*, 1910, p. 187 ; *ibid.*, 1908, p. 49.

results of such tests are shown in fig. 6.50. The standard colour is given by the light of a covered sky.

Of all artificial illuminants without special coloured glasses, the Moore light with a CO_2 filling approaches daylight most. Then follows the light

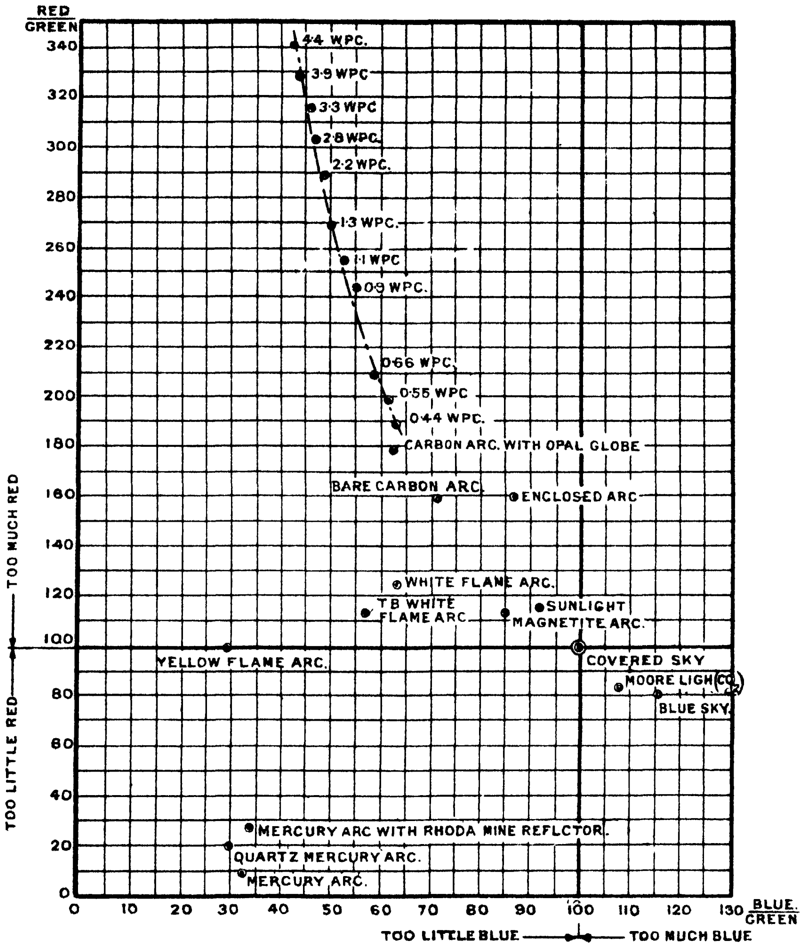


FIG. 6.50.—Colour of Lamps.

of the magnetite arc lamp. All incandescent lamps contain too much red and too little blue light, but the curve shown indicates the improvements which have taken place in the manufacture of these lamps, independently of the increase in the efficiency. The mercury arcs contain practically no red rays, and they are also deficient in blue light. Even the addition of a rhodamine reflector does not make a material difference.

6.28. TESTING OF ILLUMINATION.—The question of good lighting is an economic one, as there is a definite relationship between satisfactory illumination, and production and contentment of the employees. Illumination tests carried out also provide data for use in planning future installations, and they are useful for comparing the effectiveness of different systems of lighting. They further show us whether a specification has been fulfilled; and if the tests are repeated from time to time they will show how far a system has deteriorated with age.

The illumination not only decreases on account of the diminishing of the intensity of incandescent lamps with age, a depreciation which is inherent and beyond control, but also on account of collection of dust and dirt, which may be termed acquired depreciation and which can be reduced to a minimum by periodic cleaning.

In a machine shop great care is taken that all machinery is thoroughly cleaned at least once a week, in order to reduce depreciation to a minimum, but it is only recently that care has been bestowed on the lighting of the shop and that the lamps are periodically cleaned. Yet this is just as important for increased production as properly running machinery.

The illumination of large rooms, streets, and squares is best determined by dividing them into small squares and measuring the illumination of the centre of each. The test plane is usually placed about 3 feet or 1 metre above the floor or ground, unless the working plane is specified, and the illumination is measured in a horizontal plane which receives light from all directions. The system of dividing a large area into small squares may seem laborious, but if the lamps are equally spaced and fixed at equal heights above the testing plane, the number of squares considered may not be so large. The division of streets into squares is shown in fig. 8.10.

A proper test should include the following data :—

(1) The place, purpose, and date of the test.

(2) The number, type, and condition of the lighting units.

(3) The area to be illuminated.

(4) The spacing and height of the units.

(5) The colour of walls and ceiling.

(6) The nature of the work.

(7) The average, minimum, and maximum illuminations.

(8) The power consumed and the efficiency.

(9) The position of the testing plane.

(10) The type of building construction.

(11) Any other information which may modify the results.

In carrying out such tests and plotting the results we obtain contour lines or isolux charts such as are shown in figures 4.16 and 4.17. From these it can be determined whether the illumination is correct from the physical standpoint. This is certainly the primary condition which has to be fulfilled. Physiological considerations are of equal importance, and æsthetic considerations are further factors in good lighting.

In fig. 6.51 an example is given showing the method in which an illumination test may be carried out. The figure is self-explanatory.*

For further information the reader is referred to a paper by Messrs Rayner, Walsh, and Buckley, dealing with "The Lighting of Public Buildings," in the *Illuminating Engineer*, April 1922, p. 107.

6.29. THE MEASUREMENT OF COEFFICIENTS OF DIFFUSE REFLECTION.—F. A. Benford † uses for this purpose an integrating sphere. For a sphere the brightness of the interior depends upon the quantity of light entering it, the coefficient of reflection of its inner surface, and the solid angle of the spherical surface, if part of a sphere is employed. By varying the areas of these parts the other two factors are eliminated. Consequently, the method consists in using a sphere with removable sectors of known solid angles, the inner surface of which is coated with the material to be tested. The brightness of this surface is compared with that of, say, the diffusing glass plate in a brightness photometer. A beam of light is directed into the sphere, but must not fall directly on the surfaces under test. The two coated sectors of area S_1 and S_2 are introduced in turn, and the respective brightnesses E_1 and E_2 are observed. Then, if S is the total internal area of the sphere, the coefficient of reflection, m, is given by

$$m = S(E_1 - E_2)/E_1S_1 - E_2S_2.$$

For the sake of accuracy make S_1 large in comparison with S; S_2 about $\frac{1}{2}$ to $\frac{3}{4}$ of S_1; and avoid stray light. The method is suitable for reflection coefficients higher than 0·50.

In Chapter IV., paragraph 4.02, we found that the candle-power polar curve of a plane radiator was a circle following the law $I = I_n \cos\theta$. This holds also for uniformly illuminated white matt surfaces. Consider such a surface and assume that the light falls perpendicularly upon it, and that it is viewed under the same angle, then the brightness is a maximum. If the lamp causing the illumination is kept at the same distance from the surface but rotated around it, the brightness measured in the original direction follows the cosine law and the brightness curve is a circle. On the other hand, if the light is always thrown perpendicularly upon the test surface, but the latter is viewed under different angles, the brightness remains constant and the polar curve is a semicircle. For surfaces which are not perfectly matt the resultant curves will differ, as is indicated for a horizontal surface in fig. 6.52, where curve A holds for perfect diffusion, curve B for matt paper, C for semi-glossy paper, D for glossy paper. L indicates the direction of the incident light. Curves plotted in this way give us some indication about diffuse reflection. We compare the polar curve of one surface with that of another, and treat the polar curves of both in the same manner as is required for mean

* S. L. E. Rose and H. E. Mahan, *General Electric Review*, May 1913, p. 333.

† *General Electric Review*, January 1920.

hemispherical candle-power. The more a polar curve approaches a circle, the greater is the diffusive quality of the surface under test. A diagrammatic sketch of a suitable apparatus is given in fig. 6.53. S_1 is a

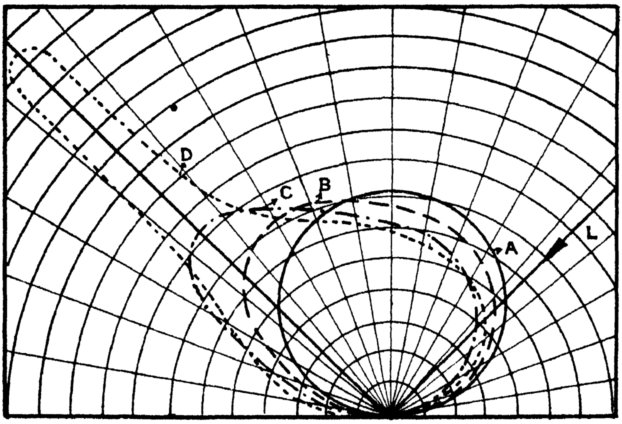


FIG. 6.52.—Diffuse Reflection Curves.

standard screen illuminated by lamp L_1 at various distances, S_2 the test screen illuminated by lamp L_2. The angles of incidence, θ, and of emission, δ, may be read on suitable scales.*

6.30. THE MEASUREMENT OF DIFFUSE TRANSMISSION.†—The

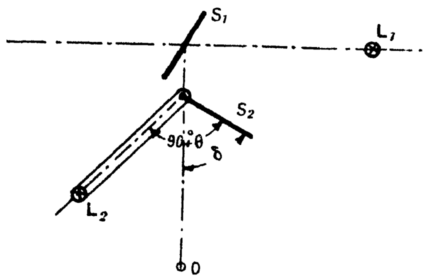


FIG. 6.53.—Apparatus for Determining Diffuse Reflection.

apparatus is shown in fig. 6.54. A light source E is placed in a black box equipped with diaphragms h_1, h_2, and h_3, and an opal glass I in the opening close to the lamp. The specimen glass G is put before the opening R. The entire box is rotatable about an axis under the specimen, but the latter can also be revolved independently. The angle of displacement is read on a scale S. For testing purposes comparison is made use of by means of a ground opal glass T illuminated by lamp C. Both

* See also Trotter, *Illuminating Engineer*, September 1919. For further methods for determining reflection factors the reader is referred to a paper by A. H. Taylor, *Illuminating Engineer*, October–December, 1920, p. 265.

† M. Luckiesh, *Electrical World*, 1912, p. 1040; 1913, p. 883.

plates, T and G, are viewed by means of a double reflecting prism P, lens L, and eye-piece D. Adjustment is improved by a rotating aperture

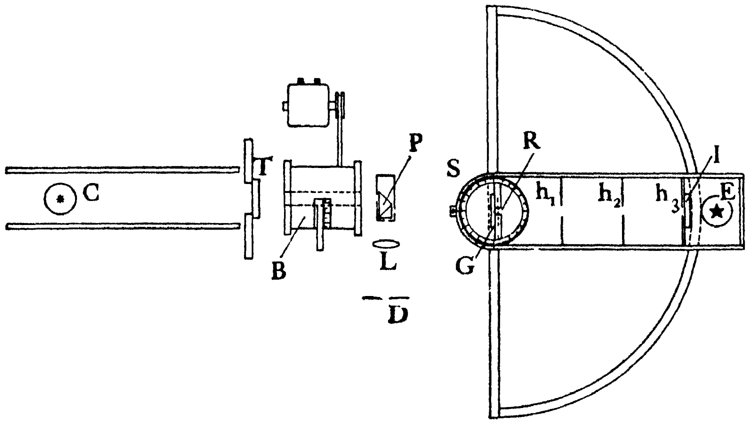


FIG. 6.54. Apparatus for Testing Diffuse Transmission.

disc B. In fig. 6.55 are given brightness distribution curves for various substances, the results being further explained in Table 6.12. The

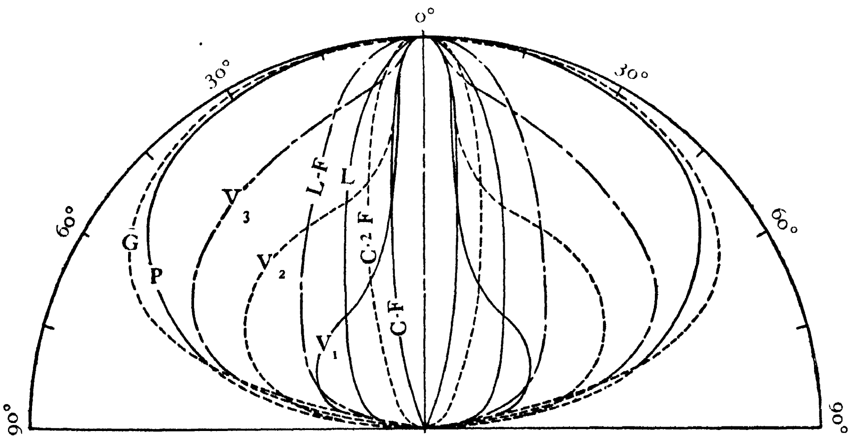


FIG. 6.55.— Brightness Distribution Curves.

transmission coefficients are found by integrating the light flux over an entire hemisphere. A perfectly diffusely transmitting (and non-absorbing) flat specimen has a transmission coefficient of 0·5 owing to the fact that one-half of the incident light will be diffusely emitted backward. Diffusing glass spheres, as ordinarily used in lighting, transmit from 75 to 90 per cent. of the total light emitted by the enclosed light-source.

[TABLE.

TABLE 6.12.—DIFFUSE TRANSMISSION COEFFICIENTS.

Designation.	Description of Glass.	Relative Normal Brightness for Constant Illumination of Specimen.	Transmission Coefficient of Flat Specimen. (Percentage.)
Perfect diffusion	Ideal diffuser	1 00	50
C-F	Crystal, one side frosted	18·3	..
C-2 F	,, two sides ,,	3 9	..
L	Lucida, $\frac{1}{8}$ in. thick	2 8	67
L-F	Same, frosted on one side	1·71	59
V_1	Veluria, $\frac{1}{8}$ in. thick	1·65	40
V_2	,, $\frac{3}{16}$,, ,,	0 79	33
V_3	,, $\frac{1}{8}$,, ,, rough inside	0 66	35
P	Dense pyro, $\frac{1}{16}$ in. thick	0·41	26
G	Welsbach shade, 503, $\frac{1}{16}$ in. thick	0 74	50
	Flashed opal	0 31	19-50
	Piece of frosted electric lamp bulb	10 6	36

6.31. PHOTOMETRIC TESTS OF PROJECTORS.—The determination of the intrinsic brilliancy of such apparatus has been described in paragraph 6.12, and that of the total flux of light in a sphere (or cube) in paragraph 6.07, so that here we are concerned with the determination of the beam candle-power. For this purpose we require a portable photometer with the necessary controlling instruments, screens, and a focussing surface consisting of a wooden partition painted white with a small hole for the tube of the photometer to pass through. Two methods may be used to obtain the distribution of candle-power across the beam. First, the projector may be kept stationary and the photometer moved across the beam from one side to another. Second, the photometer may remain stationary and the projector turned on a vertical axis through the light source until the beam has traversed the photometer test plate.

This test may be carried out indoors if a distance of 50 to 100 feet can be obtained for it. Between the projector and photometer are placed screens with holes to allow the portions of the beam under test to pass to the photometer plate and to guard against stray light. The scale for indicating the angles through which the projector is turned should be closely graduated for tests near the middle of the beam (one-quarter degree from 0 to 20 degrees) and every 5 degrees from 20 to 90 degrees.*

* See also *General Electric Review*, September 1917, p. 743.

CHAPTER VII.

SHADES, GLOBES, AND REFLECTORS.

7.01. THE OBJECT OF SHADES, GLOBES, AND REFLECTORS.—When lamps are employed for local lighting for instance, incandescent lamps for the lighting of a table the polar distribution must usually be modified in order that the maximum possible flux is made available in the region where the light is wanted. A vacuum glow lamp hanging vertically downwards gives its maximum candle-power in a horizontal direction, where the light is not required, hence a shade or reflector should be used to direct the light downwards. On the other hand, flame arc lamps with inclined carbons for street lighting should give a maximum intensity about 10 degrees below the horizontal, whereas without reflectors they produce this intensity vertically downwards. By means of a reflector underneath the lamp the distribution may be altered as desired.

Besides redirecting otherwise useless light, a shade should screen the source of light from the eye and prevent glare. It should be instrumental in softening and toning down shadows and should give a decorative effect.

It must, of course, be understood clearly that, although the illumination of a given working plane may be considerably improved by the use of a shade or reflector, the total light is always reduced, since even the whitest reflecting surface and the clearest glass absorb light.

A great deal of the effect produced depends, of course, upon the surroundings, which largely influence the type of shade most suitable. A well-diffusing globe in front of a black background might cause glare, whereas in front of a white surface glare would be completely absent. This is well illustrated in fig. 7.01.*

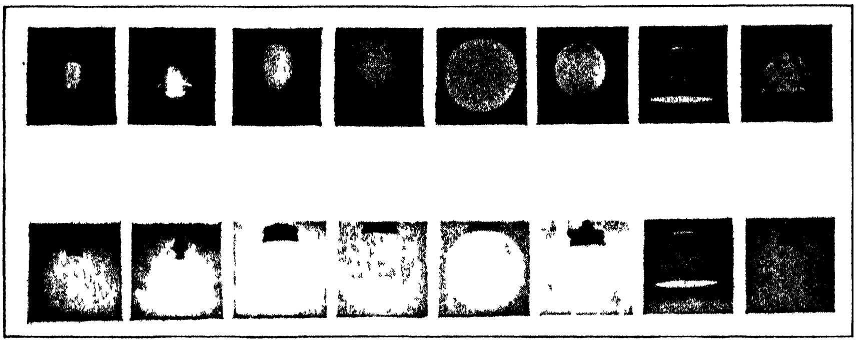
On the whole we employ three systems of lighting: direct, indirect, and semi-indirect. In the direct system the light is usually distributed downwards; in the indirect system the light is reflected upwards against the ceiling or a screen and then directed downwards into the room. This causes excellent diffusion of light, but the losses by absorption are increased. In the semi-indirect system the greater part of light is reflected against the ceiling or screen, but a smaller part is transmitted

* J. G. Clarke and V. H. Mackinney, *Illuminating Engineer*, March 1913, p. 125.

through the bowl directly into the room. This system is increasingly favoured, as the luminous bowl is very ornamental.

7.02. GENERAL PRINCIPLES.*—**Regular Reflection.**—For accurate re-direction of light regular reflection is essential. It may be obtained

Close against black background.



Close against white background.

Illustrating apparent brightness of shade and modification of "glare" effect with change of background.

Fig. 7.01. Modification of Glare Effect with Change of Background

with polished metal or mirrored glass reflectors, the principles of which are illustrated in fig. 7.02, A and B respectively.

In A the loss of light for polished silver will be about 12 per cent., for polished aluminium 38 per cent. In B part of the ray is directly reflected, the other part travels through the glass to the silvered backing,

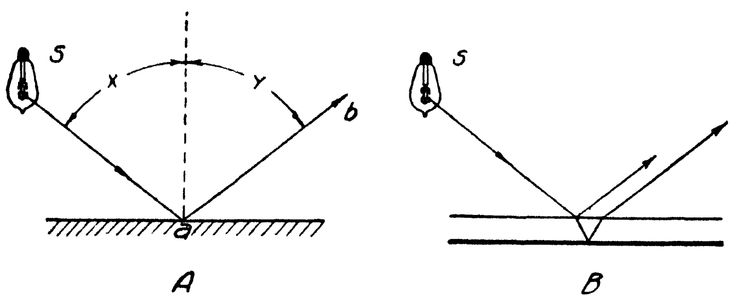


Fig. 7.02.—Regular Reflection from Polished Metal and Mirrored Glass.

from which it is reflected through the glass again and out along a line parallel to the ray reflected directly by the glass surface. Naturally, such a reflector will be less efficient than a polished metal one, as the absorption by the glass has to be added. On the whole the intensity of the reflected ray is about 75 per cent. of the incident light, the actual figure depending upon the kind of glass employed. On the other hand, such a reflector does not deteriorate as rapidly as a polished metal one,

* See also Ward Harrison, *General Electric Review*, July 1918, p. 484.

and it is more easily cleaned. It is therefore often given preference over others.

With regular reflection the redistribution of light can be easily determined. The contour of the reflector has to be such that it makes equal angles with the incident and reflected rays at the point considered. If the light rays are to be parallel— as, for instance, for automobile head-lights—the contour must be a parabola, with a source as nearly a point source as possible in the focus. If we place a point source of light into the centre of a hemispherical reflector, the light is reflected on itself so

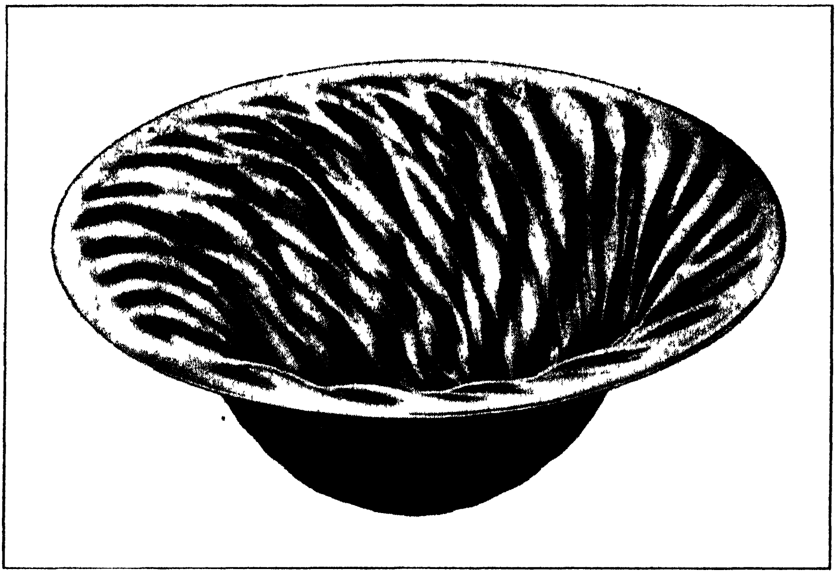


FIG. 7.03.—X-ray Reflector.

that—neglecting absorption—the intensity in the lower hemisphere is doubled.

Mirrored reflectors have the disadvantage of producing brilliant images of the light source upon the illuminated area, and thus causing a streaky or striated illumination. The striations often disappear by fluting the reflector or frosting the lamp, but this causes a loss in the control of the light.

In the system of the National X-Ray Reflector Company, the striations are avoided by a combination of spiral and vertical corrugations. Such a reflector is shown in fig. 7.03.

Polished metal and mirrored glass reflectors are chiefly employed for search-lights, indirect lighting, automobile head-lights, flood lighting, and wherever an accurate control of the light rays is essential.

7.03. DIFFUSE REFLECTION.— The reflections from semi-matt and rough matt surfaces are illustrated in fig. 7.04, A and B respectively, which are self-explanatory. A sole example of a semi-matt reflector in use is the aluminiumised-steel reflector. To make its reflecting efficiency high, care must be taken that cross reflection from one side to the other is avoided as much as possible to prevent losses by absorption.

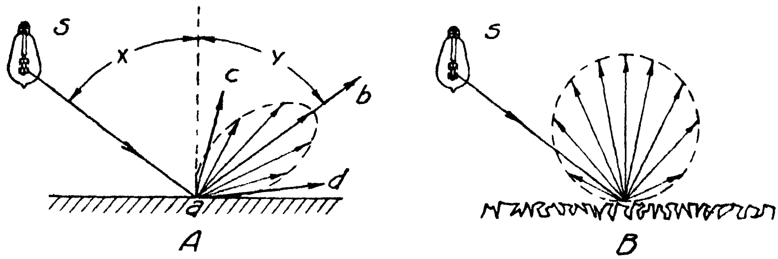


FIG. 7.04. Reflection from Semi-Matt and Rough Matt Surfaces.

With a rough matt surface, such as blotting-paper, the light is reflected in all directions, so that the shape of reflector has little effect on the resulting distribution. For instance, the latter would be the same with a light at S whether the shape of the reflector is *a a a* , or *b b b*, or *c c c* (fig. 7.05).

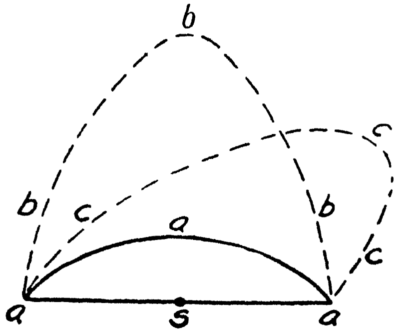


FIG. 7.05.—The Absence of Effect of the Shape of a Reflector with a Rough Matt Surface on Distribution.

The candle-power per unit apparent area is about constant, so that the intensity is a maximum in a direction perpendicular to the surface.

Rough matt surfaces become dirty easily, and are in consequence little used.

7.04. PRISMATIC GLASSWARE.—We have seen in paragraph 2.02 that glass refracts and reflects light. The latter occurs if the angle of incidence is greater than the critical angle. For glass with a refractive index of 1·6 the critical angle is about 39 degrees. These principles have been employed in the design of shades, globes, and reflectors. A. P. Trotter advocated the employment of such units as long ago as 1884, but it was not until about seventeen years ago that the idea developed, largely due to the work of Blondel and Psaroudaki of Paris and the Holophane Company in the United States. The principle of total reflection is shown in fig. 7.06. The angles of the prism are such that a ray which strikes surface *bc* is reflected to *ac* and out as shown. Each prism is thus equivalent to a narrow strip of mirror. By tilting this strip the direction of the ray can be accurately controlled, and by giving it the proper curvature the desired distribution of light can be procured.

Rounding off the tops permits the transmission of a small percentage of the light and thereby improves the appearance of the unit. With proper design striations are prevented.

Holophane glassware is made in two main types, one employing the

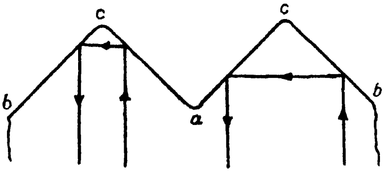


FIG. 7.06.—Principle of Prismatic Reflection.

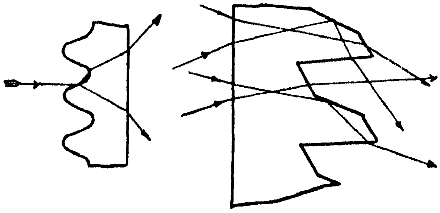


FIG. 7.07. Prisms of Holophane Shades.

principles of refraction and diffusion, and the other the principles of reflection.

Holophane Refractors.—If the light is to be refracted and diffused the globe is provided with internal and external prisms according to fig. 7.07. The internal prisms diffuse the light. Each ray is broken into two or

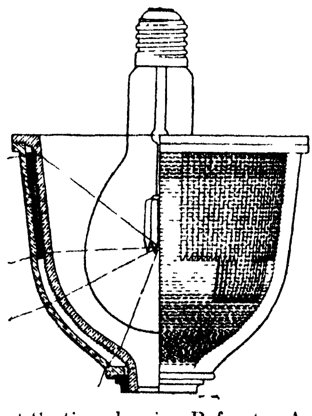


FIG. 7.08.—Part Section showing Refractor Assembly and Action of Horizontal Prisms.

more rays, and as the eye in following up the ray is unable to see the source of light, the whole globe appears more or less illuminated. This is excellently illustrated in fig. 7.08, which shows the action of the prisms of the Holophane Refractor as used for street lighting.

The external prisms of refracting globes generally have four faces, of which one or more pass the light after simple refraction, while others reflect it completely. The reflected ray is then refracted by another surface. In designing such reflectors, care must be taken that the light is not reflected back into the shade, as this would mean a loss of light.

Other Holophane diffusing globes, used for interior lighting, are illustrated in figs. 7.09 and 7.10.

Holophane Reflectors.—If the shade is to act as a reflector for directing the light in the downward direction, the prisms must be arranged accordingly. Reflectors of this type are smooth inside. The outside is formed

FIG. 7.09.—Holophane Globe.

FIG. 7.10.—Holophane Globe.

of rectangular, totally reflecting, vertical prisms, on which the light falls at angles which are greater than the critical angle. The prisms act in a manner that the light is reflected downward, and, depending upon the contour of the reflector, various types of light distribution is obtained, from extremely concentrated to extensive. Owing to the relative size of the lamp filament, and also due to the apices and valleys of the vertical

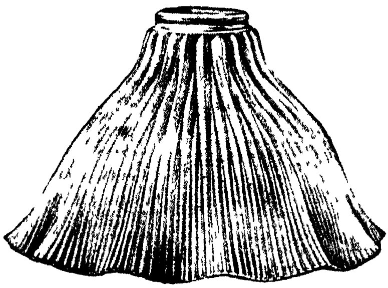


FIG. 7.11.—Holophane Focussing Reflector.

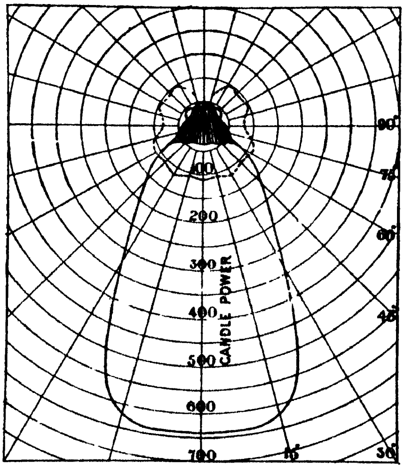
prisms, sufficient light is transmitted through the reflectors for general upward illumination, thus avoiding sharp contrasts.

A Holophane reflector of this type is shown in fig. 7.11, and its polar curve when used in connection with a 100-watt gas-filled lamp in fig. 7.12. It will be seen from the latter that the intensity in a downward direction has increased from 110 to 640 candles.

Although the area of the new polar curve is much larger than that of the original curve, it must not be assumed that the flux is now greater. As a matter of fact the flux is a little smaller than that of the naked lamp on account of some absorption of light by the reflector. This can easily be tested by finding the mean spherical candle-power for each curve.

Other types of reflectors are shown in figs. 7.13 and 7.14.

The polar distribution curves for the extensive type reflector (fig. 7.13) is shown in fig. 7.15, and the intensive type (fig 7.14) is shown in fig. 7.16.



Photometric Curve
.... Lamp alone. —Lamp with Reflector.

FIG. 7.12.—Focussing Type.

The reflectors shown so far are symmetrical, *i.e.* they show the same kind of prisms all round. For street-lighting purposes we may conveniently combine refracting and diffusing prisms, also the refracting prisms may be so designed as to concentrate the major part of the light

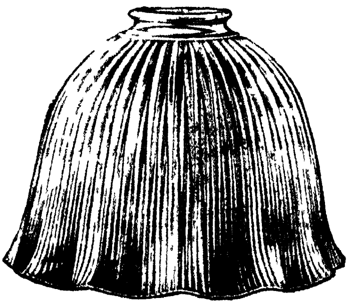


FIG. 7.13.—Holophane Extensive Reflectors.

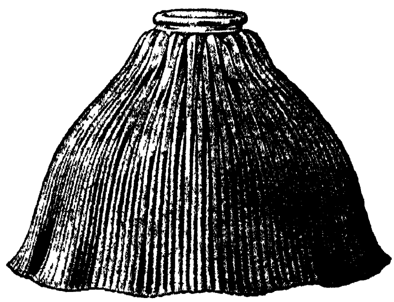
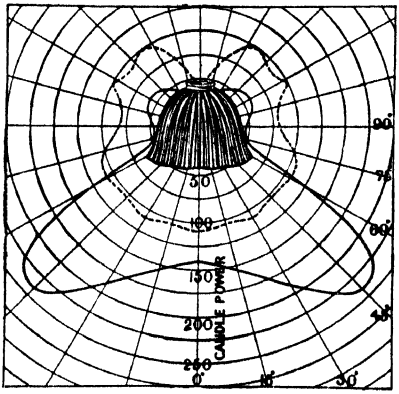


FIG. 7.14.—Holophane Intensive Reflectors.

rays so that a much greater intensity is given longitudinally with relation to the street. Such a type of Holophane street refractor is illustrated in fig. 7.17.

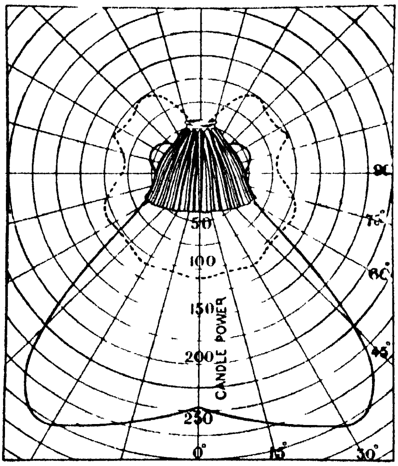
The Holophane refractor consists of two members, one of which fits smugly within the other and is then clamped together so as to form a single unit. The inside surface of the inner piece and the outside surface of the outer piece are smooth. The outside surface of the inner piece is designed with horizontal refracting prisms to bend downward the top light and to bend upward the excess of downward light, thus increasing the light given at angles from 60 to 85 degrees with the vertical.

The inside surface of the outer piece is arranged with a series of



Photometric Curve.
.. .. Lamp alone. — Lamp with Reflector.

FIG. 7.15.— Extensive Type.



Photometric Curve.
.. .. Lamp alone. — Lamp with Reflector.

FIG. 7.16.—Intensive Type.

vertical refracting and diffusing prisms, which concentrate the symmetrical lateral beam into two or four main beams.

FIG. 7.17.— Holophane 2-Way Street Refractors.

A complete series of Holophane street refractors are made, which consists of the following :—

(*a*) Symmetrical, for wide areas.

(*b*) Two-way non-axial (160 degrees), for streets between crossings and installed at side of road.

(*c*) Two-way axial (180 degrees), for streets between crossings and installed in centre of road.

(*d*) Four-way, for four-way street crossings.

The distribution of the light from the 2-way axial type refractor is given by figs. 7.18 and 7.19. The first figure represents the polar distribution in a vertical plane. The second figure shows the plan view distribution through an 80-degree cone. We see that the intensity of light is increased in the two directions approximately twelve times that of the rated candle-power of the bare lamp.

For the painting or coating of ships at night, and work of a similar

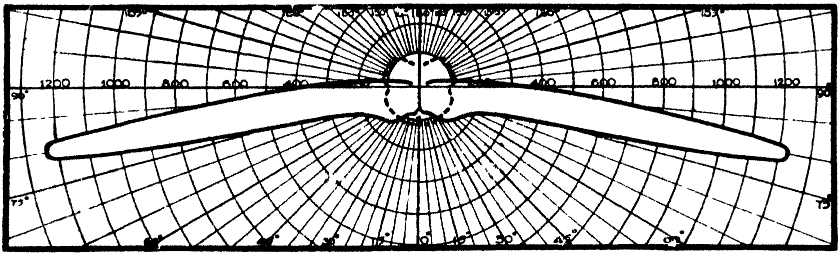


FIG. 7.18. Vertical Candle-Power Distribution Curve. Lobes 180 apart Horizontally.

nature, half-watt lamps with reflectors having "face and back" are largely employed to-day.

Another street-lighting fitting with prismatic band refractor is shown in fig. 7.20, which is so designed that the maximum intensity is in a direction, 10 degrees below the horizontal. The unit is thus suitable

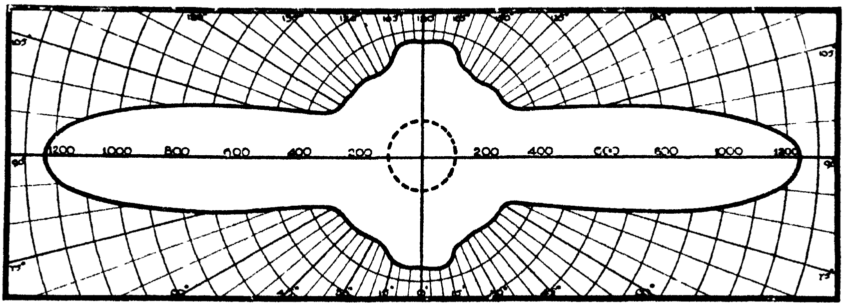


FIG. 7.19.—Plan Candle-Power Distribution Curve. Through an 80° Cone.

for lamps of high candle-power and wide spacing, and yet producing a fairly uniform illumination. A metal reflector prevents light from passing uselessly into the upper hemisphere.

For many industrial local lighting purposes it is advisable—in order to avoid glare—that not only the filament of the lamp but also the prismatic unit is completely screened from the eyes of the operator. The reflectors should therefore be sufficiently deep and be surrounded with a polished metal cover. If the general lighting is adequate, this does not produce disturbing contrasts. Both inside and outside surfaces of the complete unit are then smooth and easily cleaned, the prismatic unit is protected, and the polished metal surface increases the downward

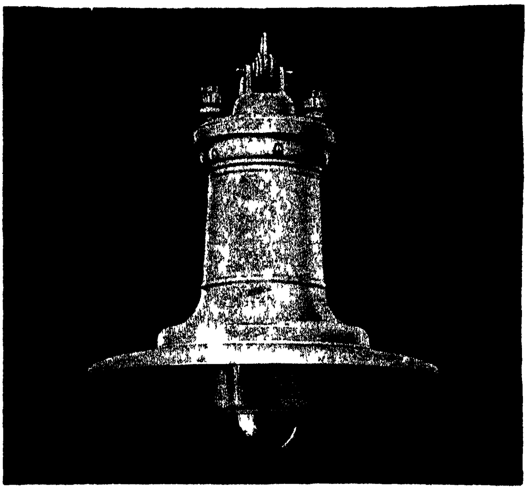


FIG 7 20 —Street lighting Reflector with Band Refractor (G E C)

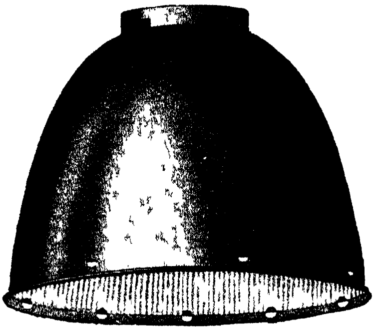


FIG 7 21 —Extensive Type

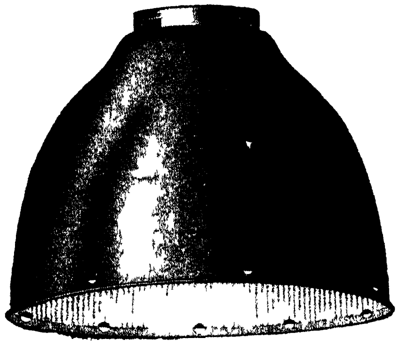
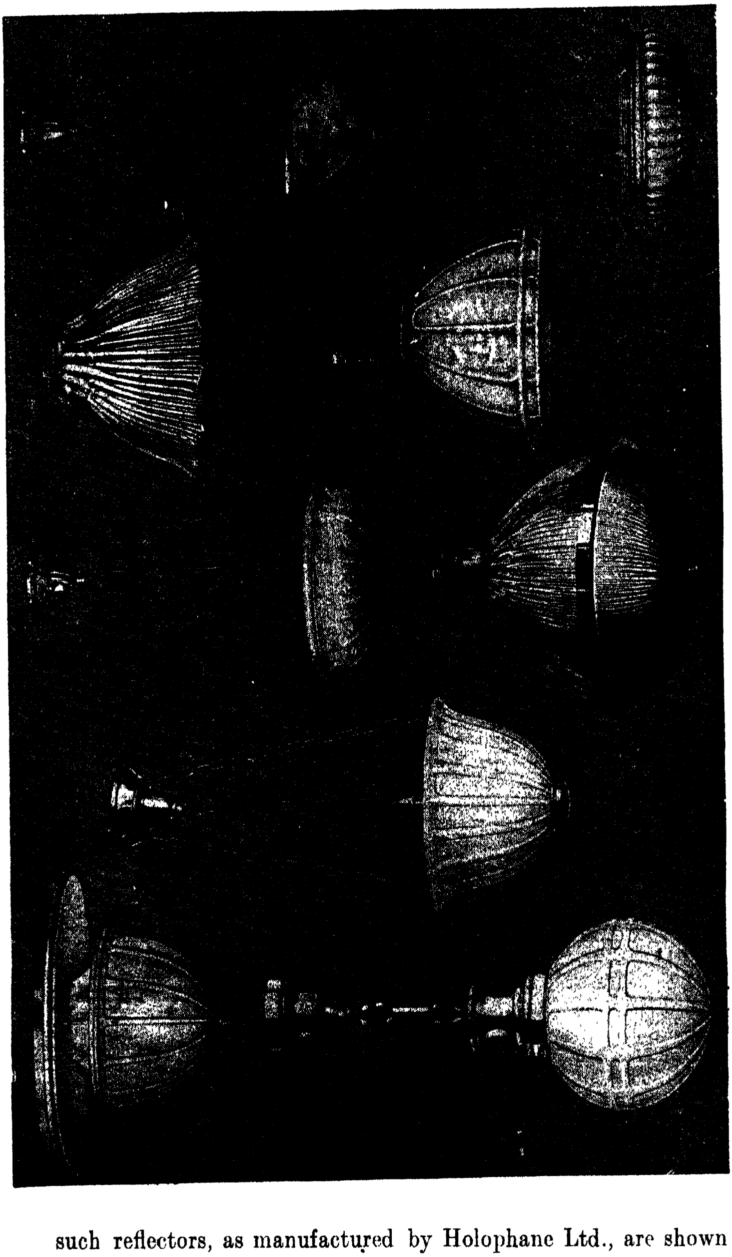


FIG 7 22 —Intensive Type

FIG 7 23 —Focussing Type

concentration of the light. Extensive, intensive, and focussing types of



Types of Store Lighting Units.

1. Semi-Enclosing Unit.
2. Opal Enclosing Unit.
3. Opal Semi-Indirect Units.
4. Prismatic Enclosing Unit.
5. Prismatic Open Reflector.
6. Opal Open Reflector.
7. Prismatic Semi-Indirect Unit.
8. Mirrored Glass Indirect Unit.

Fig. 7.24.—Different Types of Reflectors.

such reflectors, as manufactured by Holophane Ltd., are shown in figs. 7.21, 7.22, and 7.23 respectively.

In place of the metal cover a green opal shade is sometimes slipped over the prismatic reflector, known under the name of "Bank" unit. It is chiefly employed for desk illumination.

For billiard tables the metal or opal cover is often replaced by green cardboard.

For the production of a fairly uniform illumination of halls, churches, and large dwelling-rooms, Holophane reflector bowls are frequently employed. They consist of two parts, of which the upper one is reflecting, the lower one diffusing. They are usually made in three types, viz. in plain, stiletto, and crystal executions.

A reflector bowl giving a highly decorating effect is shown in illustration 1 of fig. 7.24.

If the walls and ceiling are to be fairly well illuminated, the upper half is also made diffusing and the bowl is given the shape of a sphere.

For pendants and electroliers the satin-finished Holophane shade gives a beautiful appearance, and is to be recommended.

Prismatic globes are now frequently used for arc lamps, as their

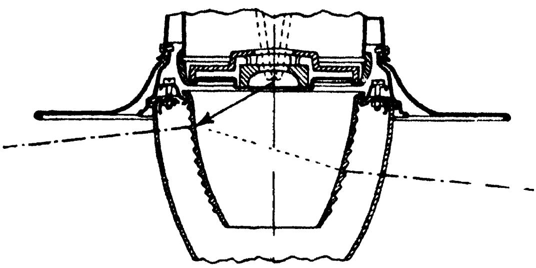


FIG. 7 25.—Refraction of Light from a Flame Arc Lamp by a Prismatic Globe.

efficiency is higher than that of opal or frosted globes. For street lighting the prisms are so constructed that the light is mainly directed into a region lying between 10 and 30 degrees below the horizontal. Such a system is illustrated in fig. 7.25. The diffusion from the prismatic globe is sufficient to allow of the use of an external clear-glass globe.

To prevent the gases produced by the arc from frosting the globe, since they contain fluoric acid, the ventilation of the lamp must be very efficient. The difference between badly and well-ventilated globes is shown in figs. 7.26 and 7.27. The extent to which the degree of uniformity of the illumination is improved by the prism glass is shown well by comparing the accompanying figs. 7.28 and 7.29 which are self-explanatory.

For luminous arcs, such as the magnetite lamp, it is even better in order to make cleaning easier to construct the prismatic refractor of two pieces of truncated conical glass, one fitting inside the other, and both forming a single unit which is smooth on both inside and outside surfaces. Excellent ventilation for these lamps is even more essential than for flame arcs.

For fittings carrying gas-filled lamps adequate ventilation must be provided, as these lamps produce considerable heat. For totally enclosed show cases, etc., such lamps are inadvisable, and even for shop windows they may cause higher insurance rates.

Hrabowski's total reflector for arc lamps with inclined carbons is

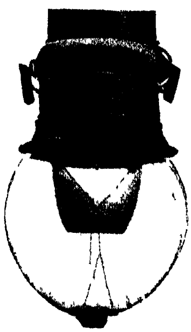


FIG. 7.26.—A Badly Ventilated Globe for Arc Lamps.

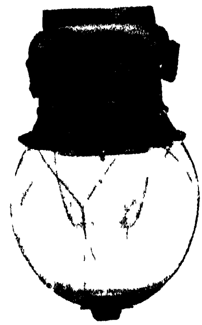


FIG. 7.27.—A Well Ventilated Globe for Arc Lamps.

shown in fig. 7.30.* It consists of two parts, a large diffusing shade of enamelled sheet iron and a ring-shaped reflector of prism glass. The latter possesses three accurately ground spherical surfaces, of which two

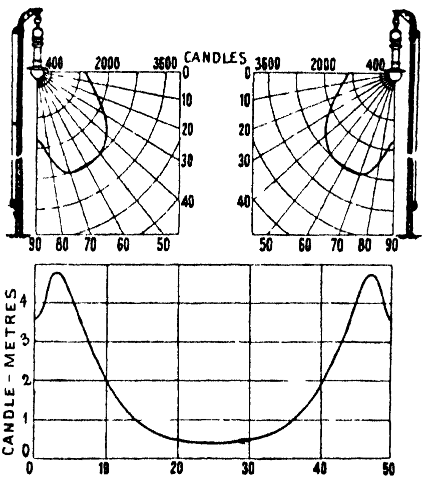


FIG. 7.28.—Illumination by Flame Arc Lamps without Prismatic Globes.

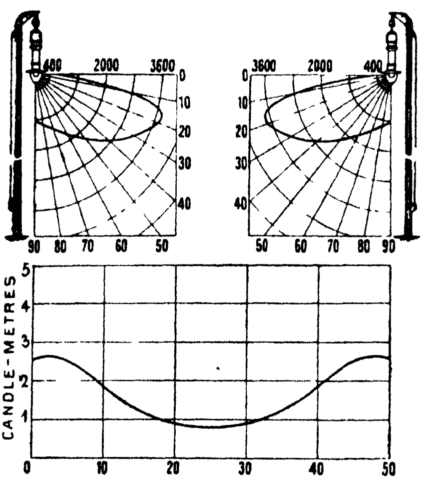


FIG. 7.29.—Illumination by Flame Arc Lamps with Prismatic Globes.

are totally reflecting. Between 0 and 45 degrees the light is allowed to pass through the clear glass globe directly. Light under these angles does not cause glare to the eye in its ordinary position, unless it is fixed very low down. The metal shade acts diffusingly, while the crystal reflector distributes the light by total reflection practically uniformly without

* Made by Siemens-Schuckert Werke, Berlin; see also *E.T.Z.*, 1910, pp. 11–13.

much loss over the whole area to be illuminated. The action of these prisms is clearly indicated in the figure.

The chief advantage of this type of reflector lies in the small loss of light by absorption, since a clear glass globe may be employed, and the avoidance of glare, as the rays are mainly directed downwards and therefore do not enter the eye. The system is especially suitable for the

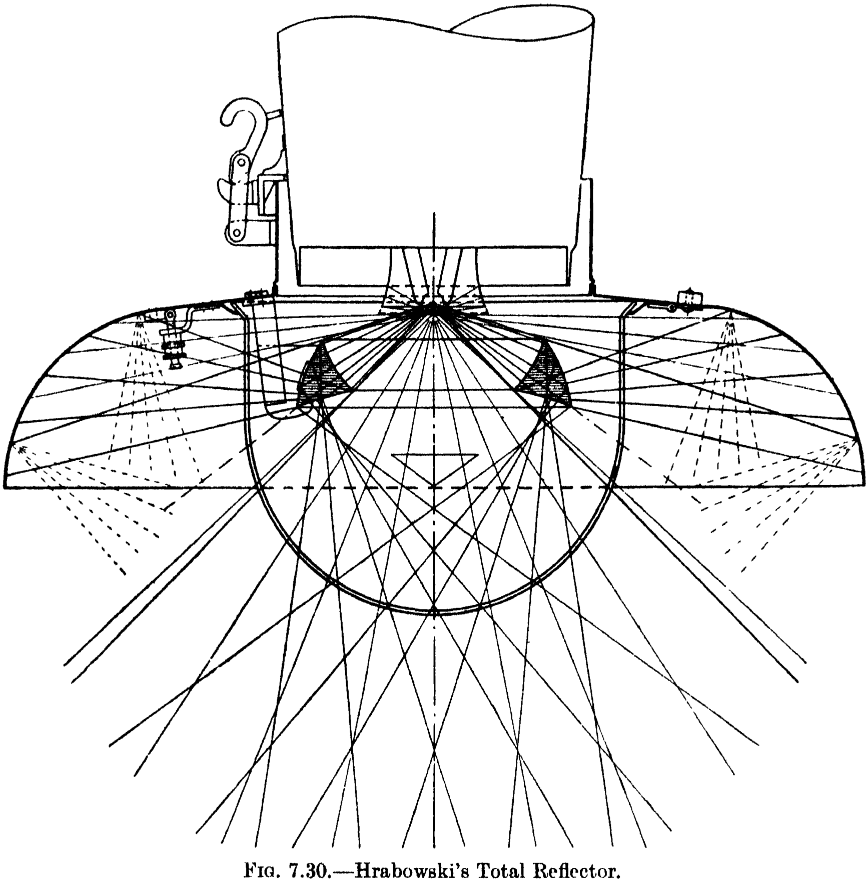


FIG. 7.30.—Hrabowski's Total Reflector.

lighting of high shop windows and for planes of a limited area which require a high illumination.

Flame arcs may also be used with this system, since the glass prisms become sufficiently hot to prevent the gases from depositing on them.

7.05. OPAL GLASSWARE.—Opal glass may be considered to consist of clear glass in which fine white particles are held in suspension. There are usually two types, dense and light opal. A ray of light which strikes such glass is partly reflected, as in the case of a polished metal surface, and partly transmitted. The latter part passes on until it strikes a white particle or air bubble, whence it is dispersed in all directions.

The principle is shown in fig. 7.31. A ray which on its passage does not strike a white particle goes out in a line parallel to the original striking ray. The filament would be faintly visible in the direction of such a ray. In a diffusing opal globe the filament of the illuminant is therefore just visible.

The transmission of opal glass depends on the number of white particles in the clear glass. Glass transmitting about 60 per cent. is classed as very light, while glass allowing only 10 per cent. to pass is called very dense. A totally enclosing globe, although consisting of glass with a transmission of only 60 per cent., may nevertheless have an efficiency of 80 per cent., as in addition to transmitting 60 per cent. of a

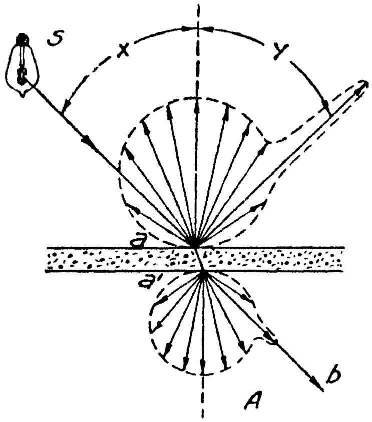


FIG. 7.31.—Reflection and Transmission by Opal Glass.

direct ray from the lamp the same point transmits light coming from other parts of the illuminated globe. A common commercial type has usually a 40 per cent. transmission; of the remaining 60 per cent., 10 per cent. is reflected directly, 10 per cent. absorbed by the glass, and 40 per cent. reflected in all directions.

Dense opal glass need not necessarily be thick, but a thin layer of a dense mixture may be flashed on ordinary glass, this being known as "flashed opal." The absorption by this mixture is less than of ordinary opal glass with the same diffusing quality, so that flashed opal is best suitable for totally enclosed globes.

Opal glass possesses the advantages of a smooth surface and is thus easily cleaned; and as the unit appears luminous it adds to its appearance. For these reasons it is extensively used.

Opal glass is highly suitable for semi-indirect lighting, employed for reducing the brightness of the source so as to make it comparable with the surroundings for which purpose the opal must be sufficiently dense.

Opal glass is headed under various names. Veluria is a light-density opal with a velvet surface. When lighted it shows the true pink opal fire. It is a blown glass and cannot be pressed.

Druid is an opal of heavier density than veluria, with a smooth surface and amber tinge. It may be pressed or blown.

Sudan is a heavy-density opal and reflects a large percentage. It is white and uniform in texture and thus highly suitable for indirect lighting effects. The glass may be blown or pressed, usually the latter.

All these types may be ornamented by blowing or pressing them in moulds with the decorations cut into them, or by etching the surfaces of glass blown to shape in smooth moulds. The moulded decorations stand out in high relief, while the etchings are applied in two ways, relief and engraved. The colours are fired and unfired, the former being permanent.

A number of opal reflectors are illustrated in fig. 7.24.

Where cleaning is apt to be neglected and the ceilings are low, the totally enclosing globe is best of a cone shape, the apex being downwards and the opening placed close to the ceiling. Dust cannot then collect on the globe.

7.06. PORCELAIN-ENAMELLED REFLECTORS. As regards its

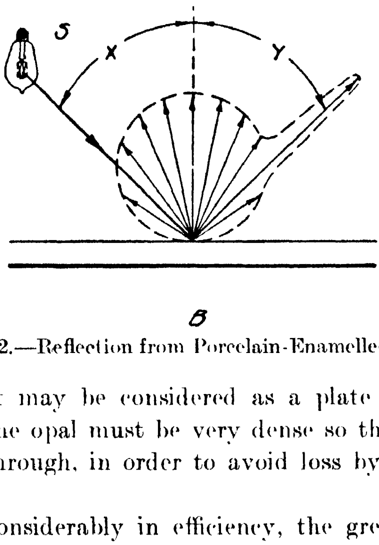


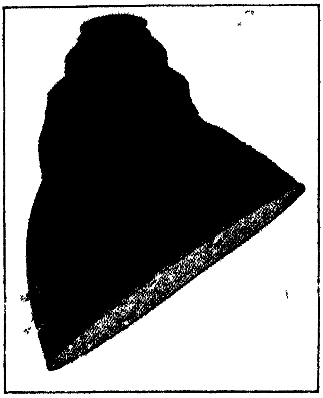
FIG. 7.32.—Reflection from Porcelain-Enamelled Steel.

optical character, it may be considered as a plate of opal glass with a steel backing. The opal must be very dense so that as little light as possible will pass through, in order to avoid loss by absorption on the steel backing.

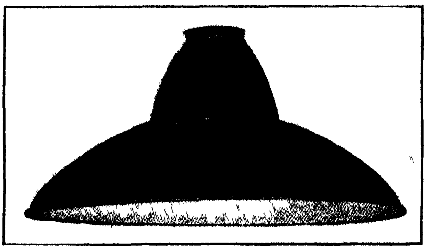
Enamels vary considerably in efficiency, the greyer it appears the greater the absorption.

The characteristic distribution of a porcelain-enamelled surface on steel is shown in fig. 7.32.

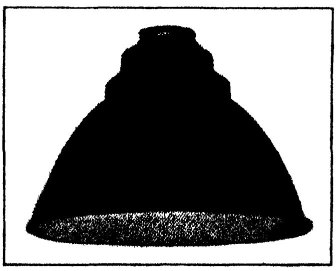
Reflectors of this type are chiefly employed for industrial purposes, where robustness, ruggedness, and permanency of reflecting surface are important. Both the dome and bowl-shaped reflectors are largely used. They are illustrated in fig. 7.33, together with an angle reflector, and the corresponding polar curves for 750- and 1000-watt gas-filled lamps in fig. 7.34. If this same reflector is finished in aluminium, as explained in paragraph 7.03, the polar curve is completely altered, it becoming of a focussing nature. The shadows are the softer and the annoyance from glaring reflections are the less, the larger the diameter of the source, other things being equal. To make sure of avoiding reflections in polished surfaces a polished metal cap is placed over the tip of the lamp. The lower edge



Angle (Asymmetrical)

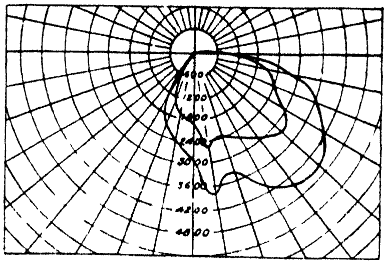


Dome.

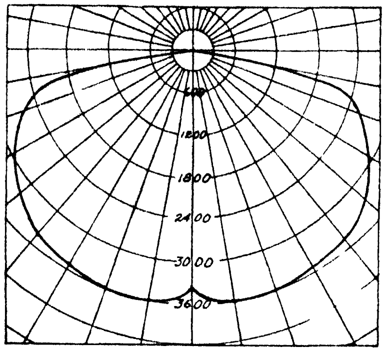


Bowl.

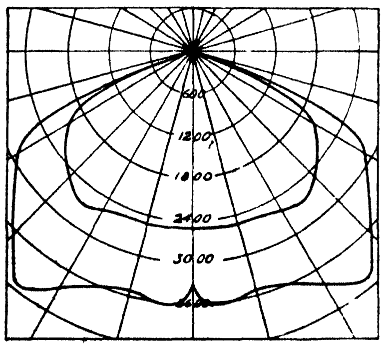
FIG. 7.33.—Angle, Dome, and Bowl-Shaped Porcelain-Enamelled Steel Reflector



Angle (Asymmetrical)



Dome



Bowl

FIG. 7.34.—Polar Curves for Fittings of Fig. 7.33.

of the reflector should always extend appreciably below the lamp filament.

For street lighting in small places, where a low-intensity illumination is sufficient, 1000 to 2000 lumen lamps may be used in connection with radial wave reflector. For spacings of 100 feet or less a 20-inch flat radial wave reflector may be used, which gives a fair illumination between the lamps and more light underneath them.

For spacings of 100 to 200 feet, the dome radial wave reflector is more suitable, when more light is delivered under an angle of 10 degrees below

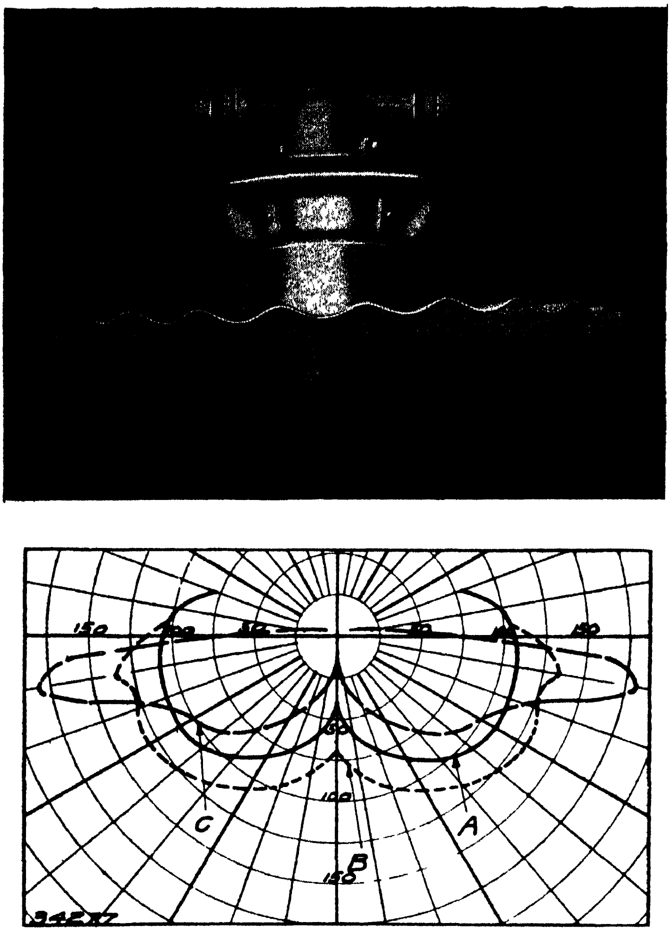


FIG. 7.35.—Dome Radial Wave Reflector (G.E.C.).

the horizontal through the centre of the lamp. Such a fitting made for a central span arrangement is shown in fig. 7.35. For all spacings above 200 feet the band refractor should be installed in order to obtain a fairly uniform illumination.

The polar curves in fig. 7.35 hold for 100-watt lamps, A referring to a 20-inch flat radial wave reflector; B to a 20-inch dome type as illustrated; and C to a 6½-inch prismatic band refractor.

7.07. DIFFRACTIVE OR FROSTED GLOBES AND SHADES.—The characteristic of these is similar to that of a semi-matt surface. The principle is indicated in fig 7 36 The lower edge of the glass is etched

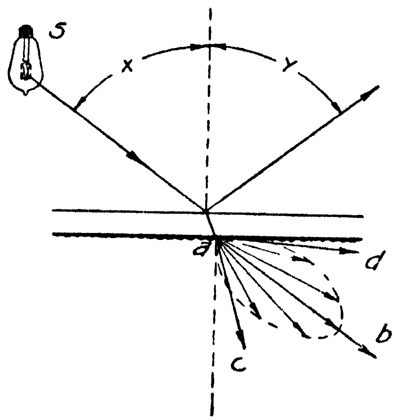


FIG 7 36 — Transmission of Frosted Glass

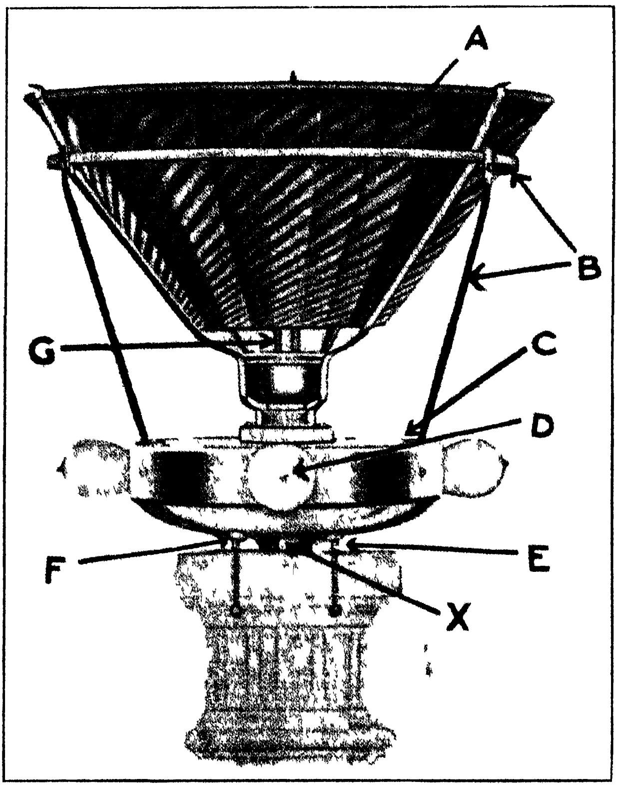


FIG 7 37 —Curtis X Ray Pedestal Lamp.

or sand-blasted The filament of the lamp is not visible, and the globe does not appear uniformly illuminated, but the light appears to be concentrated in the centre of it If the luminant is a metal filament lamp, we see an apparently cylindrical radiator only slightly larger than the cylinder formed by the filament.

Etched glass should be employed to spread the transmission of light rather than as a reflector. If the frosted surface is not of a very fine texture it easily collects dirt, and is difficult to clean. Modern tendency prefers stippled or pebbled glass, which has the diffusing characteristics of etched glass but is more easily kept clean.

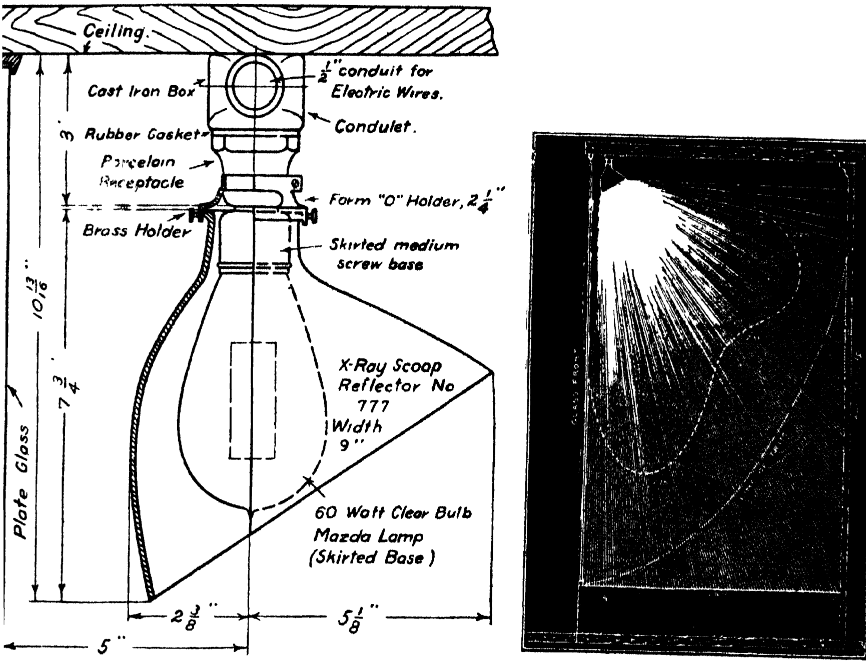
7.08. MISCELLANEOUS REFLECTORS. The National X-Ray Reflector Company have adapted their so-called eye-rest system to portable

FIG. 7.38.—Room Illuminated with X-Ray Pedestal Lamp.

lamps. Fig. 7.37 illustrates the adapter for a pedestal. A switchcord E lights three small tungsten lamps D (10 watts), giving the silk shade a decorative illuminative effect and adapting the lamp for reading purposes. Switchcord F lights the larger lamp contained within the reflector A, which throws the light against the ceiling, thereby illuminating the room. As the bottom of A is open, light from G falls on the white disc C, which diffuses the light and illuminates the shade (not shown) without having to run the small lamps D. The next figure, 7.38, shows a sitting-room lighted with a portable pedestal lamp.

For the lighting of shop windows the reflectors must be so constructed that they illuminate the goods on show, but not the onlooker. The lamps themselves must not be seen, and no light should be wasted on sidewalks, or the ceiling of the window, or above the display of the goods into the showroom.

The above-mentioned company manufactures four types of angle reflectors for this purpose, the angles differing according to the height and width of the show window and the height of the display. They are called scoop, visor, helmet, and poke-bonnet, of which the scoop and



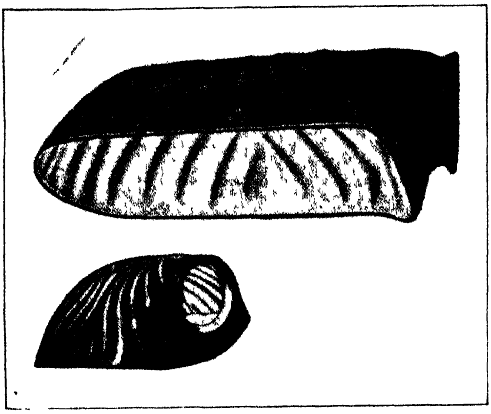
a *b*

Fig. 7.39. -The Scoop Angle Lamp and its Polar Curve.

poke-bonnet are shown in figs. 7.39 and 7.40 respectively, together with the corresponding polar curves (see also paragraph 9.10).

The number of reflectors required depends, of course, upon the illumination desired, the goods exposed, and the size of lamps used. The latter are usually of the 60- or 100-watt tungsten or gas-filled types, for which the spacing is on the average— scoop, 15 inches; visor, 24 inches; helmet, 36 inches; and poke-bonnet, 24 inches.

In place of a number of separate reflectors a continuous trough is often employed for shop-window or black-board lighting. The troughs are constructed on the same principle as reflectors, and a continuous row of ordinary lamps may be used, or preferably long tubular lamps consisting of a single straight tungsten wire supported in a number of places. The lamps or filament are arranged horizontally. The contour of the reflector is such that a fairly uniform illumination is produced over a vertical surface.



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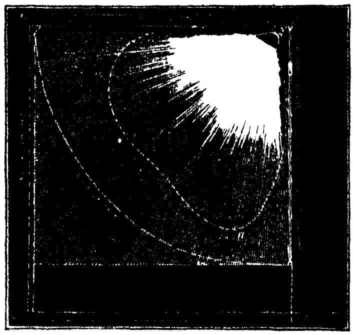


Cross-section of window showing distribution of light from Poke-Bonnet with two 40-watt lamps.

b

FIG. 7.40. The Poke Bonnet Lamp and its Polar Curve.

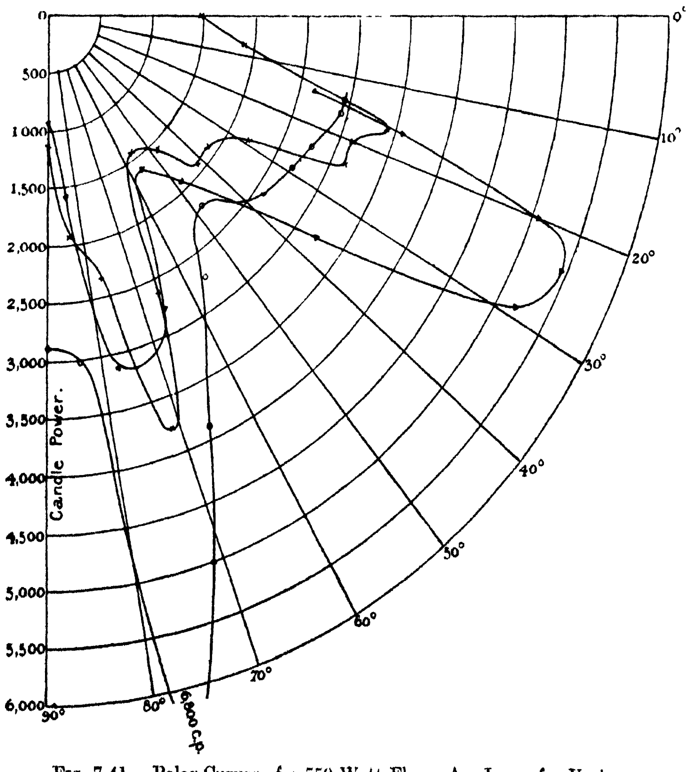


FIG. 7.41.—Polar Curves of a 550-Watt Flame Arc Lamp for Various Positions of the Arc.

FURTHER EXAMPLES OF STREET-LIGHTING FIXTURES.—When prismatic refractors are employed for redirecting light rays, the resulting distribution depends a great deal upon the position of the lamp with regard to the refractor In other words, prismatic globes and reflectors have an optical centre, and if the illuminant is only slightly out of it the light distribution varies considerably. Fixtures of this type must therefore be constructed for given types of lamps, or the position of the

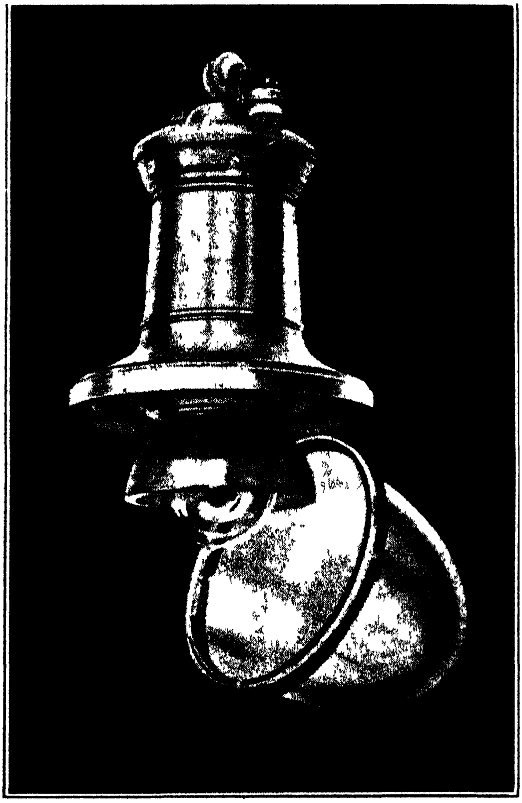


FIG. 7.42.—Street-Lighting Unit with Stippled Globe and Dome Refractor.

illuminant must be made adjustable. Fig. 7.41 illustrates the variation of light distribution by changing the position of the arc of a 550-watt flame arc lamp with a clear outer and dioptric inner globes.*

On the whole, dioptric globes are expensive and possess a definite optical centre. Pearce and Ratcliffe at Manchester obtained good results with a partially frosted outer globe, which is inexpensive to produce, the degrees of frosting of which may be varied or graded as required. This has an optical centre, and shadows under the lamps are eliminated.

Figs. 7.42 to 7.44 give further illustrations of street-lighting fittings

* Pearce and Ratcliffe, *J.I.E.E.*, vol. l., No. 219, p. 622.

with their polar curves, as manufactured by the General Electric Company and used to a considerable extent in America.

Fig. 7.42 shows a pendant unit equipped with a stippled globe and a prismatic dome refractor. With a dome refractor there are no diffusing prisms, so that some kind of diffusing globe is advisable. A stippled globe consists of crystal glass pressed in one piece with a stippled finish on the inside surface. The unevenness of the surface is sufficient to modify the brilliancy of the light. A polar curve of such a lamp is given in fig. 7.43, to which the following particulars are added for curve B:—

Lamp clear, volts, 50·5; amperes, 6·6; watts, 330; mean hemispherical candle-power, 622; watts per m.h.s.c.p., 0·53; downward lumens, 3910;

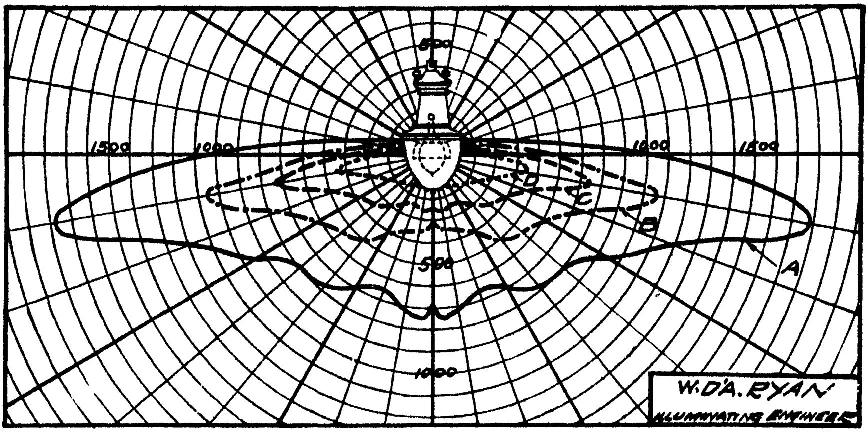


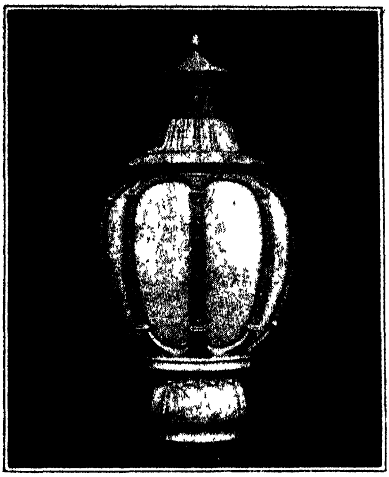
FIG. 7.43.—Polar Curve for Unit of Fig. 7.42.

downward lumens per watt, 11·9; mean spherical candle-power, 366; watts per m.s.c.p., 0·90; total lumens, 4580; total lumens per watt, 13·9; per cent. total lumens of lamp, 76·5 (6000 lumens for clear lamp alone). Curves A, C, and D hold for 1000, 400, and 250 candle lamps (m.h.s.c.p.).

An ornamental Novalux unit with an 8-panel diffusing glass globe suitable for 400, 600, or 1000 c.p. incandescent lamps is given in fig. 7.44. The same fitting may also be used for luminous (magnetite) arcs. Fig. 7.44, *c*, shows polar curves for such a unit, the various polar curves holding for the following arcs: —

A. 6·6-ampere long-life electrode and medium diffusing glass.
B. 5-ampere high-efficiency electrode and medium diffusing glass.
C. 5- „ long-life „ „ „ „
D. 4- „ high-efficiency „ „ „ „
E. 4- „ long-life „ „ „ „

If the light is to be deviated into regions lying between 10 degrees and 30 degrees to the horizontal, a refractor is added. Such a unit with



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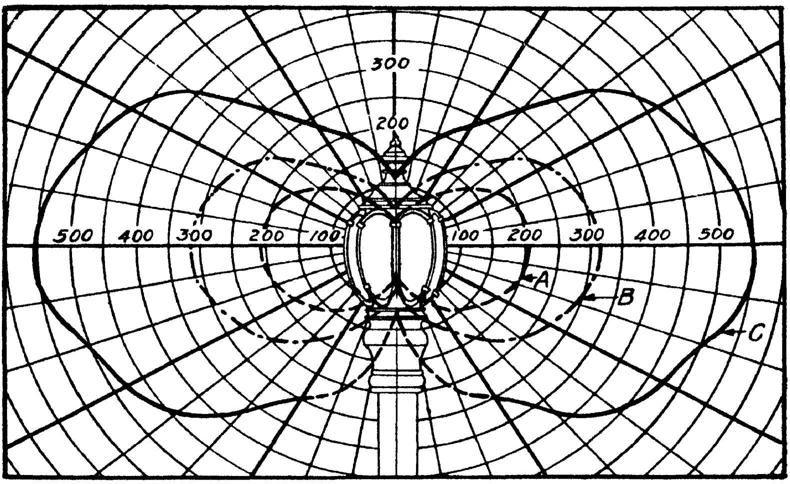

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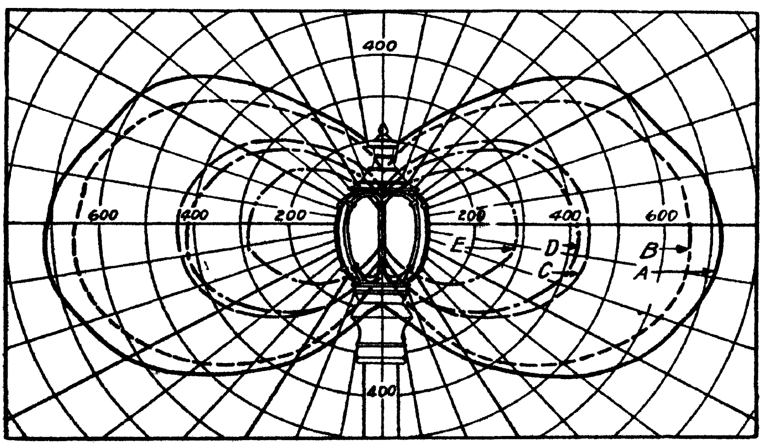
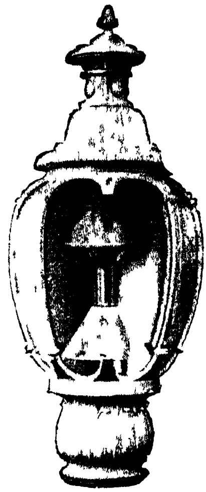


c

FIG. 7.44.—Novalux Street-Lighting Unit (G.E.C.).

polar curves is shown in fig. 7.45 for 250, 400, and 600 c.p. series lamps (15, 20, and 20 amperes respectively).



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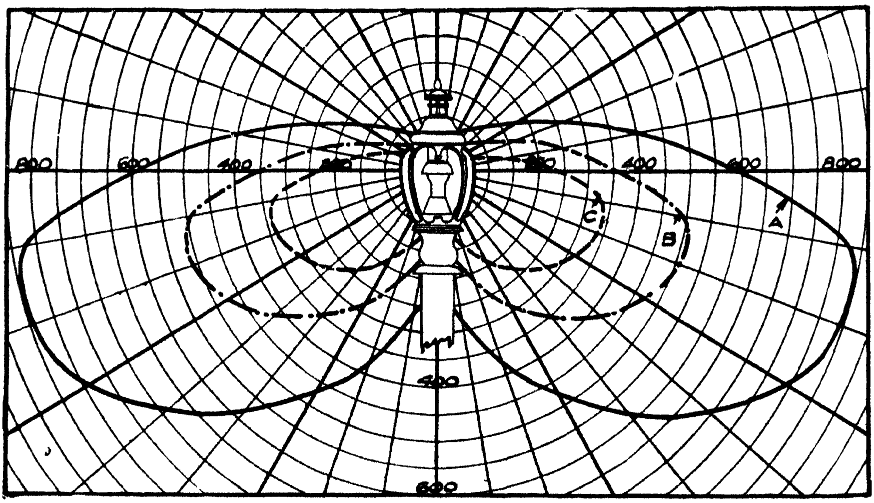


b

FIG. 7.45.—Ornamental Novalux Unit with 8-Panel Stippled Glass Globe and Dome Refractor.

7.09. SUMMARY.—Speaking generally of shades and reflectors, it is not always possible to obtain the highest efficiency, as the production of a decorative and tasteful effect may be more important. An antique chandelier has often been retained on account of its history, although it may have been an inconvenient fitting for conversion to electric light. It may even be the only one which will suit the general character of the room.

Where, however, new buildings are erected there is no reason why the lighting should not be carried out on correct scientific lines. At the present day the variety of fixtures with efficient reflectors and shades is so great that the architectural and artistic aspect can easily be satisfied, together with an efficient lighting scheme. Even in street lighting a decorative effect may often be aimed at with advantage. In a fine residential suburb with beautiful houses and gardens, a cheap street-lighting pole and fitting will be out of place. A well and artistically lighted business street will even draw customers. So far the decorative possibilities of outdoor lighting have been little appreciated.

Summarising the present situation of the lighting-fixture industry, we may state:

(1) For interior lighting the nature and period of the building is as important as the illumination efficiency, and the architect should be asked to select the fitting. Where it is desired to preserve the nature of the surroundings of an antique room, the light fitting may be constructed to resemble the particular period.

(2) Industrial lighting should always be in the hands of the illuminating engineer, whom the architect should consult.

(3) Where no particular architecture is aimed at, any efficient and physiologically correct system may be used if it is adapted to the requirements of the room. In some cases it is advisable to consider the method of illumination before the room is actually designed.

(4) On the whole, utility must be the first consideration; we must aim at—the correct illumination from the physical and physiological standpoints; then comes the design, which has to fulfil the required conditions; and finally appears the artist, who endeavours to make the fixture attractive, without, however, adding a construction whereby the fixture loses its character.*

7.10.—THE PROJECTION OF LIGHT.†—General Considerations.—In light projection we deal with the redirection of light flux by means of suitable optical systems or opaque reflectors, so that it may be utilised within small solid angles. The principles are indicated in the accompanying figures, 7.46 to 7.48.

In fig. 7.46 we have in the upper part a simple convex lens with the illuminant in the focus. The rays would all be parallel for a point source, but for one with physical dimensions a cone of light is projected with an angle of divergence equal to 2β, depending upon the size of the source, the focal length, and the angle α at which the light is emitted. With an increase in the diameter of a lens relatively to the focal length, the thickness, and thus the absorption, increase rapidly, and the control

* For further information on the design of Lighting Fixtures, see *Illuminating Engineer*, March 1915, p. 103.

† See also "Light Projection: Its Application," by G. J. Edwards and H. Magdsick, *Am. Illum. Eng. Soc.*, 1917. The reader is also referred to a series of articles by Frank A. Benford appearing in the *General Electric Review*, 1923/1924/1925.

becomes limited by the increasing spherical and chromatic aberration. To reduce these disadvantages Fresnel built stepped or corrugated lenses, consisting in effect of a large convex lens with sections of the glass reduced as shown in the lower part of fig. 7.46. By adding concentric curved prism rings at the back (not shown) light emitted in this direction may be made useful for the beam by total reflection and refraction.

Viewed within the beam, the sections of the lens give rise to a series of

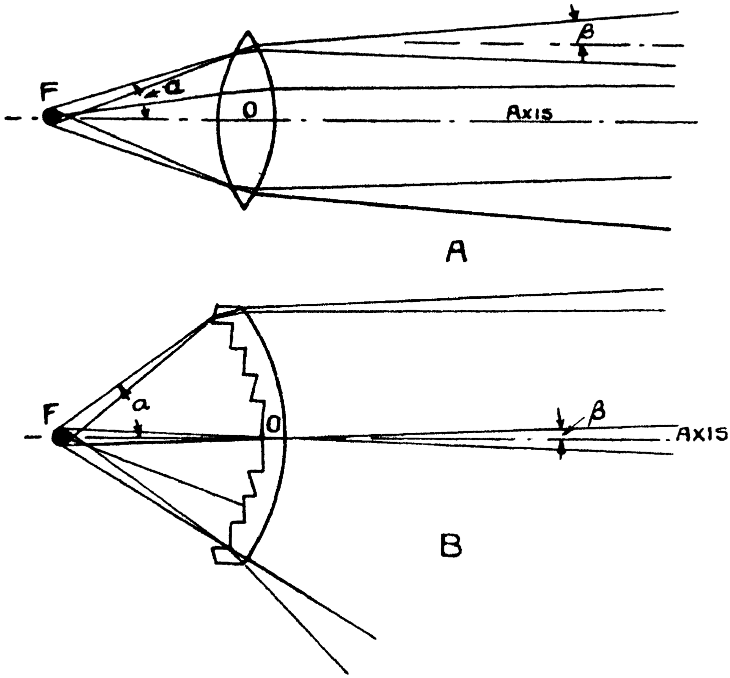


FIG. 7.46.—Projection of Light with Lenses.

dark rings, as the light striking the risers (horizontal lines) is deflected at a large angle from the axis. For reasonable effective angles (the solid angle subtended by the lens at the focus) the contour may be so adjusted as to obtain a good control of the light.

In fig. 7.47 the light is concentrated by means of opaque reflectors. In the upper part of the figure the reflector has a simple spherical shape. Light from a point source in the centre would be redirected upon itself, but with a larger source spreading takes place, and with a source in the axis at half the radius rays are reflected with only a small divergence from the parallel as long as the effective angle of the mirror is not large. Mangin constructed a mirror with the radius of the inner surface less than that of the outer, as indicated in the lower part of fig. 7.47. The divergence of the beam is then kept within narrow limits by means of the varying degree of refraction introduced by such a lens, as long as the effective angle of the mirror does not exceed 120 degrees.

The most effective results are obtained with parabolic mirrors, as for

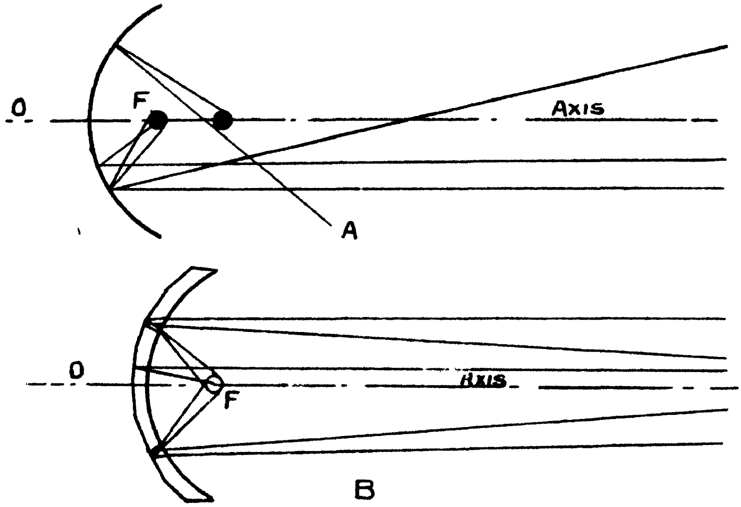


FIG. 7.47.—Projection of Light with Spherical Reflectors.

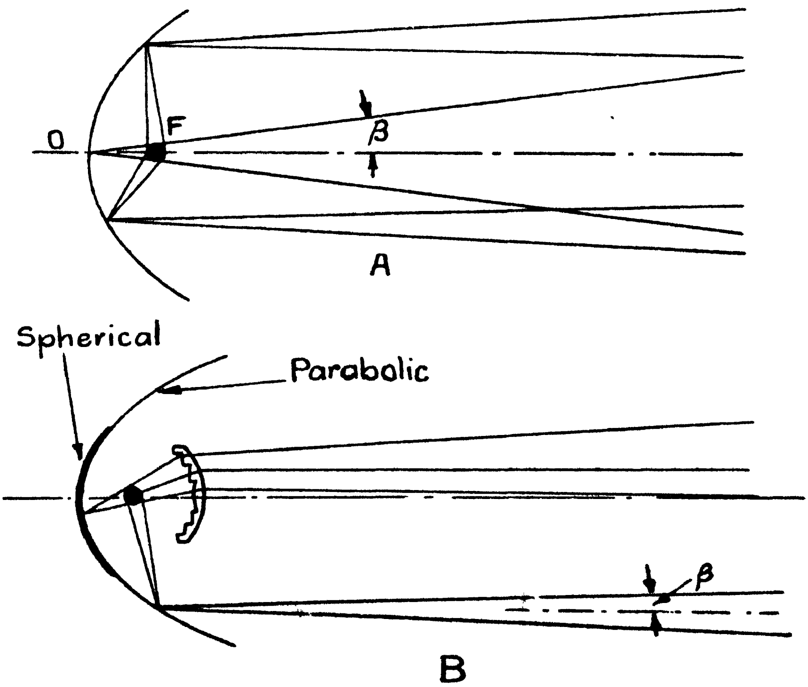


FIG. 7.48.—Projection of Light with Opaque Reflectors.

a point source all rays from the focus are redirected parallel to the axis. If the source has physical dimensions, the beam is spread, the divergence being greatest at the axis, decreasing with increasing angle (see fig. 7.48).

Within the angle of the cone emanating from the edge of the mirror, the beam contains light from all parts of the surface, and hence it is only in this region that the measured candle-power obeys the inverse-square law.

A combination parabolic-spherical reflector with a concentrating lens is shown in the lower part of fig. 7.48.

The brightness of the surface of any system employed is always equal to the brightness of the source at the respective angle multiplied by the coefficient of transmission or reflection. The intensity of the beam within this range is thus given by the product of the brightness and the projected area of the surface, *i.e.* equal to $\pi a^2 i$, where a is the radius of the surface and i the intrinsic brightness. The multiplying factor of a projector is therefore approximately given by the ratio of the squares of the diameter of the mirror to the diameter of the source, neglecting absorption. Alterations in the focal lengths and the effective angles do not change the results. In order to obtain beams of great intensities it is therefore necessary to have sources with high intrinsic brilliancies. The accompanying table, 7.01, gives values of i for some electric sources.

TABLE 7.01.—INTRINSIC BRILLIANCIES (EDWARDS AND MAGDSICK).

Source.	Candles per sq. mm.	Candles per sq. inch.
Flame arcs for search-lights	388 to 540 to 1100	250,000 to 350,000 to 700,000
Pure carbon arcs . .	125 to 190 *	80,000 to 120,000
Magnetite arc . . .	62 ,, 93	4,000 ,, 6,000
Mazda C projection type .	14 ,, 28	9,000 ,, 18,000
,, C regular . .	5·5	3500
,, B concentrated .	1·85	1200
,, B regular . .	1·2	750

Where it is desired to intercept a relatively large amount of the flux produced by the illuminant, as for search-lights, flood-lighting purposes, head-lighting, etc., the parabolic mirror is mainly employed, from 30 to 60 per cent. of the available flux being directed into the beam, whereas for very accurate control, such as is required for moving-picture display, magic-lantern work, etc., lenses are preferable. In the latter case only from 5 to 10 per cent. of the available light flux is usefully employed.

The width of a beam depends upon the effective angle of the system, the size of the source, and the focal length. If R be the ratio of the diameter of the reflector or lens to the focal length, then the percentage of solid angle subtended at the focus is expressed by $\frac{R^2}{R^2+16}100$ for parabolic reflectors and $\left(0{\cdot}5-\frac{1}{\sqrt{4+R^2}}\right)100$ for condensing lenses.

* *J.I.E.E.*, vol. lviii. p. 89.

A parallel beam cannot be produced with a parabolic reflector if the source has physical dimension, and in the case of glass mirrors on account of the thickness of the glass there is refraction which interferes with the parallelism of the beam. But by giving the convex surface a curve somewhat different from a parabola, so that the refraction produced combines with the effect resulting from the size of the source, a parallel beam may be obtained.

Arc lamps used to be almost solely employed for electric projection work, on account of the high intrinsic brilliancy of the crater of a direct current arc. To-day, focussing incandescent lamps have been constructed, and while a 100-watt 110-volt ordinary tungsten lamp filament encloses a cylinder 70 millimetres long and 30 in diameter, a similar projection type lamp requires only 12 × 12 millimetres (gas-filled), and a 6 volt 108-watt head light lamp filament is contained in a space of $2\frac{1}{2}$ by 5 millimetres only.

If a source is moved out of the focus, we have a spread or contraction: the former, if the illuminant is placed behind the focal point; the latter, if ahead of it. In this case we have crossing of rays, so that the beam may after all spread considerably. This is often usefully employed. By directing the beam on any convenient surface about 100 feet distant, and moving the illuminant backward and forward until the smallest spot of light is obtained on the lighted surface, maximum beam concentration is obtained.

The character and nature of the surface of the reflector is important. Polished nickel has a reflection coefficient of about 54 per cent., aluminium 62 per cent., and silver 88 per cent. Silvered glass mirrors reflect from 70 to 80 per cent. of the light and are usually preferred, as they can be more easily accurately ground than metal reflectors and do not tarnish so easily. Silver deteriorates quickly where air circulates freely, and especially in an atmosphere of salt or fumes from stacks. Nickel and aluminium are somewhat better in this respect, and the latter does not require replating.

Large glass mirrors, such as are employed for 60-inch search-lights, are, however, expensive. The General Electric Company of America has therefore developed a metal mirror which is less expensive and yet fulfils the conditions asked from a glass reflector.* A glass mirror with accurate shape is employed as a former and silvered on the outside by the ordinary mirror-silvering process. When dry it is removed and placed in a silver-plating solution, where the silver is built up to a thickness of several ten-thousandths of an inch. After washing the form is put into a copper-plating bath, and copper is deposited on the silver to a thickness of 0·030 inch. The mirror is then again washed, dried, and provided with a cement backing in the form of a plaster coating to an accurate thickness of $\frac{1}{2}$ inch. When this coat is dry and hard the mirror, with back, is

* *General Electric Review*, September 1919, p. 660.

removed from the glass and the silver surface is cleaned. No polishing is required, as the silver leaves the glass with a high degree of polish. To protect the silver surface from atmospheric conditions it is coated with lacquer. To obtain greater strength the backing is supported by sheet-steel made up in sections and perforated in order to allow the plastic compound to come through and clinch tightly to the steel.

The manufacture of glass mirrors consists of mixing and melting the glass, pouring and rolling into sheets of the required thickness, cutting, moulding at a temperature of 1350 degrees F. (730 degrees C.), annealing, grinding, smoothing, polishing, silvering, copper-plating at the back, and backing.

The annealing must be very gradual, the mirror being kept for ten hours at 1350 degrees F., then cooled to 900 degrees F. at 10 degrees per hour, then to 700 degrees at the rate of 20 degrees per hour, and then at a natural rate to room temperature by opening the kiln door.

The grinding is accomplished by a wheel guided by templates or by different forms of laps. The best form of grinder and abrasive is still in doubt. This also applies to the best form of lap for smoothing and polishing.

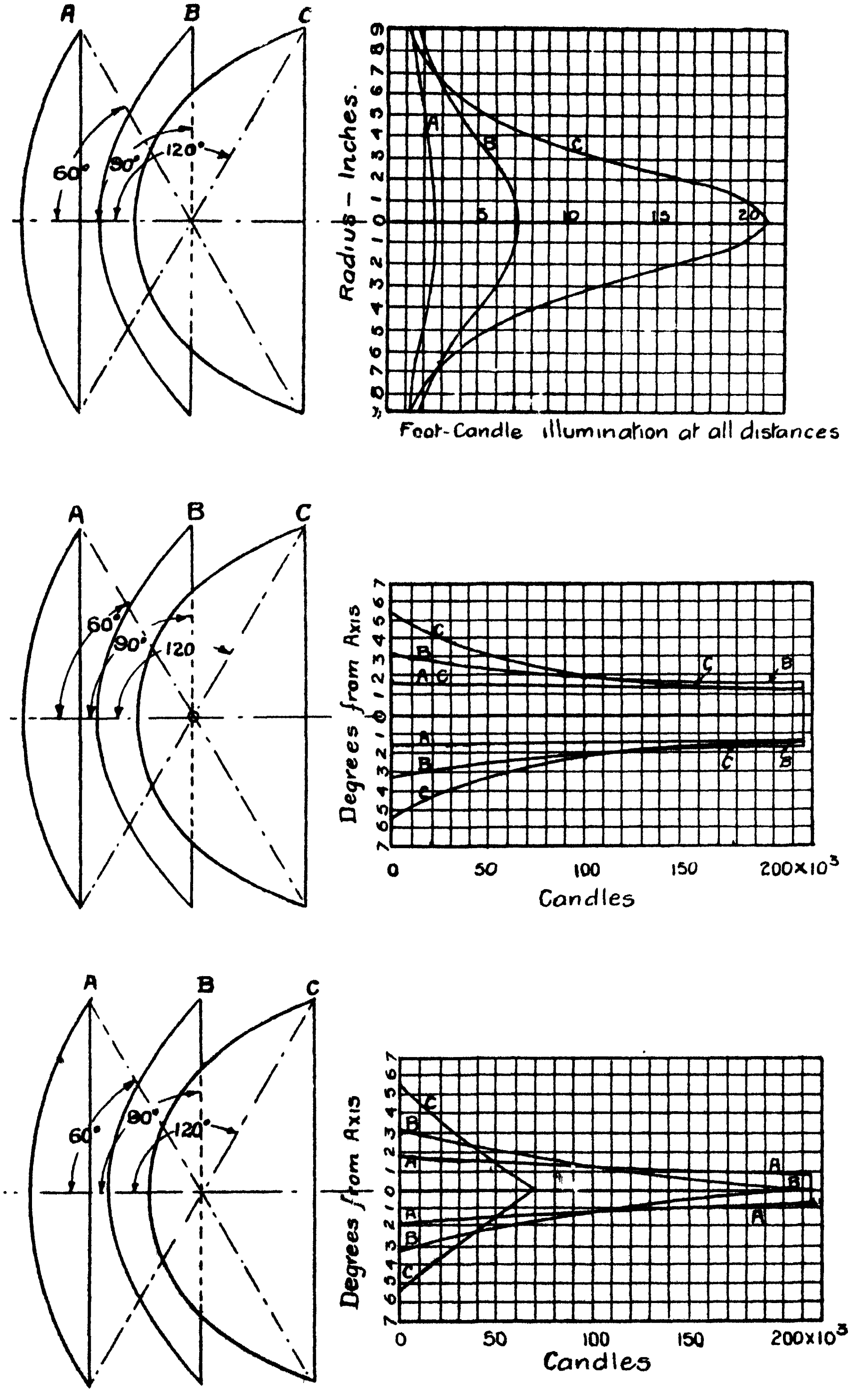
The silvering is accomplished by dipping the cleansed glass into the silver bath, where it is left for two and a half hours. To the copper plating on top of the silver several coats of paint are applied. Wire mesh is attached when the third or fourth coat is still quite tacky, and then a special paint of the consistency of putty is added, which is waterproof. Finally, a good coat of black enamel is applied and the mirror is placed in an oven at a temperature of 202 degrees F. (90 degrees C.) and baked for twenty-four hours.

Beam characteristics for various relationships between the diameters of parabolic reflectors and the focal lengths for point, spherical, and disc sources are shown in figs. 7.49, 7.50, and 7.51 respectively.*

In fig. 7.49 all the rays are parallel. As reflector C intercepts far more light than either A or B, the intensity of its beam is of course much greater and the inverse square law does not hold at all. For a point source of 1000 candles and 12,570 lumens, a mirror subtending a solid angle of 50 per cent. and a reflection coefficient of 75 per cent., the flux in the beam would be $\frac{12{,}570}{4\pi} \times 0{\cdot}5 \times 0{\cdot}75 = 375$ lumens, whence the average illumination at any distance (neglecting absorption by the atmosphere) is $\frac{375}{S}$, where S is the cross-section of the beam.

In fig. 7.50 the source is spherical. The maximum beam intensities are the same for all cases, and the same intensity will be directed at all angles within which light is received from the entire surface of the reflector. This angular spread is determined by the size of the source

* Frank A. Benford, jun., *Trans. Am. Illum. Eng. Soc.*, vol. x. p. 905.



FIGS. 7.49 to 7.51.—Beam Characteristics of Parabolic Mirrors.

and its angular radius viewed from the edge of the mirror. The intensity at other angles is proportional to the area of the mirror contributing light. The intensity varies, for fixed focal length, with the square of the tangent of one-fourth the effective angle; for fixed angle, as the square of the focal length. The axial intensity depends upon the brightness of the source, but is not affected by its size.

These characteristics of the beam apply at distances beyond the point at which the rays from the extreme edge of the reflector cross the axis (see also fig. 7.48). This point of maximum density from which the inverse square law holds is expressed by

$$L_0 = \frac{R\left(F + \frac{R^2}{4F}\right)}{12r} \text{ feet,}$$

where R is the radius of the mirror, F the focal length, and r the radius of the source in inches. The equation for the axial density or illumination beyond this point is

$$E = \frac{4\pi m I F^2}{SL^2} \tan^2 \tfrac{1}{2}\alpha = \frac{\pi m i R^2}{L^2} \text{ ft.-c.} \qquad 7.01$$

whence the beam candle-power

$$I_b = \pi R^2 i m \quad . \quad . \quad . \quad . \quad . \qquad 7.02$$

I is the intensity of the source, s the area of the light source in square inches, α the angle measured about the focus, in degrees, L the distance from the focal point to a point in the beam, and m the reflection coefficient of the mirror.

For a disc source the distance from the focus at which the inverse square law begins is

$$L_0 = \frac{R\left(F + \frac{R^2}{4F}\right)}{12r \cos \alpha} \quad . \quad . \quad . \quad . \quad . \qquad 7.03$$

A wider opening than 180 degrees is not effective, as the projected area becomes zero at 90 degrees from the axis. This results in the maximum intensity of the beam for mirror C to be much smaller than for reflectors A and B, as in the equation for I_b the effective radius R for C is much smaller.

In practice it is convenient to tabulate the so-called utilisation factors of parabolic projectors, by means of which the useful flux of the beam is readily found. Table 7.02 gives such factors for mirrors from 6 to 20 inches in diameter and various focal lengths.

Thus an aluminium reflector with a reflection coefficient of 0·62, a 500-watt gas-filled lamp delivering 7400 lumens, a mirror diameter of 16 inches with a focal length of 3 inches, delivers usefully into the beam

0·64 × 0·62 × 7400 = 2937 lumens from the mirror. The actual beam flux is somewhat augmented by direct light from the source, the total being about 3000 lumens.

TABLE 7.02. – UTILISATION FACTORS OF PARABOLIC PROJECTORS (G E.C.).

Diam. in Inches.	Focal Lengths in Inches								
	1.	$1\frac{1}{8}$	$1\frac{1}{4}$.	$1\frac{3}{8}$	2.	$2\frac{3}{8}$.	$2\frac{1}{2}$	3	5
6	0·69	0·64	0·59	0·54	0·36	0·28	0·23	0·20	0·08
8	0·80	0·72	0·70	0·68	[illegible]	0·41	0·35	0·31	0·14
10	0·86	0·83	0·80	0·77	0·61	0·52	0·45	0·41	0·20
12	0·90	0·88	0·85	0·83	0·69	0·61	0·54	0·50	0·27
14	0·93	0·91	0·89	0·87	0·75	0·68	0·62	0·58	0·33
16	0·94	0·93	0·91	0·89	0·80	0·74	0·68	0·64	0·39
18	0·95	0·94	0·93	0·91	0·83	0·78	0·73	0·69	0·46
20	0·96	0·95	0·94	0·93	0·86	0·81	0·77	0·74	0·50

7.11. SEARCH-LIGHTS.* – The rating of search-lights has been somewhat erratic. It is frequently expressed as the "range," which is the distance at which an object illuminated by the projector can be recognised. This range depends, however, on the transparency of the atmosphere; the dimensions of the object illuminated; the colour, form, and nature of the surface of this object; the degree of contrast with the surroundings, etc. To this must be added that the beam itself often forms an effective concealment for the target, the bright blue-tinted shaft of light forming a kind of curtain in front of the object. It will be obvious from this that two search-lights can be properly compared only if tested under similar conditions on the same object. We have also seen that the inverse square law holds under certain conditions and at definite distances only. It is therefore best to speak of the apparent or equivalent candle-power of the beam, *i e.* of a source subject to the inverse square law which would give on a screen at a specified distance the same illumination as the search-light in question.

To recognise an object by distinguishing coarse details, one reckons that in clear weather an approximate illumination of 0·15 to 1·5 foot-candles is required, the actual figure depending largely upon the colour of the object and surroundings. The range of a high-intensity flame arc 60-inch search-light with $i = 250{,}000$ would then, according to equation 7.02, vary from L=43,000 to L=14,000 feet, if we reckon a total utilisation factor of 0·4 (which includes the reflection coefficient of

* See also *Electrician*, 11th April 1919, p. 444, and *J.I.E.E.*, August 1920, vol. lviii., No. 294, p. 651.

the mirror). The equivalent candle-power of the beam in this case is $I_b = EL^2 \fallingdotseq 280 \times 10^6$ candles. (The maximum reached to-day is 2000×10^6 candles.)

Sometimes the power of a search-light is expressed by its multiplying power, *i.e.* by the ratio of the equivalent beam candle-power to that of the arc itself. If we employ a $\frac{5}{8}$-inch positive carbon with a crater of about $\frac{1}{2}$ inch, the candle-power of the crater is roughly $\frac{0{\cdot}5^2\pi}{4} \times 250{,}000 = 43{,}750$. This gives a multiplying factor of $\frac{280 \times 10^6}{43{,}750} = 6400$. As, however, not only the crater but the arc itself produces light, the correct factor can be obtained by tests only.

As a lamp of this type carries 150 amperes at about 80 volts, or 12 kilowatts, it will be obvious that under prolonged working the electrodes become incandescent along the whole length. Even other working parts become red hot (see also paragraph 2.22).

The condition of the atmosphere has a great influence on the range. If the latter is 30,000 feet in very clear weather, it will not be more than 20,000 under average conditions. A slight haze or rain will reduce it to 10,000 feet, and in a slight fog or at early dawn it will hardly exceed 3000 to 5000 feet. The range of a search-light is therefore a very in definite thing.

During the War search-lights were wonderfully improved. Not only have the beam candle-powers been greatly increased, but the weights of the equipments have been reduced considerably. Whereas an old 60-inch projector weighed up to 9000 lbs., the army requirements demanded 60-inch search-lights weighing less than 1000 lbs. Moreover, the projectors had to be manufactured at a limited cost in quantities; in other words, the design had to be suitable for repetition work.

The General Electric Company of America solved the problem by making the mechanism in the form of a cartridge with all the controls at the rear away from the heat of the arc, and providing an opening in the mirror for the insertion of the cartridge. The reader will find a complete description of search-light development in the special issue on Search-lights, *General Electric Review*, September 1919. A photograph of a high-intensity mechanism is shown in fig. 7.52. In order to get rid of the fumes from the flame arc, a flat metal chimney is fixed to the holder of the positive electrode. Provision is made for the rotation and axial feed of the positive electrode. Current is supplied to this electrode by means of spring-actuated silver contact brushes, to which connection is made by flexible silver conductors of flat section. Between these contacts and the crater the electrode is provided with a copper tube with cooling flanges.

The negative electrode possesses axial feed only, otherwise the arrangement of contacts and protection is similar. The burning length for the negative electrode of $\frac{7}{16}$ inch diameter is 8 inches, for the $\frac{5}{8}$-inch positive 15 inches, lasting fully one hour.

In order to be able to start and try the arc without external visible evidence, it has been the practice in enclosed types by arresting the beam as it leaves the mirror by means of a suitable shutter mechanism. Occultation in the open type is best effected by means of a cylindrical shutter, which intercepts the light between the source and the mirror, which serves at the same time as a ventilating duct. The arc itself is viewed by means of a special optical system, whereby it can be seen exactly as it would appear a few feet farther abreast of the arc. The image is located within a few inches of the controlling handles. The

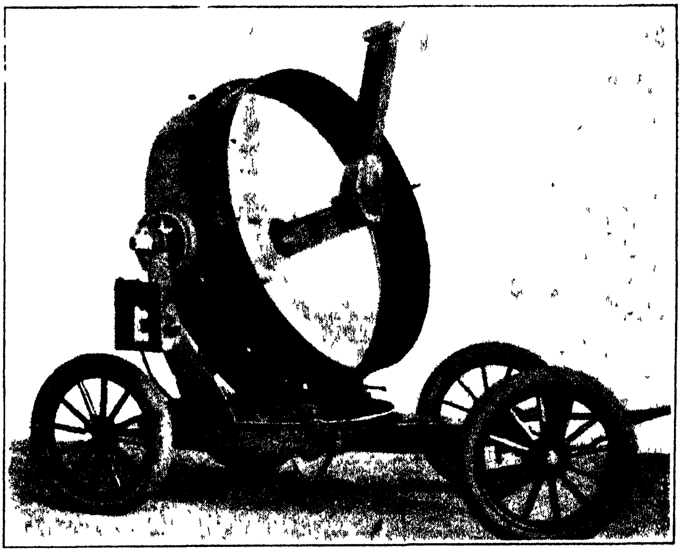


FIG. 7.52.—High-Intensity Search-light (G.E.C.).

arrangement of a lens within a few inches of a source of 12 kilowatts of energy is rendered feasible by the relatively low illumination required in the image. This allows the use of a very small objective, a few millimetres in diameter, which endures conditions that would otherwise cause fracture to larger pieces of glass. For short ranges the arc may be replaced by the gas-filled focussing lamp. To utilise in this case as much light as possible sphero parabolic reflectors are employed with a lens in front for redirecting light. The principle is shown in the lower part of fig. 7.48. The accompanying table, 7.03, gives further details of search-lights with metal filament concentrated filaments.*

Care must be taken that the filament is properly focussed in these reflectors, in order to obtain the maximum beam intensity.

* F. W. Wilcox, *Illuminating Engineer*, February 1915, p. 68.

TABLE 7.03.—VALUES WITH SEARCH-LIGHTS EMPLOYING METAL FILAMENT LAMPS CONCENTRATED FILAMENTS.

Diam. of Mirror.	Focus.	Particulars of Lamps.	* Maximum Beam c.-p.	Spread to 10 per cent. maximum intensity.	Average Beam c.-p. (across horizontal diameter of beam) over spread to 10 per cent. of maximum intensity.	Maximum pick-up distance. Man in dark clothes. In feet.	Multiplying Factor.
9 1/16 in.	2 1/4 in.	6-volt 108-watt G-30 Head-light	900,000	5 deg.	192,000	2870	6000
		34-volt 250-watt G-30 Head-light	300,000	8 deg.	165,000	1820	840
		110-volt 500-watt G-40 Stereopticon	700,000	9 deg.	355,000	2500	980
16 in.	5 in.	6-volt 72 watt G-25 Head-light	550,000	5 deg.	270,000	2290	5240
		34 volt 100-watt G-25 Head-light	100,000	8 deg.	55,000	1200	800
		34 volt 250 watt G-30 Head-light	250,000	8 deg.	137,000	1700	700
		110-volt 250-watt G 30 Stereopticon	225,000	8 deg.	129,000	1760	721
		110-volt 500-watt G-40 Stereopticon	650,000	8 deg.	379,000	2160	630
12 7/8 in.	3 in.	6-volt 72-watt G 25 Head light	325,000	5 deg.	175,000	1860	3090
		34-volt 100-watt G-25 Head-light	60,000	8 deg.	33,000	977	180
		34-volt 250 watt G 30 Head-light	150,000	8 deg.	82,000	1410	420
		110-volt 100-watt G-30 Stereopticon	27,000	8 deg.	15,000	708	337
		110-volt 250-watt G-30 Stereopticon	125,000	8 deg.	69,000	1305	400
12 7/8 in.	1 1/8 in.	6-volt 36-watt G-18½ Head-light	126,000	3½ deg.	68,000	1310	2520

Furnished with polished aluminium or silver-plated brass reflector.

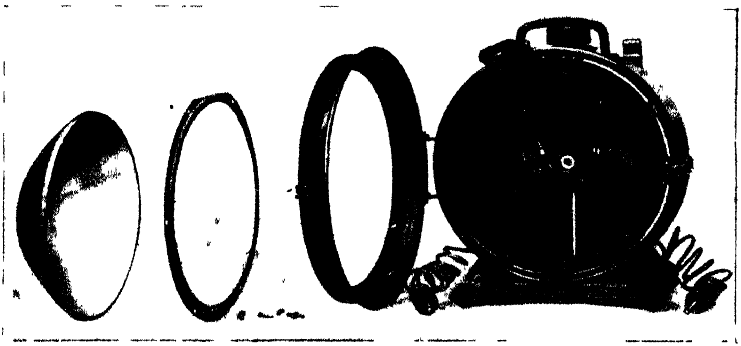
7.12. HEAD-LIGHTS FOR VEHICLES.– 6-volt or 30-volt incandescent focussing lamps are mostly used, in sizes of 23, 36, 56, 72, and 108 watts, worked from a dynamo, or a storage battery, or a small turbo-generator in case of locomotives.

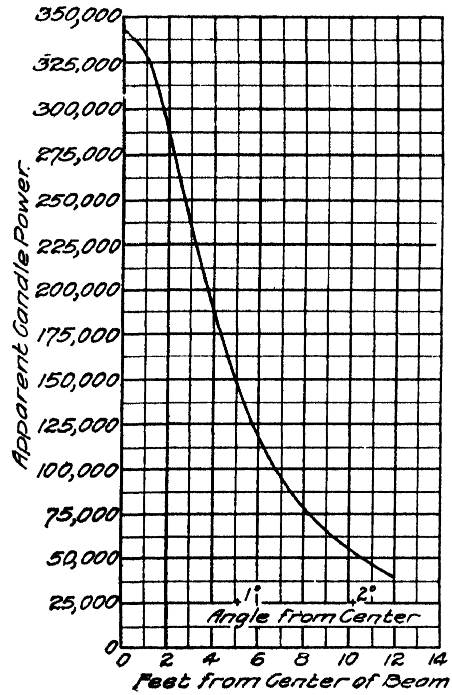
A portable interurban railway type of head-light is illustrated in fig. 7.53, and its photometric test curve for a 6-volt 12-ampere Mazda lamp, and a parabolic mirrored glass reflector of 12 inches diameter and 2⅛ inches focus, with readings taken at 300 feet, in fig. 7.54.*

For tramways the head lamps serve as markers only, and the beam candle-power usually does not exceed 15,000 candles, the spread being considerable ($\beta = 4$ to 5 degrees). For suburban and interurban runs, however, a higher intensity is required not only for warning, but also to illuminate the objects on the track at a sufficient distance to enable the car to stop before reaching them. For direct current supply the luminous (magnetite) arc is especially suitable, a beam candle-power of 400,000 being possible with a 4-ampere high-efficiency electrode, the spread with a

* *Trans. Amer. Illum. Eng. Soc.*, 1914, p. 918.

stepped 12-inch lens being only about 1 degree. With 400,000 candles dark objects are visible at about 1000 feet, light objects at 1800 feet, which is sufficient, as a heavy express train going at 60 miles an hour can





FIGS. 7.53 and 7.54.—Head-light for Trains and its Test Curve.

be brought to a standstill with modern brakes over 1300 feet on the level.

Formulæ, giving the distances at which a person dressed in light (C), medium (B), or dark (A) coloured clothes can be picked up by incandescent head-lights of various beam candle-powers, have been worked out by J. L. Minik.* The results are shown in fig. 7.55.

* *General Electric Review*, September 1918, p. 632.

The principal problem in head-light design is a reflector which will give effective illumination for driving purposes without producing glare. But the angle which separates the useful light upon the roadway from that which might cause glare is extremely small. The difficulty is aggravated by the fact that the position of the plane (say through the axis of the reflector) above which glare occurs varies with inequalities in the road. For instance, when the car moves up an embankment in the road the lamps point upwards, and the light will strike the eyes of pedestrians beyond the rise, even if on the level the light is below this plane.

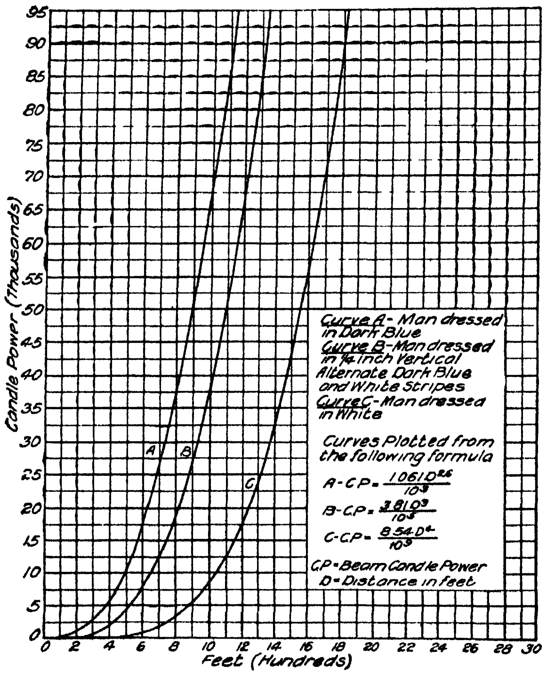


FIG 7 55.—Pick-up Distances for Different Colours.

There are three types of roads which an automobile head-light is to illuminate. First we have the ordinary country road, where there is very little traffic and where few obstructions are met by the motorist. In this country (South Africa) there are, of course, innumerable gates which separate one farm from another, and which in some districts average one to the mile. The road is rough and the driver has to look out for ruts, ditches, and cross-drains. He does not require a great deal of light, as the speed on these roads is limited. The lighting in this case is a simple matter. A lamp is required which need not carry very far, but which should have a fair spread so that immediate surroundings, such as ditches and fences, are noticed. The traffic is small, and the avoidance of glare is unimportant.

The next type of road is the city road, which is independently illuminated. The lamps here act simply as position markers, and the reflector should be so constructed that the beam is a narrow one and does not rise above the axis of the lamp. As the speed in cities is also limited, the beam need not carry very far, and hence the lamp used need not be of an extremely high candle-power.

The third type of road is the macadamised road, say from one town to another, or from a town to an outlying residential suburb, on which vehicles are constantly moving in both directions, but which are not independently lighted. These roads present the real difficulties in the head-lighting problem. In years to come they will probably be independently illuminated, thereby increasing the safety in traffic over them.

In the meantime the problem for these roads consists of designing a head-light which will enable the motorist to see far and well ahead, to observe the immediate surroundings, and to pass a vehicle coming in the opposite direction without causing glare to the driver of the latter. The problem has been tackled in three different ways, but a general solution has not yet been obtained.

(1) The single fixed system having the high-intensity beam below the plane passing through the axis of the lamp. The advantages are an excellent road illumination without glare for other folks and fixed lighting conditions. The disadvantages consist of a varying height of beam due to road curvature, an absence of light on immediate surroundings (telegraph poles, fences, ditches), an absence of control over any uproad glaring beam, and a limited range of illumination when approaching the foot of a hill.

(2) The controllable system, by means of which the position of the beam of light may be altered. It permits a good illumination of the road surface at all times, gives warning to a driver approaching a cross-road, informs pedestrians of the approach of a car from great distances, and gives security to the driver. As the control is, however, left to the discretion of the driver, there will surely be some abuse at one time or another.

(3) The diffusing system, in which the light is cut down and spread over a large angle. It reduces the magnitude of the glare, but as the reduction in intensity cannot be carried too far, the glare will exist to the oncoming pedestrian or vehicle until the car has been passed, except on well-lighted streets. Moreover, the glare appears in all positions forward of the car where the background is dark, on account of the wide angle beam, whereas the road illumination is low and does not reach far.

Summarising, we may say that the reduction of glare is obtained (1) by means of dimming the light by joining resistance in the lamp circuit; (2) by diffusing the light with frosted glass fronts; (3) by cutting off disturbing light either by altering the position of the lamp, or by means of a blind over the top half of the glass front, or by deep louvres in front of the lamp confining the beam below the horizontal, or by a cap over the top of the lamp bulb. The latter may have a reflecting surface so as to reduce the absorption; (4) by redirecting the light with lenses or prismatic glass fronts; (5) by a special type of reflector involving the use of a split or double reflector having its upper and lower halves of different focal lengths or shape, or having the foci separated by the filament length; (6) by tilting the reflector mechanically.

It will be seen from these remarks that the head-light problem is not yet solved, and there is a great difference of opinion between experts, how the problem is to be solved satisfactorily.*

At a meeting of the London "Safety First" Committee the following recommendations were made †:

(*a*) No portion of the beam of light shall fall outside a plane parallel to and 42 inches above the roadway, measured at a distance of 100 feet from the vehicle.

(*b*) There shall be sufficient light to enable a person or object of substantial size to be distinguished at a distance of 100 feet ahead of the vehicle. (This probably requires a beam of 500 to 1000 candle-power if dark objects are to be distinguished at the distance specified. In these circumstances the illumination, at a distance of 100 feet, would be 0·05 to 0·1 foot-candle. In obtaining this value the design of the lens and reflector is more important than the candle-power of the lamp, but a suitably designed lamp consuming 10 to 15 watts of electricity, or an acetylene lamp consuming $\frac{3}{4}$ to 1 cubic foot of gas per hour, would probably suffice.)

(*c*) The illumination produced on the roadway at a distance of 100 feet shall not sensibly diminish for a distance of 5 feet on either side of the centre of the beam.

(*d*) There shall be sufficient side illumination to reveal any person, vehicle, or substantial object, on either side of the vehicle or 10 feet ahead of it.

Similar regulations have been suggested by a Committee of the Illuminating Engineering Society in the United States, the summary being as follows:—

Nature of Beam.—No head-light should be permitted such that the reflected or beam light is projected above a plane 42 inches above the road and parallel to it, measured 100 feet ahead of the vehicle. No limitation is imposed to the lateral spread of the beam provided it is kept below this level.

Scattered Light.—No light is tolerated which at 5 feet above the road

* See also *General Electric Review*, March 1917, p. 246.

† *Illuminating Engineer*, June 1918, p. 165; *ibid.*, September 1918, p. 209; *ibid.*, April 1920, p. 114.

surface is more than a certain candle-power. The practical limit is of the order of 100 to 500 c.p., 1 degree above the horizontal or 5 feet above road level at 150 feet distance. The exact limit is left for further consideration.

Minimum Road Illumination and Width of Beam.- No driving is to be permitted where the road illumination is less than 0·001 foot-candles. The normal illumination provided at distances from 50 to 100 feet ahead of the vehicle should not be less than 10 feet in width upon the road surface. No regulation regarding the colour of head-lights is suggested.

In some cars the main reflectors contain two lamps, of which one, the larger one, is placed in the focus, being ordinarily used for lighting. In addition there is a small lamp above the larger one which throws its light largely downwards, so that glare is avoided. In well-illuminated towns the light from these small lamps is sufficient, and they are also found convenient when vehicles approach from opposite directions. Light from the larger focussed lamps would blind a driver crossing from the opposite direction for about thirty seconds, and during that time accidents might happen. The double-lamp reflector is thus a decided improvement.

In addition there is sometimes an adjustable "spotting" lamp fitted to the wind screen, in a convenient position for the driver, enabling him to investigate the immediate surroundings and rises in the road, as the lamp can be tilted in any direction.

In place of the double-lamp reflector two filaments in a single bulb have been tried, one in the focus of the reflector, the other above. The burning out of one filament makes the whole lamp useless.

7.13. FLOOD-LIGHTING PROJECTORS. The projectors employed are parabolic, and they consist either of highly polished aluminium, or of silver-plated glass. The silver plating is usually sealed by a heavy coating of copper, which acts as a protector and assists in radiating the heat from the lamp.

When a projector is trained perpendicularly upon a surface, the area illuminated is a circle; if not perpendicularly, an ellipse. It is usually best to let the light fall on the surface from two different angles in order to minimise shadows, which might be thrown by protrusions such as ledges, cornices, pillars, etc., which would happen if the light came from one direction only. Light thrown perpendicularly upon a surface tends to produce spots of light rather than uniform illumination.

Spectacular effects may be obtained by the use of colour screens with flood-lighting projectors. In mixing light, the three primary colours are red, blue, and green (not red, blue, and yellow, as is the case with pigments), which should be as pure as possible. Coloured gelatine sheets are usually employed.

The projectors should always be so placed that the light does not enter the eyes of pedestrians. For this reason buildings along streets are not illuminated below 15 feet above the footpaths.

For pageant lighting the projectors may be mounted in two or three groups at the rear and sides of the grandstand.

The area (ellipse) to be illuminated from a single projector is expressed as follows (see also fig. 7.56):—

$$\text{Area} = S = \frac{\pi}{4} L\, B,$$

where

$$L = D\{\tan(\alpha + \tfrac{1}{2}\beta) - \tan(\alpha - \tfrac{1}{2}\beta)\}.$$

$$\text{Eccentricity} = e = \frac{\sin\alpha}{\cos\frac{1}{2}\beta},$$

$$B = L\sqrt{1-e^2},$$

$$R = D \sec\alpha.$$

For a circle $L = B$, $e = o$, $R = D$.

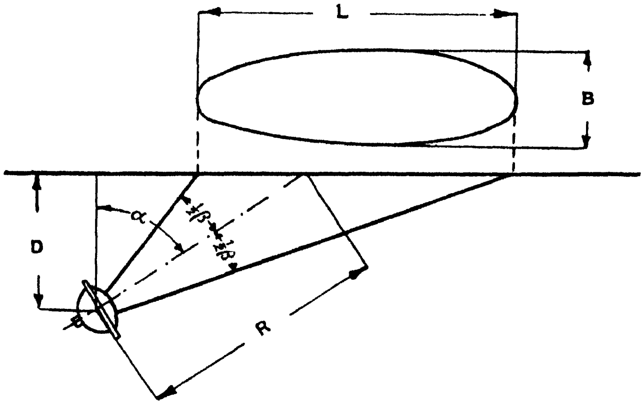


FIG. 7.56.—Area Illuminated by a Flood-Light Projector.

7.14. LIGHTHOUSES. They are not employed for illumination, but for orientation purposes only. Lens systems with accurate control are now almost universally used. The primary requisites are reliability, simplicity, and a low cost of operation.

The majority of lighthouses are still equipped with oil-lamps, as electric plant would require skilled labour and be therefore expensive. But some more important lighthouses, and those on large vessels, where high-intensity beams are essential, are fitted with electric lamps.

The lens systems are divided into orders, according to their focal lengths, commencing with the sixth order for a focal length of 6 inches, and finishing with the first order at 36 inches. For fixed beams the lenses are cylindrical in form about a vertical axis. Such a lens is shown in fig. 7.57. Usually the central dioptric part covers an angle at the source of 60 degrees and contributes about 60 per cent. of the light. The lower prisms cover about 20 degrees and furnish 10 per cent. of the beam light. They are catadioptric, acting by both refraction and total reflection. The upper prisms act similarly, but cover 50 degrees and give 30 per cent. of the light The latter issues as a belt of narrow vertical divergence.

A lens with a horizontal axis is illustrated in fig. 7.58, in which both vertical and horizontal concentration is secured, resulting in a very narrow but intense cone. Two such hemispherical lenses may be used, known as the bi-valve lens, giving high-intensity beams at 180 degrees. They may be utilised rotating about the source to produce intense

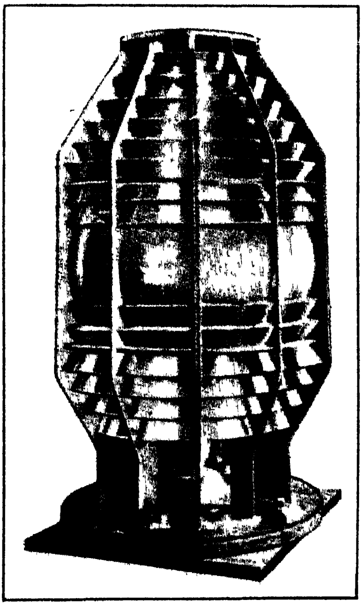


FIG. 7.57. Fourth Order Six Panel Fixed Lens.

flashing effects. By altering the design any desired sequence of flashing with controlled period of flash and interval may be obtained.

The visibility of a point source is proportional to the candle-power and inversely proportional to the square of the distance, but independent of the brightness for sources subtending an arc of less than two minutes. The range in miles may be expressed by

$$R = 1{\cdot}53\sqrt{I} \text{ for white light in clear weather,}$$
$$= 1{\cdot}09\sqrt{I} \quad ,, \quad ,, \quad ,, \text{ rainy} \quad ,,$$
$$= 1{\cdot}63\sqrt[3]{I} \quad ,, \text{ green} \quad ,, \text{ clear} \quad ,,$$

in which I is the candle-power.

7.15. LIGHT SIGNALS.—Electric lamps are coming more and more into use in semaphore signals, having been found more satisfactory than arms. On the Chicago-Milwaukee-St Paul Railway three signals, red, green, and white, are aligned vertically. Behind each lens are two lamps, one operating at a low efficiency to prevent failure of the signal. The normal daylight range is 3000 feet, and even when opposed to

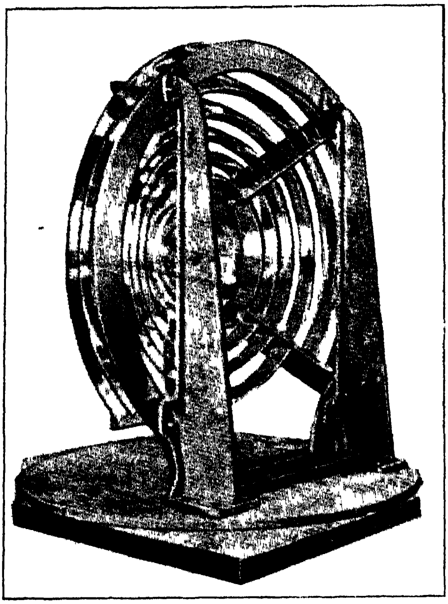


FIG. 7.58.—Fourth Order Range Lens.

direct sunlight not less than 2000 feet. It is stated that they are more easily seen than semaphore arms, and two to three times as far in snowstorms.

7.16. PROJECTION OF TRANSPARENCIES.—Magic Lantern.—The elements of the optical system for lantern-slide work are shown in fig. 7.59. Until a few years ago arc lamps were almost exclusively used where an electric supply was available. The direct-current arc was somewhat tilted until the direction of the maximum candle-power coincided with the axis of the system.

The condenser reduces the flux of light on account of absorption but little. It directs a converging beam through the lantern slide into the objective lens, the focal length of which is determined by the distance to the screen and the size of the picture desired. Focussing for different distances of the picture is accomplished by moving the objective lens relatively to the slide. To obtain a uniform illumination over the whole picture it is necessary that from any point in it a view through the objective lens and slide-holder discloses condenser surface covering the entire area. The slide-holder has to be placed close to the condenser in order to limit the size of the latter. The dimensions of the slide-holder opening are usually $3 \times 3\frac{1}{2}$ inches, and in order that the whole opening receives proper illumination the beam of light must have a diameter somewhat larger than the diagonal of the opening. This means that the efficiency is low, but it is somewhat improved by placing a spherical mirror at the back of the source, as indicated in fig. 7.59.

The arc has the disadvantage of unsteadiness, and it is only by constant manipulation possible to keep the light source in the best position. This applies even largely to lamps with automatic feeding

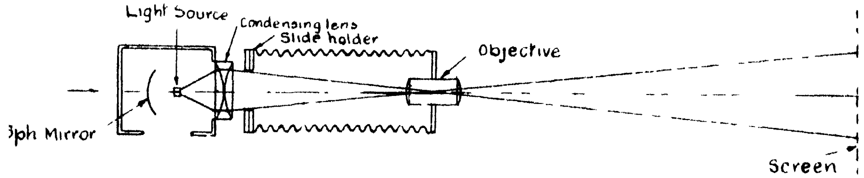


FIG. 7.59. - Lantern Slide Projection.

mechanisms. In addition the colour of the light is nearer the violet end of the spectrum, to which the eye is less sensitive than to a more yellow light as given by a tungsten lamp. This means that the illumination with arc lamps must be about 25 per cent. larger than with incandescent lamps. To-day the focussing type of gas-filled incandescent lamp is coming more and more into use.

The condensers, consisting of two plano-convex lenses, have usually a diameter of $4\frac{1}{2}$ inches, and from $6\frac{1}{2}$ to 11 inches focus. The electrodes used in the electric arcs are from $\frac{1}{4}$ to $\frac{5}{8}$ inch in diameter, carrying from 1 to 25 amperes.

7.17. MOTION-PICTURE WORK.- The optical system is shown in fig. 7.60. The intensity requirements are far more severe than for

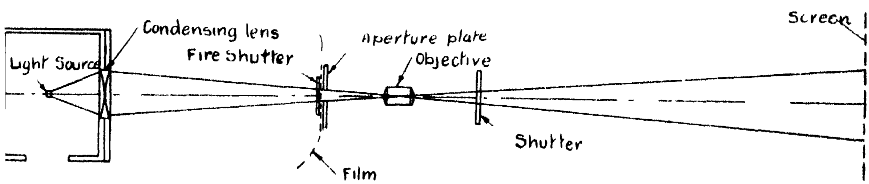


FIG. 7.60.—Optical System for the Projection of Motion Pictures.

lantern-slide work, so that a high intrinsic brilliancy is essential. The aperture of the plate through which the film is fed has an area of 0·680×0·906 inch, which makes it essential to place it far forward into the narrow part of the beam. The losses are increased by the necessity of employing a shutter, or sectored disc, in order to cut off the light during the shifting of the film, which occurs about 16 times a second. To prevent flickering a two- or three-wing shutter is provided, so that the light is shut off 32 or 48 times per second.

On the whole, pure carbon arc lamps have been chiefly employed, carrying from 40 to 110 amperes, with electrodes from $\frac{1}{2}$ to 1 inch (13 to 25 millimetres) in diameter for the positives, and $\frac{5}{16}$ to $\frac{7}{8}$ inch (7 to 22 millimetres) for the negatives. Alternating currents are not as good as direct currents, as no distinctive crater is formed and as stroboscopic effects must be avoided. A three-wing shutter with a frequency of 48 will give rise to such effects on a 50-cycle supply.

Since the advent of the focussing type of incandescent lamp the arc lamp is gradually being displaced on account of its disadvantages. By overrunning a gas-filled tungsten lamp so as to reduce its life to about 100 hours the intrinsic brilliancy can be increased to 22,000 per square inch (34 per square millimetre). The distribution of the light from such

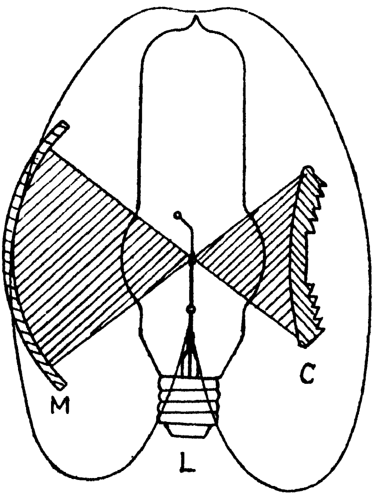


FIG. 7.61.—Incandescent Lamp (Mazda) for Motion-Picture Work.

a lamp, taking 30 amperes at 25 volts, which is illustrated in fig. 7.61, is shown in the same figure. To increase the useful light flux, the focal length of the lens has to be considerably reduced. The two plano-convex condensers of the arc lamp are replaced by a corrugated condenser, in order to reduce the thickness so as to make a short focus possible, and to break up the image of the filament which would be projected by a plano-convex condenser. For arc lamps this is unnecessary, as the crater of the arc is homogeneously luminant. The corrugations of the lens break up the image. A spherical mirror is again placed at the back of the source, and the arrangement should be such that the reflections of the filaments fall into the space between the filaments, as shown in fig. 7.62. Complete dimensions of lamp, spherical mirror, and corrugated condenser are given in fig. 7.63, which is self-explanatory. The utilisation of the light flux for such a system is indicated in fig. 7.64. As an overrun lamp may fail at any instant, two lamps are placed into one housing, and by a simple lever movement the burnt-out lamp is replaced. With a 750-watt lamp

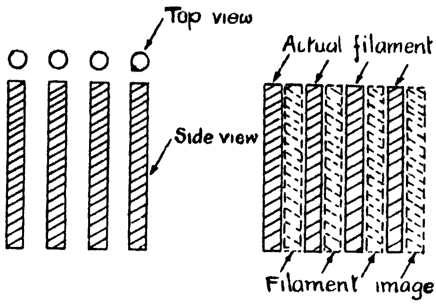


FIG. 7.62.—Filament of Mazda Lamp and its Reflection.

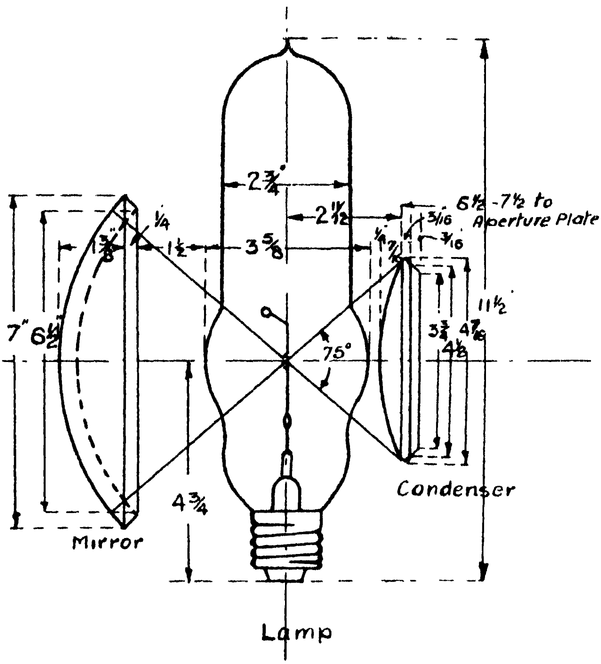


FIG. 7.63.—Dimensions of Optical System (Mazda) for Motion-Picture Work.

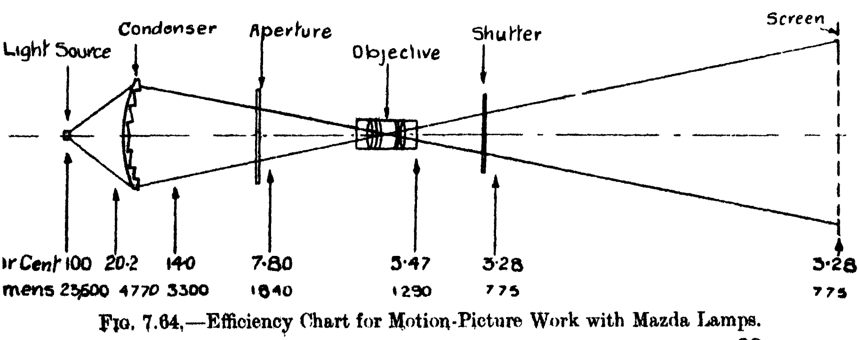


FIG. 7.64.—Efficiency Chart for Motion-Picture Work with Mazda Lamps.

a 12- to 16-feet square picture at a distance of 100 feet gives excellent results. The illumination is more pleasing and steadier than with arc lamps, and less costly to run in spite of the short life of the lamps. There is no carbon dust, and hence less wear and tear of films and mechanism.

Great progress has been made during the last few years in the production of portable cinema outfits, to ensure lightness, safety against fire, etc.*

7.18. SPECIAL LAMP FITTINGS. In powder and munition stores, and wherever there is the danger of explosions, the mains must not be

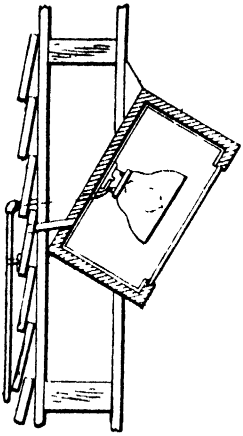


FIG. 7.65. - Fitting for Munition Store.

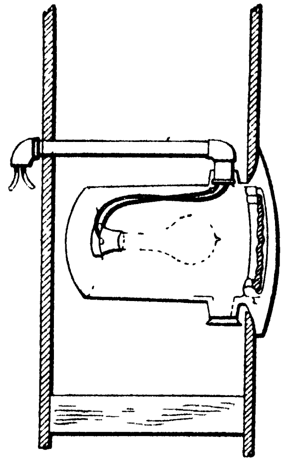


FIG. 7.66. Fitting for Munition Store.

laid on in the rooms themselves, but upon the external walls, where they can be easily inspected. Fittings suitable in such cases are illustrated in figs. 7.65 and 7.66.

In fig. 7.65 the system consists of an iron box lined with asbestos, which contains the lamp and shade. The angle at which the box is fixed depends upon the direction in which the light is required.

In places where acid vapours are present the arrangement of fig. 7.66 is preferred. Ventilation is obtained by means of a steel tube, which also carries the leads. On the inside the fitting is covered with glass, which can be removed for exchanging the lamp.†

* See also *Illuminating Engineer*, June 1920, p. 179, and *A. E. G. Mitteilungen*, August 1920, p. 94.

† *Electrical World*, 1921, p. 268.

CHAPTER VIII.

ILLUMINATING ENGINEERING.

8.01. EFFICIENCIES OF ILLUMINANTS.—The efficiencies of modern illuminants have increased wonderfully since the production of Edison's first carbon lamp in 1881, and whereas the latter consumed 5·8 watts per rated maximum candle-power, to-day we obtain 2 candles per watt. From a commercial standpoint the improvement is, however, not nearly so favourable, as the prices of fuel have also risen enormously. Further progress is therefore desirable, and the question arises, What are the extreme values of luminous efficiencies possible for monochromatic light, white light, and black-body radiation? Efficiency here means the ratio of the output of luminous flux measured in lumens (or watts) to the input in watts supplied to the lamp. As, according to Ives, a watt of luminous flux represents 629 lumens, the maximum efficiency in lumens per watt is expressed by this figure.

From fig. 3.04 it follows that we would obtain the most favourable results if all energy conducted to a lamp could be radiated as light for a wave-length of $54{\cdot}5 \times 10^{-6}$ centimetres. The output of such a lamp might be considered the maximum theoretically obtainable, having an efficiency of 100 per cent., and producing 629 lumens per watt.

If all the energy supplied to a lamp were radiated within the visible spectrum, and distributed so as to produce white light, we should obtain about 240 lumens per watt. Table 8.01 gives values for other illuminants, and the corresponding efficiencies.

Further, for mercury vapour lamps it must be stated that with ballast resistances and diffusing globes the efficiencies are not more than 50 per cent. of those given in the table.

Although with modern high prices of fuel the efficiency of illuminants is of primary importance, there are other factors which are essential for satisfactory illumination, such as steadiness of light, absence of glare, quality of colour, size of unit as determining uniformity and diffusion of illumination, cost of maintenance and renewal, characteristic of circuit, settling the amount and cost of station apparatus, etc. Some defects may be overcome by the sacrifice of efficiency. Glare may be avoided by employing proper shades and globes; higher cost of maintenance may be more than counterbalanced by a lower cost for power.

TABLE 8.01.—RELATIVE VALUES OF LUMINOUS EFFICIENCIES.

Sources.	Values of Luminous Efficiencies in Lumens per Watt.	Relative Values of Luminous Efficiencies in Terms of that of Monochromatic Radiation at Wave-Length $54{\cdot}5 \times 10^{-6}$ cm.
Monochromatic light, $\lambda = 54{\cdot}5 \times 10^{-6}$ cm.	629	100 per cent.
White light of maximum efficiency .	240	38 ,,
Black-body radiation at 5000–6000° C.	125	20 ,,
Quartz-mercury vapour arc . .	50–60	8·0–9·6 ,,
Luminous flame arc	40–60	6·4–9·6 ,,
Glass mercury arc	12–24	1·9–3·8 ,,
Gas-filled tungsten lamp . . .	16	2·5 ,,
D.C. open arc	16	2·5 ,,
Vacuum tungsten lamp . . .	10	1·6 ,,
Nernst lamp	5	0·8 ,,
Carbon lamp	3	0·48 ,,

The values given are, of course, very approximate only.

Table 8.01 is not altogether representative as regards the efficiencies stated. It is based on photometric tests in the laboratory, and the results do not always work out the same in practice. What we have to consider is the flux made useful, and one lamp with a lower efficiency but a more

TABLE 8.02. RELATIVE EFFICIENCIES OF ILLUMINANTS (STEINMETZ).

	Available Mean Sph. C.-p. per Watt.	(Street Lighting.) 10° C.-p. per Watt.	Available Mean Sph. C.-p.
3·1 watt per h. c.-p. carbon filament . .	0·21	0·4	Any
2·5 watt per h. c.-p. gem filament . . .	0·26	0·5	Any
450-watt 6·6-amp. series enclosed a.-c. carbon arc	0·39	0·5	175
Nitrogen Moore tube	0·45	..	..
480-watt 6·6-amp. series enclosed d.-c. carbon arc	0·62	1·0	300
1 watt per h. c.-p. Mazda lamp . . .	0·64	1·25	Any
500-watt d.-c. "intensified" carbon arc . .	0·78	..	..
4-amp. 300-watt d.-c. standard magnetite arc .	1·0	2·2	300
Neon Moore tube	1·1	..	..
0·5 watt per c.-p. gas-filled Mazda lamp . .	1·28	2·5	above 350
4-amp. 300-watt d.-c. special magnetite arc .	1·4	3·0	(420)
6·6-amp. 500-watt d.-c. standard magnetite arc	1·5	3·2	750
Mercury lamp in glass tube, best values . .	1·55	..	..
6·6-amp. 500-watt d.-c. special magnetite arc .	1·7	3·6	850
220-watt a.-c. titanium arc	1·9	4·0	420
300-watt yellow flame arc, best values . .	1·95	4·0	[585]
500-watt white flame arc, best values . .	1·95	4·0	[975]
Mercury lamp in quartz tube, best values .	2·0	..	..
Experimental 350-watt a.-c. titanium arc .	2·7	5·4	(950)
Melting tungsten in vacuum	2·88	..	..
500-watt yellow flame arc, best values . .	3·1	6·2	[1550]
Experimental 500-watt a.-c. titanium arc .	3·6	7·0	(1800)
Titanium arc, best values (high power) . .	5·2	..	..

efficient reflector than another may yet be the more economical type. Again, one type of lamp may be supplied more easily with the correct shade or reflector than another. For interior illumination the flux is chiefly required in a downward direction, whereas in street lighting—in order to obtain a fairly uniform illumination—the light flux is mainly desired in a direction at an angle of 10 degrees below the horizontal. Illumination may depend largely on the flux radiated in one hemisphere, and where this is the case it is important that the consumption per mean hemispherical candle-power is low. Table 8.02 gives values of the efficiencies of commercial units. The available mean spherical candle-power per watt is obtained by assuming a reduction of 20 per cent. for the reflector of incandescent lamps, 22 per cent. for arc lamps.

This table does not take into account the sizes of lamps. On the whole, the larger the lamp the lower is the specific consumption. Relative efficiencies of various candle-power illuminants are given in Table 8.03.

TABLE 8.03. RELATIVE EFFICIENCIES OF VARIOUS CANDLE-POWER ILLUMINANTS (STEINMETZ).

200 M.S.C.-P.		300 M.S.C.-P.		400 M.S.C.-P.		500 M.S.C.-P.		1000 M.S.C.-P.	
Type.	Watts.	Type.	Watts.	Type.	Watts.	Type.	Watts.	Type.	Watts.
A.C. carbon	490	A.C. carbon	620	Mazda	620	Standard magnetite.	400	Gas-filled Mazda.	780
D.C. carbon	380	D.C. carbon	480	Standard magnetite.	350	Gas-filled Mazda.	390	Standard magnetite.	700
Mazda	310	Mazda	470	Gas-filled Mazda.	310	Special magnetite.	350	Special magnetite.	550
..	..	Standard magnetite.	300	Special magnetite.	290	White flame arc.	350	White flame arc.	520
..	..	Special magnetite.	250	Titanium arc.	210	Yellow flame arc.	280	Yellow flame arc.	400
..	..	..	..	..	..	Titanium arc.	250	Titanium arc.	360

Although large lamps, such as the quartz-mercury vapour lamp or the flame arc lamp, may be the most economical illuminants, they cannot always be employed, as they are too large for giving a more or less uniform illumination. On the other hand, gas-filled lamps may now be had in all sizes for low voltages, and even from 20 watts upwards for voltages as high as 250. But though the term half-watt is somewhat misleading for these lamps (see Table 6.02), they are a great improvement upon the old 3·5-watt per candle carbon lamp, so that in spite of the increased cost for fuel and labour, and the consequent rise in the cost of electricity, there is to-day no need from the standpoint of cost to instal inadequate and unsatisfactory illumination.

8.02. QUANTITY OF LIGHT REQUIRED.—This question has been considered in a general way in paragraph 3.02, where the physiological aspects were reviewed. The tendency during the last few years has been a very much marked increase in the illumination of all places where work is being done. The following table, 8.04, gives the illuminations for industrial work as accepted by the American Engineering Standards Committee.

TABLE 8.04.—APPROXIMATE FOOT-CANDLES IN GOOD LIGHTING PRACTICE ON THE SPACE OR AT THE WORK.*

$\frac{1}{20}$ TO $\frac{1}{4}$ FOOT-CANDLES ($\frac{1}{2}$ to $2\frac{1}{2}$ metre-candles)

Roadways and Yard Thoroughfares.

1 TO 2 FOOT-CANDLES (10 to 20 metre-candles)

Storage Spaces: aisles and passageways in work-rooms, excepting exits and passages leading thereto.

2 TO 5 FOOT-CANDLES (20 to 50 metre candles)

Auditoriums and Assembly Rooms.

Assembling: rough.

Boilers, Engine Rooms, and Power Houses: boilers, coal and ash handlings, storage-battery rooms, auxiliary equipment, oil switches, and transformers.

Chemical Works: hand furnaces, boiling tanks, stationary driers, stationary or gravity crystallising, mechanical furnaces, generators and stills, mechanical driers, evaporators, filtration, mechanical crystallising, bleaching.

Clay Products: grinding, filter presses, kiln rooms, moulding, pressing, cleaning, and trimming

Elevator, Cars and Landings (freight and passenger).

Forge Shops and Welding: rough forging.

Foundries: charging floor, tumbling, cleaning, pouring, and shaking out.

Glass Works: mix and furnace rooms, casting.

Hallways: stairways, exits, and passages leading thereto.

Leather Manufacturing: vats, cleaning, tanning, and stretching.

Locker Rooms.

Meat Packing: slaughtering.

Machine Shops: rough bench and machine work and rough assembling.

Milling and Grain Foods: cleaning, grinding, or rolling.

Packing: rough.

Paint Shops: dripping, spraying, firing.

Paper Manufacturing: beaters, machine grinding.

Plating.

Receiving and Shipping.

Soap Manufacturing: kettle houses, cutting, soap chip and powder.

Steel and Iron Mills: charging and casting floors, muck and heavy rolling, shearing, rough by gage, pickling and cleaning, soaking pits, and reheating furnaces.

* "Code of Lighting," Amer. Illum. Eng. Soc., 1922.

Store Rooms and Stock Rooms: rough.
Textile Mills: (Cotton) opening and lapping, carding, drawing-frame, roving, dyeing; (Woollen) carding, picking, washing, and combing.
Toilet and Wash Rooms.
Woodworking: rough sawing and rough bench work.

5 TO 10 FOOT-CANDLES (50 to 100 metre-candles).

Assembling: medium, fine.
Chemical Works: tanks for cooking, extractors, percolators, nitrators, electrolytic cells.
Clay Products: enamelling; colouring and glazing.
Cloth Products: light goods.
Electric Manufacturing: storage battery, moulding of grids, coil and armature winding, mica working, insulating processes.
Engine Rooms and Power Houses: switch-boards, engines, generators, blowers, compressors.
Forge Shops and Welding: fine forging and welding.
Foundries: fine moulding and core making.
Glass Works: grinding, glass-blowing machines, cutting, pressing, knitting, sorting, stitching, trimming, and inspecting.
Hat Manufacturing: dyeing, stiffening, braiding, cleaning and refining, forming, sizing, pouncing, flanging, finishing, and ironing; sewing: light goods.
Ice Making: engine and compressor rooms.
Inspecting: rough, medium.
Leather Manufacturing: cutting, fleshing, and stuffing, finishing and scarfing.
Leather Working: pressing and winding, grading, matching, cutting, scarfing; sewing: light goods.
Machine Shops: medium bench and machine work, ordinary automatic machines, rough grinding, medium buffing and polishing.
Meat Packing: cleaning, cutting, cooking, grinding, canning, and packing.
Milling and Grain Foods: baking, roasting.
Office: private, general.
Packing: medium, fine.
Paint Shops: rubbing, ordinary hand-painting and finishing, fine hand-painting and finishing.
Paper Manufacturing: calendering, finishing, cutting, and trimming.
Polishing and Burnishing.
Printing Industries: matrixing and casting, miscellaneous machines, presses; proof-reading, lithographing, electrotyping.
Rubber Manufacturing and Products: calenders, compounding mills, fabric preparation, stock cutting, tubing machines, solid-tyre operations, mechanical goods building, vulcanising, bead building,

pneumatic tyre building and finishing, inner-tube operation, mechanical goods trimming, treading.

School : class-room, study-room, library.

Sheet Metal Works : miscellaneous machines, bench work ; punches, presses, shears, stamps, welders, spinning.

Shoe Manufacturing : hand-turning, miscellaneous bench and machine work ; inspecting and sorting raw material, cutting, lasting, and welding : light goods.

Soap Manufacturing : stamping, wrapping, and packing, filling and packing powder.

Steel and Iron Mills : bar, sheet, and wire products ; automatic machines, rod, light, and cold rolling, wire drawing, shearing, fine by line.

Store Rooms and Stock Rooms : medium, fine.

Structural Steel Fabrication.

Textile Mills : (Cotton) spooling, spinning, drawing in, warping, weaving, quilling, inspecting, knitting, slashing ; (Silk) winding, throwing, dyeing, quilling, warping, weaving, and finishing ; (Woollen) twisting and dyeing ; drawing in, warping ; weaving ; knitting machines : light goods.

Wood Working : sizing, planing, standing, machine and bench work, gluing, veneering, cooperage, finishing.

10 TO 20 FOOT-CANDLES AND ABOVE
(100 to 200 metre-candles and above).

Assembling : extra fine.

Cloth Products : dark goods.

Glass Works : glass cutting (cut glass), inspecting fine.

Glove Manufacturing : dark goods : sorting, stitching, trimming, and inspecting.

Hat Manufacture : sewing : dark goods.

Inspecting : fine.

Jewellery and Watch Manufacturing : engraving, stone setting, fine repairing.

Leather Working : grading, matching, cutting, scarfing ; sewing : dark goods.

Machine Shops : fine bench and machine work, fine automatic machines, fine grinding, fine buffing and polishing.

Office : drafting-room.

Paint Shops : extra fine hand-painting and finishing (automobile bodies, piano cases, etc.).

Printing Industries : linotype, monotype, type-setting, imposing stone, engraving.

Shoe Manufacturing : inspecting and sorting raw materials, cutting, stitching ; dark goods.

Textile Mills : woollens ; weaving dark goods.

It should be noted that in reality there is no sharp demarcation between one section and the next, and that, as the figures given are approximate ones, 10 metre-candles are equivalent to one foot-candle. The correct relationship is 10·7 to 1.

8.03. LOCALISED AND GENERAL ILLUMINATION.- As long as the illuminants were very inefficient, localised lighting was principally employed as the cheapest and most effective system. The results were, however, not always satisfactory. In looking away from a well illuminated bright object into comparative darkness, glare is experienced and fatigue results. In modern industries it has been found that good lighting gives not only increased comfort, but results in increased production; in other words, it pays. In many cases, however, especially where very fine work is to be carried out--for instance, for watch-making, operating tables, fine metal work,- it would be too expensive and unnecessary to illuminate the whole place to an extent of 10 to 20 foot-candles and more. In such cases local lighting is still used. On the whole, experiments have shown that for ordinary factory work, of the total illumination required about 40 per cent. should be supplied generally and about 60 per cent. locally, in order to obtain the best result.

During the last few years local lighting has been more and more done away with and a high general illumination of 10 and more foot-candles is employed in shops in which fairly close work is being carried out. It has been found that with adequate lighting the turnover is increased and the increased cost of lighting is more than made up.

8.04. DISTRIBUTION OF LIGHT. -Satisfactory illumination depends largely upon proper diffusion. Diffusion is a relative form and is largely dependent upon the direction of the rays. If, for instance, a large opal bowl illuminates an object close to it, the latter is illuminated by diffused light, but if the object is at a considerable distance, so that the light rays are almost parallel, there is but little diffusion. Sharp shadows should always be avoided, but shadows must not be prevented altogether, as they are essential for distinguishing fine details. A good deal depends upon the nature of shadows. They are usually very distinct when produced by a single illuminant without a diffusing globe. One often notices this in street lighting, when the lamps are fixed on low posts without proper diffusing shades. It is then difficult to distinguish the object from the shadow which it casts, and the latter appears like an obstruction. There is too little light in the shadow. This applies also to the lighting of a room by a single lamp. Where this is done—as is possible when the room is not too large—it is advisable to employ a well-diffusing globe and light walls. With a large metal filament lamp we still get sufficient local light upon the table below and at the same time a general illumination which allows the eye to rest and recover its sensitiveness without experiencing a glare when returning to the paper. Sharp shadows cause irritation, as the eye has to be strained to distinguish the shadow from the object.

Hence the illumination must be sufficiently diffused to make the edge of the shadow look blurred.

The best diffusion is usually obtained with indirect lighting. At the same time, this type of lighting is not always to be recommended, even if we neglect the matter of cost. We notice articles by distinguishing different shades. Suppose we employ a hollow sphere with diffusing white walls, such as Ulbricht's globe. It will be obvious that if we insert another white sphere and a white flat disc of similar diameter, the two can only with difficulty be distinguished. If we could produce perfect

Fig. 8.01.—Studio lighted with Union "OI" Inverted Arc Lamp.

diffusion, it would be impossible to see the articles at all. In rooms with white ceilings and white walls, the diffusion is a good deal less perfect than in a hollow sphere; hence shadows will be formed. This is excellently illustrated in figs. 8.01 and 8.01A (reproduced by permission of the Union Electric Company, Ltd.), which represent an artist's studio lighted by Union Special "OI" inverted arc lamps,* fig. 8.01 showing the point of view from which photo of 8.01A was taken. At the same time we can obtain satisfactory results very often without indirect illumination if we take care that the proportion of directed and diffused light is correct.

In addition to the type of illuminant, the reflecting power of the surroundings, and the distance of the shadow-casting body away from

* J. Eck, *Electrician*, 23rd June 1911; *Illuminating Engineer*, 1911.

the radiator, the sharpness of the shadow depends upon the relative position of the shadow-casting body to the radiator

If we hold a stick parallel to a Moore tube it casts a sharp shadow, if

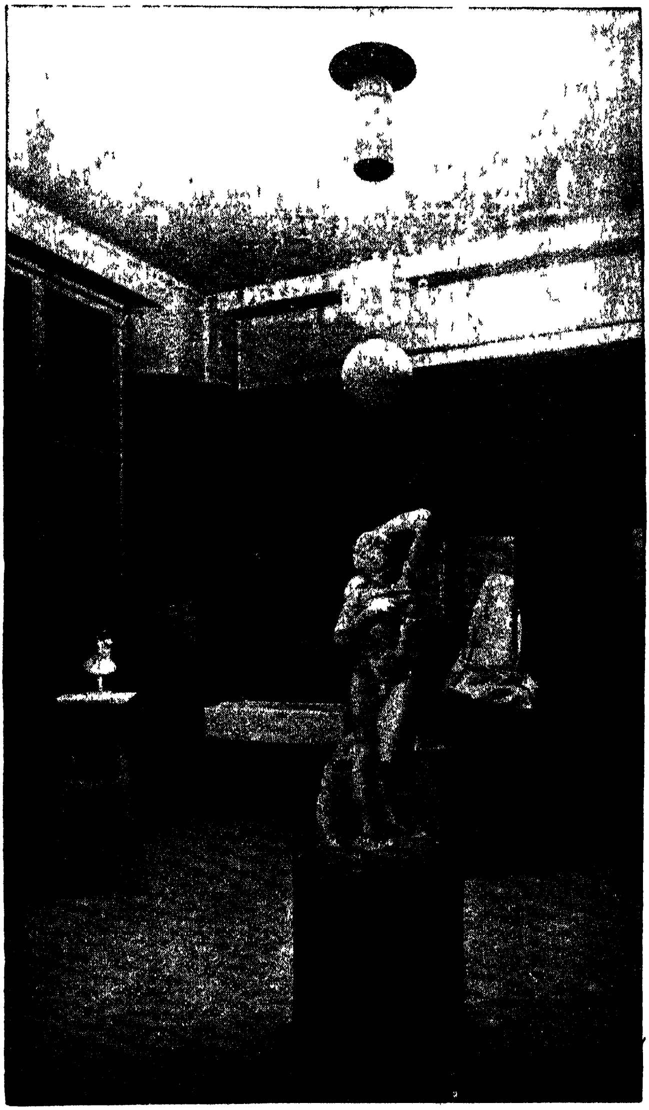


FIG 8 01A —Studio lighted with Union "OI" Inverted Arc Lamp

placed at right angles, hardly any A stick placed under a street lamp with a high candle-power on a low post in a manner that the light falls at an angle of, say, 30 degrees upon the stick causes a black shadow, whereas at considerable distance the shadow is less distinct In the latter case the next lamp takes some part in the illumination, causing it to be more diffused. Even in a room with a uniform illumination we may find that from a physiological standpoint the illumination is satisfactory only in a few places, as can easily be tested by casting shadows. Where a number of lamps cast the shadow of, say, a rod, in different directions, the illumination of the shadows is sufficient to see in the shadows; but near a corner of the room this might not be the case, since here this illumination may be due chiefly to one lamp, and the shadow thrown is in consequence very dark. It will be obvious from these remarks that the quality of an illumination must almost entirely be judged by the ability with which we recognise fine details; the illumination should in consequence be neither too little nor too much diffused. As we have to deal with two sciences, it follows that a judgment cannot be so easily formed. Testing the illumination with photometers may satisfy the physical science, but it gives no indication as regards the physiological quality. It is in the latter direction in which investigations are largely wanted. An attempt has been made by Dr Konrad Norden * to bring the physiological quality of an illumination within the range of mathematics. He expresses diffusion as the extent to which shadows are illuminated. The more we illuminate the shadows cast by a single radiator by means of other illuminants the more perfect is the resulting diffusion.

If E is the actual illumination prevailing at any point in a room, a the diminution in illumination due to the obscuring of any one of the component sources furnishing the total illumination, then $\frac{a}{E}$ is regarded as a criterion of the shadow caused by this source, and is termed the "Shadow Quotient." This factor may be determined by measuring E and $E-a$. Norden uses a strip comprising a graded series (of fifteen hues, from dark black through grey to white), the reflecting power of each hue being known. A small rod is caused to cast a shadow on a white border to this series of tints, and the tint which, when receiving the unrestricted illumination, matches in brightness the white surface in the shadow of the rod, is observed.

The possibility of expressing the diffusion, or rather the shadow power, is, however, at present of somewhat little practical value until we know exactly what diffusion we ought to have. The colour and type of the surroundings will play an important part as regards this shadow power.

From the remarks made previously it will be obvious that the mounting height and spacing distance have a considerable effect upon the nature of shadows. For low ceilings the lamps must be placed closer and be of smaller candle-power than for high ones. The National Lamp Works of the General Electric Company recommends the following table for mounting heights of tungsten lamps :—

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* *E.T.Z.*, xl. p. 376, 31st July 1919.

TABLE 8.05.—MOUNTING HEIGHTS FOR TUNGSTEN LAMPS (G.E.C.).

Mounting Height in Feet.	Size of Lamps in Watts.
7 to 10	40
8 ,, 12	60
10 ,, 14	80
12 ,, 16	100
14 ,, 20	150
17 ,, 27	250
25 ,, 35	400
30 ,, 40	500

The type of reflector used is of importance for the spacing of lamps. Fig 8.02 gives suggestions which have been found satisfactory in practice.

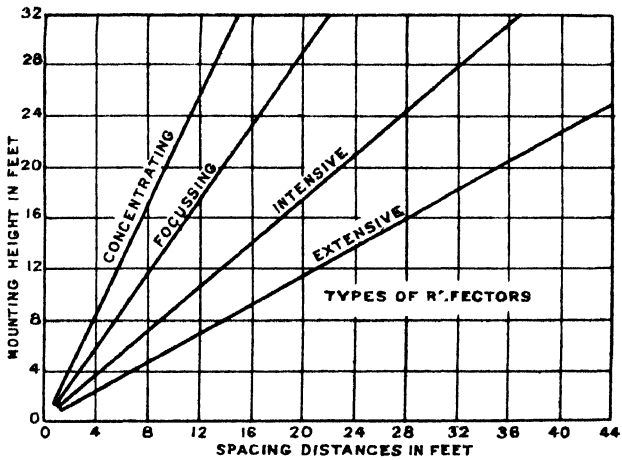


FIG. 8 02.—Mounting Heights and Spacing Distances.

8.05. IMITATING DAYLIGHT.—A room may be well illuminated from the physical standpoint and light and shade may be properly distributed, and yet it may not give complete satisfaction. This will probably be largely due to the want of variety. Nature's lighting is the least monotonous, due to the fact that there is a constant change in colour and distribution. Artificial lighting, on the other hand, is usually arranged symmetrically, with monotonising effects, which is quite unnecessary, as electric lighting lends itself so easily to changes. We still consider lighting too much from the utility standpoint, and study our moods too little. Yet we all know what a reviving effect a bright sunny morning, with its constantly changing aspect in light and shade, has upon us, while a dull day makes us feel depressed. As modern humanity is largely obliged to live the greater part of the twenty-four hours within doors, it follows that the appearance of a room must influence our moods. Even in a dining-room, for which the lighting is somewhat fixed on account of the position of the table, cheering changes may often be introduced without much extra cost. If the family is small and there are no visitors, a nicely hand-wrought table lamp with a red or green silk shade (inside white) will give a cosy effect. The warm light makes us think of olden times. When visitors are present, a few ceiling lights will produce a festive air and add life.

In lounges, studies, and drawing-rooms the addition of properly shaded table-lamps will destroy symmetry but add comfort and cosiness. In some cases it may even be advisable to have a variety in the colours of shades.

Very often it will be found that slight touches cause great improvements. Where a lamp irritates, its replacement by a frosted one may result in complete satisfaction. All-white Mazdas can now be obtained giving 10 lumens per watt. Where a smooth plain shade gives streaky light, a fluted one may avoid this. If we require colour effects, with the aid of red, green, and blue glasses our wants can be satisfied. Artificial sunlight and moonlight are at our disposal. In fact, the possibilities with electric lighting are enormous, and we are just at the beginning.

The nature and colour of the surroundings are of great importance as regards the quality of the illumination. On the whole we prefer so-called warm colours, such as orange, red, and yellow. A room which gets no sunlight may be given a warm appearance by letting the skylight enter through yellow hangings, whereas in countries which have excessive sunlight the coverings and furnishings should be of green and blue tints. Daylight may to-day be imitated very closely by properly coloured lamps. If the appearance of an object is too cold, the backgrounds must be draped in warm colours. For illuminating paintings, such illuminants should always be employed, and, if desired, with a warm setting.

8.06. THE PROBLEM OF COLOUR MATCHING. The light of the sun, when entering the atmosphere, is somewhat modified by particles of vapour, dust, and clouds, the shorter blue waves being partly absorbed. Some of the light is scattered and is received as skylight, so that the total light is a mixture of direct filtered sunlight and skylight. The character of daylight will thus depend upon the state of cloudiness, the angle at which daylight enters, and the nature of the surroundings. It is thus not a constant quantity. For accurate colour matching we prefer on the whole light from a northern sky (northern hemisphere), where there is no direct sunlight, chiefly because it is more constant in its character than the average daylight. For this reason silk dyers always work in light from a northern sky.

For colour matching Trotter advocated twenty-eight years ago that the colour of the electric arc might be made to approach daylight by the employment of glass or any other medium with stains or dyes which would absorb the rays of those colours which are excessive in the arc (see also fig. 6.50). Accurate colour-matching units are now available, in which gas-filled lamps are placed in a metal reflector arranged to concentrate the light through a blue-green glass filter plate.* They light a table top with an area of 6 to 8 square feet on which coloured fabrics are inspected. The efficiency of such a unit on account of high absorption is, of course, low.

Where the requirements are less exacting, the gas-filled lamp is given a blue bulb, the filament being run at a somewhat higher temperature than that of the ordinary gas-filled bulb. The watts absorbed are about 35 per cent. in excess of those of an ordinary gas-filled lamp of the same candle-power.

It should be added that in rooms for colour matching the surroundings should be white, as other colours influence the character of the light. The blue colour of the lamp bulb does not add any colour to the light, but subtracts excess yellow-red light

M. Ch. Martin advocates the directing of light on to a reflector which is covered with a mosaic of green and blue paint, designed so as to give the correct quality of directed light.† Such an arrangement is, of course, also inefficient on account of the high absorption of green and blue surfaces. Ives and Luckiesh employ a screen of gelatine dyed with rozaine.

Each application must, of course, be considered separately. For judging paintings, the blue must not darken and the yellow not turn pale under artificial light. A deficiency of the blue in the light makes the hue of flour appear yellow.

Coloured lamp bulbs have a shorter life than clear ones on account of the increased heat due to absorption. There is therefore scope for the manufacturer in producing a lamp bulb of small absorption but giving the correct colour effects.

Instead of subtracting excessive red and yellow light, a similar result may be obtained by adding illuminants strong in green and blue light. On account of great absorption this method is also not yet satisfactory.

8.07. LIGHTING AND ARCHITECTURE. It has been the general practice to erect a building and fit in the artificial lighting afterwards, even if the building is mostly used at night. This system has often resulted in very poor lighting. Good effects are only obtainable if the architect and the illuminating engineer work hand in hand, and both should possess imagination. It is for the engineer to suggest where the outlets are to be; he should decide upon the spacing and size of the units and the variation of the ornament in order to get correct reflection and diffusion, and it is for him to explain to the architect what the effects of colour, shade, and diffusion have on a hall or large room in general.

In the majority of cases the architect has been at fault. He may have had all the necessary imagination as regards the effects of daylight, but as regards the artificial lighting he thought too much of the expenditure.

* *General Electric Review*, June 1920, p. 527.

† *Illuminating Engineer*, November 1919.

Yet the artistic value of an interior depends entirely upon how it is seen, and this can be done only if light, shade, and colour are properly distributed, and all essential details are recognised. A beautiful room, which is properly lighted and which is correctly seen, will influence the mood and behaviour of the inmates.

It must also be observed that artificial lighting of architecture often produces illusions, which must be taken into account. With the lights between the eyes a dark ceiling will appear lofty, and a bright object amidst dark surroundings will look larger than similar dark objects amidst light surroundings. A beautiful ceiling should not be hidden by the employment of direct units with opaque shades, but if the walls of a room are decorated with low reliefs, direct units above the reliefs are usually more efficient for pointing out the ornamental details than indirect lighting. Reliefs of ceilings are often best illuminated by so-called cornice lighting, in which the illuminants are hidden by a cornice, the light being reflected obliquely upon the relief. In fact, many satisfactory effects may be obtained by hidden lamps.

Above everything care must be taken that the illuminants are accessible for cleaning, which is easily forgotten for hidden lamps. Moreover, the cleaning must be regular and systematic. A system, which has been satisfactorily designed, must be kept efficient if good average results are to be obtained. Even with proper cleaning it is advisable to add a depreciation factor in all illumination design, and a 25 per cent. addition will in most cases be found satisfactory. It allows for the ageing of lamps and some dust.

The decrease in the efficiency of illumination with time, due to the collection of dust, is well seen from fig. 8.03, where A, B, C, D, and E

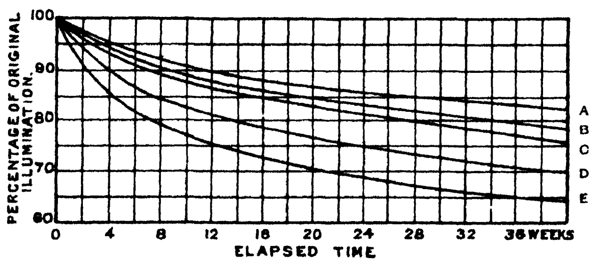


FIG. 8.03.—Depreciation of Light due to Collection of Dust.

refer to dome enamel steel, bowl enamelled steel, dense opal glass, prismatic glass, and light density opal glass shades respectively. The figure holds for fairly dust-free rooms.

Speaking generally, uniformity of illumination is to be aimed at, as it is not easy to obtain excess diffusion. At the same time a pleasing effect may be preferable to great uniformity, and even a painting may sometimes be beautified by lighting it with light and shade.

8.08. ILLUMINATION CALCULATIONS.—General Considerations.— In the first place we must see that the illumination is sufficient. Table 8.04 may form a basis for our calculations. Considering the position of

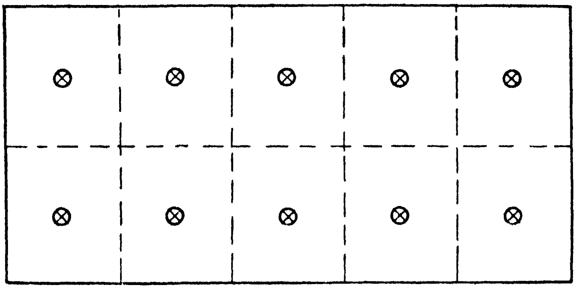


FIG. 8.04.—Distribution of Incandescent Lamps.

the outlets, it is best to place them parallel to the sides of the walls, or at the corners of equilateral triangles, according to figs. 8.04 and 8.05 respectively. In the former case we divide the room into a number of

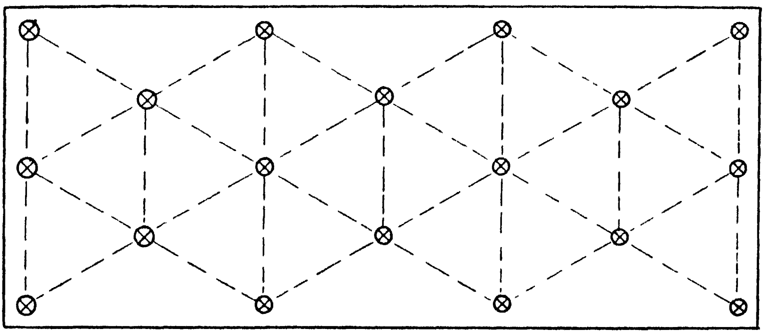


FIG. 8.05.—Distribution of Incandescent Lamps.

squares (or rectangles), according to the number of lamps used, and then place a lamp into the centre of each square (or rectangle).

The illumination obtained in a spherical chamber is expressed by

$$E=\frac{\phi}{S}\left(1-\frac{1}{m}\right).$$

Thus for light yellow wallpaper we find

$$E=\frac{\phi}{S\times 0{\cdot}51},$$

which shows that the illumination is nearly twice as large as it would be in a room with dead-black surroundings. Few rooms are spherical or possess a hemispherical ceiling, so that the reflection follows other laws than those expressed by the above equation. The increase in the illumination depends, then, also upon the size of the room, its height, and the position of the lamps.

If ceiling, walls, and floor take part in the reflection, and if the size of the room is not too large, we should have to use for m the average value, expressed by

$$m = \frac{S_1 m_1 + S_2 m_2 + S_3 m_3}{S_1 + S_2 + S_3} \quad . \quad . \quad . \quad 8.01$$

in which S_1, S_2, S_3 are the areas and m_1, m_2, and m_3 the reflection coefficients of ceiling, walls, and floor respectively. In many cases the reflection from the floor is negligible, especially as the test plane is 1 metre

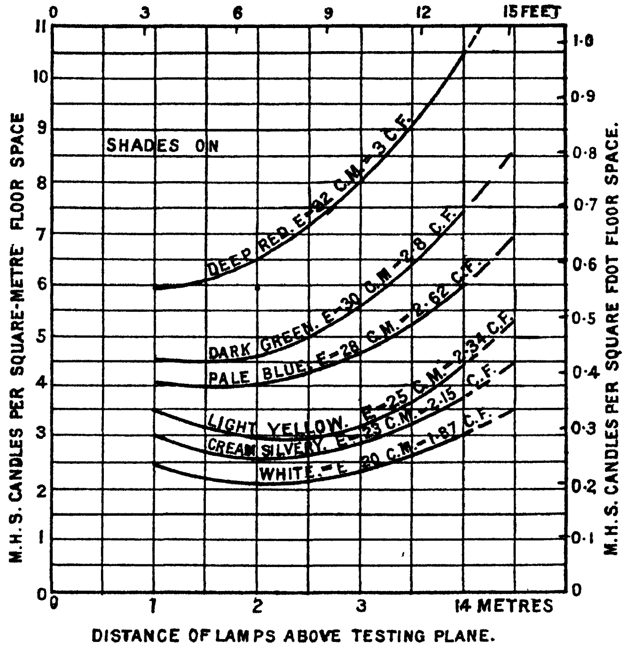


FIG. 8 06.— Illumination required per Unit Area. (Shades on.)

above it. Moreover, furniture, tables, etc., should reflect light as little as possible, to prevent glare.

For practical purposes, not too much reliance should be placed on the value of the reflection coefficient as calculated from formula 8.01, as this value will vary with the shape of the room. Better results are obtained by experiment, and although they cannot be accepted as standards in all cases, they very often give us sufficient information for providing the best illumination for given conditions.

For this purpose tests were carried out in a room 10×6·5=65 square metres (700 square feet), and the results as indicated in figs. 8.06 and 8.07 were obtained.*

Although these tests were carried out with comparatively low illuminations, they can easily be used for higher values simply by multiplying by the factor which is to indicate the increase.

* For details of the tests, see first edition.

Example (*a*) —We are asked to light a room 11 3×5 5=62 square

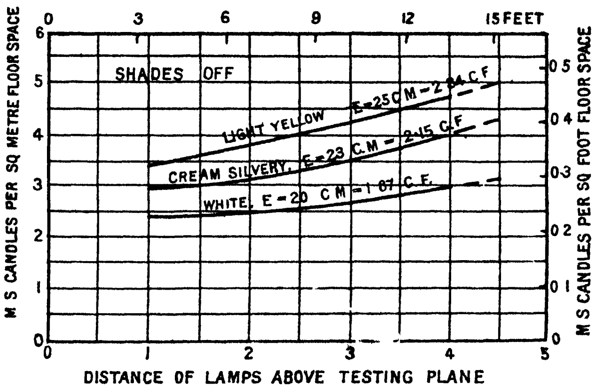


Fig 8 07 —Illumination required per Unit Area (Shades off)

metres (37×18=666 square feet) and having very light walls and ceiling (the room is the common room of the students in the Hiddingh

Fig 8 08 —Illumination of a Student's Common Room *

Hall of the University of Cape Town), so as to produce an average general illumination of about 23 metre-candles (2 15 foot-candles) If we take the curve for cream-silver (the whitewash was not perfectly white) and place the lamps close to the ceiling, which is 5 6 metres (18 4 feet)

* *Illuminating Engineer.*

high, or 4·6 metres (15 feet) above table height, we require per square metre floor space about 4·5 candles (see fig. 8.01) (0·12 candle per square foot), or a total of 280 candles (mean spherical). The actual number of lamps installed is 10, of the 50-watt tungsted type, with a mean spherical intensity of 35 candles, so that the illumination is somewhat larger than is required, to allow for a reduction caused by ageing, etc., in the ratio $\frac{350}{280}=1{\cdot}25$. The illumination should therefore be $1{\cdot}25 \times 23 = 28{\cdot}7$ metre-candles. On testing, the average illumination was found to be 28 metre-candles, which shows a very fair agreement with the figures given in the curves. With the ten lamps uniformly distributed, the degree of uniformity is very high, the value $\frac{\text{maximum illumination}}{\text{minimum illumination}}$ in the testing plane being 1·2.

An untouched photograph of the room is given in fig. 8.08.

8.09. INDIRECT AND SEMI-INDIRECT ILLUMINATION.—Where great diffusion of light is required, indirect illumination will usually give the most satisfactory results. For a given illumination inverted light has to be stronger than direct light, since part of it is absorbed by the reflector. In low rooms the ceiling acts as reflector, whereas for very high ceilings (over 6 metres) it is more economical to use a special reflector above each lamp. The direct light is prevented from reaching the area to be illuminated by means of a reflector placed underneath the lamp. This reflector directs the flux of the lower hemisphere upwards. If it is semi-transparent, we speak of semi-direct illumination. This system is more ornamental, as the bowl or reflector is luminous. It is increasingly employed to-day, the direct transmission being usually about 6 to 12 per cent. of the total flux. It is, of course, impossible to draw the boundary line between direct, semi-direct, and indirect systems.

Speaking generally, indirect light should not be installed in rooms with dark walls and ceilings. Even if we place efficient reflectors above the lamp, the result is not pleasing. If the lighting of a drawing office is to be indirect, the walls and ceiling should be constructed accordingly, the ceiling preferably with a frieze extending down the walls, and the colour of both should be white, or at least a very light yellow. Even then 30 to 50 per cent. of the light is absorbed by the reflecting surfaces.

Of importance is the distance of the lamp from the reflecting surface, as is seen from fig. 8.09. We notice that the illumination is a maximum when the centre of the radiator is about 750 millimetres (27·5 inches) from the ceiling. Actually the best distance depends upon the types of lower reflector and lamps used, and should in each case be determined by an experiment.

Fittings are now so constructed that the lamps take up the correct position automatically.

Where, on account of the great height of the ceiling, a special reflector has to be employed above the lamp, its size should be very large and the lower reflector must be so constructed that no light is reflected past the upper shade, since it would be largely wasted.

The average amount of light required for indirect illumination may be seen from the accompanying Tables 8.06 and 8.07. Both hold for reflecting surfaces about 5 metres (16·4 feet) high. Table 8.06 has been plotted for rooms not exceeding one hundred square metres (1070 square feet) in area, in which the reflection from the walls is considerable, whereas Table 8.07 stands for rooms in which the reflection from the walls is negligible on account of the large size of the rooms. It will be understood readily that less light is required in the latter case, since there

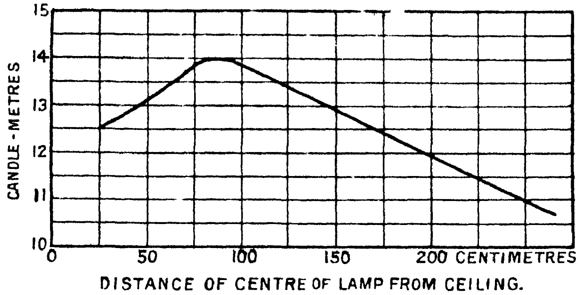


FIG. 8.09.—Best Distance of Radiator from the Reflecting Ceiling.

is no absorption by the walls, the light being able to fall directly on the illuminated area after reflection from the ceiling. Further, the tables are meant for well-distributed lights, *i.e.* the number of square metres floor space allotted to each lamp should not exceed thirty (about 300 square feet). If we use large units, the uniformity of the illumination is reduced greatly, and we might as well employ the direct method. The *average illumination* is little affected by the size of the radiators and the distribution. In both tables the reflectors below the lamp have a reflection coefficient of 0·7. The reflection coefficients of the walls and ceilings considered are 0·7, 0·57, and 0·50 for white, cream silvery, and light yellow respectively.

TABLE 8.06.—INTENSITY OF LIGHT REQUIRED PER UNIT AREA OF FLOOR SPACE (WALLS AND CEILING REFLECTING).

Colour of Walls and Ceiling.	Illumination.		M.S. Candles per Unit Area.	
	Metre-candles.	Foot-candles.	Square Metres.	Square Feet.
White . .	15	1·4	3·8	0·35
Cream silvery .	18	1·68	5·5	0·52
Light yellow .	30	1·87	7·0	0·65

TABLE 8.07.—INTENSITY OF LIGHT REQUIRED PER UNIT AREA OF FLOOR SPACE (CEILING ALONE REFLECTING).

Colour of Ceilings.	Illumination.		M.S. Candles per Unit Area.	
	Metre-candles	Foot candles.	Square Metres.	Square Feet.
White . .	15	1·4	3·1	0·29
Cream silvery .	18	1·68	5·0	0·47
Light yellow .	20	1 87	6 4	0·60

Example (*b*).—We are asked to light a room 10 metres long and 10 metres wide to the extent of 45 metre-candles in a horizontal plane 1 metre above the floor. The room is 5 metres high; ceiling and walls are white.

We divide the room into four squares and place a lamp into the centre of each one. Per square metre floor space we require for 15 metre-candles 3·8, hence for 45, $3 \times 3{\cdot}8 = 11{\cdot}4$, or in all 1140 M.S.C.P. Each lamp must therefore give about 285 M.S.C.P. Four 300-watt gas-filled lamps would answer the purpose and allow for depreciation.

8.10. FLUX OF LIGHT METHOD.—Where reflection is negligible we may proceed as in Chapter IV., paragraphs 4.08 to 4.13, by plotting proper contour lines. Too much account must not be taken of reflection as a rule, especially for outdoor illumination, as lamps depreciate with age, and dirt and dust collect on them, so that the increase due to reflection may soon be counterbalanced. If reflection is taken into account, depreciation must be likewise. Assuming that one counterbalances the other, or that reflection is negligible, as is the case for outdoor lighting, the methods given in Chapter IV. are applicable. They are, however, laborious. The work is simplified if the lights are arranged symmetrically and if their horizontal distributions are circles, which is very nearly the case even with arc lamps if diffusing globes are used.

Further simplifications are introduced by dividing the square or street into rectangles or squares * (from 20 to 30 in number), and by determining the illumination for the centre of each one. For this purpose we must know the distances of these centres from those lamps which take part in the illumination of these points, and by means of the polar curves determine the illumination of the centres from each lamp. By adding all the calculated values and dividing the sum by the total number of squares, we get the average illumination. (See also paragraph 6.28.)

The method looks laborious, but if the lamps are equally spaced and the lights symmetrical and fixed at equal heights above the road surface the number of squares considered need not be so very large. The method

* Dr Bloch, *E.T.Z.*, 1906, p. 493.

is at least useful in cases where the illumination is already installed. The division into squares of places and streets is indicated in fig. 8.10.

For a precalculation of street lighting, Dr Bloch advocates a further simplification.* The street is divided into such a number of rectangles or squares that for each one we have one lamp, which is placed in the centre. This area is then changed into an equal circular one, and it is assumed that no other lamp takes part in the illumination. This introduces two errors. By changing the rectangle into a circle and calculating the illumination for the latter, we obtain a value which is too large. On the other hand, by neglecting the light from other sources, we obtain an average value which is too small. These errors partly neutralise one another; the remainder may be expressed by a factor K_1, with which the calculated average illumination has to be multiplied in order to obtain a more correct value. Dr Bloch gives this factor for street lighting as $K_1 = 1{\cdot}2 - 0{\cdot}1\gamma$, where γ is the ratio $\dfrac{\text{distance between lamps}}{\text{width of street}}$.

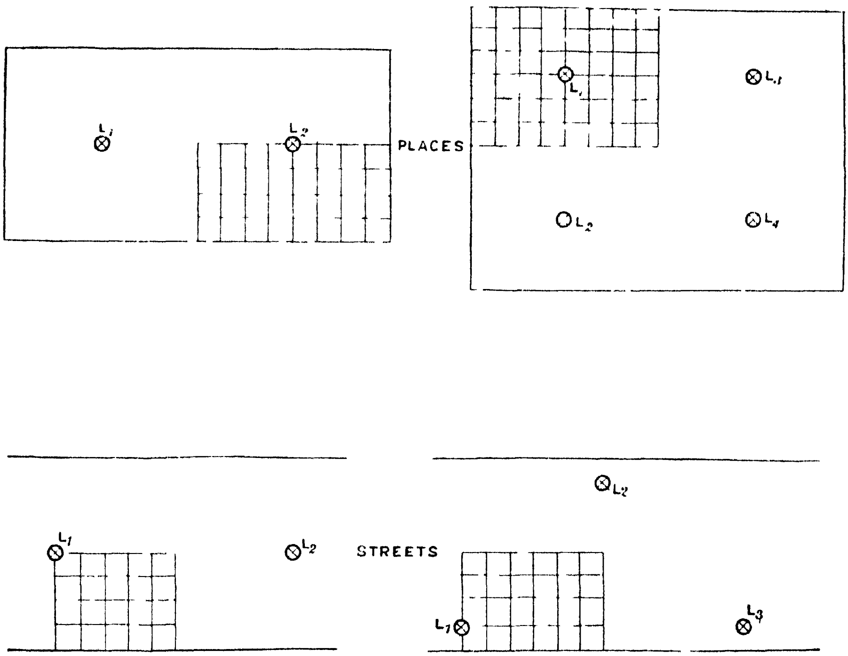


FIG. 8.10.—Dividing an Area into Squares.

The distance between the lamps is measured in the direction of the street, even if the lamps are staggered. The average illumination is found from equation 6.05a, viz.

$$\overline{E} = \frac{\phi^{\theta}}{S}.$$

(See also fig. 6.04.)

* See *E.T.Z.*, 1906, p. 493.

The method shown in fig. 6.04 possesses the advantage that the luminous flux has to be derived from the luminous intensity or polar curve once only, and that we can obtain from it the value of the flux for any lamp height and any radius a_1 of the circular area to be illuminated. It may even be applied for lamps of different intensities, as long as their light distribution is similar; the values of ϕ^θ taken from the curve have then simply to be multiplied by a known ratio.

It is advisable to plot normal luminous intensity (polar) and luminous flux curves always ready for use for different types of lamps, for a round number of mean spherical or mean hemispherical candles– for instance, for 3000 candles (see fig. 6.04).

When the mean horizontal illumination and the area are specified, we find

$$\phi^\theta = \mathrm{S}\overline{\mathrm{E}}.$$

For the radius corresponding to the area S and a given or assumed height h we find the angular region θ_1, and from the luminous flux curve the corresponding value ϕ^{θ_1} at 3000 M.H.S.C.P. From the ratio of the calculated value ϕ^θ to the value of ϕ^{θ_1} for 3000 candles we then obtain the required intensity of the lamp.

In the formula

$$\overline{\mathrm{E}} = \frac{2\pi}{\mathrm{S}}\int_0^\theta \mathrm{I}d(\cos\theta) = \frac{\phi^\theta}{\mathrm{S}}$$

the height h is contained indirectly. For if for a constant area S the lamp is raised more and more, the angular region, and thus the flux, becomes smaller and smaller. The degree of uniformity, is, however, improved thereby.

Example (*c*).—A street 60 metres wide is to be illuminated by arc lamps 100 metres apart. The polar distribution of the lamp used is shown in fig. 6.04. The lamps are fixed on poles 16 metres high or 15 metres above the standard plane. We are asked to find the average illumination.

The area to be illuminated is $60 \times 100 = 6000$ square metres. This area corresponds to a circular one with a radius of 43·7 metres. We plot the angle θ_1 given by the height of 15 and the radius of 43·7 metres and find the flux inside this angle from the luminous flux curve. We get $\phi^{\theta_1} = 12{,}700$ lumens. The factor K_1 is expressed by

$$\mathrm{K}_1 = 1{\cdot}2 - 0{\cdot}1\gamma = 1{\cdot}2 - 0{\cdot}1 \times \frac{100}{60} = 1{\cdot}033,$$

whence

$$\overline{\mathrm{E}} = 1{\cdot}033 \times \frac{12{,}700}{6000} = 2{\cdot}18 \text{ metre-candles.}$$

Example (*d*).—A street 150 feet wide shall be given an average illumination of 0·25 foot-candle. The lamps are to be of the type shown in fig. 6.04, fixed on poles 45 feet high (or 42 feet above the testing plane) and 300 feet apart. Find the mean spherical candle-power required.

We have

$$\bar{E}=K\frac{\phi^{\theta}}{S},$$

$$K=1{\cdot}2-0{\cdot}1\times\frac{300}{150}=1{\cdot}0,$$

whence

$$\phi^{\theta}=\frac{150\times300\times0{\cdot}25}{1}=11{,}250 \text{ lumens.}$$

We plot again the angle θ_2 corresponding to a height of 42 feet and a radius of

$$\sqrt{\frac{150\times300}{\pi}}=119{\cdot}5 \text{ feet,}$$

and find $$\phi^{\theta_2}=12{,}000.$$

The ratio $$\frac{11{,}250}{12{,}000}=0{\cdot}937;$$

hence the mean hemispherical candle-power of the lamp must be $0{\cdot}937\times3000=2800$ candles approximately.

In a similar manner we can find for given areas, illumination, and

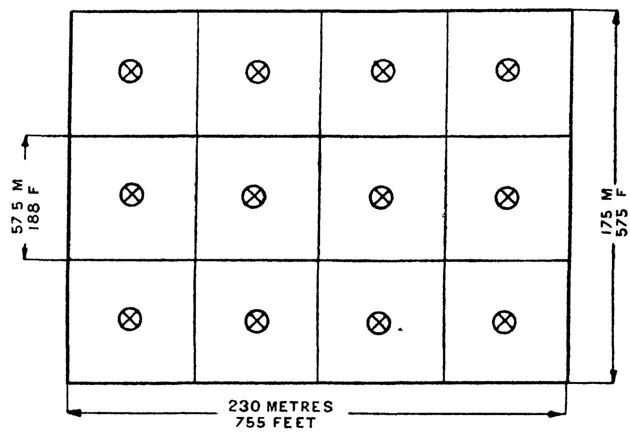


FIG. 8.11.—Arrangement of Arc Lamps.

M.H.S.C.P., the height at which the lamps must be fixed, or for standard poles, illumination, and lamps, the distances between the lamps.

Reflection has been entirely neglected in these examples. In manufacturing towns it will be negligible, but in countries such as South Africa, where the buildings are white, the illumination is considerably increased and improved in uniformity by the reflection from the houses.

Example (*e*).—It is required to illuminate a town square as uniformly as possible by means of arc lamps with polar curves according to fig. 8.12.

The area has a length of 230 metres, and a breadth of 175 metres, containing therefore 40,000 square metres. The illumination must not be less than 5 metre-candles.

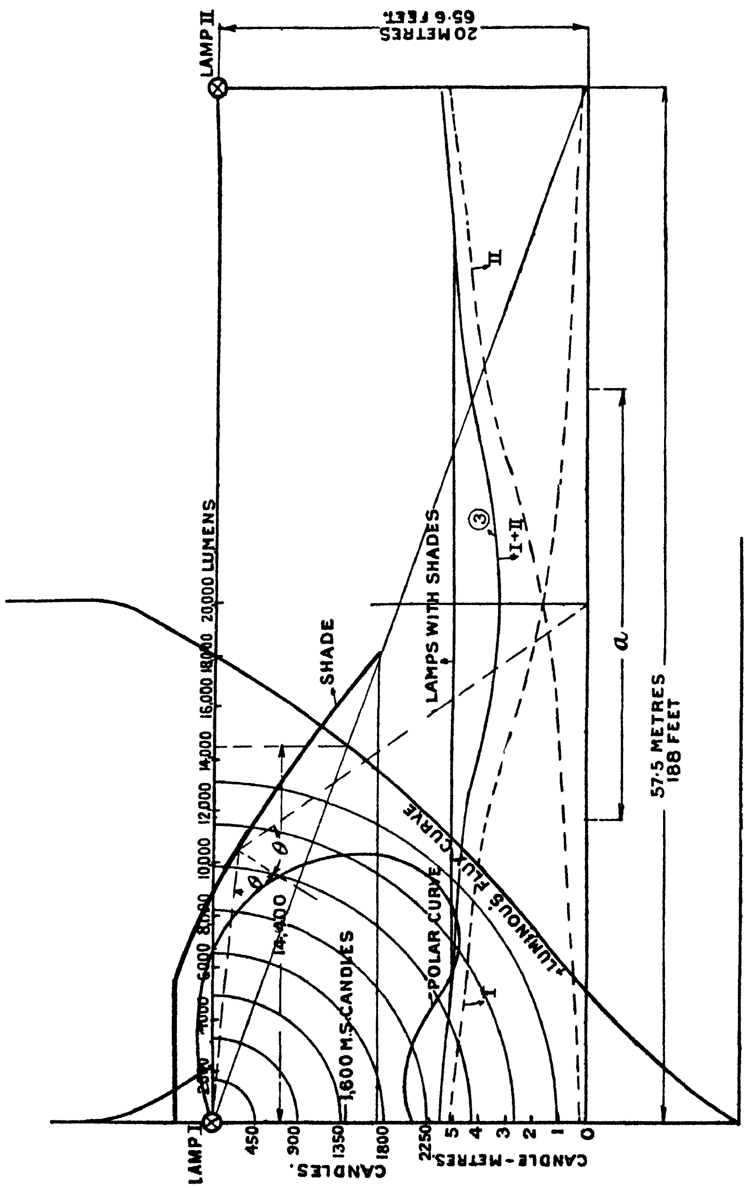


FIG. 8.12.—Design of Reflector for Arc Lamps.

The flux from each lamp is 20,000 lumens (from 1600 M.S.C.P.), so that, since we require a flux of $5 \times 40,000 = 200,000$ lumens, ten lamps are wanted, assuming that the whole flux is utilised. As the flux into the upper hemisphere is already small, we shall be safe if we assume a total loss of 20 per cent., which means that we must employ twelve instead of ten lamps.

Therefore divide the area into twelve squares of 57·5 metres a side, and place one lamp in the centre of each square, according to fig. 8.11. The distance between the lamps is then 57·5 metres. We may now proceed in two ways.

(*a*) Provide each lamp with a reflector which limits the flux approximately to its particular square. This method is physiologically poor, because the shadows thrown by objects will be very dark and appear like obstructions, as no other lamp is able to illuminate the shadow and enable us to see objects in it.

(*b*) Use the natural distribution of the light of the lamp as far as possible, and only where the light is insufficient allow the reflector to add to the illumination. The method, indicating the design of the reflector, is clearly shown in fig. 8.12. Let the light of each lamp be able to reach as far as the post of the next lamp. Above the angle corresponding to this distance, the shade cuts off the light. Curve 3 gives the illumination when the lamps are without reflectors. The illumination is already uniform. The degree of uniformity is further improved by utilising the light flux above the angle and by directing it chiefly to areas half-way between the lamps. The value of this flux is 5600 lumens. Suppose 30 per cent. of it is absorbed by the reflector, *i.e.* 1680 lumens, then 3920 lumens from each lamp are available for raising the illumination between the lamps. The area of the ring surface, indicated by the letter *a* in fig. 8.12, which requires an increase in the illumination, is about 3600 square metres, so that the average increase is about $\frac{2 \times 3920}{3600} = 2{\cdot}17$ metre-candles. The illumination without the reflector, right under the lamp, is 5·6 metre-candles; half-way between it is 3·3. By adding 2·17 to the latter, we get 5·47. We must, however, direct somewhat more light towards the area of minimum illumination and less where the curve rises, by shaping the reflector accordingly, and the illumination can be made as uniform as desired.

8.11. DETERMINATION OF THE RATIO K_u.—In order to be able to judge the quality of an illumination we should know the ratio $K_u = \frac{\text{maximum illumination}}{\text{minimum illumination}}$. This ratio is easily obtained if we possess the illumination curve for each lamp. It has already been pointed out in Chapter IV. (see fig. 4.18) that the degree of uniformity of an illumination is not altered if we vary the distance between the lamps as long as the height of the radiator above the illuminated area is changed proportionally, *i.e.* as long as $\frac{2a_1}{h}$ remains constant. Neither do we alter the factor K_u if we replace a set of lamps by another set of characteristically the same distribution. For every particular type of lamp we may therefore plot the ratio K_u for various values of $\frac{2a_1}{h}$ always ready for use, as has been done for the Siemens T.B. lamp, illustrated by its polar curve in fig. 8.12, in the accompanying fig. 8.13.

To illustrate the method, let us take the lamp of fig. 8.12. The

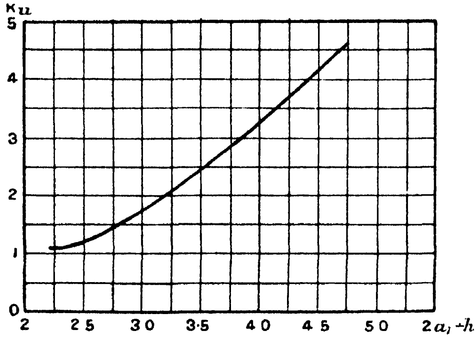


FIG. 8.13.—The Ratio K_u for various Values of $\frac{2a_1}{h}$ for a Siemens T.B. Lamp.

lamps are fixed in the centre of a road 30 metres wide. The illumination will be a minimum half-way between the lamps near the edge of the road and not on the line joining the lamps (see fig. 8.14). The distance from

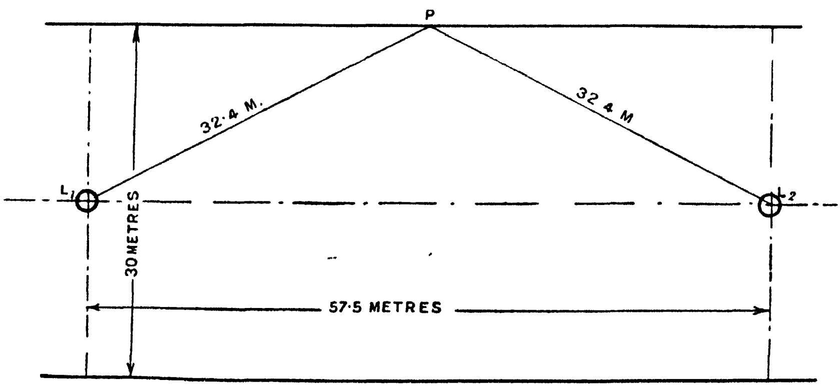


FIG. 8.14.—Arrangement of Lamps.

L_1 to L_2 through P is 64·8 metres, so that $\frac{2a_1}{h}=3{\cdot}24$. For this ratio we get from fig. 8.13 for K_u a value of 2·06, while for the middle of the road $\frac{2a_1}{h}=2{\cdot}87$ and $K_u=1{\cdot}625$.

8.12. P. HÖGNER'S METHOD FOR DETERMINING THE MEAN HORIZONTAL ILLUMINATIONS OF STREETS AND SQUARES.*—

* *E.T.Z.*, 1910, p. 234. See also Thomälen, *E.T.Z.*, 19th December 1912, p. 1313, who has corrected Table 8.08.

As streets and squares are usually rectangular, they may easily be subdivided into a number of squares, according to fig. 8.15. The determination of the illumination is then reduced to the evaluation of the illumination of these squares. The method is indicated in fig. 8.16. The height of the illuminant shall be unity, we then have for any given point P of the X Y plane (fig. 8.16) $x = \tan\beta$, $y = \tan\gamma$, where β and γ are the angles, by

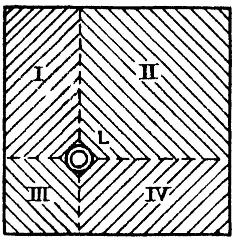


FIG. 8.15.—Subdivision of Area (Hogner).

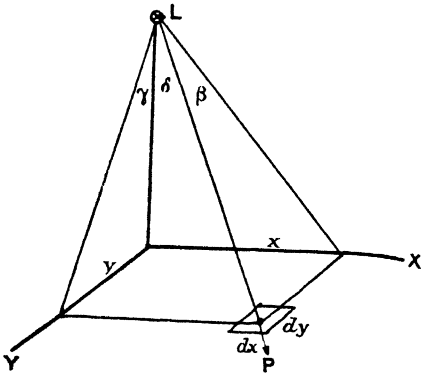


FIG. 8.16.—Determination of ω

which the main planes through point P are inclined towards the vertical plane. If the connecting line between the illuminant and point P forms the angle δ with the perpendicular,

$$\tan^2\delta = x^2 + y^2 \text{ or } \cos\delta = \frac{1}{(1+x^2+y^2)^{\frac{1}{2}}}.$$

The elementary area round P is $dxdy$. Its projection upon a plane perpendicular to a ray L P is $dxdy \cos\delta$. This is at the same time an elementary area of a spherical surface of radius L P. The corresponding solid angle, *i.e.* the surface area on the sphere of radius unity, is then

$$d\omega = \frac{dxdy\cos\delta}{\text{LP}^2}. \quad \text{As } \frac{1}{\text{LP}^2} = \cos^2\delta,$$

$$d\omega = dxdy\cos^3\delta = \frac{dxdy}{(1+x^2+y^2)^{\frac{3}{2}}}.$$

Hence the spherical angle corresponding to the elementary area in fig. 8.16 is

$$\omega = \int_{x_1}^{x_2}\int_{y_1}^{y_2} \frac{dxdy}{(1+x^2+y^2)^{\frac{3}{2}}}$$

$$= \tan^{-1}\left(\frac{1+y_2^2+y_2\sqrt{1+x_2^2+y_2^2}}{x_2}\right) - \tan^{-1}\left(\frac{1+y_1^2+y_1\sqrt{1+x_2^2+y_1^2}}{x_2}\right)$$

$$-\tan^{-1}\left(\frac{1+y_2^2+y_2\sqrt{1+x_1^2+y_2^2}}{x_1}\right)$$

$$+\tan^{-1}\left(\frac{1+y_1^2+y_1\sqrt{1+x_1^2+y_1^2}}{x_1}\right) \quad . \quad 8.02$$

In the accompanying Table 8.08 the spherical angles ω have been plotted under the assumption that the principal planes are placed 10 degrees apart. The corresponding values of tan α, where α is the angle

TABLE 8.08.—VALUES FOR ω AND TAN α (HÖGNER-THOMÄLEN).

L.	10°	20°	30°	40°	50°	60°	70°	80°	90°
10°	tg α = 0·1235 ω = 0·03015	0·282 0·02928	0·457 0·02750	0·702 0·02492	1·002 0·02156	1·430 0·01755	2·150 0·01295	3·733 0·00794	11·430 0·00268
20°	tg α = 0·282 ω = 0·02928	0·379 0·02853	0·5385 0·02711	0·750 0·02489	1·035 0·02188	1·453 0·01805	2·160 0·01354	3·740 0·00840	11·433 0·00285
30°	tg α = 0·475 ω = 0·02750	0·5385 0·02711	0·660 0·02621	0·842 0·02472	1·102 0·02243	1·502 0·01916	2·195 0·01479	3·760 0·00941	11·440 0·00321
40°	tg α = 0·702 ω = 0·02492	0·750 0·02489	0·842 0·02472	0·990 0·02420	1·220 0·02306	1·590 0·02075	2·255 0·01689	3·795 0·01116	11·452 0·00394
50°	tg α = 1·002 ω = 0·02156	1·035 0 02188	1·102 0·02243	1·220 0·02306	1·414 0 02335	1·740 0·02271	2·365 0·02005	3·860 0·01426	11·472 0·00523
60°	tg α = 1·430 ω = 0·01755	1·453 0·01805	1·502 0·01916	1·590 0·02075	1·740 0·02271	2·020 0·02448	2·580 0·02437	4·000 0·01964	11·52 0·00783
70°	tg α = 2·150 ω = 0·01295	2·160 0·01354	2·195 0·01479	2·255 0·01689	2·365 0·02005	2·580 0·02437	3·035 0·02902	4·300 0·02906	11·63 0·01386
80°	tg α = 3·733 ω = 0·00794	3·740 0·00840	3·760 0·00941	3·795 0·01116	3·860 0·01426	4·000 0·01964	4·300 0·02906	5·28 0·04260	12·024 0·03206
90°	tg α = 11·430 ω = 0·00286	11·433 0·00285	11·440 0·00321	11·452 0·00394	11·472 0·00523	11·52 0·00783	11·63 0·01386	12·024 0·03206	12·70 0·10287

formed by the vertical and the ray from the source to the centre of each section are expressed by $\tan \alpha = \sqrt{\tan^2 \gamma + \tan^2 \beta}$. With the aid of this table we are able to find for any given angle α (represented by its tangent) and the corresponding intensity as shown by the polar curve, the flux within the considered pyramid, simply by multiplying the intensity by the spherical angle. The fluxes are now arranged in tabular form, according to Table 8.09, and added up from the zero point L outwardly. The upper values represent the fluxes for the different pyramids, the lower ones the sums of the various fluxes counted from L. For instance, the flux striking the field *a b c d* is 189 lumens; for *a c f g* it is 458. The

TABLE 8.09.—VALUES FOR ϕ (SEE POLAR CURVE OF FIG. 8.18) (HÖGNER).

L.	*a* 10°	20°	30°	*b* 40°	50°	*c*
	Direction y→up to 90°.					
up to 90°←Direction x 10°	24 24	32 56	34 90	30 120	26 146	
20°	32 56 *d*	34 122	33 189	31 250 *e*	26 302	
30°	34 90 *g*	33 189	33 289	30 380	26 458	*f*

area *a b c d* reaches up to two sections of 10 degrees each on the vertical plane x and to three sections of 10 degrees each on the horizontal plane y.

It is sufficient to tabulate these values once only for lamps of similar type but different intensities, since the light fluxes are proportional to the mean hemispherical candle-powers. Thus, if we plot the table for 1000 M.H.S.C.P., we obtain the results for 500 candles by multiplying the values of the table by 0·5.

Example (*f*).—A place 15·56 metres long and 14·16 metres wide is to be

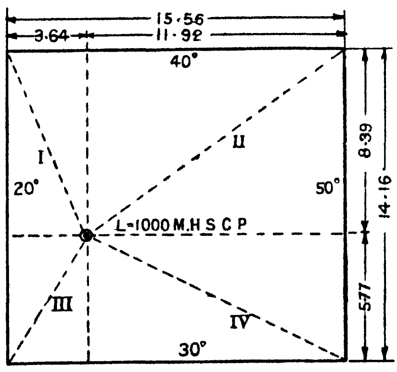


FIG. 8.17.—Position of Lamp in Example 8.06.

illuminated with an arc lamp fixed 10 metres high. The position of the lamp is shown in the accompanying fig. 8.17. We divide the area into four rectangles I, II, III, IV. Rectangle I reaches up to 20 degrees in the x axis and to 40 degrees in the y axis and receives, according to Table 8.10, from a lamp with a polar distribution according to fig. 8.18, 250 lumens. (In this table the sums only have been inserted.) For the other rectangles we have 603, 189, and 453 lumens. The total flux is thus 1500

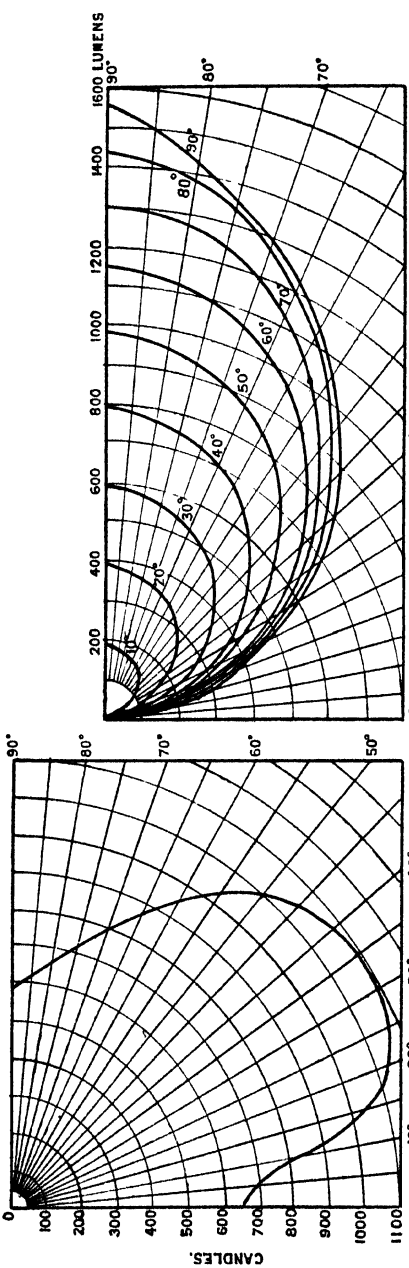


FIG. 8.18.—Polar Curve and Light Flux Diagram used in Example (*f*).

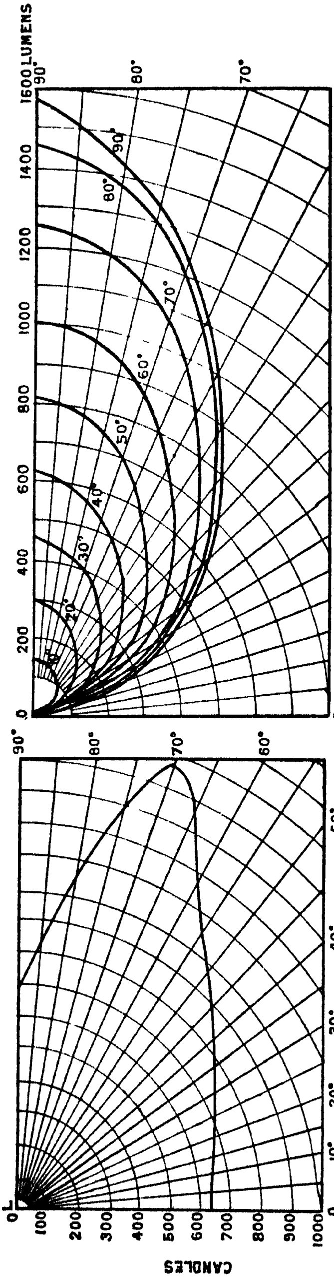


FIG. 8.19.—Polar Curve and Light Flux Diagram for Example (*g*).

lumens. The average illumination is therefore $\overline{E} = \frac{1500}{15{\cdot}56 \times 14{\cdot}6} = 6{\cdot}8$ metre-candles. The flux diagram for one quadrant is also shown in

TABLE 8.10.—VALUES OF ϕ FOR EXAMPLE (HÖGNER).

L.	10°	20°	30°	40°	50°	60°	70°	80°	90°
10°	24	56	90	120	146	165	177	185	188
20°	56	122	189	250	302	340	365	380	387
30°	90	189	289	380	458	515	558	578	590
40°	120	250	380	500	603	685	740	770	788
50°	146	302	458	603	732	840	910	955	975
60°	165	340	515	685	840	970	1060	1120	1140
70°	177	365	558	740	910	1060	1190	1265	1300
80°	185	380	578	770	955	1120	1265	1390	1425
90°	188	387	590	788	975	1140	1300	1425	1570

fig. 8.18; this diagram will be found useful when the rectangles do not end at 20, 30, etc., degrees. In the table the sums only are given.

Example (*g*).—A street 25 metres wide is to be illuminated with Excello lamps having polar curves as shown in fig. 8.19. The lamps are

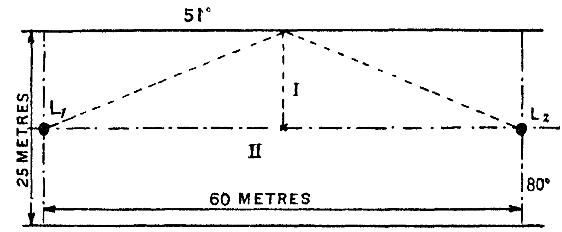


FIG. 8.20.—Arrangement of Lamps in Example (*g*).

fixed in the middle of the road 10 metres above the ground. The arrangement is illustrated in fig. 8.20. We plot Table 8.11, from which we see

TABLE 8.11.—VALUES OF ϕ FOR EXAMPLE (HÖGNER).

L.	10°	20°	30°	40°	50°	60°	70°	80°	90°
10°	19	38	57	75	94	112	130	141	144
20°	38	76	114	143	190	226	263	285	295
30°	57	114	172	229	286	345	400	436	455
40°	75	143	229	307	387	467	548	600	620
50°	94	190	286	387	490	598	705	778	816
60°	112	226	345	467	598	735	880	975	1000
70°	130	263	400	548	705	880	1075	1210	1240
80°	141	285	436	600	778	975	1210	1390	1440
90°	144	295	455	620	810	1000	1240	1440	1570

that part I of the street receives 795 lumens from lamp L_1 (inclination is

51 and 80 degrees). The total street surface receives therefore from both lamps L_1 and L_2 $4\times 795=3180$ lumens, and as the area is $60\times 25=1500$ square metres, the average illumination is $\bar{E}=\frac{3180}{1500}=2\cdot 12$ metre-candles. The lamp employed has an intensity of 1000 M.H.S.C.P. For 2000 M.H.S.C.P. the illumination would have been 4·24 metre-candles.

Example (*h*).—The same lamps are arranged according to fig. 8.21. From Table 8.11, or from the flux diagram of fig. 8.19, we obtain for area I a flux of 278 lumens and for area II, 1092 lumens. From both lamps the flux is thus $2\times(278+1092)=2740$ lumens, and the average illumination is $\bar{E}=\frac{2740}{1500}=1\cdot 82$ metre-candles. We see that, if we stagger the

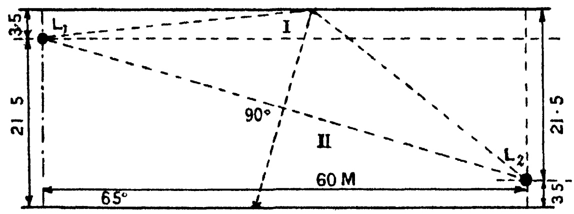


FIG. 8.21.—Arrangement of Lamps in Example (*h*).

lamps, the illumination is less than when the lamps are fixed above the middle of the road.

In a similar manner we may determine the mean illumination of vertical planes.

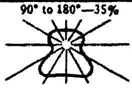
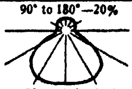
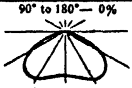
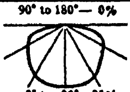
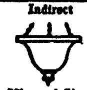
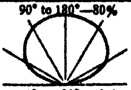
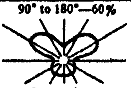
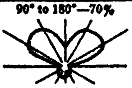
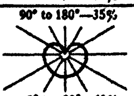
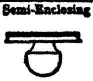
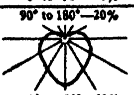
8.13. EFFICIENCY OF UTILISATION.—When light flux is to be principally directed to a given plane, the ratio of the flux delivered thereon to the total flux produced by the illuminants is called the efficiency of utilisation. This ratio depends largely upon the type of reflector used, the coefficient of reflection of the surroundings, and the ratio $\frac{\text{room width}}{\text{ceiling height}}$. The absolute height at which lamps are mounted has in itself little influence upon the percentage of light utilised, as long as the same proportions are maintained. For instance, if in one building 20×40 feet and 10 feet high there are eight 100-watt lamps, and in another 40×80 feet and 20 feet high there are eight 400-watt lamps, the illumination for similar reflection coefficients and lamp efficiencies will be the same.

In the *General Electric Review* of June 1918, Ward Harrison gives a very useful table of coefficients of utilisation for the more common type of reflectors, which also includes the amount of absorption by the shades employed. Thus in the prismatic glass reflector, of the flux produced, $100-(65+22)=13$ per cent. is lost by absorption. The table is otherwise self-explanatory.

Example (*i*).—A large draper's shop 100×60 feet with a ceiling

TABLE 8.12.—COEFFICIENTS OF UTILISATION.

This table applies to installations in *square rooms* having sufficient lighting units symmetrically arranged to produce reasonably uniform illumination. To obtain the coefficient for any rectangular room, find the value for a square room of the narrow dimension and add one-third of the difference between this value and the coefficient for a square room of the long dimension.

Reflection Factor		Ceiling	Light 70%			Medium 50%		Dark 30%
		Walls	Light 50%	Medium 35%	Dark 20%	Medium 35%	Dark 20%	Dark 20%
Reflector Type	Light Output	Ratio = Room Width / Ceiling Height						
Prismatic Glass  Bowl-Frosted Lamp	90° to 180°—22%  0° to 90°—65%	1	.42	.38	.35	.36	.34	.33
		1½	.50	.46	.43	.44	.42	.41
		2	.56	.52	.49	.50	.47	.45
		3	.63	.59	.55	.56	.53	.51
		5	.70	.66	.63	.63	.60	.57
Light Opal  Bowl-Frosted Lamp	90° to 180°—35%  0° to 90°—50%	1	.31	.27	.24	.24	.21	.18
		1½	.37	.33	.30	.30	.27	.24
		2	.43	.39	.35	.34	.31	.27
		3	.49	.45	.41	.39	.36	.31
		5	.56	.52	.48	.45	.42	.36
Dense Opal  Bowl-Frosted Lamp	90° to 180°—20%  0° to 90°—60%	1	.41	.37	.34	.35	.33	.32
		1½	.49	.45	.42	.43	.41	.39
		2	.54	.50	.47	.48	.46	.44
		3	.60	.56	.53	.53	.51	.49
		5	.67	.63	.59	.59	.57	.54
Steel Bowl  Porcelain Enameled	90° to 180°— 0%  0° to 90°—65%	1	.38	.36	.34	.35	.33	.33
		1½	.45	.43	.41	.42	.40	.40
		2	49	.47	.45	.46	.44	.44
		3	.54	.52	.50	.51	49	.49
		5	.59	.57	.55	.56	.54	.54
Steel Dome  Porcelain Enameled	90° to 180°— 0%  0° to 90°—80%	1	.43	.40	.38	.39	.37	.37
		1½	.52	.49	.47	.48	.46	.46
		2	.57	.54	.52	.53	.51	.51
		3	.63	.60	.58	.59	.57	.57
		5	.69	.66	.64	.65	.63	.63
Indirect  Mirrored Glass	90° to 180°—80%  0° to 90°— 0%	1	.22	.19	.17	.14	.12	.07
		1½	.27	.24	.22	.17	.15	.09
		2	.31	.28	.26	.20	.18	.11
		3	.36	.33	.31	.24	.22	13
		5	.42	.39	.37	.28	.26	.16
Semi-Indirect  Light Opal	90° to 180°—60%  0° to 90°—25%	1	.27	.24	.21	.20	.17	14
		1½	.34	.30	.27	.25	.22	.18
		2	.39	.35	.32	.29	.26	.21
		3	.45	.41	.38	.34	.31	.25
		5	.51	.47	.44	.40	.37	.29
Semi-Indirect  Dense Opal	90° to 180°—70%  0° to 90°—10%	1	.24	.21	.19	.16	.14	.10
		1½	.30	.27	.24	.20	.18	.13
		2	.34	.31	.23	.23	.21	.15
		3	.39	.36	.33	.27	.25	.18
		5	.45	.42	.39	.32	.30	.21
Enclosing  Light Opal	90° to 180°—35%  0° to 90°—40%	1	.23	.20	.17	.18	.16	.14
		1½	.30	.26	.23	.24	.21	.19
		2	.35	.31	.28	.28	.25	.22
		3	.41	.37	.34	.33	.30	.26
		5	.48	.44	.41	.39	.36	.31
Semi-Enclosing  Opal Bowl	90° to 180°—20%  0° to 90°—60%	1	.32	.28	.26	.27	.25	.23
		1½	.40	.36	.33	.34	.32	.30
		2	.45	.41	.38	.39	.37	.35
		3	.52	.47	.44	.45	.42	.40
		5	.59	.54	.51	.51	.48	.46

height of 14 feet is to be given an illumination of 10 foot-candles. The walls are covered with shelves and must therefore be considered dark, whereas the ceiling is of light yellow with a reflection coefficient of about

50 per cent. The arrangement of the room is shown in the accompanying fig. 8.22. The construction lends itself readily to the production of a fairly uniform illumination by placing a lamp into the centre of each square. The ratio $\frac{\text{room width}}{\text{ceiling height}}$ is thus $\frac{20}{14} = 1{\cdot}43$. From Table 8.12 we see that for the given arrangement we require a reflector of the extensive type. Employing prismatic shades, the utilisation coefficient will lie between 0·34 and 0·42, the mean value being 0·38. As the area is 6000 square

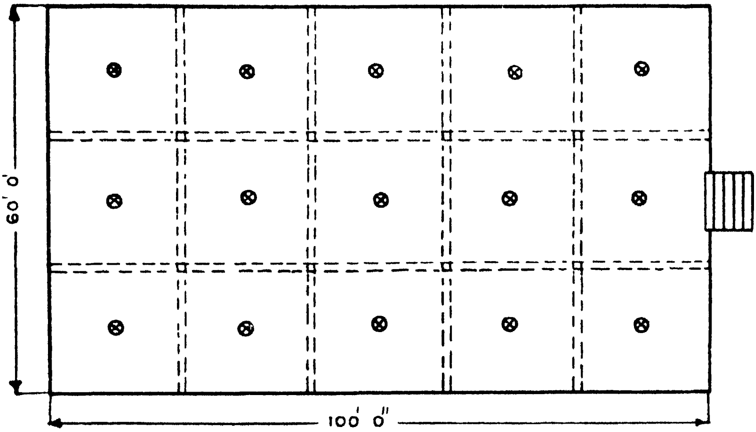


FIG. 8.22.—Illumination Design: Draper's Store.

feet and the illumination desired 10 foot-candles, the effective flux must be equal to 60,000 lumens, and the ten lamps must produce $\frac{60,000}{0{\cdot}38} = 157,900$ lumens. Reckoning further a depreciation factor of 1·25, we must instal lamps emitting $1{\cdot}25 \times 157,900 = 197,375$ lumens. With fifteen lamps this would mean 13,145 lumens per lamp. 750-watt gas-filled lamps for 110 volts give about 13,000 lumens, whereas 1000-watt lamps produce 19,000 (see Table 6.02). The former would be selected. For fifteen lamps the expenditure of power would be 11·25 kilowatts, so that per square foot of floor area it is 1·87 watts. This is high, due to the intensive illumination required. If daylight lamps have to be employed, the expenditure would be about 35 per cent. above the figure given above for the same illumination.

For facilitating illumination designs, charts may be constructed. A useful one is described and illustrated by A. J. Sweet in the *Electrical World*, 19th April 1919, and in the *Illuminating Engineer* of July 1919, p. 192, to which the reader is referred.

8.14. WATTS PER UNIT AREA METHOD.—The illumination is designed in this case by allocating a given number of watts per unit area floor space. The method is only to be recommended if the illuminating power of the type of lamp to be employed is accurately known. It then amounts to working the flux of light method backwards. For instance, in example 8.09 (*b*) the illumination is to be 45 metre-candles, and the lamps have to produce 1140 mean spherical candles to obtain this. Employing gas-filled lamps, we require about 0·9 watt per candle, so that the watts used will be 1026 watts, or 10·26 watts per square metre.

1140 M.S.C.P. give 14,328 lumens, so that with 100 square metres area the utilisation coefficient is $\frac{45}{143} \doteq 0{\cdot}32$. This agrees fairly well with the figures in Table 8.12 for indirect or semi-indirect lighting, taking into consideration that ceiling and walls are white.

A very convenient table is published by the General Electric Company in the handbook on *Incandescent Lamp Illumination*, 1916, p. 47. The figures in this table give the efficiency of the system in terms of effective lumens per watt. We simply determine the total effective lumens required for a specified illumination and divide these by the values given in Table 8.13 to obtain the watts wanted. The table has been plotted for lamps giving 10 lumens per watt (about 1 watt per mean horizontal candle-power).

TABLE 8.13.—LUMENS PER WATT CONSTANTS.

FOOT-CANDLES PER WATT PER SQUARE FOOT.

Ceiling . .	Light.			Medium.			Dark.	
Walls	Light.	Medium.	Dark	Light.	Medium.	Dark.	Medium.	Dark.
Prismatic clear .	5·3	4·7	4·3	4·6	4·3	4·0	3·7	3·6
Prismatic satin finish .	4·5	4·2	3·8	4·2	3·8	3·6	3·3	3·2
Bowl type steel reflectors E or I, aluminium or porcelain enamel	4·3	4·1	3·9	4·2	4·0	3·9	3·9	3·9
Dense opal . . .	4·8	4·6	4·3	4·5	4·3	4·1	4·1	4·1
Medium density opal . .	4·5	4·1	3·8	4·0	3·8	3·4	3·3	3·2
Light density opal . .	4·2	3·8	3·5	3·7	3·5	3·1	3·0	2·9
Shallow bowl aluminium finish and shallow dome porcelain enamel finish steel . .	4·7	4·5	4·3	4·6	4·4	4·3	4·3	4·3
Holophane realites . .	4·5	4·2	3·9	4·0	3·8	3·4	3·2	3·1
Indirect and semi-indirect .	2·8	2·5	2·3	1·9	1·7	1·5	1·0	0·9
Bare lamp	3·6	3·1	2·6	3·1	2·6	2·2	2·1	1·9

Example (*k*).—Considering the previous example in paragraph 8.13, we require per square foot $10 \times 1{\cdot}25 = 12{\cdot}5$ lumens ($1{\cdot}25$ = depreciation factor). For prismatic clear reflectors, medium light ceilings and dark walls, the factor is 4, hence the watts per square foot at 10 lumens per watt would be $\frac{12{\cdot}5}{4} = 3{\cdot}125$. As we employ gas-filled lamps which provide $\frac{13{,}000}{750} = 17{\cdot}3$ lumens per watt (Table 6.02) the actual wattage per square foot of area is $\frac{10}{17{\cdot}3} \times 3{\cdot}125 = 1{\cdot}80$ watts. This agrees fairly well with the previous results.

In all public places, such as large theatres, assembly halls, large factories, etc., in addition to the ordinary lighting circuits there should be so-called pilot systems, which are independent of the general lighting and which are available if the main circuits fail. In theatres coloured lamps may be used which indicate at the same time the way to the exit.

On board ship there is as a rule an oil or petrol engine-driven dynamo set on the top deck which supplies lighting current if the main generators have been placed out of action. The set is sometimes replaced by a secondary battery. By providing sufficient light to move about in case of accidents, panics may usually be avoided.

8.15. DETAILED INSTRUCTIONS ON INDOOR ILLUMINATION DESIGN.- **Private Houses.**—When a house is being built, a generous supply of outlets should be provided. This can then be accomplished without great additional expenditure, and the value of the house greatly increases thereby.

Bare filament lamps should not be in sight, as they are nearly always unsatisfactory. Where lamp bulbs can be seen, they should be frosted, especially if the illuminant is a gas-filled lamp. Sharp shadows will then usually be avoided. Semi-darkness should be absent, and unsatisfactory fixtures should no longer be installed. The chandelier with sloping arms and short shades, which do not shade at all, are out of date.

Entrance Hall.—Care should be taken that the doorstep, which is preferably whitened, is well lighted to the extent of 1·5 to 2 foot-candles, and the lamp is preferably so placed above the front door or adjacent to it, and shaded, that the whole entrance is properly illuminated without causing sharp shadows. Generally a frosted lamp will be preferable to a clear one. The name of the house should be made visible, either by placing it close to the lamp or by putting it across the window over the maindoor, so that the corridor lamp makes it prominent. In the latter case it is not essential to burn the lamp over the front entrance or on the stoep.

The illumination of the hall should be about 2 foot-candles, and must be well diffused. In a small hall a single lamp close to the ceiling may suffice, but where there is a large mirrored hall-stand, brackets on both sides of the stand give better results. Large halls are best illuminated with indirect or semi-indirect light, if walls and ceiling are of light colour. Low hanging chandeliers are out of date, and converted gas chandeliers or lanterns usually give poor results.

Living Room.—We must aim at a restful appearance and avoid monotony. The illumination indicated in Table 3.01 is the absolute minimum. By supplying adequate outlets it should be possible to vary the light, for instance, by means of portable lamps, such as indicated in fig. 7.37. A sole central ceiling fitting will soon become monotonous. Where it is employed, it should be placed high up, and the shades should be deep. Silk shades are very popular at the present day, but the inside lining should be white. The shades for brackets depend chiefly upon the background. If the latter is of dark colour, they must be of a very low transmission to avoid glare. Baseboard and floor outlets are usually neglected, but it is just with these that by means of portable lamps "painting with light" becomes possible. For reading in front of a fire and without portable lamps the semi-indirect fitting will give superior results to the direct system, as the light falls over the shoulder and the person does not screen off the light with his own body.

Dining-Room.—The table must be well illuminated, and again bare lamps should not be seen. In fact this applies to every room. Where a central fitting with a deep shade is employed, care must be taken that it does not prevent people on opposite sides of the table from seeing one another, and the remainder of the room must be sufficiently illuminated to avoid glare when the eye roams about. A very pleasing illumination is obtained in a room 18 feet square with a 100-watt gas-filled lamp in a deep red silk shade with a white lining and four 50-watt lamps under a white steel ceiling.

A beautiful effect is procured by installing a fairly large glass panel in the centre of the dining-room ceiling with a white chamber above, into which red, green, and blue lamps are placed. With rheostatic control any tints and effects may be produced and enjoyed.

Special single fittings for dining-rooms have also been designed, consisting of a large, heavy opal glass bowl with a central hole, above the latter being fixed a smaller cylindrical shade, the arrangement being such that the lamp inside the smaller cylinder can be raised and lowered in order to vary the solid angle for the direct table illumination. Between the inner and outer globes are three or more smaller lamps for the general semi-indirect illumination.

For the sideboard and dresser, baseboard outlets for supplying candlesticks with frosted lamps are sometimes used.

Bedroom.—For general illumination the ornamental semi-indirect or luminous bowl gives excellent results, but for the dressing-table two brackets, on each side of the table, are desirable. They should be of low transmission to avoid glare. In the case of illness a totally enclosing bowl of very low transmission is restful. For reading purposes, a properly shaded stand-lamp by the side of the bed, or a bracket above it, are usually employed. Even the shade should be out of the line of vision. For night lights the neon discharge lamp is very suitable.

Bathroom.—As the room is usually painted white or a light yellow, glare is easily avoided. A central fitting will generally suffice. For shaving, two small brackets on each side of the mirror are superior.

Study.—The arrangement of the living room may be repeated. Special arrangements may have to be made for lighting the book-shelves.

Kitchen.—The central fitting is generally unsatisfactory, as the cook in front of the stove may stand in her own light. Better results will be obtained by placing a light for the oven and another for the kitchen dresser. The indirect system will probably be most satisfactory as long as the light is sufficient. For any well-conducted kitchen this is, of course, essential.

Children's Playroom.—Light ceiling and a light upper portion of the walls with a 5-foot dark green bottom and adequate illumination from indirect or semi-indirect units give the most satisfactory results.

Billiard Room.—For a full-sized billiard table satisfactory results are usually obtained by distributing six 50-watt lamps above and over the surface of the table. Bowl-frosted lamps about 4 feet above the surface give a uniform illumination and avoid streakiness. Prismatic reflectors with green opal shades surrounding them are more pleasing than the usual cardboard type of shade. If only four lights are employed, they should be raised to about 5 feet above the surface of the table. Very good results may also be obtained with indirect illumination as long as it is high enough.

The room itself is usually dim compared with the illumination of the table, which should be about ten times as high. For the marker, a special lamp may have to be provided.

On the whole the lighting of most houses is still very primitive and unscientific. The average person has no idea of the labour-saving power of electricity, and the simplicity, convenience, and cleanliness of electric lighting, heating, cooking, and refrigeration are unknown to him. Special reference may be made to the "Home Electrical" of the General Electric Company at the Panama-Pacific International Exhibition, described in the *General Electric Review*, June 1915, p. 572, and to the "Lighting of the Home," *Illuminating Engineer*, October 1914, p. 483.

8.16. LIBRARIES.—Mixed lighting seems to be preferred for this class of work. A good general illumination of about 3 foot-candles may be obtained with direct lighting units, using totally enclosing globes out of the line of vision, near the ceiling if the latter is not higher than 14 feet. In addition there should be a lamp giving about 600 lumens for every reading table of about 40 square feet table-top area. If the general illumination is not sufficient, say at least 4 foot-candles, newspaper stands require additional lights also. Bare lamps should not be seen, and with totally enclosing globes there is little danger of direct reflection such as is indicated in figs. 8.23 and 8.24. (By altering the angle of the position of the book, direct reflection may often be avoided.) In any case, the lighting must be such that the person reading does not act as a screen to the paper, can make written notes without throwing shadows from his hand on the writing, and does not stare into bare filaments when looking up from the paper.

The quantity of light required will largely depend upon the surroundings. As the walls are mostly covered with shelves and books there will be little reflection, and if the general illumination does not suffice, it should be augmented by local lighting to about 5 foot-candles, since the type of some books may be very small.

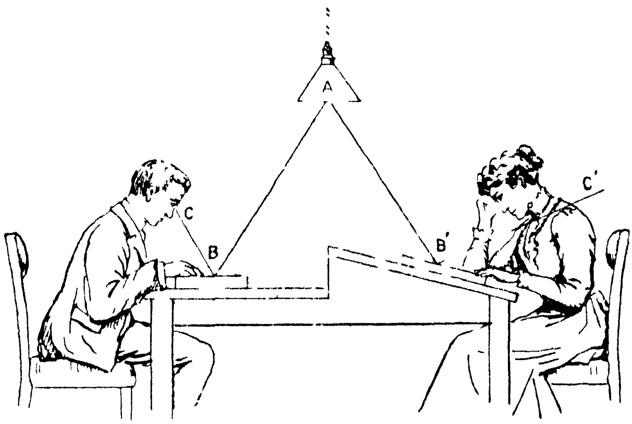


FIG. 8.23.—Effect of Regular Reflection.

Example (*l*). Fig 8.25 gives a plan of the library of the University of Cape Town. The size is 76 × 27 feet 9 inches, giving a total area of 2109 square feet (196 square metres). The room is divided by means of

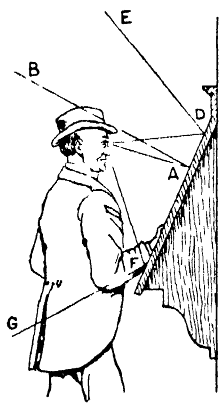


FIG. 8.24.—Lighting of Newspaper Stands.

book-shelves into twelve alcoves, each about 11 feet 6 inches by 8 feet 6 inches, leaving a central space of 10 feet 9 inches. The height of the room is 15 feet. Good general illumination is obtained with six gas-filled lamps directly under the ceiling, the lamps being bowl-frosted, producing about 11,700 lumens in all and providing an average illumination of about 2·7 foot-candles. The utilisation coefficient is about 0·48, due to the white ceiling and upper portions of the walls being white, as the book-shelves do not reach to the top. Above each alcove is a rising and falling

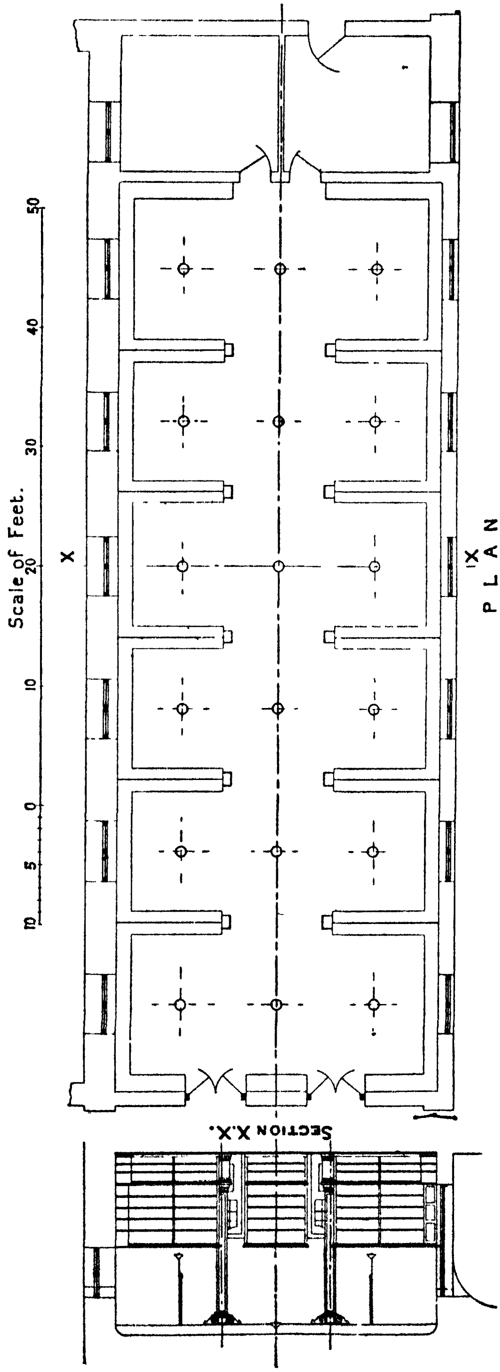
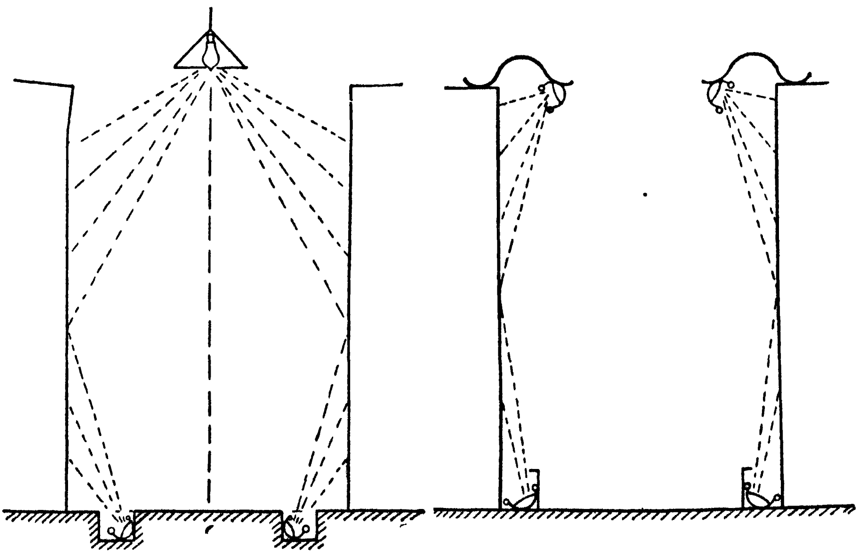


Fig. 8.25.—Lighting of a Library.

pendant which brings the illumination of the tables up to the required value of about 6 foot-candles, when the lamps are level with the tops of

FIG 8 26 —Photograph of Library (Fig 8 25) taken at Night

the book-shelves Frosted lamps are placed in deep prismatic shades of the intensive type The lighting is also sufficient for reading the titles



FIGS 8 27 and 8 28 —Lighting of Book-shelves.

of books on the shelves. A photograph taken at night and reproduced in fig. 8.26 shows that the illumination is satisfactory. Special lighting for book-shelves as sometimes employed is shown in figs. 8.27 and 8.28.

8.17. PLACES OF ASSEMBLY.—Churches.—The system of lighting churches will largely depend upon the nature of the church, whether it is evangelistic or ritualistic, and upon the architecture. The evangelistic church has often a tendency towards the Renaissance, while the ritualistic is mostly Gothic.

Whatever the type of church, the lighting should be comfortable in the broadest sense, physically, physiologically, and artistically. While it is impossible to give general rules, as each church has to be considered individually, the following remarks will apply to all :—

(*a*) The illumination must be sufficient so that eye-strain is avoided and objects in the church, which should be seen, can be distinguished easily.

(*b*) Bare filament lamps must not be seen, and diffusing shades should be of low transmission.

(*c*) People in pews should not sit in their own shadows, which means that the light must be properly directed and diffused.

(*d*) The lighting of the pulpit should not be seen by the congregation and should be of such direction and magnitude for the preacher (about 4 foot-candles) that he is not worried by regular reflection. It should be possible to illuminate special objects, such as stained glass windows, in order that they can be seen and admired. It is advisable to be able to control the magnitude of the illumination during service.

In ritualistic churches of the Gothic type the direct system is mostly employed, as the ceiling is usually too dark and high for indirect units. The general illumination should be adjustable from about 1·0 foot-candle to 3 foot-candles. Clusters round pillars are on the whole objectionable, but custom still favours the chandelier with candle-lamps. The latter should then be frosted.

The sanctuary should be brightest, but its lamps must not be seen by the congregation facing that way. Usually, the lights may be hidden behind the chancel arch in mirrored glass or trough reflectors. The altar must not be too uniformly illuminated in order that elaborately carved portions do not appear flat and dull with absence of detail. This means that the light must come from both sides, whereby deep shadows are avoided but are not entirely eliminated. The choir stalls should be well lighted, and the whole lighting should be on different switches to alter the quantity during service, if desired.

In evangelical and ritualistic churches of the Basilica type the ceilings are often flat and of a light colour, and indirect or semi-indirect units give excellent results. If the church is in the nature of a large hall, the lighting does not depend upon the architecture. Gorgeous lighting is not wanted, and illumination of 2·0 to 2·5 foot-candles with medium light ceilings gives satisfaction as long as glare is avoided.

In all churches additional outlets should be provided for portable lamps and lanterns which may be required on special occasions.

The lighting of a church with frosted candles on standards at the ends of the pews is shown in fig. 8.29.

Another direct-lighting system is illustrated in fig. 8.30, which shows

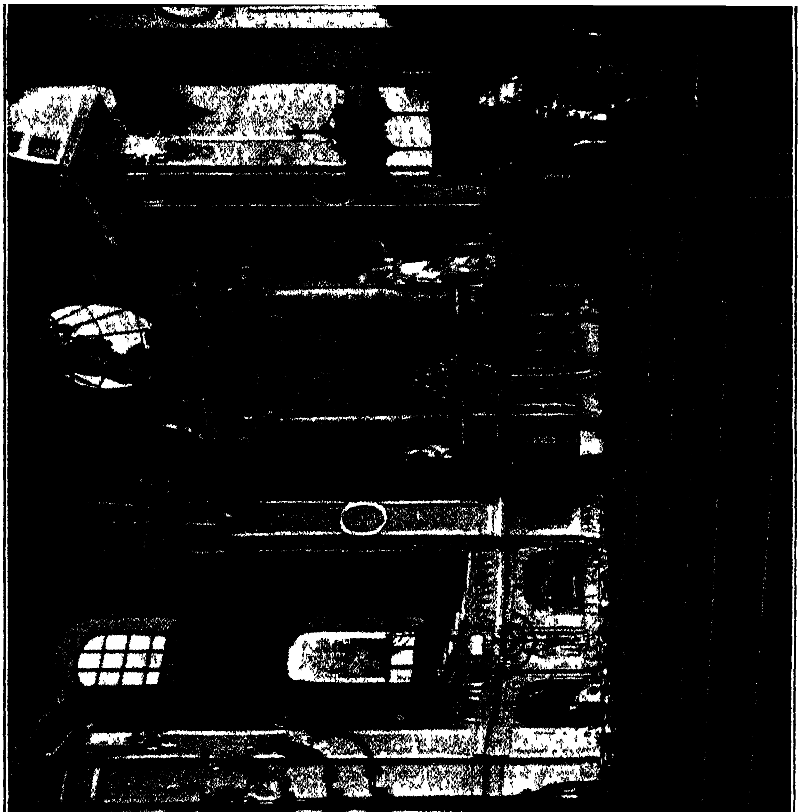


FIG. 8.29.—Lighting Installation of the Kreuzkirche, Dresden.*

St Anne's Church, Edgehill, Liverpool,† in which the lamps are concealed behind wall posts in the upper nave, resulting in excellent illumination. An indirect system of church lighting is reproduced in fig. 8.31, being that of Eberhardt's Memorial Church, Mishawaka, Ind.

It should be mentioned finally that the church entrance and steps

* *Illuminating Engineer*, 1909, p. 37. † *Ibid.*, May 1920, p. 151.

FIG 8 30 —Lighting of St Anne's Church, Liverpool

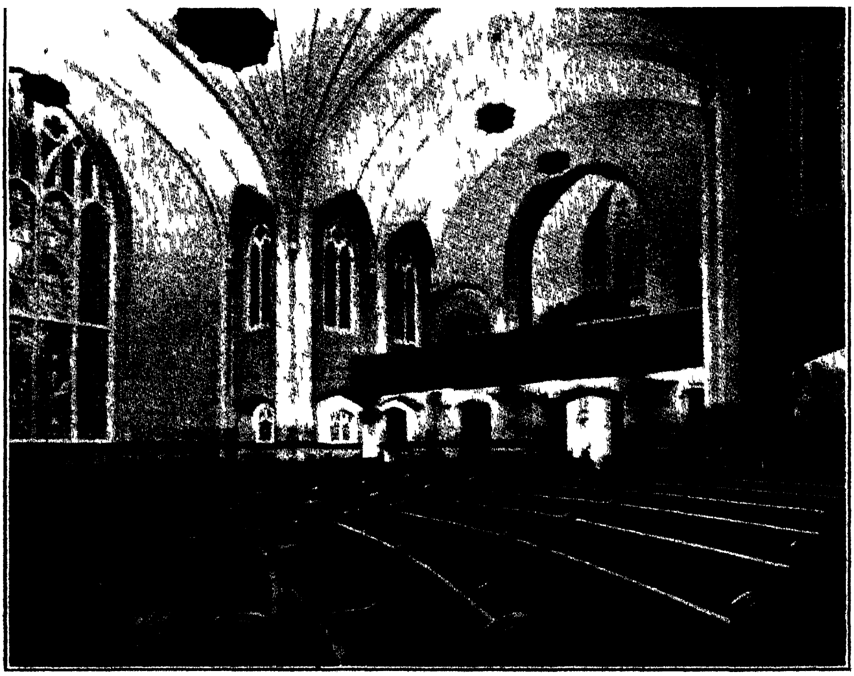


FIG. 8.31 —Lighting of Eberhardt's Memorial Church, Mishawaka (Ind.)

should be correctly illuminated to the extent of 2 foot-candles, while some exterior lighting will often attract the chance pedestrian.

8.18. LIGHTING OF THEATRES.—A theatre consists of three parts, the auditorium, the stage, and the magazine for storing costumes, etc., the latter often being larger than either stage or auditorium.

In the auditorium we must again aim at comfort, and the illumination should always be sufficient to enable a person to read the programme easily and to find his way to and from his seat.

Exits should be indicated by lamps which preferably also provide sufficient illumination for egress in an emergency. They should be on a

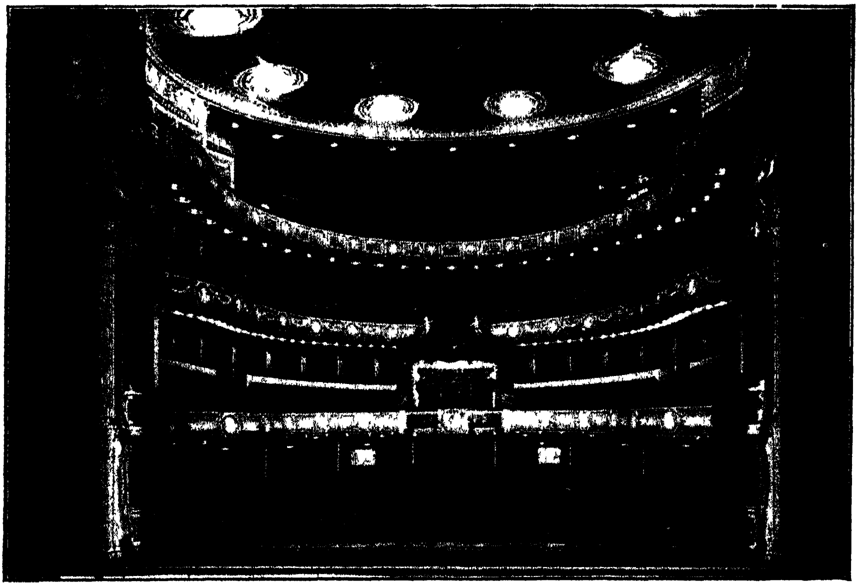


FIG. 8.32.—Lighting of a Theatre by Direct Units.

different circuit from the general lighting and should not consist of bare lamps.

The illumination should be 3·5 to 5 foot-candles between the acts, according to the colour of the decoration, and may be reduced to 1 foot-candle or less during play. The entrance lobby should be brilliantly lighted to an extent of about 10 foot-candles (without causing glare), partly for advertising, partly for ease in handling large crowds.

Whether direct, indirect, or semi-indirect units are employed will depend mainly upon the architecture. Fig. 8.32 illustrates the theatre at Cassel illuminated directly by tungsten lamps enclosed in prismatic glass globes at the ceilings, producing a very pleasant illumination.

Stage lighting is often very elaborate, as many effects have to be produced, such as the reproduction of various periods of daylight, sunrises, sunsets, ravaging fires, moonlight, etc. This means that coloured lamps have to be used extensively, and as very often the changes from darkness through twilight to the full morn has to be accomplished in an extended time, the change thus being extremely gradual, the dimmers employed must be very carefully designed in order to avoid jerky effects, which are objectionable.

Footlights are very important; they must be concealed from the audience and are intended to direct a strong light from below upon the actors to intensify the facial expressions, in order to hold the attention of the public. An invisible trough type of reflector with two rows of lamps hanging downwards provides a good arrangement. Sharp shadows must be avoided, so that proscenium lights, strip-lights, and even flood-lights may be required. The latter are extensively used for showing up special actors and their dresses. One of the latest type of flood-light is provided with a fluted parabolic mirror to avoid streakiness. In all cases it is essential that the reflectors possess a depolished surface. Arc lamps are gradually displaced by the special focussing gas-filled lamps, as the latter require no feeding, are less dangerous as regards fire, and may be controlled from the switchboard, whereas in the case of arc lamps an operator is required for each projector.

Colour screens are easily made by mounting sheets of gelatine film in a framework in front of the lamp. The beams of flood-lights should be adjustable. For amateur work a spot light is obtained by employing a stereopticon with a long focus and a concentrated filament (250 to 500 watts), which can be remotely controlled. With the lens system of the machine a very definitely outlined spot is procurable, the size and shape of which may be made adjustable by employing diaphragms in the slide holder. Coloured spots are obtained by mounting pieces of gelatine between cover glasses and using them as slides.

The switchboard must be hidden from the audience, yet the operator must be capable of viewing the whole stage.

The magazine of a large theatre is like a vast store, and the lighting should be carried out as such (see under Industrial Lighting, paragraph 9.09).

8.19. LIGHTING OF MOTION-PICTURE THEATRES.—This is still in many cases quite unsatisfactory. The illumination often varies from absolute darkness to great brilliancy, with a glaringly illuminated screen during the play.

No one enjoys viewing a play of any sort in complete darkness, and there is no necessity for it, as even with an illumination sufficient for people to find their way about the clearness of the picture need not be impaired. In fact, it is more comfortable to see when excessively sharp contrasts are absent.

Bare lamps during showing should be avoided at all costs, and whereas it is unnecessary to provide extra light for people sitting near the screen, the illumination at the other end may be as high as 0·2 foot-candle, decreasing towards the screen. With the illumination provided by reflection from the latter, the resultant illumination will then be about 0·2 foot-candle throughout.

Excellent results are procured by providing the ceiling with diffusing glass windows and arranging lamps in three circuits above, so that the illumination may be varied from 2 to 0·2 foot-candles as desired. Light from the ceiling falls mainly on the seats and is little thrown on the screen.

M'Omber * recommends the installation of an illumination of about 8 foot-candles on the footpath outside the theatre, which is reduced to 2 foot-candles in the lobby entrance, then to about 1·5 foot-candles in the lobby, and then gradually to 0·2 foot-candle under the balcony, decreasing from there gradually to zero near the screen. The visitor thus passes gradually from a brilliant illumination to the semi-darkness of the theatre.

A good result may also be obtained with dimmers, by means of which correctly placed and shaded lamps may be made to yield any desired illumination. Where these are not employed, a low-intensity green light may be used when pictures are being shown, a high-intensity white light during intervals. Moonlight effects are obtained with blue lights.

If the theatre is very narrow, wall brackets with totally screened lights of low transmission are preferable to ceiling lights.

The Committee appointed by the Illuminating Engineering Society to inquire into Eye-strain in Cinemas also recommends the following † :—

I. That the angle of elevation, subtended at the eye of any person seated in the front row, by the length of the vertical line dropped from the centre of the top edge of the picture to the horizontal plane passing through the observer's eye, shall not exceed 35 degrees, the height of the eye above the floor level being assumed to be 3 feet 6 inches.

II. That, provided recommendation I. is complied with, the angle between the vertical plane containing the upper edge of the picture, and the vertical plane containing the observer's eye and the remote end of the upper edge of the picture should not be less than 20 degrees.

The type of screen used is also of importance. It should be flat and smooth, and without a pronounced grain. Aluminium painted surfaces give a bright image, but the angle of view is limited to avoid specular reflection. With the very high reflective power of a metallic screen the glare, due to lack of good diffusivity, may be uncomfortable. C. W. Gamble obtained the most pleasing effect with a screen coated with white Duresco preparation.

Dr Nutting suggests that an ideal screen should reflect all light thrown upon it uniformly over an angle of 30 degrees. He proposes ‡

* *Electrical World*, 15th and 22nd July 1916.

† *Illuminating Engineer*, June 1920, p. 189.

‡ *Trans. Illum. Eng. Soc. U.S.A.*, vol. xi., 1916, p. 92.

three quantities as defining the effectiveness of a screen—(1) the reflecting power or the percentage of light reflected by the screen; (2) the diffuse

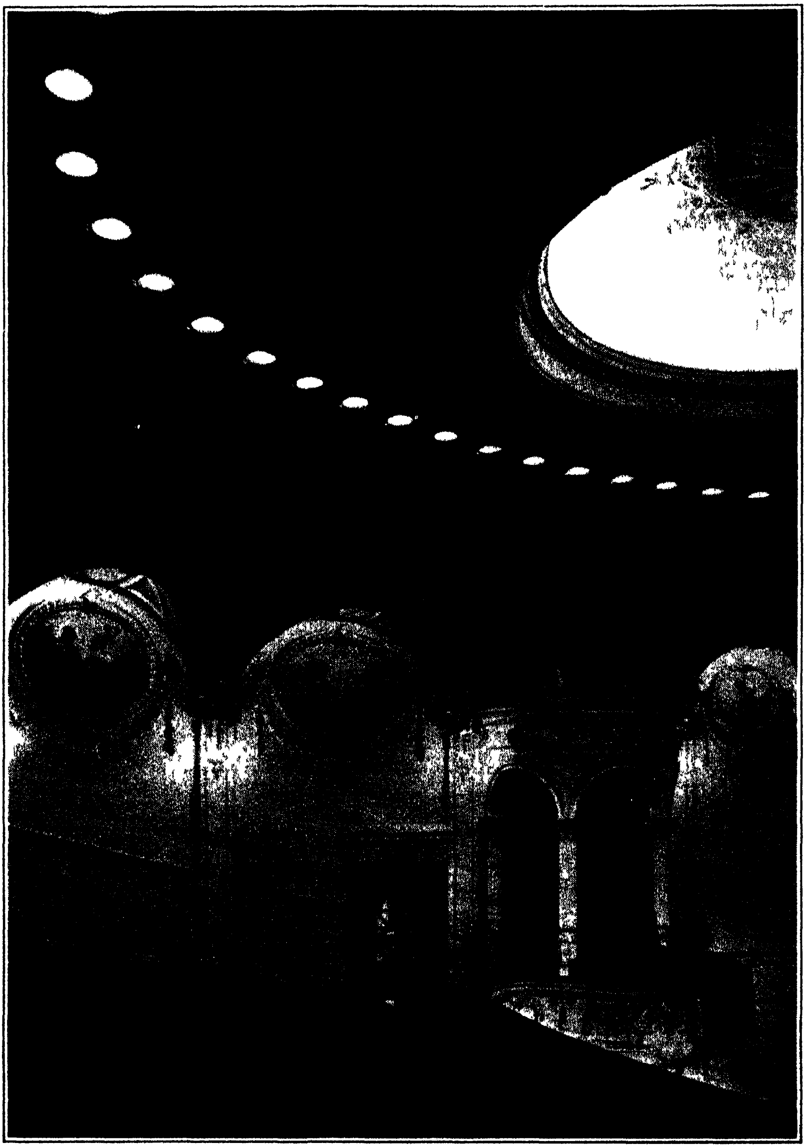


FIG. 8.33.—Lighting of a Motion-Picture Theatre.*

efficiency, or the percentage of light reflected from the screen which is emitted within an angle of 30 degrees; and (3) the total efficiency, *i.e.* the percentage of the light striking the screen which is reflected within the

* *Illuminating Engineer*, 1913, p. 479.

angle of 30 degrees as specified above. He presents the following table:—

TABLE 8.14. - EFFICIENCIES OF SCREENS (NUTTING).

Screen.	30 Per Cent. Diffusion Efficiency. Per Cent.	Reflecting Power. Per Cent.	Total Efficiency. Per Cent.
Magnesium carbonate block	25	87	22
Aluminium paint, mirroroid	55	25	14
Becker compound . .	54	63	34
Ground mirror . .	69	92	64
Ideal screen . . .	90-100	92	83-92

The ideal screen by Nutting is a mirror, the front face of which is composed of minute hexagonal facets, each being a concave mirror of sufficient diameter to reflect light at 15 degrees to the axis.

On the whole the reflecting characteristics of the screen should fit in with the type of room. For long, narrow rooms the aluminiumised paint is suitable, whereas for wide ones a perfectly diffusing surface is superior.

Fig. 8.33 illustrates the lighting of the West End Cinema (Coventry Street, London). The main illumination is derived from the central dome, decorated in blue and gold and illuminated by concealed lights imitating a blue sky, and from the ring of amber-coloured lamps behind diffusing glass discs surrounding it. Attention may also be drawn to the lighting of the panels by concealed lights. Dome and ring lights are separately controlled. The brightness of the dome is about 8 foot-candles.

8.20. THE LIGHTING OF CONCERT HALLS.—The remarks made under the lighting of theatres apply here to a large extent. The architecture will again determine the type of fitting to be used. Fig. 8.34 shows the system employed for the Concert Room at Bad Neuenahr, the fittings consisting of totally enclosing prismatic reflectors with tungsten lamps.

A large number of lamps carried by a single large fitting often give rise to difficulties when lamps have burned out and must be replaced. Lowering gears for large chandeliers have to be exceptionally strong to avoid accidents. At the same time, the architecture may sometimes justify and even necessitate the installation of chandeliers. Fig. 8.35 illustrates the use of a very elaborate crystal glass chandelier as the only suitable arrangement for the Copley Plaza Hotel, Boston, Mass.* Candelabra type lamps are used, and the fire and sparkle of the crystal glass are a desirable feature for the interior of the room.

* G.E.C. Edison Lamp Works, *Bulletin* No. 43,409, October 1916.

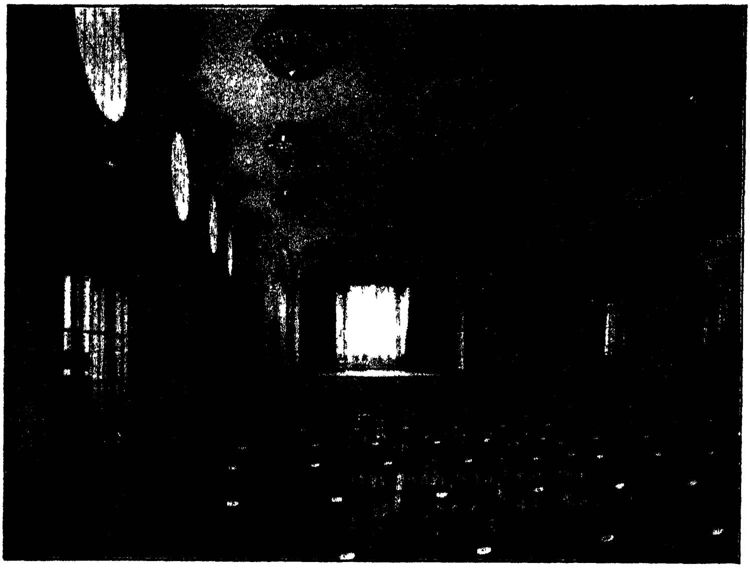


FIG 8 34 —Lighting Installation of the Concert Room at Bad Neuenahr

FIG. 8.35.—Ballroom of the Copley Plaza Hotel, Boston (G.E.C.).

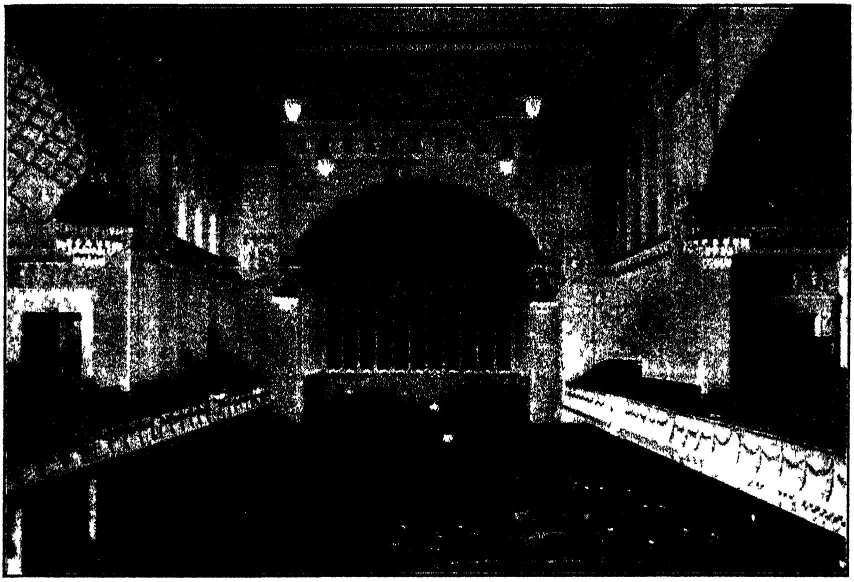


FIG. 8.36 —Lighting Installation of the Mozart Hall, Berlin

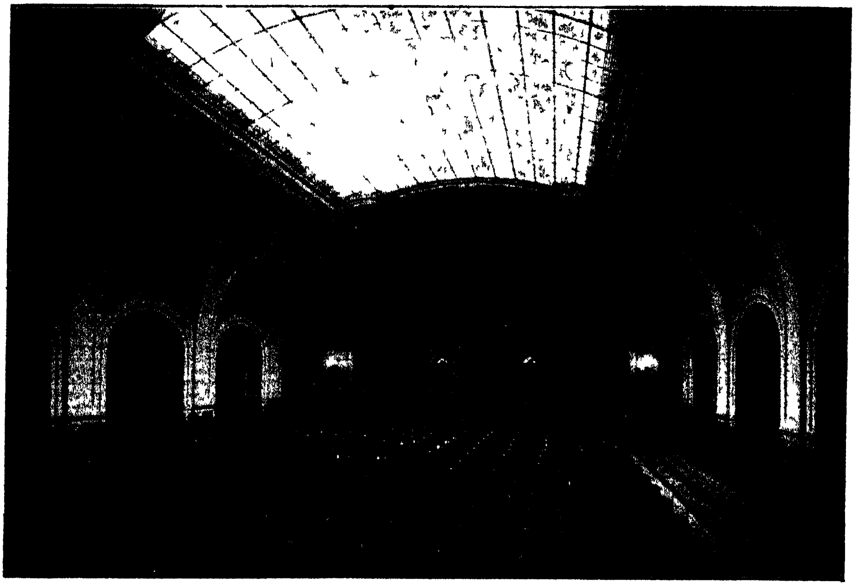


FIG. 8.37 —Arc Lamps above a Glass Ceiling

On account of the difficulty of lowering large chandeliers, flame arc lamps have been employed in well-ventilated halls, as illustrated for the Mozart Hall in the Opera House of Berlin-Schoneberg, fig. 8.36.

A very soft light is obtained by means of arc lamps placed above a glass ceiling, illustrated in figs. 8.37 and 8.38. Recarboning is accomplished by fixing the lamps to small trolleys.

To-day arc lamps are best replaced by the gas-filled incandescent

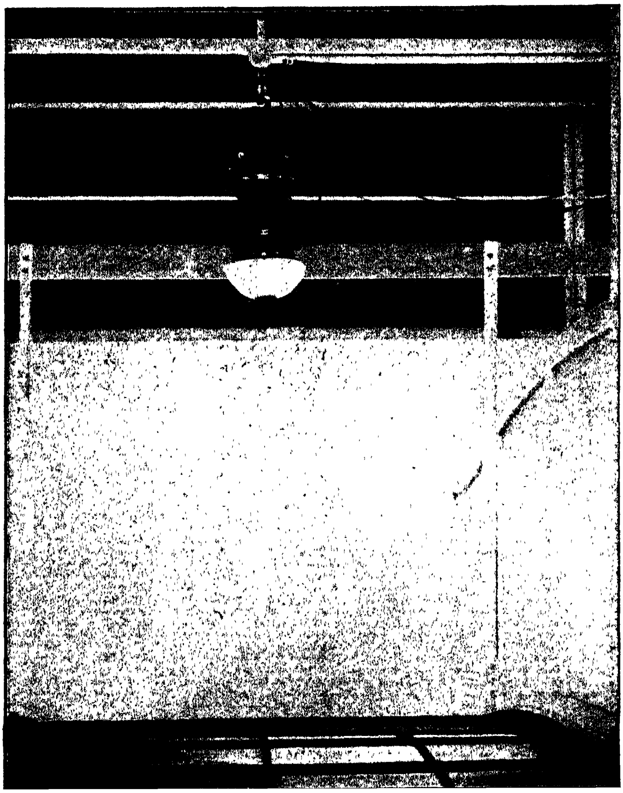


FIG. 8.38.—Arc Lamps above a Glass Ceiling.

lamp, which is nearly as efficient and certainly possesses a higher cost efficiency at a time when wages are continually soaring.

8.21. THE LIGHTING OF EDUCATIONAL INSTITUTIONS.—The illumination must be adequate and properly directed. Even the shades of direct units should be out of the line of vision. In other words, the transmission of shades should be very low, and according to the recommendations of the Illuminating Engineering Society of the U.S.A. the brightness should not exceed 250 millilamberts. Generally speaking, the indirect and semi-indirect systems yield the most satisfactory results. The distribution should be such that a person may sit as he pleases without throwing inconvenient shadows. If the direct system is used, the light should come from the left.

The maximum brightness contrast of juxtaposed surfaces in the normal visual field should not exceed 20 to 1, which means that a blackboard should not be placed on a white wall.

Ceiling and frieze should be white, but the walls are preferably of a light grey or a dark cream All woodwork should possess a dark matt finish

The illumination of class-rooms should not be less than 3 to 4 foot candles (maximum 6), and it is best to have the surface brightness of desk and blackboard about the same, not exceeding 0 3 foot candle (0 32 millilamberts), which means that the illumination of the blackboard should be higher than that of the desks Polished surfaces should be avoided throughout No images of the light sources must be reflected from the blackboard towards the pupil The illumination of the lecturer's

FIG 8 39 —The Dissecting Room, University of Cape Town

desk should be at least double that of the students desks and should be properly diffused Focussing reflectors high up, if possible near the ceiling, give good results for this table Botany classes at night should be held in artificial daylight, and such light is with advantage applied in sewing-rooms, domestic science classes, and chemical laboratories

The illumination of the blackboard should be as uniform as possible The usual system consists of lighting it by means of lamps in trough reflectors above the board and sufficiently away in front thereof to avoid too great a discrepancy between the illumination at the top and bottom of the board The reflectors are preferably of a matt surface to obtain good diffusion and should be opaque Satisfactory results are obtained by placing small lamps along the whole length of the board, at a distance in front equal to half the height of the board, but not less than 2 5 feet, and higher than is requred for the students in the top row

Dissecting-rooms in medical schools must be especially well illuminated, and, in addition to a good general illumination of 3 foot-candles, we require a further 7 to 12 foot-candles by means of local lighting. Focussing reflectors with bowl-frosted lamps will yield good results, and they may be fixed to rising and falling pendants. Fig. 8.39 shows a photograph of the dissecting-room of the University of Cape Town. The tables have marble tops and the ceiling and walls are white. It will be noticed that the tables and chairs throw practically no shadows on the floor.*

8.22. THE LIGHTING OF MUSEUMS.—The problem depends upon the construction and dimensions of the room and the character of the exhibits. It may be divided into three parts: the direction, the colour, and the intensity of the light.

As regards the first, we should see that in picture galleries the light from the illuminant is mainly directed on to the picture, and not into the eye. It must cover the whole picture, and yet it must not be possible to view an image of the illuminant in glazed pictures. The position of the illuminant is largely dependent upon this.

Considering the second demand, it is essential that the colour of the light should approach daylight as far as possible. Art experts to-day favour light from a southern sky (northern hemisphere) as being more satisfactory than the more uniform light from a northern sky. This is in favour of artificial daylight lamps, which in colour are closer to the light of the sun than that of a covered sky.

The wall decoration is preferably of a warm grey, which appears cheerful under the light of daylight fixtures.

For general illumination an intensity of about 3 foot-candles is satisfactory, while the paintings should be illuminated to a much higher extent. The actual illumination will depend upon the colour of the painting: if light, it will require less illumination than a dark one, and to see the details of a fine etching the illumination should certainly be 10 foot-candles. If the total illumination is of a general character, it must be intensive enough to study the finest etching. Floors and ceilings in picture galleries should not be too bright, and hence the downward and upward components of the light must be limited.

Fig. 8.40 shows the lighting of an art gallery, the general illumination being obtained with totally enclosing units fixed to the ceiling, while the walls are lighted by means of small lamps in trough reflectors.†

For statuary lighting the problem is somewhat different. Multiple shadows must usually be avoided, and too much diffusion results in flattening of the objects. On the whole, the number of lighting units should be limited, so that light and shade give the correct impression of the object. The direction of the light often alters the mood of the

* For further information on "School Lighting," see *Illuminating Engineer*, February 1918, p. 47; January 1919, p. 13.

† *General Electric Review*, 1914, p. 320.

object. General rules cannot be given, and each case must be treated individually.

8.23. LIGHTING OF HOSPITALS.—The lighting of sick-rooms must be restful above everything else, but it is a mistake to make it low at all times. In fact, a cheerful room has a good influence on the patient who is on the way to convalescence. The best system of lighting is the indirect one, the lamps being so wired that each fixture consists

FIG. 8.40.—Lighting of a Picture Gallery.

of several lamps which can be switched in separately, and the various units also singly. Walls and ceilings of such places are usually (or should be) of light colour, so that the indirect system is by no means inefficient.

If direct lighting is applied, bare filament lamps and even shades should be out of the line of vision. The remarks made under the lighting of bedrooms hold also here, especially for private sick-rooms.

For operating-rooms a very high-intensity illumination is required (10 to 20 foot-candles), obtained with focussing reflectors and frosted lamps (see also under the lighting of dissecting-rooms, paragraph 8.21).

For further information the reader is referred to No. 6, vol. xv., June 1922, of the *Illuminating Engineer*, which deals with "The Use of Light in Hospitals," by John Larch.

8.24. LIGHTING OF RAILWAY CARRIAGES.—In this country (Union of South Africa) the lighting of railway carriages, though electric, is universally bad. It is impossible to read in comfort in any carriage, even on long-distance journeys. The flux of light is altogether inadequate, and the shading is utterly out of date.

For a proper and up-to-date system the illumination should be at least 3 foot-candles, as in a rocking train more light is required than in a stationary apartment. On the watt per unit floor-space basis good results have been obtained by installing 1·4 watts per square foot in open carriages. A car 50 feet long and 8 feet wide would thus require about 20 units of 28 watts each. These units should be uniformly distributed in two rows, an arrangement which is superior to the central single row. Reflectors of the intensive type with high ceilings, and of the extensive class with low ceilings, if necessary with bowl frosted lamps, give satisfactory results.

On the above basis we should require for a space of $8 \times 6 = 48$ square feet, lamps totalling 67 watts in the compartment type of coach. As there is more absorption than in an open carriage, it is advisable to increase the expenditure of power to 1·6 watts per square foot. This would mean about three 28-watt lamps per compartment. The type of reflector will depend upon the construction of the coach.

A number of types of reflectors and enclosing units have been developed for car lighting. For coach lighting, where efficiency is the principal consideration, the open mouth reflector is generally used. Good results are obtained with a reflector giving the maximum candle-power at 45 degrees.

The following table gives further information :—

TABLE 8.15.—RAILWAY CARRIAGE LIGHTING (HULSE).*

Type of Reflector.	Average Illumination on 45° Reading Planes, ft.-c.			Factor of Utilisation (Efficiency) on 45° Plane Per Cent.
	Aisle Seats.	Window Seats.	Average.	
Prismatic clear . .	2·66	2·17	2·42	34·2
Heavy density opal .	2·41	1·87	2·14	30·3
Medium density opal .	2·00	1·65	1·83	25·9
Prismatic satin finish .	1·94	1·50	1·72	24·3
Light density opal . .	1·79	1·52	1·66	23·5

The lamps are spaced at 6 feet, giving 67 generated lumens per running foot of the car.

When totally enclosing units are employed, the appearance is improved,

* *Illuminating Engineering Practice*, M'Graw-Hill, 1917.

but the efficiency is much less. Table 8.16 gives results of tests with these.* The lamps are the same as before.

TABLE 8.16.—RAILWAY CARRIAGE LIGHTING (HULSE).

Type of Reflector enclosing Unit.	Average Illumination on 45° Reading Planes, ft.-c.			Efficiency on 45° Plane Per Cent.
	Aisle Seats.	Window Seats.	Average.	
Light density opal . . .	1·09	0·97	1·03	14·6
Shallow prismatic reflector with light density bowl.	1·39	1·09	1·24	17·5
Reflecting and diffusing globe .	1·44	1·24	1·34	19·0
Semi-indirect	1·56	1·24	1·40	19·8
Indirect	1·36	1·11	1·23	17·4
Bare lamp	1·17	1·13	1·15	16·3

It will be noticed that all these illuminations are on the low side, yet they are a good deal above the values experienced on the South African railways, which is felt all the more as daylight is generally so excessively bright.

8.25. LIGHTING OF RAILWAY STATIONS.—A. Cunnington † recommends a minimum horizontal illumination of 0·5, 0·25, and 0·035 foot-candles for platforms of terminal stations, important junctions with low roof over platforms only, and less important wayside stations respectively. For dealing with large crowds this is certainly too low, and this applies also to the other recommendations given in his paper. The values presented in Table 8.04 will be more satisfactory. As regards outdoor illumination and types of lamps to be used, see paragraphs 9.15 and 9.16.

* *Illuminating Engineering Practice*, M'Graw-Hill, 1917.

† A. Cunnington, *Illuminating Engineer*, vol. xii. pp. 59–88, March 1919.

CHAPTER IX.

ILLUMINATING ENGINEERING (continued)–INDUSTRIAL LIGHTING.

9.01. GENERAL CONSIDERATIONS. In these days of strikes and high costs of production it is more than ever essential that all tools for the manufacture of goods are up to date, and that conditions for working are made as comfortable as possible. Good lighting, whether natural or artificial, is probably the first important tool common to all work. Upheavals and revolutions have at last convinced manufacturers and legislators that it has been a mistake in many directions to have erected the factories in or close to large towns, instead of spreading them over rural districts, where ground and food is usually cheaper and where the workman is on the whole more contented and less liable to be swayed by the outpourings of agitators than in large towns. In the latter, on account of space, factories and workshops have to be built in three and more storeys, close together, so that the top floors alone can be given proper daylight illumination, *i.e.* light from above. The light on the other floors, being lateral, is often insufficient for the proper carrying out of the work both as regards quality and output, especially away from the windows, and the conditions of working may even be prejudicial to the comfort, safety, and health of the worker. By means of proper artificial lighting some defects of high buildings may be minimised.

The effects of good lighting, both natural and artificial, are manifold and include the following:—

(1) Reduction of accidents.

(2) Greater accuracy in workmanship and increased production for the same expenditure of labour.

(3) Less eye-strain and better working and living conditions, and thus greater contentment of the workpeople.

(4) Superior order and neatness in the plant, easier supervision and less costly management.

9.02. REDUCTION OF ACCIDENTS.—Many investigations have been carried out in this direction. The American Manufacturers' Association states that in the United States alone 500,000 avoidable accidents have occurred in one year, and the authorities, who have made a study of safeguards for the benefit of employees, maintain that 25 per cent. of the accidents were caused by inadequate lighting. It is, of course, extremely difficult to obtain definite data to show how many accidents are due to want of proper illumination. The Police Department of the City of Cleveland instituted a survey in order to determine, if possible, how many of the 1059 accidents which occurred after dark in the streets during one year would have been avoided had daylight or its equivalent been available.* The simplest way of making such an estimate would be to compare the accidents which occur between, say, 5 and 9 p.m. in mid-summer when daylight is available with the number tor the corresponding hours in mid-winter, when it is dark. The records actually show that there were 157 accidents between these hours in June and July, while for December and January the total was 193, or about 22 per cent. more. There are, however, several other variables beside the question of daylight and darkness, which one must take into account when comparing accidents in winter with those in summer. For example, there are as a rule very many less vehicles on the streets in mid-winter, hence there is less liability of accident; on the other hand, this factor is counterbalanced to some extent by the effect of slippery pavements. It is necessary therefore to separate these other variables before we can decide upon just how many of the 193 accidents on mid-winter evenings should be attributed to lack of light. Obviously, we can find the relative effect of all these other factors, except lighting, by comparing the number of accidents which occur during the middle of the day in winter months with those in the summer months, or, for that matter, those that occur in the middle of the night at both seasons of the year. On this point the records show for December and January 12½ per cent. less accidents between 9 a.m. and 4 p.m. than occurred during the same hours for June and July, and they also show 8½ per cent. less accidents for the winter months during the hours that were dark at both seasons, viz. from 10 p.m. to 5 a.m.

We are therefore justified in stating that, except for the question of light, there would have been fewer accidents between 5 and 9 p.m. in the winter months than for the corresponding summer months. To be exact, instead of 193 accidents in the winter for every 157 accidents in the summer we would have found 140 accidents in the winter had it not been for the lack of light. In other words, there were 53 accidents which can be attributed directly to lack of daylight. If we apply the same proportion, viz. the ratio between 53 and 193 to the total number of accidents occurring after dark in Cleveland during the whole year, we find that 292 of them are to be attributed to lack of light, and of these at least 14 must be classed as fatal accidents.

It is, of course, questionable whether artificial light will be as good as daylight in preventing accidents, as it would be too expensive to provide

* Ward Harrison.

the necessary intensive illumination after dark, but there is no doubt that in well-lighted streets the accidents will be far less in number than in badly lighted thoroughfares, and this, experience has amply proved.

Similar results show the investigations made in New York from July 1912 to June 1913.

It must not be forgotten that in industrial concerns accidents often prove very costly, and from this standpoint alone it may be more economical to avoid accidents as much as possible by installing proper and adequate illumination.

9.03. INCREASED PRODUCTION.—The cost of manufacturing an article consists of three items, viz. fixed cost of operation, labour, and material. Considering the first, when plant is enabled to operate on a three 8-hour shift rate, the fixed cost of operation and maintenance, including interest on the capital outlay, taxes, depreciation, etc., are distributed largely over three times the one-shift output. Anything which will lessen the cost of the so-called dark-hour output should therefore be welcomed. Good lighting is the best means of accomplishing this.

An important obstacle to economic production is spoilage. Census experts maintain that the spoiling on all goods manufactured in the United States in 1909 amounted to at least 1 per cent. of the total output, and cost 150 million dollars. They state further that 75 per cent. of the total spoilage occurred under artificial light, 25 of which could have been avoided if lighting had been adequate, resulting in a saving of about 28 million dollars.

Spoilage is often the result of fatigue, and as artificial lighting frequently occurs during that part of a shift when the operator is tired, the number of mistakes under poor light will increase according to the compound interest law.

In textile mills it has been proved that from 12 to 20 per cent. less work is done under artificial lighting than under daylight. For 1000 looms and 500 working hours under artificial lighting this means from 60,000 to 100,000 hours wasted annually, and is equivalent to 20 to 30 looms being worn out each year without producing a yard of cloth. In addition, the power to run these looms is lost.

Considering the cost of labour, we may regard man and machine to act as a combination. An increase in the efficiency of one improves that of the combination, and good lighting will certainly improve quantity and quality of work. Time lost due to darkness, and even due to the necessity of moving portable lamps, must be paid for. Bad illumination is also very detrimental to learners as regards eyesight and general welfare. If a man under poor lighting conditions is worth 2s. an hour, and 2s. 3d. with adequate lighting, it will always pay to make the necessary improvements, as the cost of wiring, power, etc., will not nearly equal that saved in this way.

As regards the third item, the materials form a very important part of the cost of the finished article. By improper manipulation material may often be spoiled or even destroyed. Under poor lighting defective articles may remain unnoticed, or, if detected, they may have to be sold at reduced rates.

9.04. THE HUMAN ELEMENT IN INDUSTRIAL WORK. Unless workpeople are happy and contented in their work, they cannot bring forth their best efforts. Consequently, no method of conducting industry is satisfactory if it leads to a waste of human effort.

The relationship between capital and labour at the present day is, in general, unfortunate. One strike follows upon another, at a time when the whole world is crying for goods. As is usually the case, the fault lies on both sides. In the olden days an employer knew his men personally and called them by their Christian names. The whole establishment was a kind of enlarged family. To-day this is no longer possible, but matters might be improved by distributing factories more over rural areas. On the whole, however, there is only one way of creating a better atmosphere between employer and employee, viz. by a more righteous adjustment of wage to production; by the absence of charity and injustice; by the presence of leading and the absence of driving; by opening the door of opportunity; by the selection of the right man for the right job; by the spirit of candour and frankness on both sides; by banishing the spirit of aloofness on the part of the management and giving the employees a voice in settling the working conditions, and by instilling in the youths of *both classes* that the spirit of grab, which has infested humanity, does not lead to happiness. Dividends of 200 per cent. are immoral.

We are here, of course, mainly concerned with the comfort and contentment of workpeople as caused by good lighting. In a well-illuminated shop dirt is easily noticed, and in consequence the workman keeps his place and machine tidy. If he enters a badly illuminated room from a sunny morning he becomes at once depressed, while if he leaves a dirty day outside and finds a warm, well-ventilated and bright, cheerful working place his spirit rises and his work progresses all the better. When a person has to look for his tools in semi-darkness and works because he has to, the labour annoys him before he commences. This is proved every day. An American firm which spent 50,000 dollars to bring the lighting up to date found out that the difficulty of procuring reliable workmen disappeared, time was saved in commencing work, complaints about fatigue ceased, and errors were largely avoided. It proved a good investment.

It should be unnecessary to add that with good illumination it is easier to keep plant and space in better order than is the case in semi-darkness, and that supervision is less difficult and fewer persons are required. Moreover, in dark and dirty surroundings the workman becomes often slovenly and is induced to idleness, and the best intentions are rendered nugatory. The cost of lighting a factory adequately is often only a very small fraction of the cost of wages.

Suppose a 100-watt lamp illuminates 100 square feet, the space required for one workman, and that the light is wanted for 1000 hours per year, the cost of current being 6d. per unit. The expenditure of installing the lamp with bowl-shaped enamelled steel reflector, including wiring and 2s. for the bulb, amounts to 30s. Reckoning interest at the rate of 6 per cent. and 10 per cent. depreciation, or a total of 16 per cent., and a life of 1000 hours for the bulb, the annual bill is as follows:—

Interest and depreciation . . .	4·80 shillings.
Power at 6d. per unit	50·00 ,,
Cleaning at 2d. per time, 24 times per year,	4·00 ,,
Renewal of lamp	2·00 ,,
Total	60·80 shillings.

The wages for 10 hours per day, 300 days per year, at 2s. per hour, amount to 6000 shillings. The ratio of cost of lighting to that of the wages per man is thus 0·01 or 1 per cent. This shows that if good lighting saves only 30 hours per year or 6 minutes per day of 10 hours, or approximately half a minute per hour, it proves a good investment.

9.05. LIGHTING LEGISLATION.—It is gratifying to see that since the publication of the first edition of this book lighting legislation has appeared in many countries. Naturally, such legislation gives mainly directions for the minimum requirements, which in practice are and should be greatly exceeded. The Committee appointed in Great Britain recommends as follows:—

(1) There should be statutory provision—

(*a*) requiring adequate and suitable lighting in general terms in every part of a factory or workshop; and

(*b*) giving power to the Secretary of State to make Orders defining adequate and suitable illumination for factories and workshops or for any part thereof or for any process carried on therein.

(2) Over the "working areas" of workrooms the illumination measured on a horizontal plane at floor level shall not be less than 0·25 foot-candle, without prejudice to the illumination required for the work itself.

(3) In all parts of iron foundries in which work is carried on or over which any person is ordinarily liable to pass, the illumination measured on a horizontal plane at floor level shall not be less than 0·4 foot-candle.

(4) In all parts of factories and workshops [not included under recommendation (2)] over which persons employed are liable to pass, the

illumination measured on the horizontal plane at floor level shall not be less than 0·1 foot-candle.

(5) In all open spaces in which persons are employed during the period between one hour after sunset and one hour before sunrise, and in any dangerous parts of the regular road or way over a yard or other space forming the approach to any place of work, the illumination on a horizontal plane at ground level shall not be less than 0·05 foot-candle.

(6) There shall be power for the Department to allow exemption in individual cases.

Unsatisfactory artificial lighting includes the following :—

(*a*) Insufficiency of illumination.

(*b*) Inside obstruction.

(*c*) Inconvenient shadows.

(*d*) Antiquated methods of lighting (glare).

(*e*) Neglect of upkeep.

An illumination is not always satisfactory by providing a sufficiency thereof, but the light must be properly directed, and the eyes of the workman must be protected, if necessary, with the correct glasses (see paragraph 3.05). Illumination values may be taken from Table 8.04, or will be found below under the paragraphs dealing with the lighting of the various places of employment. At the same time it must not be forgotten that surface brightness plays an important part. It will be seen from Table 3.01 that even for reading purposes a higher illumination is desirable in dark-coloured rooms than in those with light surroundings. In industrial work it may be stated that in general the surface brightness should be approximately constant, in other words :

$$\text{Reflection coefficient} \times \text{illumination} = \text{constant} \qquad . \quad 9.01.$$

It is, of course, impossible to fulfil these conditions entirely, as for very dark objects the illumination would have to be abnormally high, but they should be carried out as far as practicable.

9.06. GENERAL INSTRUCTIONS FOR GOOD LIGHTING.—The system of illumination to be installed in a factory depends to a very large extent upon the work carried out therein. On the whole, a general system of illumination is to be recommended, as it need not necessarily be more expensive than localised lighting. In the latter case, when lights have to be moved, they often cause glare in new positions and time is wasted in shifting them. By moving them they are often soiled and additional cleaning may be required, thus resulting in additional expenditure.

Artificial light follows daylight, and in changing from one to the other, the conditions should vary as little as possible. It is just through this period that the eye is still set to the daylight and finds even a high artificial illumination dim, until it has accustomed itself to the new conditions and become more sensitive. A gradual change is fairly easily obtained by a general system of lighting, especially if the indirect or semi-indirect methods are employed, as the light will be well diffused, but with localised lighting the workman may have to change his position to avoid inconvenient shadows and direct reflection. The system of wiring is also of importance. With lateral daylight illumination the circuits are preferably arranged so that the rows of illuminants—which should be parallel to the windows—furthest from the windows can be switched on first. In many instances it may also be desirable to instal daylight fixtures so that the colour of the light during the waning period and thereafter is altered but little inside the working room.

For an eye-rest system the choice of the background for the work is of great importance. This is especially the case for localised lighting when units are close to the work. Few modern illuminants, however well shaded, may be viewed with comfort at close quarters, and if the background of the work is dark, the working object light, the contrast may result in glare. With very low ceilings, general illumination may not always be possible, and it should then be seen that the transmission of the illuminants is low. Also, where machines differ in nature and size, or cannot be arranged in uniform rows, a system of general lighting may be inconvenient, as the outlets must be spaced according to the positions of the machines. The system is then known as *localised general or group lighting*. If additional local lights are essential, the direction of light must be considered and should, if possible, be fixed and unalterable. A case in point is the lighting of sewing-machines (see paragraph 9.14).

Good lighting must result in good seeing, and this means a proper distribution of light and shade. For some work focussed direct light may be essential, for instance, in order to examine a polished surface. In other cases, highly diffused light gives greater satisfaction. The background should be of a uniform colour and brightness, as a collection of objects and colours may give rise to severe eye-strain. Fine details are usually best seen as bright objects against dark backgrounds or dark objects against light backgrounds. Each case should be studied individually. Against excessive heat and ultra-violet light the correct glasses must be provided.

9.07. THE HYGIENIC ASPECT OF ELECTRIC LIGHTING.—Of all the different systems of artificial lighting the electrical system is the best from the hygienic standpoint. As long as proper precautions are taken to guard the eyes against ultra-violet light, and the right type of lamp is installed in the right way, perfect comfort is attainable physiologically and hygienically. From the very nature of electric light this seems self-evident, yet statements to the contrary are not infrequently made. These statements rest, however, mostly on the basis of ignorance, and cannot be substantiated by actual tests.

It must, of course, be remembered that lamps like the quartz-mercury vapour lamps must not be burned without diffusing globes, as quartz does not absorb high-frequency ultra-violet rays (see fig. 3.07). But with glass globes or tubes mercury vapour light is less fatiguing than red light. In fact, the less red there is in the colour of illuminants, the longer people can work with artificial light before fatigue sets in. As the modern illuminants, such as the gas-filled lamp, are far superior to the old carbon lamps, electric light is superior to many of the other customary illuminants which contain an abundance of red rays, as long as correct shading and diffusing is employed.

The purity of the atmosphere is usually judged by the quantity of carbon dioxide. This is, however, hardly the right way of judging the atmosphere, since even an amount of 5 per cent. of CO_2 causes no ill-effects as long as the air is otherwise pure. Only an amount of 10 per cent. of CO_2 causes choking, and such quantities are never found in even the worst places. Of course, an increase in the carbon dioxide usually means a reduction in the available amount of oxygen, but then electric incandescent lamps do not consume oxygen, and consequently produce no carbon dioxide, so that from this standpoint electric incandescent lighting is superior to all other installations. It is, however, not so much the carbon dioxide which pollutes the air as the transpirations from the skins of the people assembled, which cause the inconvenience and have a nauseating effect. The production of this poisonous toxin is not proportional to the amount of CO_2 produced by a given number of people, because where the people assembled are physically clean the air keeps pure far longer than in rooms filled with a dirty mob. The rate of the production of this poisonous toxin depends largely upon the temperature, whereas the rate of production of CO_2 is independent of it.

The accompanying Table 9.01 shows the amount of heat and of CO_2 produced by different illuminants, and illustrates the striking superiority of electric light over all other radiators. To this must be added the heat produced by the people assembled, which may be expressed approximately by the following equations:—

$$\left.\begin{array}{l} H=6(37-t) \text{ for adults} \\ H=3(37-t) \text{ for children} \end{array}\right\} \quad . \quad . \quad . \quad 9.02.$$

in which t is the temperature in degrees centigrade.

Electric lighting is, however, even more favourable than this table indicates. As an electric lamp gives off so little heat, it can be brought much closer to the area which requires local lighting; consequently, smaller units may be employed, and for this reason it is often possible to replace a 70-candle gas light by a 30-candle incandescent electric lamp.

To the production of heat by gas and other flame lights we must add that of moisture. Moisture facilitates the production of the poisonous toxin due to transpirations. Electric lamps do not increase the moisture in the atmosphere, since they glow in a vacuum, and even if arc lamps are used it will be found that the percentage of moisture usually decreases instead of increases, which is to be explained by the increase in temperature without the formation of H_2O.* The increase in the temperature is therefore practically counterbalanced by the reduction in moisture.

TABLE 9.01.—HEAT AND CARBON DIOXIDE GIVEN OFF BY VARIOUS ILLUMINANTS.

Type of Illuminant.	Kilogr. Calories per Candle per Hour.	Litres of CO_2 per Candle per Hour.	Litres of Air required per Candle per Hour
Ordinary paraffin oil lamp . .	45	10	75
Paraffin oil incandescent light .	9·7	2·2	15·5
Air gas ,, ,, .	5·5	0·83	5·8
Acetylene ,, ,, .	6·1	0·55	3 2
Coal gas ,, ,, .	8·4	0·95	6 1
,, inverted light . .	5·55	0 63	6·1
,, press light . .	4·35	0·50	5·0
Carbon filament electric light .	2 85	...	..
Metal ,, ,, .	1·33	...	...
Ordinary arc lamp	1·06	0·03	0·16
Flame ,, ...	0·22	0·011	0 17

All flame lamps which burn gases, and especially coal-gas, produce sulphuric and nitric acid. If we enter a room whose atmosphere has been lowered in quality by gas burners, we feel oppressed, and there is little doubt that throat troubles are largely caused by the products of combustion. Extensive experiments further indicate † that the increased ventilation caused by the hot gases from gas burners is largely imaginary. If we add to this the danger of poisoning by gas (New York alone has 2000 cases per year), the trouble of gas leakage (no pipes are perfectly sound, so that some gas always escapes before it is consumed by combustion), the inconvenience of lighting and additional cleaning—the unbiased mind should have no hesitation in deciding which method of artificial lighting is the better one from the hygienic standpoint.

9.08. LIGHTING OF OFFICES.—It is now generally accepted that soft, diffused light is best for office illumination. This means that the ceiling of such rooms should be of light colour, preferably white, and that indirect or semi-indirect fittings are best installed. The illumination should be high, as one generally finds short-sighted people in offices. For ordinary office work, 6 foot-candles should suffice, but for drawing offices it must be raised to 8 to 12 foot-candles. Even if semi-indirect units are employed, they should be very dense, so that the direct transmission is low, and the contrast brightness between objects in the central portion of the field of view should not exceed 100 to 1, if fatigue is not

* See K. Schlesinger, *E.T.Z.*, 1911, p. 944.

† *E.T.Z.*, 1911, pp. 981–982.

to result. This means that the intrinsic brightness of the luminous globe should be limited to about ½ candle per square inch of apparent area, which restricts the choice of units to indirect, or semi-indirect fittings of high density. An intrinsic brilliancy of about ½ candle per square inch is given by a 60-watt vacuum lamp in a 10-inch bowl of medium density, which is less efficient than indirect light and limits the size of lamps.

Desks should not possess polished surfaces, as even with a totally indirect system and well-diffused light, specular reflection is possible.

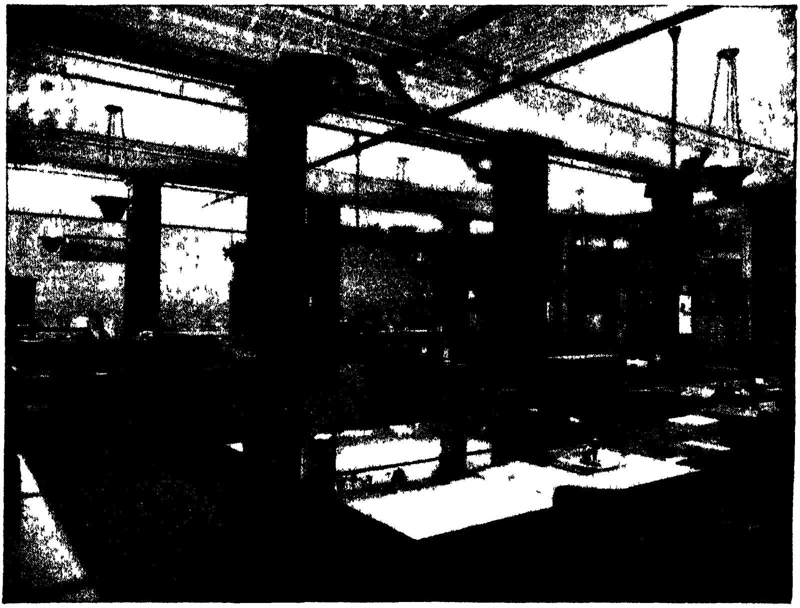


FIG. 9.01.—Office Lighted by Indirect Units (G E.C.).

This is well illustrated in fig. 9.01, in which specular reflection is apparent in the glass coverings of the desks.

Side walls of large areas should not be so white that they reflect a large amount of light into the eye, but also they should not be so dark as to provide too much contrast. A light grey colour will be acceptable.

Semi-indirect units have the advantage that they destroy the effect of flatness, which is often noticeable with totally indirect fittings, and hence this system is favoured more and more. For drawing offices, however, this does not matter much, and the principal idea is to prevent all possibilities of shadows. Where the ceiling is unsuitable for indirect light, the semi-enclosed unit (see Table 8.12) should have a top reflector of large dimensions and low brilliancy. In tracing drawings, it is best to work on the dull side rather than on the glossy one.

At the same time the diffusion must not be too good, as otherwise it may be difficult to find the holes made by compass pins.

In locating the outlets, provision should be made for possible changes in the arrangements of the office. Although a smaller number of outlets may be sufficient for proper diffusion, in a given case, yet it must not be assumed that a greater number necessarily increases the cost of wiring to any extent, since the price of a large bowl is not proportional to the diameter, but increases much more rapidly than the latter.

In fig. 9.02 is given the plan of an office 24 × 16 feet, for which four outlets would suffice to give good uniformity of illumination, but

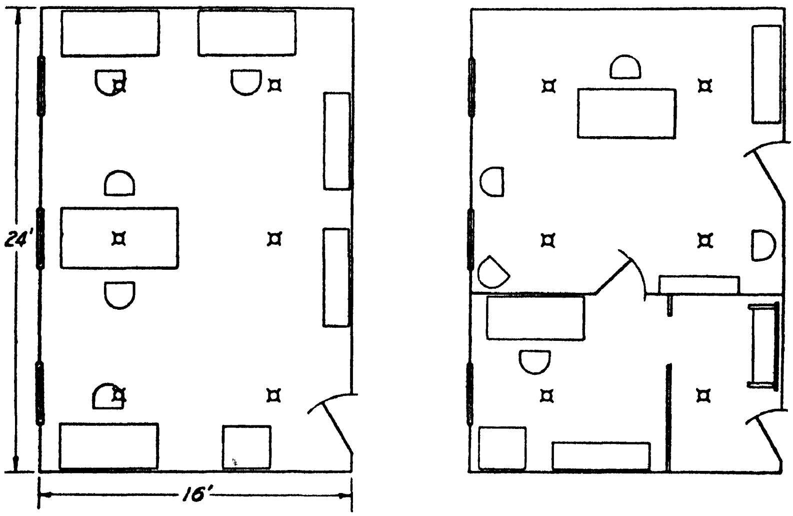


FIG. 9.02 – Spacing Outlets in an Office

by installing six the room can afterwards be rearranged so as to provide a private office. Let the room height be 12 feet, then the ratio $\frac{\text{room width}}{\text{ceiling height}} = \frac{16}{12} = 1\frac{1}{3}$. With light ceilings and medium walls, and a dense opal semi-indirect unit, the utilisation factor would be 0·27 (see Table 8.12). As the width of 16 feet exceeds the height, we require two rows and two lamps in a row, but for the above reason of possible changes in the office arrangements, we instal three lamps per row. For an illumination of 6 foot-candles the total flux required is $\frac{6 \times 16 \times 24}{0{\cdot}27} \times 1{\cdot}25 =$ 10,666 lumens, where 1·25 is the depreciation factor. Each lamp must thus provide $\frac{10{,}666}{6} = 1777$ lumens. 150-watt gas-filled lamps at 220 volts would about fulfil the conditions. Four similar 200-watt lamps would also provide the necessary flux.

9.09. STORE LIGHTING.– The illumination should be high to invite customers, to reduce the opportunities of shop-lifters, and to minimise the return and exchange of goods. Large stores in fashionable thoroughfares should naturally be brighter than small stores in side streets. The general rules about glare and proper shading hold here also. Daylight colours in many instances are not only desirable, but essential, and for accurate colour discrimination proper daylight fixtures must be installed. The illumination depends upon the goods shown. If there is a mixture from white to black, it must be high enough to study the latter. Table 8.04 gives figures which may be considered excellent practice to-day.

The installation should be so designed that for a given amount of

FIG. 9.03. Illumination of a Wallpaper Department (G.E.C.)

power we get the maximum amount of light on the counter or where it is wanted. This means that effective reflectors must be employed. For illuminating glassware, the indirect or semi-indirect systems are not suitable, as cut glass will appear dull, and we should employ clear bulbs (preferably gas-filled lamps) in prismatic focussing reflectors in order to make the goods sparkle and thus show them up. For exhibiting wall-papers, the totally enclosing units of the opalescent or prismatic types give good results, as is indicated in fig. 9.03.

As regards cigar, stationery, drug, book, and music stores, the show cases or shelves or books usually occupy at least one wall, the colour being dark. The counters should be well illuminated by employing focussing reflectors above them, while the shelves should be sufficiently bright so that titles on books or cases can be read without difficulty.

Jewellery and china stores fall under the category of glassware rooms and should be similarly treated

Considering art stores, the reader is referred to paragraph 8 21, dealing with the lighting of museums

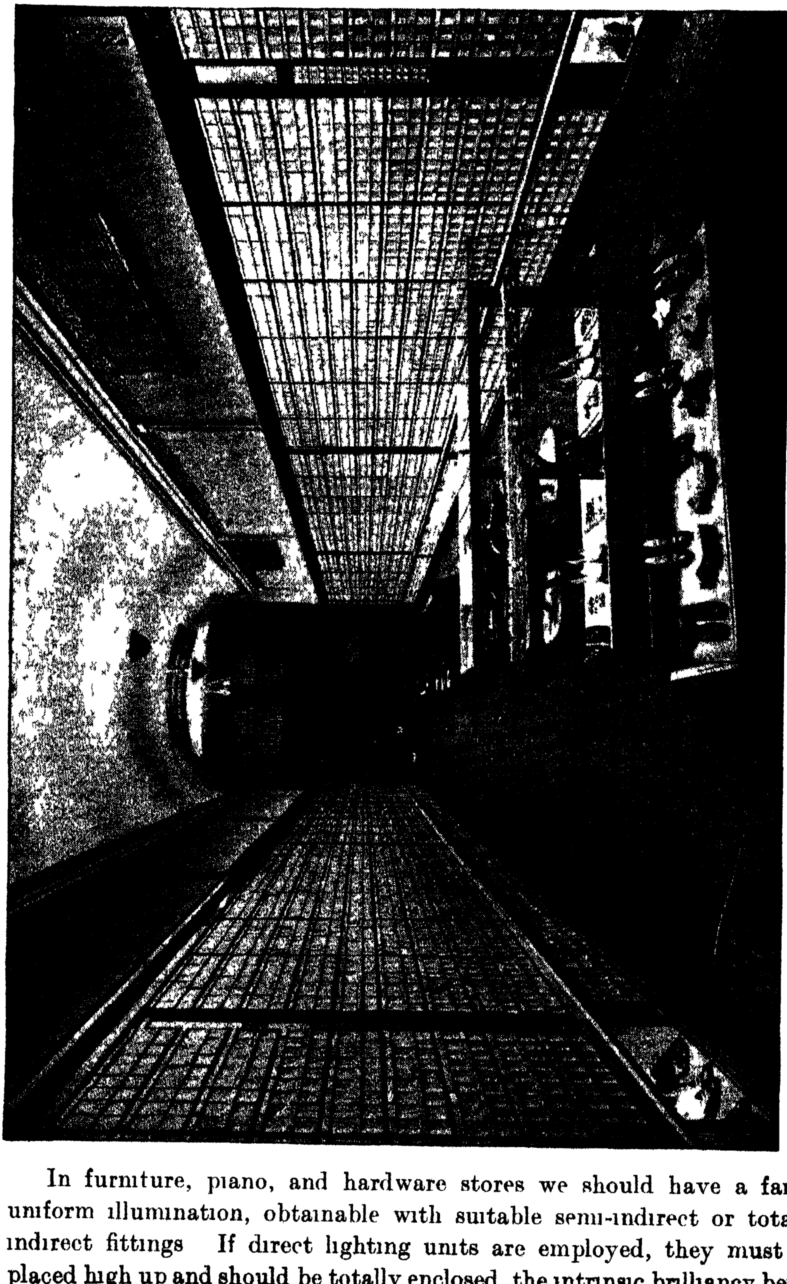


FIG 9 04 —Indirect System of Shoe Store Lighting (G E C)

In furniture, piano, and hardware stores we should have a fairly uniform illumination, obtainable with suitable semi-indirect or totally indirect fittings If direct lighting units are employed, they must be placed high up and should be totally enclosed, the intrinsic brilliancy being low. Boot stores also require a fairly uniform illumination in order to be able to read the numbers on the boxes arranged on shelves covering the walls, but somewhat higher illumination must be provided, about a foot above the floor, where boots are tried on. A few direct fixtures with focussing reflectors and bowl-frosted lamps will answer the purpose the general illumination being obtained with semi-indirect or totally indirect units. A totally indirect system of shoe-store lighting is shown in fig. 9.04.

For grocery departments, the totally enclosing direct unit of low transmission and a few focussing reflectors for the counters are satisfactory.

In millinery stores and hat shops the inspection is done in the centre of the room, while ladies' hats are displayed in high glass cases lining the walls. Any system providing a good uniform illumination will do. For the florist shop similar remarks hold, but for special show cases additional illumination may have to be provided.

In barbers' shops the faces of the patrons provide the plane of illumination, and as they lie back and look up to the ceiling they must not be inconvenienced by bare lamps. A 600-lumen bowl-frosted lamp equipped with an opalescent reflector giving an intensive distribution, hung about 7 feet 6 inches from the floor, and placed between each two chairs even with the top of the back of the chair, gives good illumination for hair cutting, and when the chair is turned back for shaving the light will be on the underpart of the patron's chin. Or use indirect light.

For dry-goods stores the illumination must be high, and if daylight fixtures are not installed throughout the store, special counters should be illuminated with correct daylight fixtures. Direct fittings must be out of the line of vision, indirect units should hang 2½ feet below a 12-feet ceiling, 4 feet from a 16-feet ceiling, and 5 feet below a 20-feet ceiling. Use the same type of fitting throughout, and arrange the outlets symmetrically and at the same height.

9.10. SHOW WINDOW LIGHTING.—A show window is a kind of a picture in which the window-dresser has endeavoured to arrange a number of objects in a manner which tends to draw and hold the attention of the onlooker. At night, the power of the display to draw depends largely upon the lighting.

Bare lamps should not be visible at all, and it is even advisable to conceal the reflectors. The degree of illumination will depend to a great extent upon the colour of the goods shown, and upon the locality. In side streets with a low street illumination a show window would appear brilliantly lighted with, say, 5 foot-candles, whereas in a well-illuminated business street the contrast may be less with 50 foot-candles.

The hanging height of the lamps has little influence on the illumination as long as the correct type of reflector is employed. Prismatic and mirrored-glass reflectors have been found to give the most satisfactory results. The fittings are usually placed along the front top edge of the window, and should be screened from view. The arrangement must be such that no specular reflection is apparent, which may happen with polished backgrounds. In such cases a curtain may be dropped close

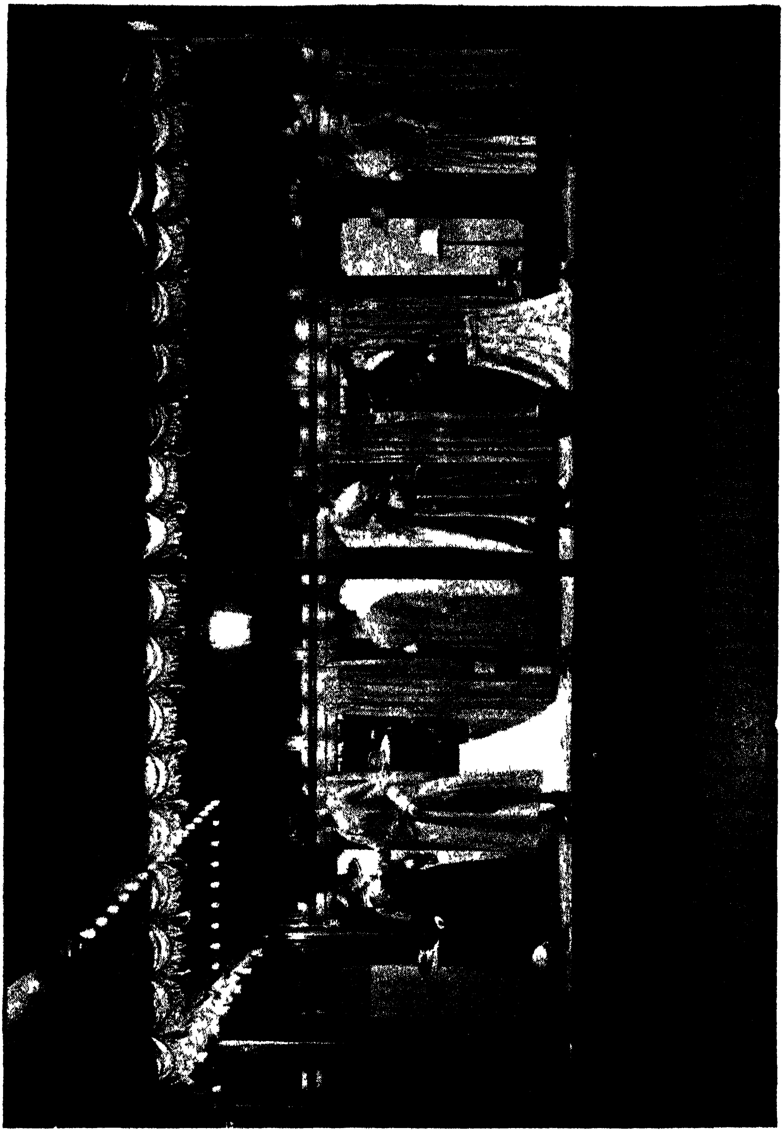


FIG. 9.05.—Shop Window Lighting (G.E.C.).

to the lamp from the ceiling between the light sources and the higher part of the background. The reflection in the window glass of bright objects in the street cannot always be prevented, unless curved window glass is used. The placing of the outlets will depend largely upon the goods exhibited, and as these vary (as a rule) from time to time, it is advisable to provide two or three times as many outlets as are ordinarily wanted. These might be wired in groups in order to be able to vary the

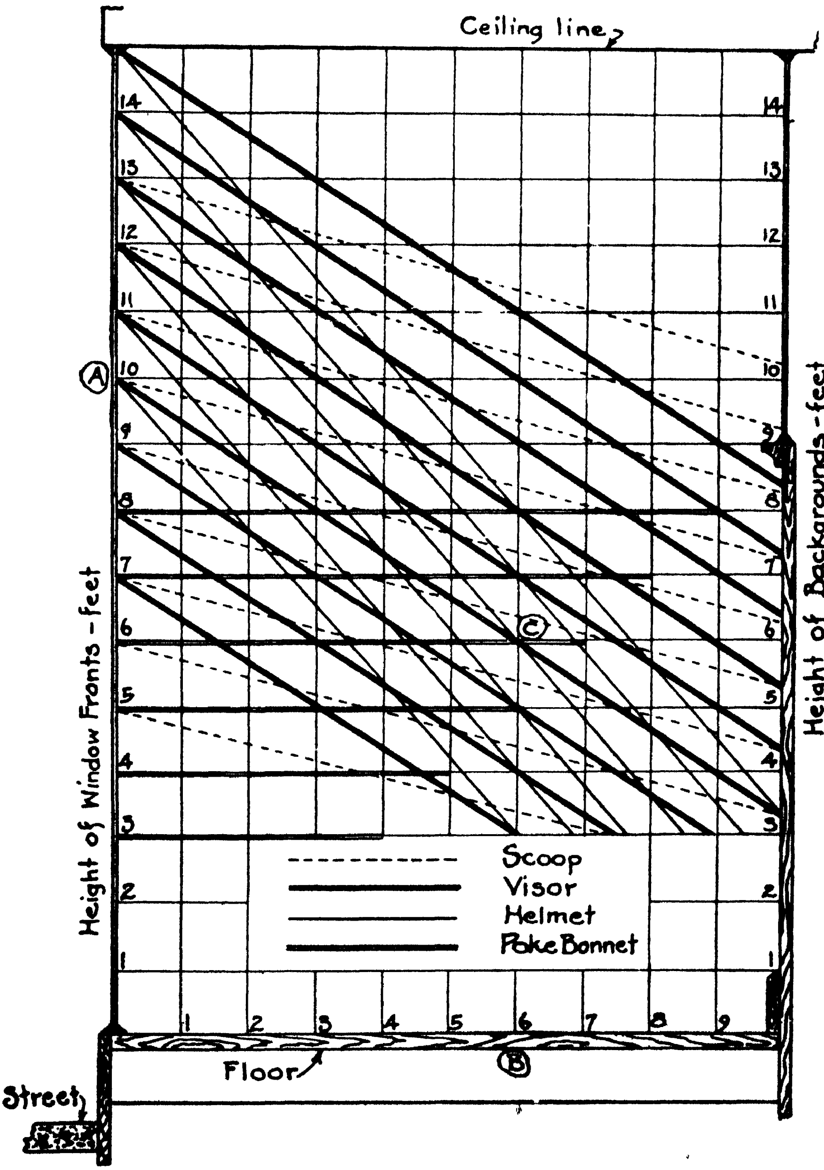


FIG. 9.06.—Chart for Determining the Proper Type of Reflector (X-Ray Reflector Co.).

direction of the light. If the display has a central figure, the latter will require a more pronounced contrast of light and shade than could be obtained with a more or less uniform illumination. With additional outlets an intelligent window-dresser will easily procure the right result.

In many cases a light matt background will greatly improve the illumination, but sometimes mirrors might be wanted if the onlooker is to see two sides of the displayed goods. Fig. 9.05 illustrates a well-lighted window with the proper use of mirrors in the background. The lighting units visible are images of outside lamps.

In some instances, where the window area of the ground-floor is restricted, success has also been achieved by using the first-floor windows for show purposes. Mirrors arranged at the proper angles are placed in front of these and can be viewed quite easily by people standing below in front of the ground-floor displays.

The correct type of reflector of those mentioned in paragraph 7.08 for any given show window may be obtained with the aid of fig. 9.06, in which the various lines represent approximately the upper boundaries of the luminous fluxes for lamps placed at different heights.

Example.—A shop window 11 feet high and 7 feet deep, with a background of 8 feet, is to be illuminated, the background consisting of a light matt surface with goods displayed thereon. Draw a vertical line for a depth of 7 feet and a horizontal line for a background of 8 feet, and join the point of intersection with 11 feet window height, when we find that the scoop is wanted. (With a height of 10 feet, a depth of 6 feet and a polished background, the visor is the correct reflector (line A–C).) The suitable spacing is 15 inches, so that for a length of 20 feet we require sixteen lamps. Reckoning with a depreciation factor 1·25 and a utilisation factor of 0·50, an illumination of 25 foot-candles requires a total flux of 8850 lumens, or per lamp 553 lumens. Sixty-watt vacuum lamps will approximately answer the purpose.

9.11. LIGHTING OF MACHINE SHOPS.— The construction of the shop will largely influence the type of system to be employed. The arrangement of the plant is usually such that the processes requiring most light are carried out near the windows, but this point must not be carried so far as to interfere with the train of manufacture. It is often cheaper to instal artificial lighting than to break up the sequence in order that each machine receives the best natural light obtainable.

Light walls and ceilings should be used whenever possible, and it pays to carry out whitewashing periodically.

For localised lighting lamps must be properly shaded, and bare lamps are out of date (see fig. 9.07). With the light properly directed it is possible to use small lamps and thus reduce the consumption. The contrast between the illuminated object and the surroundings must not be too great, so that a good system of general illumination is practically always required.

Where group lighting is desirable, for instance, for a particular type of machine, the lamps must be located so that the direction of the light is correct.

Porcelain enamelled steel reflectors are best for machine shops as being robust and less liable to breakages than glass reflectors.

The design of the illumination is similar to that of other places, and a repetition is unnecessary. If the walls consist mainly of windows, they reflect little at night and must be considered dark.

Where a large number of lamps is installed, it is desirable to make the system as flexible as possible, so that groups of lamps may be switched in

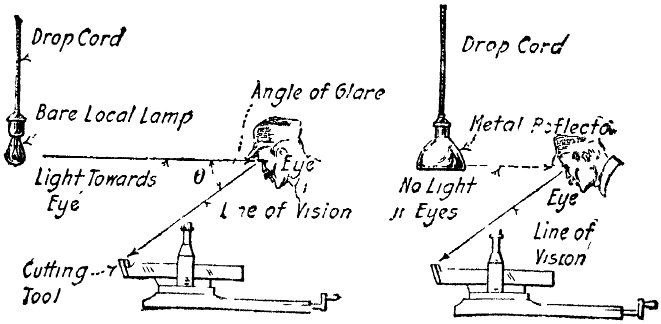


FIG. 9 07.—Shading of Lamps (G.E.C.).

as desired, either during the waning period of the day, or as particular sets of machines are wanted. The increase in the cost of wiring is soon saved by the reduction in the consumption of electricity.

For bench work and localised lighting the lamps (500 to 1000 lumens) should be placed about 5 feet above the bench and about 6 inches from the forward edge of the bench. The spacing should be about 6 to 10 feet. For double benches and rough work a single row of lamps above the middle

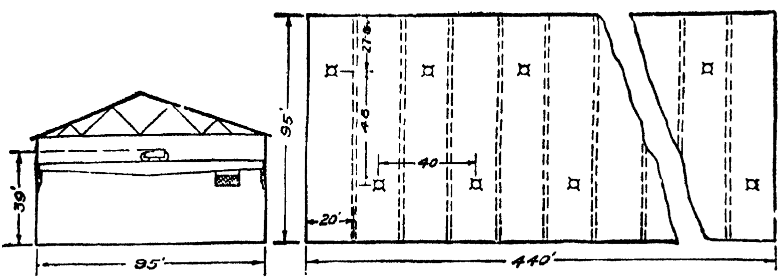


FIG. 9.08.—Plan and Elevation of a Machine Shop (G.E.C.).

of the bench (600 to 1500 lumens) gives satisfaction, but for fine work a double row, each 6 inches from the edge, and the lamps in the two rows and staggered, is more effective. A high general illumination is coming more and more into use for bench work.

Lamps for separate machine tools should always be placed so that the light falls in the proper direction, and the workman's body should not act as a screen. For boring out, a portable lamp is often essential. Care must always be taken that the illuminants do not foul travelling cranes.

In fig. 9.08 the plan and elevation of a shop for the manufacture of large engine parts is given, work which may be classed as assembly work, medium grade, for which an illumination of about 4 foot-candles is desirable. The length is 440 feet, width 95 feet, 20-foot bays. The distance from the floor to the cross beam of the roof trusses is 44 feet, and that from the floor to the top of the crane 39 feet. We can either employ units above the crane, or fix angle-units below along the sides of the shop, a method which is not always to be recommended, as glare may easily be caused. With rough work of the type mentioned disagreeable reflection need not be feared, and dome steel reflectors with clear gas-

FIG. 9.09.—Illumination of a Machine Shop (G.E.C.).

filled lamps placed above the crane will be satisfactory. Fixing the lamps 40 feet above the floor, we require for a width of 95 feet two rows in order to obtain a fairly uniform illumination. Lengthwise we fix a lamp in every alternate bay, so that the spacing is 40 feet, and stagger the lamps in the two rows. We thus obtain 22 units, and as the total flux required is 418,000, assuming a depreciation factor of 1·25 and a utilisation factor of 0·50, each lamp must produce about 19,000 lumens, which are provided by a 1000-watt gas-filled lamp. A photograph of the illumination is shown in fig. 9.09.

For fine work the illumination must be as high as 9 foot-candles.

9.12. LIGHTING OF FOUNDRIES.—For machine moulding a general illumination by means of large units hung above the crane, or medium size units and angle reflectors placed below the crane in the main bay are common. For very wide bays, it may be necessary to combine the two methods. The illumination should be about 2 to 3 foot-candles for small brass work, and at least 1 foot-candle for large iron and steel work. If both classes of work are carried out, the maximum illumination must be installed.

For bench moulding and core making in side bays, under a comparatively low ceiling, rows of lamps in bowl steel reflectors should be located about 5 feet above the bench, giving an illumination of 2 to 3 foot-candles.

In pattern-making shops the benches should be similarly lighted,

FIG. 9.10.— Lighting of a Wood-working Shop (G.E.C.).

but lathes should be given an illumination of 5 to 10 foot-candles. For planers, mortisers, drills, etc., the illumination should be at least 4 foot-candles, and if localised it must come from above and from the front of the machines.

Cupolas should be generally illuminated to an extent of 1 to 2 foot-candles, and loading yards likewise in order to facilitate the work.

As regards smith work, the illumination should be fairly low to provide sufficient contrast for seeing the hot article, but high enough to distinguish the right temper. An illumination of about 0·5 to 1 foot-candle will suffice.

9.13. WOOD-WORKING SHOPS.—For wood-working plants, the remarks made under pattern-making shops hold also. In machine shops the illumination must be high to protect the workman. A general illumination is the best. For bench localised lighting, remarks made previously under paragraph 9.11 hold again. A well-illuminated woodworking shop with direct lighting units and dome steel reflectors is reproduced in fig. 9.10.

9.14. LIGHTING OF TEXTILE MILLS.—Mill construction has greatly improved during the last decade, and to-day a good many mills are provided with individual drives, or such group driving as leaves the head room fairly free, so that the general system of illumination becomes not only feasible but advisable. It is then possible to reduce the number of outlets and use larger units, which reduces the cost of wiring, and spot lighting is avoided. The rooms so lighted look more cheerful and business-like. The design of the lighting is, of course, similar to that of other factories. The following additional remarks will be found useful:—

Cotton.—*Openers or Bale Breakers and Pickers.*—As the work is not exacting and material is handled in bulk, a low-intensity illumination of 1½ to 2 foot-candles suffices.

Carders and Drawing Frames.—A medium-intensity illumination of 3 foot-candles, obtained with 500-watt gas-filled lamps, will be found satisfactory.

Slubbers, Speeders, Spinning Frames, Twisters, and Spoolers.—The thread is becoming successively thinner, yet the various processes present the same requirements. Good illumination is wanted on vertical surfaces, and concentrating light from above is not satisfactory. For low ceilings a general illumination is not suitable, and outlets should be located over aisles between machines. In alternate aisles the lamps might be staggered. 600- to 1000-lumen lamps on 10- to 18-feet centres are found satisfactory.

If lamps can be fixed at least 6 feet above the tops of the machines, a general illumination of 3 foot-candles is preferable.

Warpers.—Each thread must be seen distinctly as it passes from the creel through the reed to the beam. With a general illumination of about 6 foot-candles this is possible. Otherwise use 750-lumen lamps in deep bowls, intensive type, above each reed, and a 400-lumen lamp with extensive reflector over each creel. An illustration of localised general lighting for cotton warping is shown in fig. 9.11.

Slashers.—A general illumination of 1½ to 2 foot-candles suffices.

Drawing-in or Tying-in.—A high-intensity illumination of 6 foot-candles, or even more, is best.

Looms.—A high-intensity illumination of 6 foot-candles or more is again considered the best practice. For low ceilings or extensive overhead shafting, localised general lighting may be essential. 75-watt gas-filled lamps, bowl frosted, in dome enamelled steel reflectors hung about 9 feet above the floor, to each group of four looms give good results. For wide looms (54 to 72 inches goods) place a 600-lumen lamp in a similar reflector above the weaver's alley between each pair of machines. A night photograph of a modern weaving-shed is shown in fig. 9.12.

Inspection – Install a high general illumination of 6 or more foot-candles

Wool. The goods are now darker than in the case of cotton, and the illumination should be somewhat higher. The figures given under

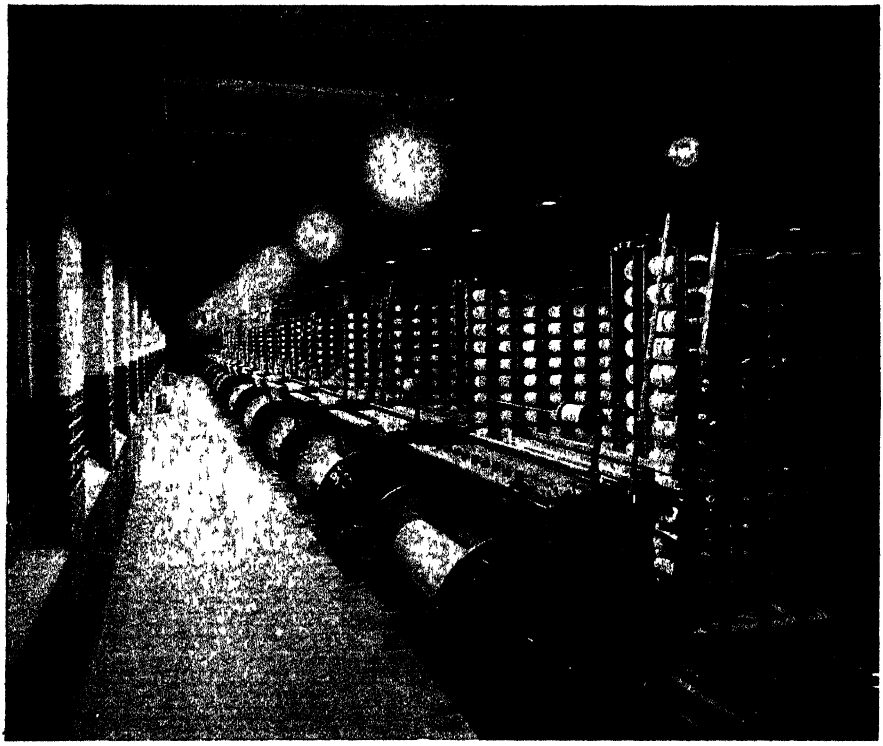


FIG. 9.11.—Localised General Illumination for Cotton Warpers (G.E.C.).

cotton should be increased by about 30 per cent. Otherwise the remarks made for cotton hold also here.

Silk.—*Throwing Frames.*—A medium-intensity illumination of 3 to 4 foot-candles is advisable and superior to the old-fashioned localised lighting with the moving of the lamp to find the trouble and faulty work, resulting in lamp breakages and non-detection of faults.

Winding and Quilting.—*Swiss Warpers.*—A high-intensity illumination of 6 foot-candles is wanted for this class of work.

Horizontal Warpers.—As the reel of such a warper is often 8 yards in circumference, the outlets must be carefully placed. When full, the reels present a wall shutting off the light from the areas at the back of the warper.

For individual warpers use 1000-lumen lamps equipped with dome steel reflectors, about 9 feet from the floor, over the beam. The position of the lamp should be such that the operator will not cast a shadow on his work when "beaming off," and the height should be adjustable so that reflections from the reels, when revolving, are not annoying to the operator.

For warpers in rows place the lamps between parallel machines.

Weaving.—A high-intensity illumination is essential for this most

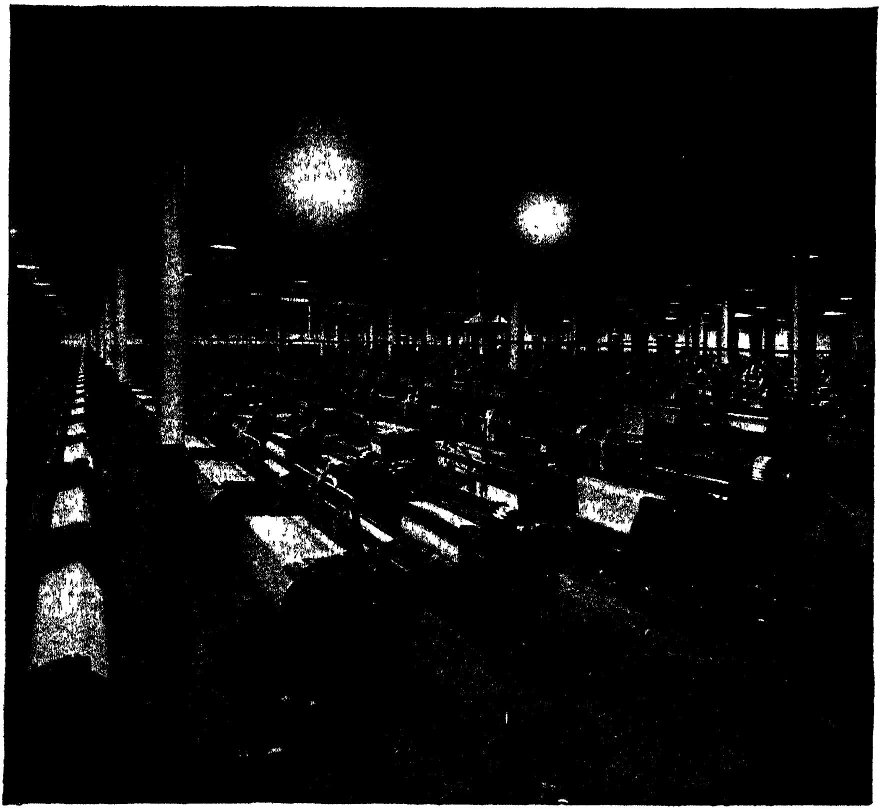


FIG. 9.12.—Illumination of a Modern Weaving-Shed (G.E.C.).

important operation in silk manufacture. For plain box looms and the number of shafts less than five use 150-watt bowl-frosted gas-filled lamps and dome reflectors between rows of looms, one unit to every four machines, and also place at intervals of every four machines a similar unit along the aisles at the side of the room, to permit repairs to be made.

For extensive overhead shafting use localised lighting, and 600-lumen lamps are preferable, with bowl reflectors, hung over the harness or between the harness and the reed.

Localised lighting of silk ribbon looms is illustrated in fig. 9.13.

Colour Matching.—A night photograph of a room for cotton classifica-

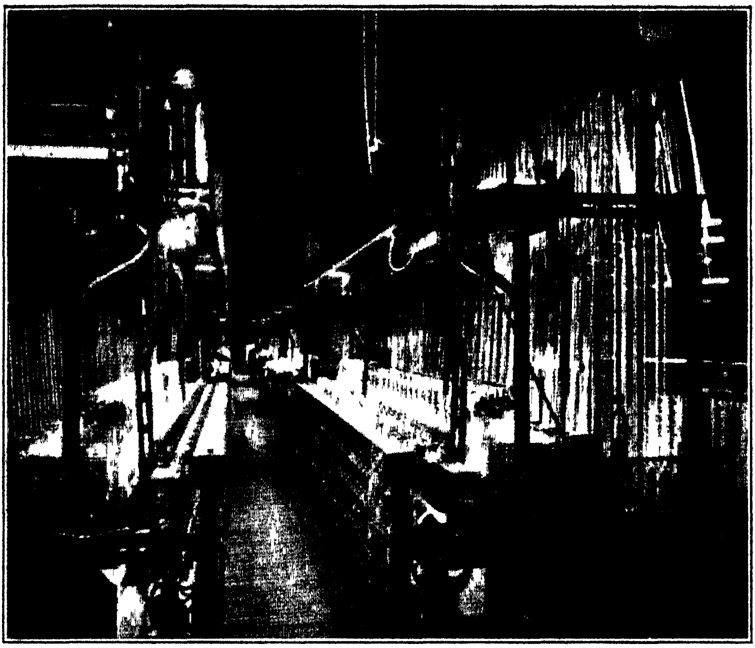


FIG 9 13 —Localised Lighting of Silk Ribbon Looms (G.E C).

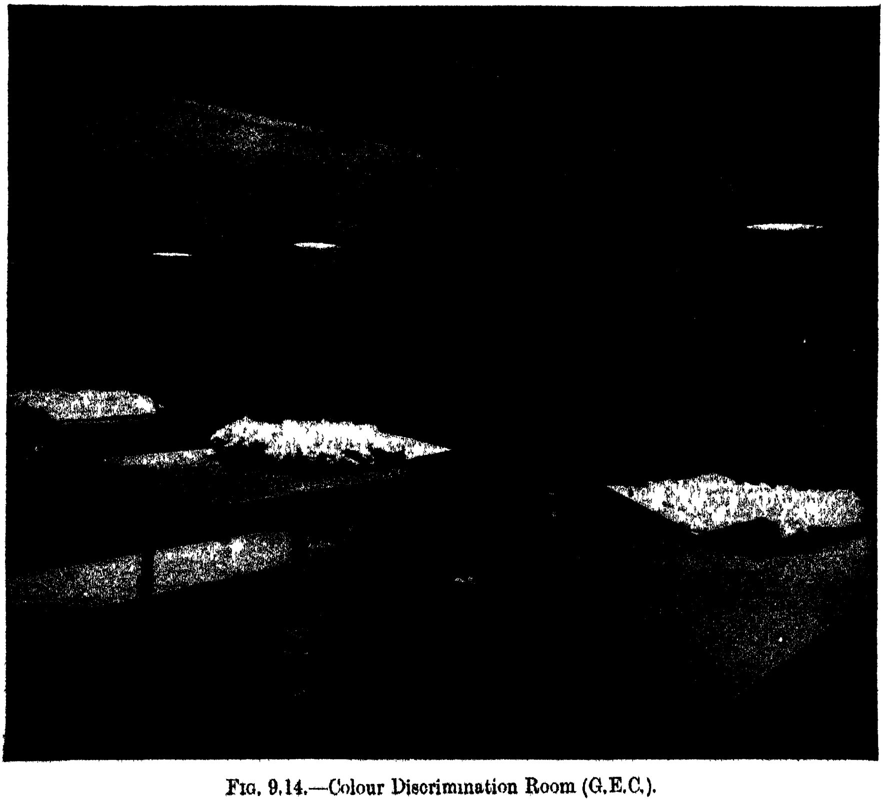


FIG. 9.14.—Colour Discrimination Room (G.E.C.).

tion and accurate colour discrimination by means of proper daylight units is shown in fig. 9.14.

Sewing Rooms.—A high general illumination of about 10 foot-candles is preferable for the average kind of goods, but for very dark fabrics this may even be too low. Where localised lighting has to be employed for sewing-machines it is essential to bring the light close to the work away from the eye, and the lamp itself must be completely hidden. In fig. 9.15 an arrangement is shown in which, by means of a small lamp, fed from a battery, an illumination of 20 and more foot-candles is produced on

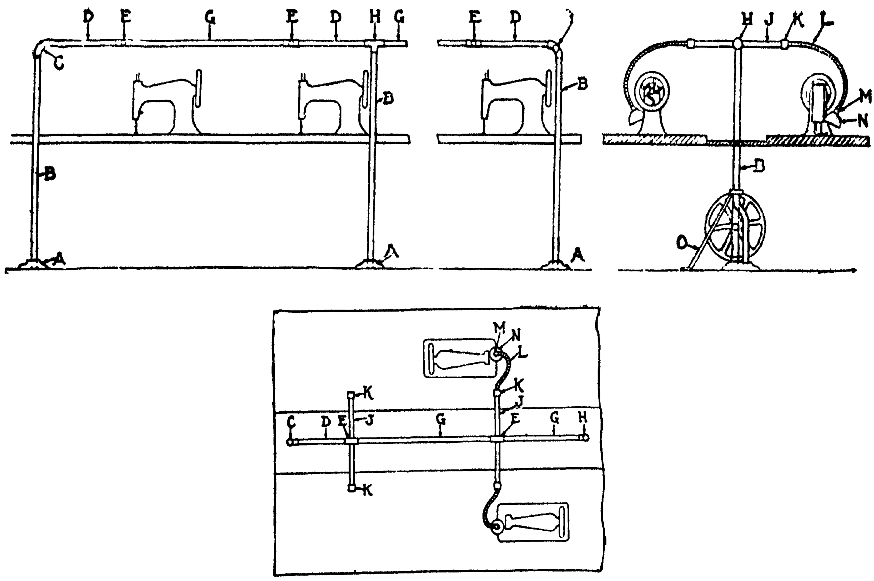


FIG. 9.15.—Localised Lighting of Sewing-Machines (G.E.C.).

the work. To prevent contrasts and glare, the general illumination must be fairly high as well.

9.15. OUTDOOR ILLUMINATION.—Street Lighting: General Considerations.—The main objects of street lighting at present are: to enable people to recognise one another, to distinguish objects on the ground, and to read an address in at least some parts of the illuminated area. Streets may be divided into the important business streets, less important streets adjoining the first kind, with which may also be reckoned the main thoroughfares in suburbs which lead to the city, streets in factory districts, outlying suburban roads, and finally boulevards and parks.

The lamps may be placed on poles in the centre of the street if the latter is wide enough to allow an island being placed round the pole; or they may be suspended above the middle of the road from opposite poles or houses; or they are fixed on poles or to brackets on one side only, or on both sides, either opposite or staggered.

For intensive illumination lamps must be placed on both sides, at close intervals, either opposite or staggered. If only one row of lamps is installed, the centre pole or suspension system is preferable to lamps near the sidewalks. The latter system is mainly employed in narrow streets and factory districts, and they are arranged on one side only if the poles for carrying the overhead system of distribution serve as lamp-posts at the same time. To improve the uniformity of illumination somewhat the lamp bracket may be made to extend 5 to 6 feet from the pole into the street. In such cases the lamps may be placed close together, say, on every second or third pole, the spacing being from 100 to 200 feet. Where network poles are not available, the tendency is to use large lamps and wider spacing. The mounting height increases, of course, with the spacing in most cases. Each case and type of street must be considered individually. The numerous examples given in Chapter VIII. will enable the reader to provide the correct spacing and mounting heights for a given average illumination and type of lamp; or for given spacing and mounting heights the right lamp.

The ideal system of street lighting would be the installation of an illumination sufficiently high and non-glaring to enable all vehicles to travel about without artificial car lights. This would mean an average illumination of at least 1 foot-candle, which, although obtained and exceeded in some principal streets, is greatly left behind in side streets, mainly on account of cost. In fact, if one studies the illumination of a city generally, it is still very primitive. To this must be added the inconvenience and even danger to pedestrians caused by glaring and excessively intensive head-lights of vehicles which rush about, while, on the other hand, drivers of motor cars become helpless when they leave dark suburban roads and suddenly enter a brilliantly illuminated business thoroughfare, especially if the street lamps are glaring.

The war, which gave an impetus to better indoor illumination, to improve the output of factories, largely retarded progress in outdoor lighting. Only in the United States has outdoor illumination shown rapid improvement, especially in business thoroughfares. Merchants have recognised that it is mostly in the evenings that people have time to look into shop windows, promenade about and see the town, and they have combined and pay for the greater part of the cost which intensive street lighting entails. The system is being extended rapidly throughout the States, as merchants find that it pays them to defray additional expenses for street lighting (see also paragraph 9.17).

In Great Britain no agreement has as yet been reached as to how street lighting should be judged. A Committee was appointed in 1913, which later in the year reported, the recommendations being as follows * :—

* *Illuminating Engineer*, May 1913.

Draft Standard Clauses for Including in a Specification for Street Lighting.

As submitted for the approval of the Councils of the Institution of Electrical Engineers, the Institution of Gas Engineers, the Institution of Municipal and County Engineers, and the Illuminating Engineering Society.

Intent of Tender.

1. The Form of Tender headed " Lighting of " includes the provision, fixing, connection, and maintenance of all lamps necessary for obtaining the illumination specified as Class . . . . in and according to the conditions of the standard specification.

Unit of Measurement.

2. This specification is based on illumination, the unit of measurement being 1 foot-candle.

Classification of Streets.

3. For convenient reference the streets are classified as having a minimum illumination as follows : -

Class A	0·01 foot-candle.
,, B	0·025 ,,
,, C	0·04 ,,
,, D	0·06 ,,
,, E	0·10 ,,

Street lighting at a lower minimum illumination than 0·01 candle-power may be specified by the height and distance apart of the lighting units, and the candle-power as measured in the direction of the thoroughfare at an angle of 10 degrees below the horizontal.

Minimum Illumination.

4. The " minimum illumination " of a street means the minimum illumination on a horizontal plane at a height of 3 feet 3 inches above the ground level, and may be measured by means of—

(*a*) Any suitable illumination photometer ; or

(*b*) Any suitable photometer adapted for use in the street which will measure the candle-power of the lamps in those directions which meet at the point of minimum illuminations. In this case the minimum illumination will be calculated by adding together the values of the illumination received from each lamp that materially contributes to the result.

Special Illumination.

5. The special illumination of certain points indicated on the map, such as the corners of cross streets, may be dealt with by specifying the positions and height of lamps and illumination at those points.

Type of Photometer.

6. The photometer shall be of the . . . . type, or of such other type as may be agreed between the parties.

Position of Lighting Units.

7. The approximate positions of the lighting units are indicated on the accompanying map, and are correct within the limits of deviation marked thereon. The contractor shall indicate the positions of all the lighting units, either by completing the said map or by a descriptive schedule accompanying his tender.

Particulars of Lighting Units.

8. Detailed particulars of each type of lighting unit included in the tender must be inserted in the space provided for that purpose in the specification, and must include a statement of the height at which it is proposed to place the centre of light of each type of unit above the street surface, subject to a declared minimum.

Drawings.

9. Drawings of all details as required by the specification shall accompany the tender.

Samples.

10. Samples shall be submitted if required before the acceptance of the tender.

Number of Lighting Units.

11. The number of each type of lighting unit required must be inserted in the tender, with, if called for, a quotation for the provision, fixing, and connection of the necessary apparatus, and the price per annum for maintenance and for . . . . hours' lighting, on which the tender is based.

Additional Lighting Units.

12. The contract will provide for additional lighting units if required, such increase not to exceed . . . . per cent., and to be paid for at the quoted rate per lighting unit.

Tests.

13. A test of the illumination shall be made under such normal atmospheric conditions as will not appreciably affect the accuracy of the result, and at a fairly selected point not being in the shadow of a mantle, lamp, electrode, lantern bar, post, tree, or other obstruction.

When a minimum illumination or candle-power of lighting unit is specified, it shall be held that such minimum is obtained if the average of the measurements of any three minima between consecutive lighting units of the same type does not fall below it.

Contract to be Signed.

14. The tender contains the usual clause that the provisions, conditions, and prices named therein shall form the basis of a contract containing the necessary legal provisions to ensure its fulfilment.

Heads of Clauses for Contract.

15. The contract will also include provisions for—

(1) Ensuring the lighting of all lamps during fog at prices to be quoted.

(2) Execution of work in such manner as may be necessary for the convenience and safety of the public.

(3) Indemnifying the Council against claims arising out of the execution or maintenance of the work or failure of the lighting.

(4) Payment of moneys due for work done.

(5) Defining the responsibilities of the contractor, and to enforce the conditions of the specification and tender with due regard to practical difficulties.

The following clause being suggested as a guide :—

The intention of the contract is that during the maintenance guarantee period of a construction contract, and during the term of a lighting contract, the contractor shall assure himself that the lamps he provides are during lighting hours fulfilling in all respects the requirements of the contract, and he shall not claim relief from the conditions of the contract on the grounds of non-notification on the part of the Council of any failure to comply with the terms of the contract.

NOTE : *Special Clauses.*

1. Each specification may contain special clauses to meet the needs of the particular locality.

Detail Prices.

2. In cases where the specification only calls for the supply, delivery, erection, and connecting up of the lamps, or any of these items, the following further details may be called for :—

(*a*) The cost of the necessary fittings (excluding cost of renewable parts, such as lamps or mantles) delivered on site.

(*b*) The cost of erecting same.

(*c*) The cost of connecting the same to source of supply.

(*d*) The quantity of gas, oil, or electricity, required to maintain the degree of illumination specified, and the pressure at which such gas, oil, or electricity is to be supplied.

Detail Maintenance.

3. It may also be necessary in some cases to call for the cost of maintenance divided up under the following headings :—

(1) Maintenance of all parts such as posts, fixtures, or fittings, including cost of cleaning and painting at stated intervals.

(2) Maintenance of all renewable parts such as mantles, lamps, or carbons, including labour connected therewith.

In the discussion which followed upon the presentation of the report before the Illuminating Engineering Society a good deal of adverse criticism was provided. It centred chiefly about the minimum illumination by which the lighting is to be judged, the testing of it in a horizontal plane 3 feet 3 inches above the ground, and the inability to measure the illumination at all if it falls below 0·01 foot-candle— which is the case in about 80 per cent. of all streets—for which the ordinary illumination photometer is useless.

The author does not agree with all the recommendations of the Committee. The lighting of a street cannot be judged by the minimum illumination alone, and comparisons are impossible. Take a point source of 100 candles, and the illumination measured in one case under an angle of 70 degrees, in another case under 80 degrees, and let the measurement be carried out at a distance of 25 metres from the pole, then the heights of the illuminant will be 9·09 and 4·41 metres respectively. The corresponding horizontal illuminations will be 0·048 and 0·027 metre-candle. In other words, the higher the pole the better the illumination. If we had measured the illumination on screens perpendicular to the rays the illuminations would be 0·14 and 0·155 metre-candle for high and low poles respectively.

A specification of this nature therefore lends itself to fraud by an unscrupulous contractor, and, although this may be avoided by carefully scrutinising paragraphs 7, 8, and 11, there are other disadvantages by stipulating the minimum illumination as a criterion. Take class A, with a minimum illumination of 0·01 foot-candle and an average one of 0·02, and another street with the same minimum but an average illumination of 0·04 foot-candle. The latter street illumination is far superior to the former, but according to the specification they are equal. With bright spots distributed objects such as pedestrians and vehicles are distinguishable as silhouettes against the bright background of light reflected from the shiny surface of the street.

To judge the illumination of a street properly we require the average illumination and the ratio of maximum to minimum illumination, or its reciprocal. Both determinations are easily made, as the examples in Chapter VIII. show. At least the writer and others have found it so. Most lamps used for street lighting are symmetrical, so that a single polar curve suffices, from which the flux curve is constructed (see paragraph 6.04). A test sheet, such as is constructed by the General Electric Company (U.S.A.) for street-lighting fixtures, and reproduced in fig. 9.16, gives all the information wanted. Any illuminating engineer may then find by means of Högner's or any other suitable method the average illumination, no matter how the lamps are arranged. By dividing the flux striking an area by the area itself, we obtain the true average

FORM 6 NOVALUX PENDENT UNIT.

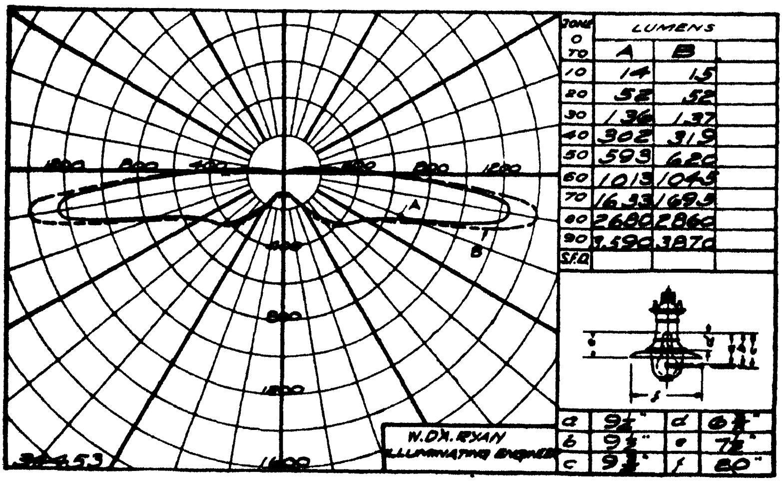
LYNN WORKS, GENERAL ELECTRIC COMPANY.

600-CANDLE-POWER EDISON MAZDA SERIES LAMP, PS-40 BULB.

	A.	B.
Lamp	Clear.	Clear.
Volts	50·8	50·8
Amperes	6·6–20	6·6–20
Watts (rated)	330	330
Mean hemispherical candle-power	572	616
Watts per mean hemispherical candle-power	0·58	0·54
Downward-lumens	3590	3870
Downward lumens per watt	10·9	11·7
Mean spherical candle-power	315	336
Watts per mean spherical candle-power	1·05	0·98
Total lumens	3960	4225
Total lumens per watt	12·0	12·8
Per cent. total lumens of lamp	66	70·5

PHOTOMETRIC TEST.

INITIAL DISTRIBUTION OF CANDLE-POWER IN A VERTICAL PLANE.



ZONE 0 TO	LUMENS A	LUMENS B
10	14	15
20	52	52
30	136	137
40	302	319
50	593	620
60	1013	1045
70	1633	1695
80	2680	2860
90	3590	3870
S.F.Q.		

READINGS TAKEN AT 25-FOOT RADIUS.

Lamp operated at 6000 total lumens.
Steel reflector Cat. No. 170556.
White porcelain enamel reflecting surface.
A–8½-inch new bowl type refractor with lower half of inner section velvet finish.
B–8½-inch new bowl type refractor clear.

FIG. 9.16.—Test Sheet of a Street Lamp (G.E.C.).

illumination, no matter how large or how small it may be. There is also no reason why the road surface should not be used as the test surface, instead of a plane about a metre above it, since the illumination is calculated (as is also recommended by the Committee for streets with an illumination below 0·01 foot-candle) and not actually measured. In case of doubt or dispute the distribution of a lamp is measured in a laboratory. The results are independent of reflection and just to both sides. By adding the ratio K_u or its reciprocal the character of the illumination is fixed.

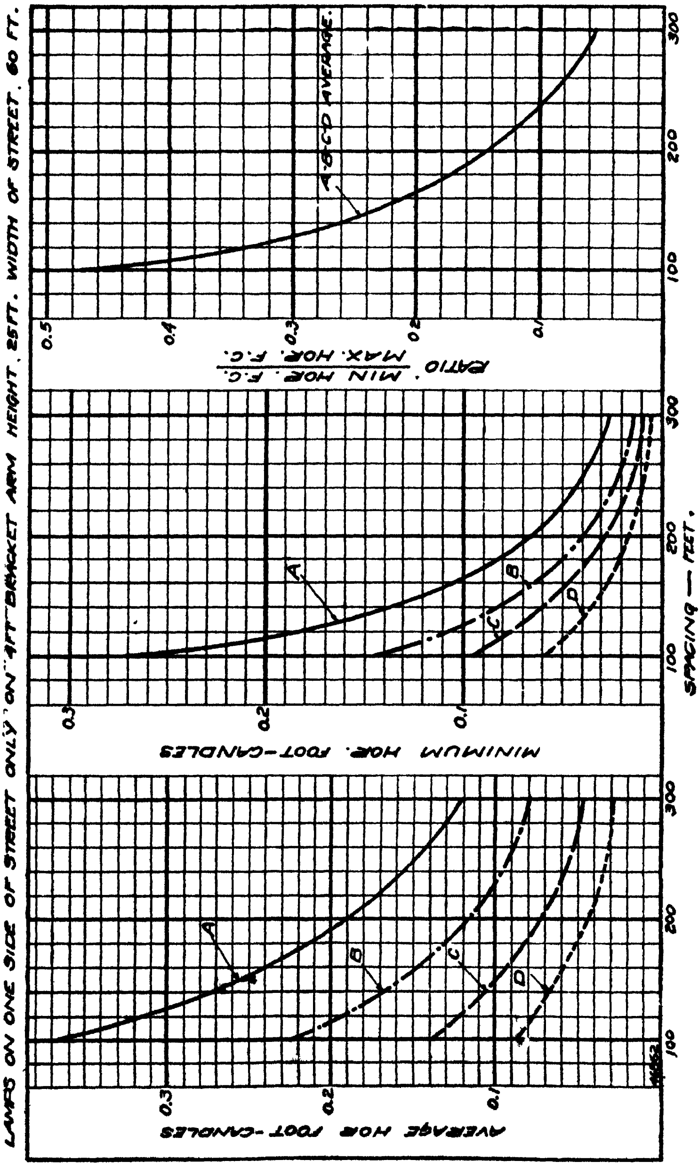


Fig. 9.17.—Illumination Values on Street Surface along Centre Line of Street (G.E.C.).

In fig. 7.43 polar curves were given for Novalux fixtures with gas-filled lamps. Fig. 9.17 gives the resultant illumination for a street 60 feet wide. Curves A, B, C, D hold for 1000, 600, 400, and 250 candle (M.H.S.C.P.) lamps respectively. The figure is otherwise self-explanatory.

With a known average illumination we can also compare streets as regards costs. Consider Example (*g*), in which the lamp produces 1000 M.H.C.S.P., or a flux in the lower hemisphere of 6280 lumens. The total flux of the lamp is 7500 lumens and the power consumed 300 watts. The street area per lamp is 1500 square metres, so that the power per square metre amounts to 0·2 watt, resulting in an average illumination of 2·12 metre-candles. The utilisation factor is $\frac{3180}{7500}=0{\cdot}424$, and the expenditure of power per metre-candle per square metre illuminated road surface is $\frac{0{\cdot}2}{2{\cdot}12}=0{\cdot}0945$ watt.

Test sheets such as illustrated in fig. 9.16 will also prevent a contractor from being penalised in streets with heavy foliage, in which the "average" minimum illumination may be exceptionally low.

9.16. TYPES OF LAMPS TO BE USED.—Gas-filled incandescent, magnetite, and flame arc lamps are principally used to-day. As the gas-filled tungsten lamp can be obtained in almost any sizes, clusters are disappearing. Magnetite lamps possess the advantage of sparkle, which the man in the street, who, by the way, is still largely uneducated physiologically, often prefers to the still incandescent light. Flame arc lamps with yellow light are best in foggy weather, and for railway yards they are therefore superior to other illuminants, as even in slightly misty weather numbers can be read at great distances.

On the whole, the cost efficiency will often determine which lamp is best to be installed. It will be found that this depends principally upon the cost of current and the time of burning.

9.17. COST OF ELECTRIC LIGHTING.—We shall consider four types of lamps, producing each 1000 M.S.C.P., and absorbing 780, 520, 500, and 400 watts for gas-filled tungsten, enclosed flame arc, mercury vapour, and open flame arc lamps respectively. The life of a tungsten lamp is taken as 800 hours, of the burner of a vapour lamp 1000 hours, but whereas a gas-filled lamp costing £2 is useless when burned out, a quartz burner, costing originally £7, 10s., has still a value of £2, 10s. after becoming unsuitable for the lamp. The cost of the fitting of the incandescent lamp, excluding lamp bulb, is £2; that of the mercury vapour lamp £5. The enclosed arc lamp costs £8, 10s.; it must be recarboned every 100 hours. A hundred pairs of carbons cost £5. The carbons in the open lamp last eighteen hours; 100 pairs cost £3, 10s. For waste we reckon 10 per cent. For interest on the capital outlay we add 5 per cent. The life of the three arc lamps is five years, that of the fitting of the gas-filled lamp ten years. As depreciation money is put out on interest, we reckon in the former case 18·1 per cent. for depreciation; in the latter, 7·95 per cent. The cleaning of incandescent and mercury vapour lamps occurs once a month, at 6d. a time; that of the long-burning enclosed lamp once a week; and that of the yellow flame lamp with every recarboning, at 8d. a time. On this basis the following table has been compiled :—

TABLE 9.02.—COST OF ELECTRIC LIGHTING (FOR ONE YEAR).

No. of Burning Hours per Year.	Gas-filled Tungsten Lamp.	Enclosed Flame Arc Lamp.	Quartz-Mercury Arc Lamp.	Yellow Flame Arc Lamp.	Cost of Current.
500	£3 13 10	£4 19 9	£6 14 7	£4 13 8	One penny per unit.
1000	6 11 4	6 5 7	10 5 5	7 12 9	
2000	12 6 4	9 2 1	17 17 1	13 10 10	
3000	17 15 0	11 16 5	24 8 9	19 9 3	
500	£5 6 4	£6 1 5	£7 15 5	£5 10 4	Twopence per unit.
1000	9 16 4	8 8 11	12 7 1	9 6 1	
2000	18 16 4	13 8 9	22 0 5	16 17 6	
3000	27 10 0	18 6 5	30 13 9	24 9 3	
500	£6 18 10	£7 3 11	£8 16 3	£6 7 0	Threepence per unit.
1000	13 1 4	10 12 3	14 8 9	10 19 5	
2000	25 6 4	17 15 5	25 13 9	20 4 2	
3000	37 5 0	24 16 5	36 18 9	29 9 3	
500	£8 11 4	£8 4 9	£9 17 1	£7 3 8	Fourpence per unit.
1000	16 6 4	12 15 7	16 10 5	12 12 9	
2000	31 16 4	22 2 1	30 7 1	23 10 10	
3000	47 0 0	31 6 5	43 3 9	34 9 3	
500	£11 16 4	£10 8 1	£11 18 9	£8 17 0	Sixpence per unit.
1000	22 16 4	17 2 3	20 13 9	15 19 5	
2000	44 16 4	30 15 5	38 13 9	30 4 2	
3000	66 10 0	44 6 5	55 13 9	44 9 3	

This table is extremely interesting, as it shows us that for short burning and a low cost of current the gas-filled tungsten lamp is the most economical illuminant, whereas for long burning and a high cost of power the flame arc lamps hold the field. Each case must, of course, be considered individually by carefully taking into account local conditions as regards wages, etc. The argument holds, of course, for industrial lighting also, but in the latter case preference will often be given to the gas-filled lamp, as it can be obtained in small sizes. Consideration must also be given to the cost of controlling apparatus, wiring, etc., which has been neglected in the above table.

9.18. THE CONTROL OF STREET LIGHTING.—In Europe and South Africa all incandescent lamps are connected in multiple, and in the case of arc lamps only a few are joined in series to standard voltages suitable for glow lamps. In America the series system is employed to a large extent for arc and incandescent lamps. It has the advantage that low-voltage lamps can be used, which possess more robust filaments and are more efficient than high-voltage lamps. All lamps burn with the same current and thus produce the same intensity. In case of failure of a lamp an equivalent resistance may be inserted, or the lamp is short-circuited and the current is kept constant by special station apparatus (see also paragraph 6.20).

With the multiple arrangement, all lamps burn at different voltages and thus different intensities, those near the feeding-points being brightest. Special feeders are required or time switches must be installed for the switching in and out of the street lamps. Pilot wires used for measuring the voltage of the feeding-points may be simultaneously employed for accomplishing this.*

The disadvantages of the series system are the high voltages and additional controlling apparatus, but arc and incandescent lamps may be joined in series as well as in parallel as long as their currents are equal.

9.19. EXAMPLES IN OUTDOOR ILLUMINATION. – Fig. 9.18 illustrates the lighting of Main Street, Salt Lake City.† The system consists of seventy standards, each carrying three 6·6 ampere ornamental luminous arc lamps. Spacings are about 100 feet, lamps being on both sides, and the over-all height of the standards is 29 feet. The particulars about costs are as follows: –

Total cost	$28,220.40
City's share	2,685.91
Property owners' share	25,534.39
Taxable property, linear feet	6,372.00
Total cost per foot	4.43
Operating cost for three years	29,334.65
Property owners' share for three years	25,174.04
City's share for three years	4,160.61
Operating cost per foot front per year	1.54
Property owners' share	1.32
City's share	0.22

The system is being extended for State Street and Broadway, by the addition of 504 ornamental luminous lamps, costing 140,000 dollars.

A further development has been the employment of the gas-filled lamp in duoflux lighting units, in which there are two lamps, one of 750 and another of 250 candles (M.H.S.C.P.), the former being switched off, say, at midnight. This is better than switching off intermediate lamps, as only the intensity, and not the distribution, is altered. A section

* Bohle, *Transactions S.A. Society of Civil Engineers*, May 1917.

† *General Electric Review*, May 1920, p. 362.

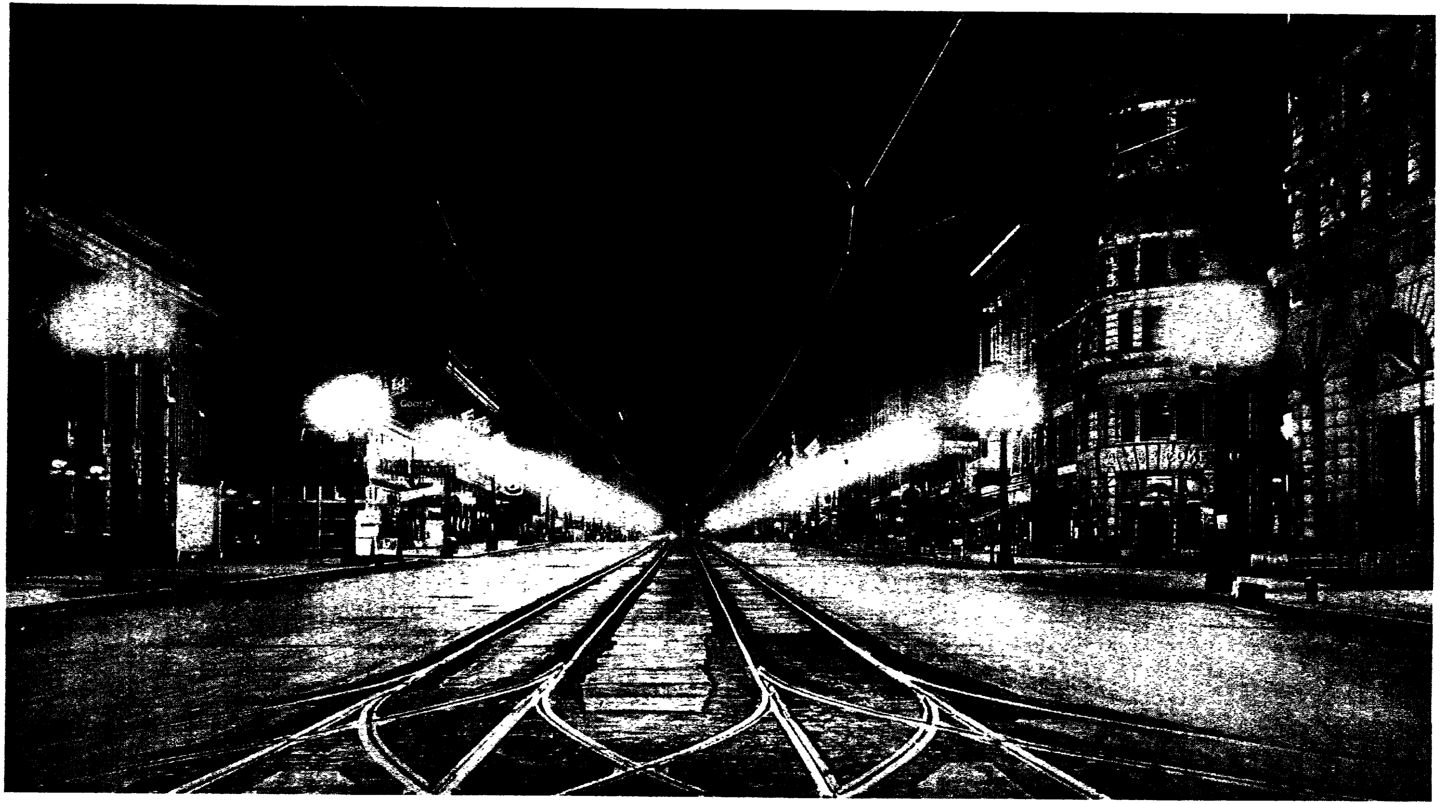


Fig. 9.18.—Illumination of Main Street, Salt Lake City.

[*To face p.* 398.

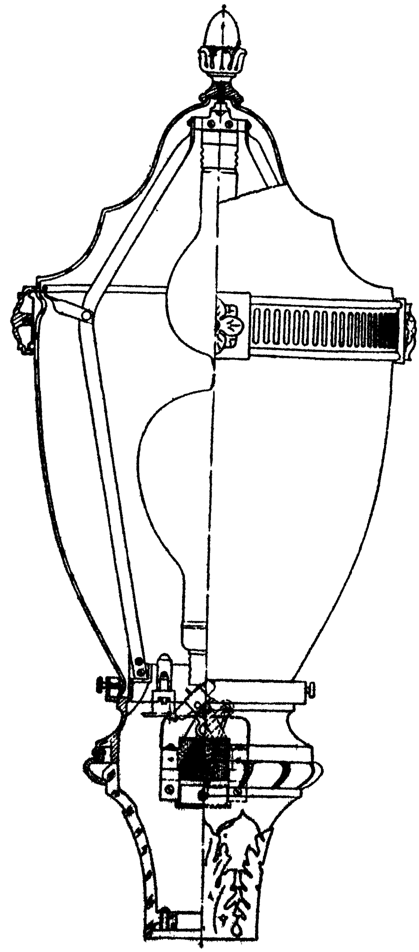


Fig. 9.19.—Section through Duoflux Unit (G.E.C.).

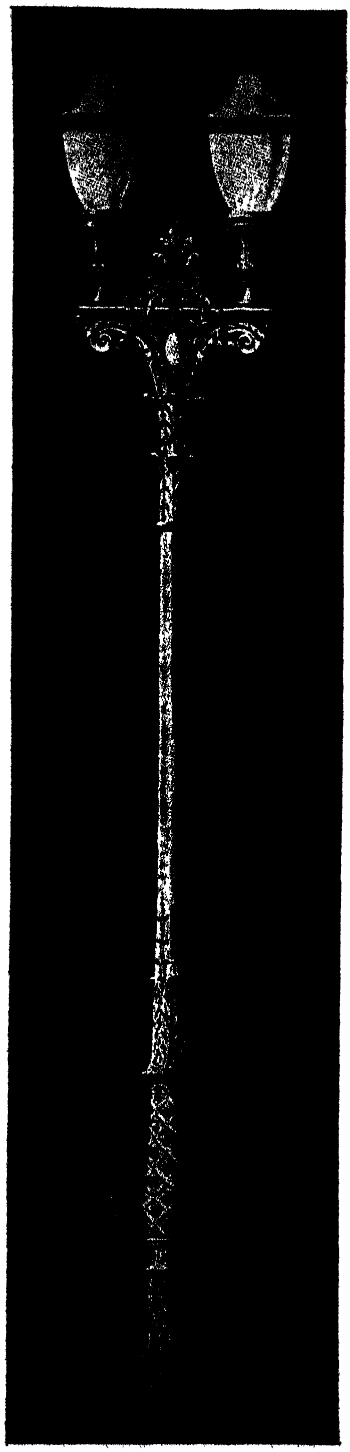


Fig. 9.20.—Ornamental Lamp Standard (G.E.C.).

through a duoflux unit is shown in fig. 9.19 and a standard for two units in fig. 9.20.

The illumination of State Street, Chicago, by means of 1000-watt

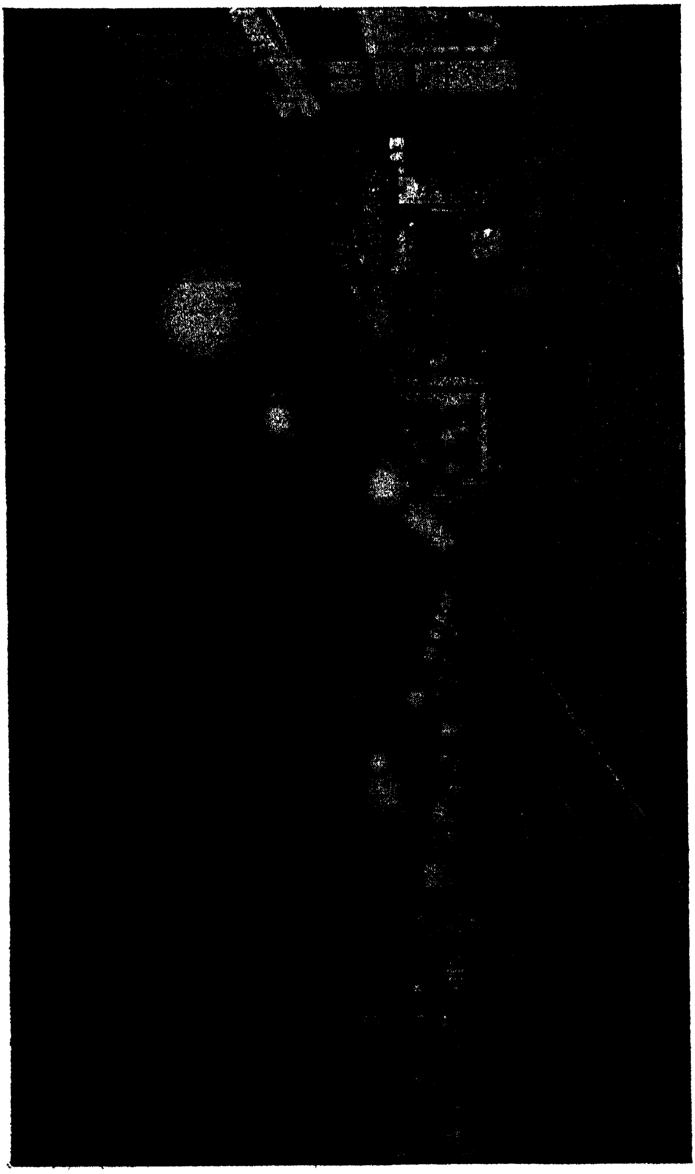


Fig. 9.21.—Illumination of State Street, Chicago (G.E.C.).

gas-filled lamps in Novalux fixtures joined to each trolley pole by means of brackets, is reproduced in fig. 9.21.

As regards the heights of lamps, practice varies throughout the world. America and France favour comparatively low posts even for large lamps, while in Germany and Austria lamps are placed up to 40 feet high. In England the general practice is to fix lamps of 75 candles about 12

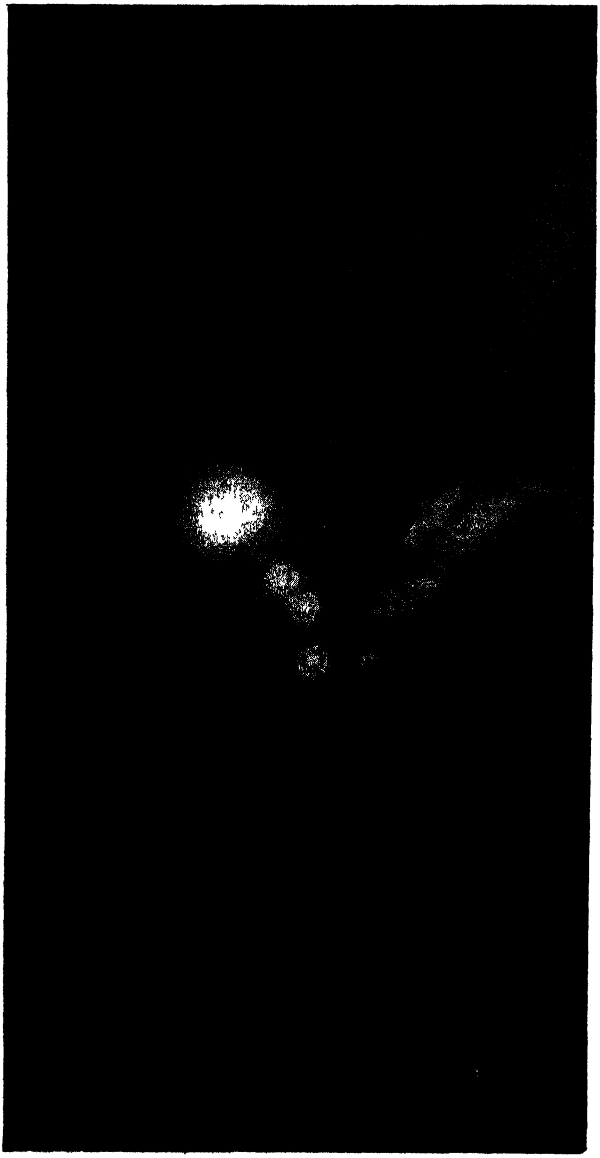


Fig. 9.22.—Illumination of Highway Road.

feet high, and to increase this height approximately proportionally to the candle-power, a lamp of 3000 candles being 30 feet up.

A highly interesting type of highway lighting is illustrated in fig. 9.22, which illustrates the illumination of Paradise Road, Swampscott, U.S.A. Each unit contains a 250-candle-power 4-ampere Mazda lamp placed inside a fitting known under the name of Novalux Highway Lighting Unit. It is illustrated separately in fig. 9.23, and the way in which it acts is shown in fig. 9.24, while the polar distribution is given by fig. 9.25. It will be noticed that the unit can be swivelled in any direction and that the distribution is especially suitable for large spacing, which may reach 600 feet.*

FIG. 9.23.—Highway Lighting Unit.

9.20. FLOOD LIGHTING.—The type of reflector to be installed, and the intensities required, depend upon the following :—

(*a*) The distance from the projector to the surface to be illuminated.

(*b*) The location of a building, whether it stands in a well-illuminated business street, park, or other place where there is no stray light.

(*c*) The colour of the building surfaces, whether dark or light.

The accompanying Table 9.03 gives particulars about the desired illuminations for different localities :—

TABLE 9.03.—ILLUMINATIONS FOR FLOOD LIGHTING.†

Nature of Buildings.	Character of Surroundings.		
	Well-illuminated Streets.	Residential Quarters.	Parks.
Dark-coloured Buildings .	20 foot-candles	15 foot-candles	10 foot-candles
Medium- ,, ,, .	15 ,, ,,	10 ,, ,,	5 ,, ,,
Light- ,, ,, .	10 ,, ,,	5 ,, ,,	3 ,, ,,

* From *General Electric Review*, August 1921, p. 760.

† *Ibid.*, September 1918, p. 633.

In using this table, it should be seen that the angle between the axis of the beam and the surface illuminated is not less than 70 degrees (see

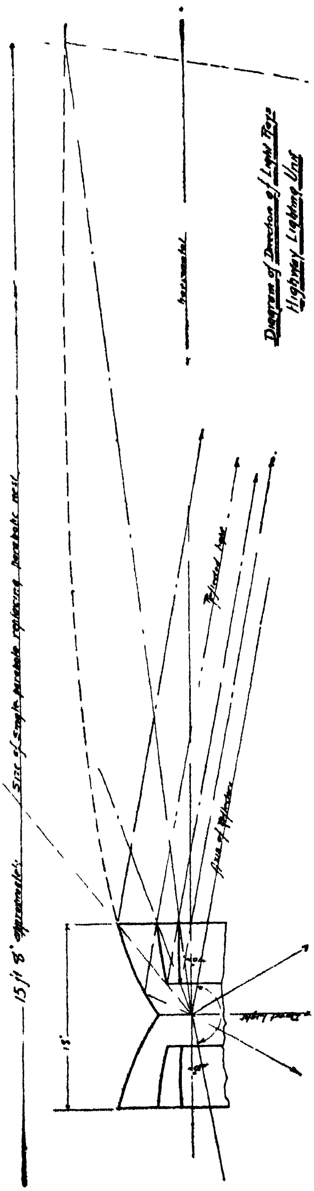


FIG. 9.24.—Reflection by Highway Lighting Unit.

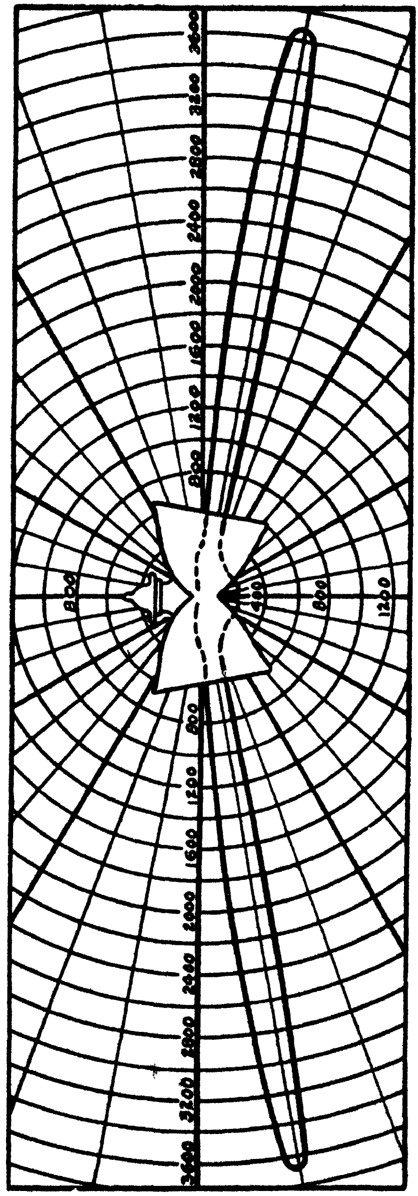
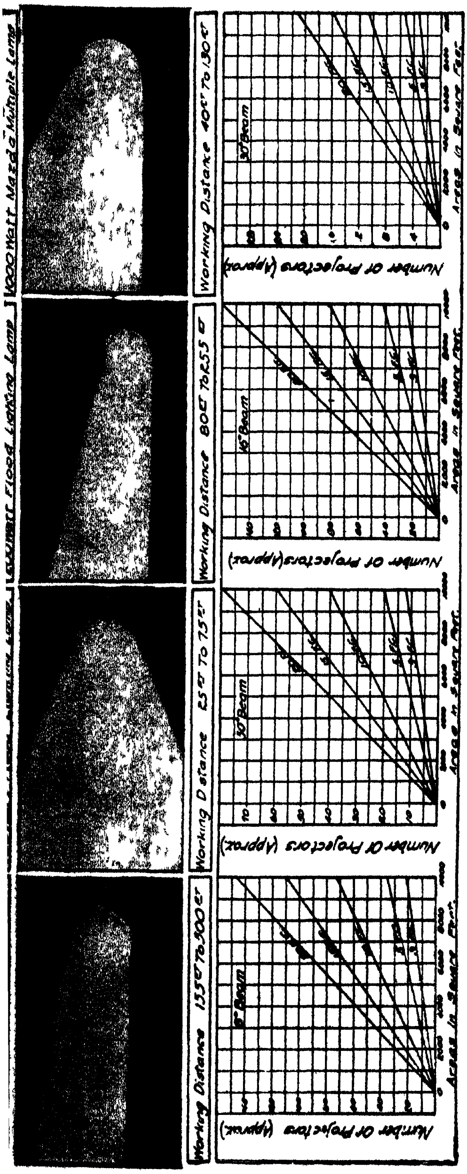


FIG. 9.25.—Polar Curve of Highway Lighting Unit.

also paragraph 7.13). By means of figs. 9.26 and 9.27, the number of reflectors required may easily be obtained.

Example.—Suppose an area of 10,000 square feet in a well-illuminated street has to be lighted from a distance of 130 feet, the colour of the building being dark From fig 9 26 we see that for a distance of 130 feet a L12 reflector is suitable, and in order to obtain an illumination of 20



Diameters, Areas And Intensities For One Unit Only

[illegible]	8° Beam			50° Beam			16° Beam			30° Beam		
	Diameter Feet	Area Square Feet	Average Foot Candles	Diameter Feet	Area Square Feet	Average Foot Candles	Diameter Feet	Area Square Feet	Average Foot Candles	Diameter Feet	Area Square Feet	Average Foot Candles
25	3 5	9 6	148 000	22 3	389	6 750	7	38 5	33 800	13.4	141	67 100
50	7 0	38.5	37 000	44.6	1556	1 680	14	154 0	8 430	26.8	564	16 800
100	14 0	154 0	9 250	93 0	6793	0 385	28	616 0	2 110	54 0	2290	4 140
200	28 0	616 0	2 310	186 0	27172	0 096	56	2463 0	0 527	108.0	9161	1 030
[illegible]	[illegible]	[illegible]	0 580	372 0	108687	0 024	112	9852 0	0 132	216.0	36644	0 258
[illegible]	[illegible]	[illegible]	0.257	558.0	244546	0 011	168	22167 0	0 058	324.0	82448	0 115
[illegible]	112.0	[illegible]	0 148	744 0	434748	0 006	224	39408 0	0 033	432.0	146574	0 065
[illegible]	140.0	[illegible]	[illegible]	930 0	[illegible]	0 004	280	61575 0	0 021	540.0	229022	0.041

foot-candles we require twenty-one reflectors with 1000-watt gas-filled projection lamps each. Fig. 9.28 illustrates the flood-lighting of the Capitol, Washington. The dome is 135 feet in diameter at the base and 218 feet high above the roof. It is painted white. Around the base are

FIG. 9 28.—Flood-Lighting of the Capitol (G.E.C.).

[*To face p.* 404.

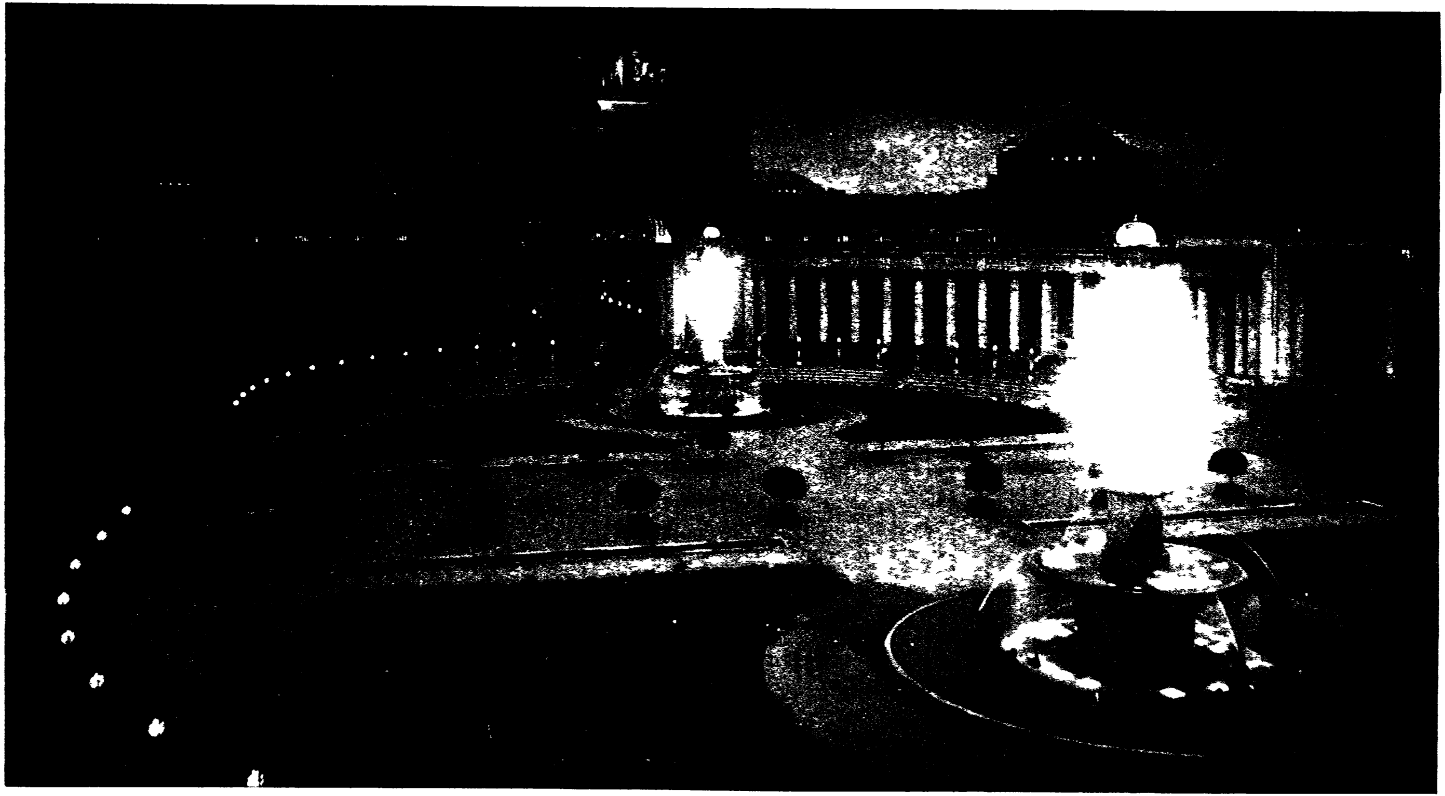


FIG. 9.29.—The Fountains of the Rising and Setting Sun in the Court of the Universe at the Panama Pacific Exposition

[To face 404

thirty-six fluted columns, representing the thirty-six States in the Union at the time of design. It is lighted by means of four banks of twenty-one projectors each, possessing 400-watt lamps, about 200 feet from the base.

Flood-lighting is, of course, not solely employed for spectacular purposes, but is also largely used for speeding up industrial work. This was especially the case in America during the war, when whole shipyards were intensively illuminated for night work by means of flood-lighting projectors.

Tennis-courts, bowling-greens, rifle-ranges, and all kinds of recreation grounds are to-day illuminated so as to be suitable at all periods. There is nothing new in the design of the illumination of these, as long as the correct type of reflector is employed.

9.21. SPECTACULAR LIGHTING.—The illumination of the Panama-Pacific Exposition in 1915 was quite a revelation in this respect. Whatever method of illumination had been invented was employed, and neither money nor ingenuity was spared to make the illumination a wonder and success. It would be impossible to include a full description in this volume, and the reader is referred to an article appearing elsewhere.* Of special interest was the lighting of the "Court of the Universe," where an area of nearly half a million square-feet was illuminated by two fountains, rising 95 feet above the level of the sunken gardens, one symbolising the rising sun and the other the setting sun.

The shaft and ball surmounting each fountain were glazed in heavy opal glass, coated on the outside in imitation of travertine stone, in which tungsten lamps were installed, producing a combined initial intensity of 500,000 M.S.C.P. without causing any glare. For relief lighting, incandescent lamps were placed in specially designed cup reflectors located in the central flute to the rear of each column. The perimeter of the sunken garden was marked by balustrade standards consisting of Atlantes supporting urns in which were placed tungsten lamps of low candle-power. Their function was purely decorative.

The balustrade of this court, 70 feet above the sunken garden, was surmounted by 90 seraphic figures with jewelled heads. These were cross-lighted with 180 incandescent search-lights, the demarcation of the beams being blended out by the light from the fountains of the rising and setting sun. Fig. 9.29 gives a photograph of the system.

The tower of jewels was illuminated with 10,200 Nova-gems, or so-called exposition jewels, the rotunda and colonnade of the Palace of Fine Arts by means of artificial moonlight. This effect was produced by search-lights placed on neighbouring buildings and supplemented by concealed lighting in the rear cornice soffits of the colonnade.

9.22. ILLUMINATED SIGNS.—This system of lighting is far too little employed, and might with advantage be greatly extended for

* *General Electric Review*, June 1915, p. 579.

showing people how to find their ways about and for attracting the attention of pedestrians to special buildings, places of interest, etc.

The simplest system consists of a box in which the illuminant is placed behind a screen of opal glass on which letters are traced. By changing the letters the character of the intended notice is altered. Signs of this nature are suitable for railway stations, theatres, etc.

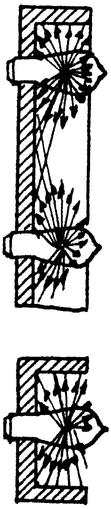


FIG. 9.30.

Another system consists of illuminating signs by means of reflectors, as is done in flood-lighting, and need not be described any further.

Finally, signs and lamps form units. The system should be so constructed that, when looking at a sign, we must not distinguish the individual lamps, but only the letters or outline of the sign.

Lamps used for this purpose are usually of low power. 5, 10, and 20 watts being standard ratings. Raised letters stand out prominently by day and night, but flat letters are more easily cleaned or are partly self-cleaning. Grooved letters are more efficient, as less lamps are required per letter, as the sides of the groove reflect otherwise wasted light, but they can be viewed properly within a restricted angle only. The lamps are so arranged in the letters that most of the light is given off at the sides and little from the ends, as illustrated in fig. 9.30. Bowl-frosted lamps in troughs, with V-shaped filaments, give excellent results if the frosting reduces the direct light to about the same intensity as that reflected from the trough. Frosting possesses, however, the disadvantage of increasing losses and reducing the efficiency by easily accumulating dirt.

On the whole, the closer the lamps are placed in a letter the greater is the legibility. The spaces between letters and parts of a letter should not be too small and should exceed $\frac{\text{maximum reading distance}}{1000}$ for solid letters.

BIBLIOGRAPHY.

The following list gives the principal papers and communications which have appeared after the publication of the first edition of this book.

ABBREVIATIONS.

Am. Ill. Eng. Soc. Trans.	Transactions of the American Illuminating Engineering Society.
Am. Inst. Electr. Eng. Proc.	Proceedings of the American Institute of Electrical Engineers.
Am. Electrochemical Soc. Trans.	Transactions of the American Electrochemical Society.
Atti del' Assoc. Elettr. Ital.	Atti della Associazone Elettrotecnica Italiana.
Bureau of Standards, Bull.	Bulletin of the Bureau of Standards.
Bureau of Mines, Bull.	Bulletin of Bureau of Mines.
Electr. Rev. and West. Electn.	Electrical Review and Western Electrician.
Electr. World	Electrical World.
Eng. Club Phil. Journal	Journal of the Engineering Club, Philadelphia.
E.A.	Elektrotechnischer Anzeiger.
E.T.Z.	Elektrotechnische Zeitschrift.
G.E.R.	General Electric Review.
Ill. Eng.	Illuminating Engineer (London).
J.I.E.E.	Journal of the Institution of Electrical Engineers.
Inst. Civ. Eng. Proc.	Proceedings of the Institution of Civil Engineers.
Optical Soc. Trans.	Transactions of the Optical Society.
Rev. Gén. d'Él.	Revue Générale de l'Électricité.
West. Soc. Eng. J.	Journal of the Western Society of Engineers.
Z.V.D.I.	Zeitschrift des Vereins Deutscher Ingenieure.
Soc. Int. Electr. Bull.	Bulletin de la Société Internationale des Électriciens.

CHAPTER I.

" Calibration of Photometric Standards," R. W. Shenton, *Electr. Rev. and West. Electn.*, 62, pp. 154–155, Jan. 18, 1913.

" Electric Arc as a Standard of Light," J. F. Forrest, *Electrician*, 71, pp. 729–732, Aug. 8, 1913; pp. 1007–1010, Sept. 26, 1913.

" About Units of Light," G. Brodhun, *E.T.Z.*, June 26, 1913.
" Pentane Standard as a Working Standard," E. C. Crittenden and A. H. Taylor, *Bureau of Standards*, *Bull.* 10, pp. 391–417, 1914.
" Brightness," J. R. Cravath, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 394–412, May 1914.
" Nomenclature and Definition of Photometric Magnitudes and Units," A. P. Trotter, *Ill. Eng.*, 7, pp. 339–358, July 1914.
" Acetylene Lamp Standard," L. A. Jones, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 716–733, 1914.
" Influence of Air Pressure on the Luminous Intensity of the Hefner Lamp," A. Boltzmann and A. Basch, *Elektrotechnik u. Maschinenbau*, 40, pp. 511–512, Oct. 29, 1922.

CHAPTER II.

" Drawn Tungsten Filaments," B. Duschnitz, *E.A.*, 30, pp. 197–199, Feb. 23; pp. 223–224, March 2; pp. 249–251, March 9; and pp. 277–278, March 16, 1913.
" Mercury Quartz Tube Lamp for 500 Volts," *E.T.Z.*, 34, p. 331, March 1913.
" Automatic Current Regulation during Exhaustion of Incandescent Lamps," *Electr. Rev.*, 71, pp. 688–689, Nov. 1, 1912.
" Metal Filament Lamps," G. Mongini, *Atti del' Assoc. Elettr. Ital.*, 17, pp. 690–697, Aug. 15, 1913.
" The Manufacture of a Modern Metal Filament Lamp," O. Ruff, *Z.V.D.I.*, 57, pp. 1615–1620, Oct. 11, 1913.
" Tungsten Lamps of High Efficiency," I. Langmuir, *Am. Inst. Electr. Eng. Proc.*, 32, pp. 1895–1914, Oct. 1913.
" Nitrogen-filled Tungsten Lamps," I. Langmuir and J. A. Orange, *Am. Inst. Electr. Eng. Proc.*, 32, pp. 1915–1926, Oct. 1913.
" The Determination of the True Temperatures of Incandescent Lamps," O. Lummer, *Licht und Lampe*, June 19, 1913.
" Carbon and Impregnated Electrodes for Arc Lamps," A. T. Baldwin, *Electr. World*, 62, pp. 793–797, Oct. 18, 1913.
" Contribution to Knowledge of the Moore Lamp," J. Bujes, *E.T.Z.*, 35, pp. 57–61, Jan. 15, 1914.
" Alternating-Current Arc in Mercury-Vapour," E. Darmois and M. Leblanc, *Comptes Rendus*, 158, pp. 258–260, Jan. 26, 1914; pp. 401–404, Feb. 9, 1914.
" Cooling Effect of Leading-in Wires on Filaments of Street Series Incandescent Lamps," T. H. Amrine, *Am. Ill. Eng. Soc. Trans.*, 8, pp. 385–399, Nov. 1913.
" The Manufacture of Drawn-wire Tungsten Lamps," J. W. Howell, *G.E.R.*, 17, pp. 276–281, March 1914.
" Quartz Mercury Vapour Lamp," E. Weintraub, *G.E.R.*, 17, pp. 270–275, March 1914.
" Luminosity of Neon Tubes as a Function of their Diameter," G. Claude, *Comptes Rendus*, 158, pp. 692–694, March 9, 1914.
" Relative Emissivities from Tungsten Lamps," W. W. Coblentz, *Electr. World*, 64, pp. 1048–1051, Nov. 28, 1914.
" A Three-Phase Incandescent Lamp," *Revue Électrique*, 22, pp. 233–234, Nov. 18, 1914.
" Improvement in the Luninous Arc," *Electr. World*, 64, pp. 661–663, Oct. 3, 1914.
" Characteristic Equations of Tungsten Filament Lamps and their Application in Heterochromatic Photometry," G. W. Middlekauff and J. F. Skogland, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 734–774, 1914.
" Radiation from Quartz Mercury-Arc Lamps," C. Winther, *Zeitschrift für Elektrochemie*, 20, pp. 109–110, Feb. 15, 1914.

"Arc Lamps for Photographic Purposes," V. A. Clarke, *Electr. World*, 64, pp. 956–961, Nov. 14, 1914.

"Tungsten Lamps in Photography," M. Luckiesh, *Electr. World*, 64, pp. 954–955, Nov. 14, 1914.

"Approximate Uniform Point-source Incandescent Lamp," A. E. Kenelly, R. W. Chadburn, and G. D. Edwards, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 126–133, 1915.

"New Type of Arc Electrodes," I. Ladoff, *Electr. Rev. and West. Electn.*, 66, pp. 691–695.

"Improvements in Glow-lamps," *Engineer*, 120, p. 264, Sept. 10, 1915.

"Reducing Blackening in Gas-filled Lamps," *Electr. Engineering*, 11, p. 366, Sept. 2, 1915.

"Computation of Characteristics of Tungsten Lamps," J. F. Skogland, *Bureau of Standards, Bull.* 12, pp. 269–287, 1915.

"Gas-filled Lamps," M. Pirani and A. R. Meyer, *E.T.Z.*, 36, pp. 493–496, Sept. 23; pp. 507–510, Sept. 30, 1915.

"Reduction Factors for Electric Lamps," K. Zickler, *Elektrotechnik und Maschinenbau*, 33, pp. 469–473, Sept. 26; pp. 481–484, Oct. 3, 1915.

"Filament Temperatures of Electric Lamps," M. Pirani and A. R. Meyer, *Elektrotechnik und Maschinenbau*, 33, pp. 397–401, Aug. 15, and pp. 414–417, Aug. 22, 1915.

"Tungsten Arc," E. A. Gimmingham and S. R. Mullard, *J.I.E.E.*, 54, pp. 15–19, Dec. 1, 1915.

"Chemistry of the Flame Arc," W. C. Moore, *Am. Electrochemical Soc. Trans.*, 27, pp. 435–458, 1915.

"Zirconium-Iron Alloys for Lamp Filaments," *Met. and Chemical Eng.*, 13, p. 924, Dec. 1, 1915.

"Inside Temperature of Helical Tungsten Filaments," B. E. Shackelford, *Journal Franklin Institute*, 180, pp. 619–621, Nov. 1915.

"Limits of Efficiency in Light Production," O. Lummer, *Elektrotechnik und Maschinenbau*, 33, pp. 627–629, Dec. 26, 1915.

"Light and Illumination," C. P. Steinmetz, *West. Soc. Eng. J.*, 20, pp. 737–751, Nov. 1915.

"Evaporation of Tungsten Lamp Filaments," U. Bordoni, *Elettrotecnica*, 3, pp. 503–515, Aug. 15, 1916.

"A High-efficiency Carbon-filament Lamp," *Electr. World*, 68, p. 453, Sept. 2, 1916.

"Arcs under Pressure," W. Mathiesen, *E.T.Z.*, 37, pp. 549–553, Oct. 12, and pp. 567–570, Oct. 19, 1916; *E.T.Z.*, 38, pp. 573–575, Dec. 6, 1917.

"The Nernst Vapour Lamp," *E.T.Z.*, 37, pp. 544–545, Oct. 5, 1916.

"An Arc with Unconsumed Electrodes," W. A. Darrah, *Am. Electrochemical Soc. Trans.*, 29, pp. 613–638, 1916.

"Tungsten Filaments," W. Böttzer, *Phys. Zeits.*, 18, pp. 108–109, March 1, 1917; O. Ely, *Z.V.D.I.*, 62, pp. 15–20, Jan. 12, 1918.

"Enclosed Arc with Low Voltage Drop," *Wireless Age*, 5, pp. 453–454, March 1918.

"The Tungsten Arc," O. Kruh, *Elektrotechnik und Maschinenbau*, 36, pp. 345–348, Aug. 4, 1918.

"Diminution of Ultra-violet and Total Radiation of Quartz Tube Mercury-vapour Lamps during Life," W. W. Coblentz, M. B. Long, and H. Kahler, *Bureau of Standards, Bull.* 15, pp. 1–20.

"Neon Lamps for Direct Currents," F. Schröter, *Zeitschrift für Elektrochemie*, pp. 132–137, May 1, 1918.

"The Chemistry of the Tungsten Lamp," A. Brann and A. M. Hageman, *Electric Journal*, 16, pp. 198–201, May 1919.

"A New Glow Lamp," F. Schröter, *E.T.Z.*, 40, pp. 186–188, April 24, 1919.

"Blackening of Tungsten Lamps," *K. Akad. Amsterdam, Proc.*, 21, 8, pp. 1062–1077, 1919.

"The Ediswan Pointolite Lamp," *Electrical Review*, 86, pp. 9–10, Jan. 2, 1920.

"Neon Arc-Lamp," F. Skaupy, *Zeitschrift für technische Physik*, 1, 9, pp. 189–191, 1920.

"Incandescent Vapour Lamps," F. Schröter, *Zeitschrift für technische Physik*, 1, 6, pp. 109–116, and 1, 8, pp. 149–159, 1920.

"Knowns and Unknowns in Light-Production," G. M. J. Mackay, *Am. Ill. Eng. Soc. Trans.*, 15, pp. 545–556.

"Expansion Effects in Wires used for Sealing into Glass," J. Salpeter, *Zeitschrift für technische Physik*, 1, 9, pp. 205–208, 1920.

"The Theory of Illuminants Dependent on Luminescence," F. Schröter, *Elektrotechnik und Maschinenbau*, 38, pp. 237–242 and 251–257, May 1920.

"The Pintsch Glow-Discharge Lamp," F. Schröter, *E.T.Z.*, 42, pp. 121–125, Feb. 10, 1921.

"Arc with Heated Electrodes," W. Mathiesen, *E.T.Z.*, 42, pp. 375–376, April 14, 1921.

"Developments in Quartz Tube Mercury-Vapour Lamps," M. Leblanc, *Soc. Franç. Elect., Bull.* 1, pp. 89–101, Feb. 1921.

"A Low-Voltage Self-Starting Tungsten Arc-Incandescent Lamp," D. M. Moore, *Am. Ill. Eng. Soc. Trans.*, 16, pp. 346–350, Oct. 10, 1921.

"Temperatures Attained in Glow Lamps," C. L. Dows and W. C. Brown, *Am. Ill. Eng. Soc. Trans.*, 16, pp. 284–317, Oct. 10, 1921.

"The Sputtering of Incandescent Tungsten Filaments," A. Goetz, *Physikalische Zeitschrift*, 23, pp. 136–142, March 15, 1922.

"Luminescence as a Factor in Artificial Lighting," E. L. Nichols, *Am. Ill. Eng. Soc. Trans.*, 16, pp. 331–345, Oct. 10, 1921.

"End-Loss Corrections in Glow Lamps," A. G. Worthing, *Journal Franklin Institute*, 194, pp. 597–611, Nov. 1922.

"Incandescent Lamps," J. W. Howell and H. Schroeder, *Am. I.E.E.J.*, pp. 809–814, Aug. 1923.

"Design of Large Incandescent Lamps," P. G. Nutting, *Optical Soc. of America Journal*, May 1923.

"Sealing Base Metals through Glass," W. G. Housekeeper, *Am. I.E.E.J.*, 42, pp. 954–960, Sept. 1923.

"The Temperature and Brightness of Tungsten Lamps," W. E. Forsythe, *G.E.R.*, 26, pp. 830–834, Dec. 1923.

"Experimental Work on Sources of High Illuminating Power," E. Podszus, *E.T.Z.*, 45, pp. 523–525, May 22, 1924.

"Tungsten Arc Lamps," C. Müller, *Zeitschrift für technische Physik*, 5, 6, pp. 250–253, 1924.

"Manufacture of Electric Lamps," C. Clerici, *Elettrotecnica*, 11, pp. 546–548, Aug. 1924.

"Luminescence or Cold Light," W. S. Andrews, *G.E.R.*, 28, pp. 103–108, Feb. 1925.

CHAPTER III.

"Action of Extreme Red and Ultra-violet Light on the Eye," A. Broca, Jouast, de la Gorce, and Laporte, *Soc. Int. Electr., Bull.* 3, Ser. 3, pp. 101–113, Feb. 1913.

"The Effect on Foveal Vision of Bright Surroundings," P. W. Cobb and L. R. Geissler, *Psych. Rev.*, 20, p. 425, 1913 ; 21, p. 23, 1914.

"Radiant Energy and the Eye," M. Luckiesh, *Electr. World*, 62, pp. 844–846, Oct. 25, 1913.

"Effect of Artificial Illumination on Vision," F. K. Richtmeyer, *Electr. World*, 64, pp. 519–521, Sept. 12, 1914.

"Glasses for Protecting the Eyes in Industrial Processes," M. Luckiesh, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 472–485, May 1914.

"Experiments on Illumination with the Ferree Eye-fatigue Test," J. R. Cravath, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 1033–1059, 1914.

"Efficiency of the Eye under Different Lighting Conditions" ; "Effect of Varying Distribution and Intensity of Light," C. E. Ferree and G. Rand, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 407–447, 448–501, Aug. 1915.

"Retinal Sensibilities related to Illuminating Engineering," P. G. Nutting, *Journal Franklin Institute*, 180, pp. 482–484, Oct. 1915.

"General Report on Glare," *Am. Ill. Eng. Soc. Trans.*, 10, pp. 987–999, Dec. 30, 1915.

"Vision and the Brightness of Surroundings," P. W. Cobb, *Am. Ill. Eng. Soc. Trans.*, 11, pp. 372–398, May 1, 1916.

"Effect on the Eye of Lamps in Reflectors of Different Densities," C. E. Ferree and G. Rand, *Am. Ill. Eng. Soc. Trans.*, 11, pp. 1111–1133, Dec. 1916 ; 12, pp. 464–487, Dec. 1917 ; 13, pp. 50–60, Feb. 1918.

"Effect of Variations in Intensity of Illumination on Functions of Importance to the Working Eye," C. E. Ferree and G. Rand, *Am. Ill. Eng. Soc. Trans.*, 15, pp. 769–792.

"The Psychological Aspect of Brightness," B. Jones, *Am. Ill. Eng. Soc. Trans.*, 15, pp. 723–762, Dec. 1920.

"Effect on Intensity of Illumination upon Speed of Reading," M. Luckiesh, A. H. Taylor, and R. H. Linden, *Electr. World*, 78, pp. 668–670, Oct. 1, 1921.

"Ultra-Violet Light, Its Uses and Possibilities," L. C. Krueger, *G.E.R.*, pp. 316–323, May 1922.

"The Nature of Glare," *Am. Ill. Eng. Soc. Trans.*, 17, pp. 743–750, Dec. 1922.

"Illumination and the Eye," L. F. Pello, *Elettrotecnica*, 11, pp. 548–551, Aug. 1924.

"Researches in Glare," U. Bordoni, *Elettrotecnica*, 11, pp. 585–599, Sept. 1924.

CHAPTER IV.

"Calculation of Illumination Curves," F. A. Benford, *Am. Ill. Eng. Soc. Trans.*, 7, pp. 695–722, Dec. 1912.

"Intensity and Luminous Flux from Linear Sources," K. Norden, *E.T.Z.*, 34, p. 292, March 13, 1913.

"Graphic Solution of Illumination Problems," N. S. Dickenson, *Electr. World*, 62, pp. 586–589, Sept. 20, 1913.

"Light-reflecting Values of Coloured Paints," H. A. Gardner, *Journal Franklin Institute*, 181, pp. 99–108, Jan. 1916.

"A Method of Determining the Resultant Illumination derived from Indirect Lighting," J. Ondracek, *Elektrotechnik und Maschinenbau*, 38, pp. 273–277, June 13, and pp. 595–599, Dec. 19, 1920.

"Methods of Calculating Illumination in Rooms," J. Ondracek, *Elektrotechnik und Maschinenbau*, 39, pp. 437–442, Sept. 4, 1921.

"Light Distribution from Lamps," Teichmüller, *Journal für Gasbeleuchtung*, 61, p. 229, 1918 ; *Zeitschrift für Instrumentenkunde*, 41, pp. 305–308, Oct. 1921.

"Calculation of Illumination in Various Planes," J. H. Kurlander, *Electrical Review*, Chicago, 79, pp. 885–887, Dec. 1921.
"Scattered Light," C. Michalke, *E.T.Z.*, 43, pp. 275–276, March 2, 1922.
"Contribution to the Theory of Internal Illumination," R. Ulbricht, *E.T.Z.*, pp. 1262–1265, Oct. 12, 1922.

CHAPTER V.

"Purkinje-effect with Flicker and Equality-of-brightness Photometers," M. Luckiesh, *Electr. World*, 61, pp. 620-621, March 22, 1913.
"A Precision Photometer Bench and Accessories," E. P. Hyde and F. E. Cady, *Electr. Rev. and West. Electn.*, 61, p. 942, 1912.
"A New Differential Watt-per-candle Meter," E. P. Hyde, *Electr. Rev. and West. Electn.*, 62, p. 248, 1913.
"Visual Acuity in White Light," W. Luckiesh, *Electr. World*, 62, p. 1160, 1913.
"Acuteness of Vision and Brightness of Surroundings," P. W. Cobb, *Am. Ill. Eng. Soc. Trans.*, 8, pp. 292–301, June 1913.
"Standard Surfaces for Photometer Screens," Bechstein, *E.T.Z.*, 36, pp. 114–115, March 1915.
"Paint for Integrating Photometers," A. Utzinger, *E.T.Z.*, 36, pp. 137–138, March 25, 1915.
"Compensated Test-plates for Illumination Photometers," C. H. Sharp and W. F. Little, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 727–745, Nov. 1915.
"The Use of Portable Photometers," W. F. Little, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 766–792, Nov. 1915.
"Physical Photometry with Alkali Cells," W. Voege, *Elektrotechnik und Maschinenbau*, 33, pp. 626–627, Dec. 26, 1915.
"A Box Photometer," L. O. Grondahl, *Am. Ill. Eng. Soc. Trans.*, 11, pp. 152–163, March 1916.
"A Simple Illumination-Tester," C. H. Sharp, *Electr. World*, 68, pp. 569–570, Sept. 16, 1916.
"Integrating Sphere," F. A. Benford, Jun., *Am. Ill. Eng. Soc. Trans.*, 11, pp. 997–1013, 1916.
"An Integrating Hemisphere," F. A. Benford, Jun., *Am. Ill. Eng. Soc. Trans.*, 13, pp. 323–351, 1918.
"A New Illumination Photometer," D. Tuck, *Am. Ill. Eng. Soc. Trans.*, 15, pp. 539–542, 1920.
"New Photometer of High Sensitiveness," G. Gehlhoff and H. Schering, *Zeitschrift für technische Physik*, 1, 11, pp. 247–256, 1920.
"Photoelectric Cell Photometer," W. E. Story, Jun., *Am. Ill. Eng. Soc. Trans.*, 15, pp. 827–845, 1920.
"New Forms of Zonal Photometer," J. Teichmüller, *Elektrotechnik und Maschinenbau*, 38, pp. 201–208, May 2, 1920.
"Selectivity of Paint and Window in Photometric Sphere," F. E. Cady, *Electr. World*, 77, p. 368, Feb. 12, 1921.
"Sector Discs, their Calibration and Use in Photometry," F. E. Cady, *Am. Ill. Eng. Soc. Trans.*, 16, pp. 138–145, Aug. 30, 1921.
"Paints for Integrating Spheres," A. H. Taylor, *Am. Ill. Eng. Soc. Trans.*, 16, pp. 587–590, Dec. 1921.
"Heterochromatic Photometry and the Flicker Photometer," A. H. Taylor, *Am. Ill. Eng. Soc. Trans.*, 16, pp. 574–586, Dec. 1921.
Ill umination Photometer with Shadow-measuring Attachment," W. Bechstein, *Z.V.D.I.*, 68, pp. 1271–1272, Dec. 6, 1924.

CHAPTER VI.

" Metallic Filament Lamps on Alternate Current," A. Larsen, *E.T.Z.*, p. 231, Feb. 27, 1913.

" Influence on Life of enclosing Tungsten Lamps in Outer Globes," G. Sundén, *E.T.Z.*, 34, pp. 992–993, Aug. 28, 1913.

" A Differential Method of Rating Lamps as to Filament Brightness for Use with Fluctuating Voltages," A. G. Worthing, *Lighting Journal*, 1, p. 272, 1913.

" Colour Discrimination by Artificial Light," L. Bloch, *E.T.Z.*, 34, pp. 1306–1311, Nov. 13, 1913.

" Graphical Representation of the Colour of Illuminants," E. Jasse, *E.T.Z.*, 34, pp. 1454–1456, Dec. 18, 1913.

" Instantaneous Candle-power of Arc Lamps," J. Sahulka. *Elektrotechnik und Maschinenbau*, 32, pp. 7–9, Jan. 4, 1914.

" Photoelectric Cells in Photometry," F. K. Richtmeyer, *Am. Ill. Eng. Soc. Trans.*, 8, pp. 459–469, Nov. 1913.

" Errors in Photometry," E. J. Edwards and W. Harrison, *Am. Ill. Eng. Soc. Trans.*, 8, pp. 633–651, Dec. 1913.

" The Flicker of Incandescent Lamps on Alternating-Current Circuits," I. Langmuir, *G.E.R.*, 17, pp. 294–300, March 1914.

" Instrument for Measuring Glaze on Paper," L. R. Ingersoll, *Electr. World*, 63, pp. 645-647, March 21, 1914.

" Heterochromatic Photometry," M. Luckiesh, *Electr. World*, 63, pp. 1105–1107, May 16, 1914.

" Determination of Glare," P. G. Nutting, *Electr. World*, 63, p. 1156, May 23, 1914.

" Brightness: Its Measurement and Significance," H. E. Ives, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 183–202, March 1914.

" The Colour of Illuminants," L. A. Jones, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 687-709, 1914.

" Photometry of Half-watt Lamps," C. H. Sharp, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 1021–1032, 1914.

" The Integrating Sphere and Arc-Lamp Photometry," N. K. Chancy and E. L. Clark, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 1–37, 1915.

" Photometry of Gas-filled Lamps," D. H. Tuck, *Electr. World*, 65, p. 78, Jan. 9, 1915.

" Light-filters for Use in Photometry," C. E. K. Mees, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 990–997, 1914.

" Use of Coloured Absorbing Solutions in Photometry," H. E. Ives and E. F. Kingsbury, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 795–813, 1914; 10, pp. 253–258, 1915.

" Direct Determination of Luminous Efficiency of Light Sources," E. Karrer, *Lighting Journal*, 3, pp. 27 and 37–38, Feb. 1915.

" Practical Rating of Glow Lamps," F. W. Wilcox, *Ill. Eng.*, 8, pp. 163–185, April 1915.

" Method of Correcting Abnormal Colour Vision and its Application to the Flicker Photometer," H. G. Ives and E. T. Kingsbury, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 259-270, 1915.

" Street Illumination Tests," J. W. Lieb, *Electr. World*, 65, pp. 1521–1522.

" Use of Artificial Light in Photography," H. Lux, *E.T.Z.*, 36, pp. 203–205, April 29, 1915.

" Photometric Measurements by Unpractised Observers," Utzinger, *E.T.Z.*, 36, p. 115, March 11, 1915.

"New Method of Heterochromatic Photometry," v. Pirani, *E.T.Z.*, 36, pp. 202–203, April 29, 1915.
"Overshooting in Tungsten Lamps," A. G. Worthing, *Lighting Journal*, 3, pp. 256–257, Nov. 1915.
"Graphical Determination of Mean Spherical Candle-power," J. Kuhn, *Elektrotechnik und Maschinenbau*, 33, pp. 500–501, Oct. 10, 1915.
"Interlaboratory Tests of Glass Screens and Tungsten Lamps," G. W. Middlekauff and J. F. Skogland, *Am. Ill. Eng. Soc. Trans.*, 11, pp. 164–186, March 1916.
"Sampling for Lamp Testing," P. S. Millar and L. J. Lewinson, *Electr. Rev. and West. Electn.*, 68, p. 1062, June 10, 1916.
"Forced Life Tests of Incandescent Electric Lamps," L. J. Lewinson, *Am. Ill. Eng. Soc. Trans.*, 11, pp. 815–835, Nov. 1916.
"Colouration of Lamp Globes," M. Luckiesh, *G.E.R.*, 20, pp. 671–672, Aug. 1917.
"The Flickering of Metal Filament Lamps," K. Simons, *E.T.Z.*, 38, pp. 453–455, Sept. 13; pp. 465–467, Sept. 20; and pp. 474–476, Sept. 27, 1917.
"Double-Arc Lamps for Low-Frequency Three-Phase Working," A. Blondel, *Rev. Gén. d'Él.*, 2, pp. 975–981, Dec. 22, 1917.
"Overshooting in Metal Filament Lamps," C. J. Berry, *Electr. World*, 71, pp. 459–462, March 2, 1918.
"Testing Miners' Lamps," H. H. Clark and L. C. Ilsley, *Bureau of Mines, Bull.* 131, Washington, 1917.
"Renovation of Discoloured Arc-Lamp Globes," A. Herz, *Electr. World*, 72, pp. 935–936, Nov. 16, 1918.
"Measurements of Transmission Factors for Glass," M. Luckiesh and L. L. Mellor, *Journal Franklin Institute*, 186, pp. 529–545, Nov. 1918.
"Photometry of Searchlights," Gehlhoff. *Elektrotechnik und Maschinenbau*, 37, pp. 346–347, Aug. 3, 1919.
"The Application of Pyrometry to Problems in Lamp Design," J. H. van Horn, *Am. Inst. of Mining Eng.. Bull.* No. 153, pp. 2247–2269, Sept. 1919.
"Searchlight Testing," F. A. Benford, *G.E.R.*, 22, pp. 668–675, Sept. 1919.
"A Device to Facilitate Heterochromatic Photometry," *E.T.Z.*, 40, pp. 484–485, Sept. 25, 1919.
"The Precision of Photometric Measurements; Observation Errors with Different Types of Photometers," F. K. Richtmeyer and E. C. Crittenden, *Optical Society of America J.*, 4, pp. 371–387, Sept. 1920.
"The Measurement of Reflection Factors," C. H. Sharp and W. F. Little, *Am. Ill. Eng. Soc. Trans.*, 15, pp. 802–810, Dec. 1920.
"New Device to Facilitate Heterochromatic Photometry," V. Voss, *Zeitschrift für Beleuchtungswesen*, 25, p. 53, 1919; *Zeitschrift für Instrumentenkunde*, 41, pp. 29–31, Jan. 1921.
"Tests of Electric Torches," T. Spooner and C. F. Royce, *Journal of Electricity*, 19, pp. 150–152, April 1922.
"Some Features of the High-Intensity Motion-Picture Arc," F. A. Benford, *G.E.R.*, pp. 555–559, Sept. 1922.
"Improvements in Equipment for Use with the Integrating Sphere," A. H. Taylor, *Journal Franklin Institute*, 194, pp. 543–546, Oct. 1922.
"Neon Glow Discharge Lamps on A.C. Circuits," R. A. Brookbank and L. E. Ryall, *Electrician*, 90, pp. 4–6, Jan. 5, 1923.
"Distribution of Luminosity throughout a Potential Cycle in a Neon Glow Discharge Lamp," E. Karrer and A. Poritsky, *Journal Franklin Institute*, 198, pp. 93–97, July 1924.

CHAPTER VII.

" Portable Electric Mining Lamps," H. H. Clark, *Bureau of Mines, Tech. Paper* No. 47, 1913 ; *Tech. Paper* No. 75, 1914.

" Efficiency and Engineering Characteristics of Reflectors," G. H. Stickney and A. L. Powell, *Electr. World*, 62, pp. 477–481, Sept. 6, 1913.

" Investigation of Diffusing Glassware," M. Luckiesh, *Electr. World*, 60, p. 1040, 1912 ; 61, p. 883, 1913.

" Some Notes on the Use of Shades and Reflectors," J. G. Clark and V. H. Mackinney, *Ill. Eng.*, pp. 125–154, March 1913.

" Marble Shades and Reflectors," W. Voege, *E.T.Z.*, 35, pp. 199–203, Feb. 19, 1914.

" Characteristic of Enclosing Glassware," V. R. Lansingh, *Am. Ill. Eng. Soc. Trans.*, 8, pp. 447–458, Nov. 1913.

" Design and Maintenance of Miners' Electric Lamps," F. J. Turquand, *Electrician*, 72, pp. 807–809, Feb. 20, 1914.

" Tests on Kinematograph Apparatus," F. Laporte, *Soc. Int. Electr., Bull.* 4, Ser. 3, pp. 381–384, April 1914.

" Portable Electric Mine Lamps," H. O. Swoboda, *Am. Inst. Electr. Eng. Proc.*, 33, pp. 655–667, April 1914.

" Photometric Analysis of Glassware used for Semi-indirect Lighting," *Am. Ill. Eng. Soc. Trans.*, 9, pp. 220–241, March 1914.

" Reflecting Power Standards," P. G. Nutting, L. A. Jones, and F. A. Elliott, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 593–597, 1914.

" Range of Searchlights," A. Blondel, *Ill. Eng.*, 8, pp. 85–90, Feb. 1915, March 1915.

" Searchlights," C. S. McDowell, *Am. Inst. Electr. Eng. Proc.*, 34, pp. 195–208, Feb. 1915.

" Conditions affecting the Candle-power and Steadiness of Searchlights," Hertha Ayrton, *Ill. Eng.*, 8, pp. 78–81, Feb. 1915.

" Searchlights, their Scientific Development and Practical Applications," P. G. Ledger, *Ill. Eng.*, 8, pp. 53–77, Feb. 1915.

" New Development in the Projection of Light," L. C. Porter, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 38–54, 1915.

" The Beck Searchlight," W. Wedding, *E.T.Z.*, 35, pp. 901–902, Aug. 6, 1914.

" Power Formulæ for Lighthouse Lights," A. Brebner, *Inst. Civ. Eng. Proc.*, 199, pp. 388–390, 1914–1915.

" Visibility," C. C. Paterson and B. P. Dudding, *Ill. Eng.*, 8, pp. 210–226, May 1915.

" Installation Curves for Glow-lamps and Shades," S. W. Cuttriss, *Electr. Eng.*, 11, pp. 371–372, Sept. 9, 1915.

" Electric Searchlights," U. Bordoni, *Elettrotecnica*, 2, pp. 790–799, Dec. 25, 1915.

" Efficiency of Projectors and Reflectors," H. T. Harrison, *Electrician*, 76, pp. 842–843, March 17, 1916.

" Limit of Visibility of Revolving Light-beams of Small Divergence," A. Blondel, *Comptes Rendus*, 162, pp. 587–592, April 17, 1916.

" Sperry High-efficiency Searchlight," *Engineering*, 102, pp. 205–206, Sept. 1, 1916.

" Modern Electric Searchlight Projectors," J. H. Johnson, *Engineer*, 122, pp. 227–229, Sept. 15 ; pp. 252–254, Sept. 22 ; and pp. 294–296, Oct. 6, 1916.

" Hirsch Portable Electric Lamp," H. H. Hirsch, *North of England Inst. of Mining and Mech. Eng. Trans.*, 66, pp. 175–185, April 1916.

"Sources of Light for Projection," R. B. Chillas, *Am. Ill. Eng. Soc. Trans.*, 11, pp. 1097–1110, Dec. 1916.

"Automobile Headlights," W. F. Little, S. C. Rogers, E. J. Edwards, *Am. Ill. Eng. Soc. Trans.*, 12, pp. 123–137, 158–168, 172–173, April 1917.

"Combined Refractor and Diffusing Globe for Street Lighting," W. Harrison, *Am. Ill. Eng. Soc. Trans.*, 12, pp. 305–318, Oct. 1917.

"Use of Glow Lamps for Projection Apparatus," O. Kruh, *Elektrotechnik und Maschinenbau*, 35, pp. 573–575, Dec. 2, 1917.

"Glow Lamp for Projection Purposes," L. C. Porter, *G.E.R.*, 20, pp. 979–983, Dec. 1917.

"Light Projection with Gas-filled Lamps," R. P. Burrows and J. T. Caldwell, *Electr. World*, 71, pp. 766–769. April 13, 1918.

"A New Arc for Electric Searchlights," V. Bellini, *Elettrotecnica*, 5, pp. 286–287, July 25, 1918.

"Methods of Directing and Concentrating Light," H. T. Harrison, *Ill. Eng.*, 11, pp. 72–91, March 1918.

"Report on Automobile Headlights," *Am. Ill. Eng. Soc. Trans.*, 13, pp. 259, 283–291, July 1918; 14, pp. 64–99, March 1919.

"Large Arc Lamp Projectors," M. Grosjean, *Rev. Gén. d'Él.*, 6, pp. 445–458, Oct. 4; 479–487, Oct. 11; 513–527, Oct. 18, 1919.

"Metallic Reflectors for Long-range Lighthouses," J. Rey, *Comptes Rendus*, 169, pp. 471–473, Sept. 8, and pp. 616–618, Oct. 6, 1918.

"Metal Mirrors for Searchlights," R. B. Hussey, *G.E.R.*, 22, pp. 652–655, Sept. 1919.

"Open Type Searchlight," C. A. B. Halvorson, *G.E.R.*, 22, pp. 704–713, Sept. 1919.

"Searchlight Electrodes," W. H. Hardman, *G.E.R.*, 22, pp. 685–688, Sept. 1919.

"The Garbarini Rotating Arc," *Rev. Gén d'Él.*, 7, p. 508, April 10, 1920.

"Regulations for Automobile Headlights," C. H. Sharp and W. F. Little, *Eng. Club Phil. Journal*, 37, pp. 47–51, Feb. 1920.

"Projection Screens," C. W. Gamble, *Optical Soc. Trans.*, 21, No. 1, pp. 34–40, 1919–20.

"Report of Committee on Automobile Headlight Specifications," *Am. Ill. Eng. Soc. Trans.*, 15, pp. 848–863. Dec. 1920.

"New Form of Lamp for Kinema Projection," *Elektrotechnik und Maschinenbau*, 38, pp. 555–556, Nov. 1920.

"Comparison between Dioptric and Ordinary Globes for Street Lighting," Heyck, *Elektrotechnik und Maschinenbau*, 38, pp. 425–426, Sept. 5, 1920.

"High-Intensity Projection Lamp for Kinema Theatres," *Electrical Review*, Chicago, 78, pp. 937–938, June 11, 1921.

"Motor-Car Headlights: Ideal Requirements and Practical Solutions," A. Garrard, *Ill. Eng.*, 14, pp. 92–102, April 1921.

"Searchlight Developments in the Prussian War Department," W. Hort, *Zeitschrift für technische Physik*, 2, 9, pp. 261–263, 1921.

"The Grubb Motor-Car Headlight," *Electrical Review*, 89, p. 467, Oct. 7, 1921.

"Terminology and Standardisation of Illuminating Glassware," S. G. Hibben, *Electrical Review*, Chicago, 79, pp. 735–737, Nov. 12, 1921.

"Range of Lighthouse with Metal Reflectors," J. Rey, *Comptes Rendus*, 174, pp. 289–291, Jan. 30, 1922.

"Recent Improvements in the Sheringham Daylight," S. H. Groom, *Ill. Eng.*, 14, pp. 215–218, Nov. 1921.

"Wiskott Reflectors," O. Gerhardt, *Zeitschrift für Beleuchtungswesen*, 27, Nos. 5–14, 1921.

"An Interim Report by the Committee on Motor Vehicle Lighting," *Am. Ill. Eng. Soc. Trans.*, 17, pp. 103–111, Feb. 1922.
"Motor Headlights," *Optical Soc. Trans.*, 23, pp. 256–294, 1921–1922.
"The High Intensity Kinema Arc," F. A. Benford, *G.E.R.*, 25, pp. 555–559, Sept. 1922.
"The Probability of Detecting an Aeroplane by a Searchlight Beam," J. Rey, *Comptes Rendus*, 175, pp. 466–469, Sept. 18, and pp. 580–583, Oct. 9, 1922.
"A New Projection Arc Lamp for A.C.," B. Schafer, *E.T.Z.*, 44, pp. 335–336, April 12, 1923.
"Lighthouses and Light Vessels," S. G. Kibben, *Am. Ill. Eng. Soc. Trans.*, 18, pp. 241–272, March 1923.
"Motor-Car Headlights," L. Bruninghaus, *Rev. Gén. d'Él.*, 13, pp. 705–709, April 28, 1923.
"Electric Lamps for Lighthouse Service," L. G. Porter, *G.E.R.*, 26, pp. 565–570, Aug. 1923.
"The Projection of Light," W. J. Jones and E. A. Marx, jun., *Ill. Eng.*, 16, pp. 62–72, March 1923.
"Motor Headlight Requirements," P. G. Nutting, *Journal Franklin Institute*, 196, pp. 529–535, Oct. 1923.
"Studies in the Projection of Light," F. Benford, *G.E.R.*, Part. i., vol. 26, pp. 75–82, Feb. 1923; Part ii., vol. 26, pp. 160–167, March 1923; Part iii., vol. 26, pp. 230–234, April 1923; Part iv., vol. 26, pp. 280–290, May 1923; Part v., vol. 26, pp. 575–582, Aug. 1923; Part vi., vol. 26, pp. 624–631, Sept. 1923; Part vii., vol. 26, pp. 780–787, Nov. 1923; Part viii., vol. 26, pp. 818–827, Dec. 1923; Part ix., vol. 27, pp. 199–207, March 1924; Part x., vol. 27, pp. 252–260, April 1924; Part xi., vol. 27, pp. 504–510, Aug. 1924; Part xii., vol. 27, pp. 625–633, Sept. 1924; Part xiii., vol. 27, pp. 698–705, Oct. 1924; Part xiv., vol. 27, pp. 749–757, Nov. 1924; Part xv., vol. 27, pp. 830–838, Dec. 1924; Part xvi., vol. 28, pp. 193–197, March 1925.

CHAPTERS VIII. AND IX.

"A Study of Natural and Artificial Light Distribution in Interiors," M. Luckiesh, *Am. Ill. Eng. Soc. Trans.*, 7, p. 388, 1912.
"Electric Sign Lighting with Tungsten Lamps," O. P. Anderson, *G.E.R.*, pp. 175–182, March 1913.
"Department Store Lighting," H. W. Shalling, *Am. Ill. Eng. Soc. Trans.*, 8, pp. 17–39, Jan. 1913.
"The Influence of Coloured Surroundings on the Colour of the Useful Light," M. Luckiesh, *Am. Ill. Eng. Soc. Trans.*, 8, p. 61, 1913.
"Some Notes on Interior Illumination," H. Bohle, *Ill. Eng.*, pp. 411–416, Aug. 1913.
"The Electric Lighting of a Covered Lawn Tennis Court," *Ill. Eng.*, pp. 507–509, Oct. 1913.
"Shadows by Natural and Artificial Light," J. S. Dow and V. H. Mackinney, *Ill. Eng.*, pp. 618–635, Dec. 1913.
"The Importance of Direction, Quality, and Distribution of Light," M. Luckiesh, *Ill. Eng.*, pp. 636–637, Dec. 1913.
"Steel Mill Lighting," C. E. Clewell, *Electr. Journ.*, 10, pp. 502–514, June 1913.
"Factory Illumination Calculations," W. Harrison, *Electr. World*, 62, pp. 1001–1005, Nov. 15, 1913.
"Illumination of Street Railway Cars," L. C. Porter and V. L. Staley, *Electr. Rly. Journ.*, 42, pp. 1089–1092, Nov. 22, 1913.

"The Mercury Lamp in Industrial and Exterior Lighting," H. Becker, *Z.V.D.I.*, 57, pp. 1983–1988, Dec. 13, 1913.

"Factory Lighting," M. H. Flexner and A. O. Dicker, *Am. Ill. Eng. Soc. Trans.*, 8, pp. 470–487, Nov. 1913.

"Comparison of Estimated and Observed Values of Illumination in some Lighting Installations," W. C. Clinton, *Ill. Eng.*, 7, pp. 189–215; pp. 229–242, May 1914.

"Standard Clauses for Inclusion in a Street-Lighting Specification," J. Abady, *Electrician*, 73, pp. 179–182, May 8, 1914.

"Railway Carriage Lighting," E. K. Scott, *Ill. Eng.*, 7, pp. 246–264, May 1914.

"Relative Hygienic Effects of Electric and Incandescent Gas Lighting," E. Ronzani, *Annali d'Igiene Sperimentale*, 23, No. 3, 1913.

"Design of Illuminated Signs," A. H. Ford, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 445–458, May 1914.

"Industrial Lighting with Flame Arcs," S. L. E. Rose and H. E. Butler, *Lighting Journal*, 2, pp. 191–196, Sept. 1914.

"Illumination and Electrical Features of the Panama Canal," *Electr. World*, 64, pp. 21–28, July 4, 1914.

"Industrial Lighting with High Candle-power Tungsten Lamps," S. L. E. Rose and H. E. Butler, *Lighting Journal*, 2, pp. 240–242, Nov. 1914.

"Production of Artificial Daylight," M. Luckiesh, *Electr. World*, 64, pp. 570–572, Sept. 19, 1914.

"Artificial Daylight," M. Luckiesh and F. E. Cady, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 839–872, 1914.

"Requirements for Modern Street-Car Lighting," L. C. Doane, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 82–100, 1915.

"Lighting of Metal Working Plants," A. L. Powell and R. E. Harrington, *Am. Ill. Eng. Soc. Trans.*, 9, pp. 814–838, 1914.

"Glare as a Factor in Street Lighting," A. J. Sweet, *Electr. Rev. and West. Electn.*, 66, pp. 439–443.

"Artificial Daylight Units," C. H. Sharp, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 219–221, 1915.

"Electric Lighting for Motion-Picture Studios," L. G. H. Smith, *Electr. World*, 65, pp. 1040–1042, April 24, 1915.

"Calculation of Illumination from Indirect Units," R. C. Powell, *Electr. World*, 65, pp. 1463–1464.

"The Lighting of Rifle Ranges," *Ill. Eng.*, 8, pp. 251–281, June 1915.

"Readability Curves in Electric Sign Design," R. E. Cleveland, *Lighting Journal*, 3, pp. 127–129, June 1915.

"The Illumination of Streets," P. S. Millar, *Am. Inst. Electr. Eng. Proc.*, 34, pp. 1379–1398, July 1915.

"Artificial Lighting of Tennis Courts," H. T. Spaulding, *Lighting Journal*, 3, pp. 102–104, May 1915.

"Mobile Colour and Stage Lighting," B. Jones, *Electr. World*, 66, pp. 245–249, July 31; pp. 294–297, Aug. 7; pp. 346–349, Aug. 14; pp. 407–409, Aug. 21; pp. 454–456, Aug. 28, 1915.

"Flux Method of obtaining Average Illumination," F. A. Benford, jun., and H. E. Mahan, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 593–603, Oct. 1915.

"First Report of the Departmental Committee on Lighting in Factories and Workshops," *Ill. Eng.*, 8, pp. 369–390, Sept. 1915.

"Street Lighting," H. E. Butler, *Electr. World*, 66, pp. 1027–1028, Nov. 6, 1915.

"Illumination of Mines," R. P. Burrows, *Am. Inst. Mining Eng. Bull.*, pp. 2237–2245, Nov. 1915.

" Code of Lighting," *Am. Ill. Eng. Soc. Trans.*, 10, pp. 605–641, Nov. 1915.
" Industrial Lighting with Mercury Vapour Lamps," W. A. D. Evans, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 883–904, Dec. 30, 1915.
" Effective Illumination of Streets," P. S. Millar, *Am. Ill. Eng. Soc. Trans.*, 10, pp. 1039–1079, Dec. 30, 1915.
" Choice of Best Type of Lamp for a Required Illumination," v. Glinski, *E.T.Z.*, 37, pp. 2–4, Jan. 6, 1916.
" Street Lighting on a Cost of Service Basis," G. W. van Derzee, *Electr. World*, 67, pp. 758–760, April 1, 1916.
" Illumination in the Navy," C. S. McDowell, *Am. Ill. Eng. Soc. Trans.*, 11, pp. 573–586, June 1916.
" Coloured Glass in Illuminating Engineering," H. P. Gage, *Am. Ill. Eng. Soc. Trans.*, 11, pp. 1050–1067, Dec. 1916.
" Comparative Study of Arc Lamps and Gas-filled Tungsten Lamps," Heyck, *Z.V.D.I.*, 61, pp. 625–630, July 28, 1917.
" Lighting in the Textile and Clothing Industry," C. E. Clewell, *Electr. World*, 70, pp. 152–155, July 28, 1917.
" Street Lighting with Modern Electric Illuminants," S. L. E. Rose and H. E. Butler, *G.E.R.*, 20, pp. 945–963, Dec. 1917.
" The Diffusion of Light and its Definition," N. A. Halbertsma, *Elektrotechnik und Maschinenbau*, 36, pp. 225–232, May 19, 1918.
" Illumination and Hygiene," Reichenbach, *Elektrotechnik und Maschinenbau*, 66, pp. 239–246, May 26, 1918.
" Desirable Propoitions of Local and General Lighting," F. C. Caldwell and W. M. Holmes, *Am. Ill. Eng. Soc. Trans.*, 13, pp. 303–322, Aug. 1918.
" Intensity of Illumination and Productive Power," W. A. Durgin, *Am. Ill. Eng. Soc. Trans.*, 13, pp. 417–428, Dec. 1918.
" Lighting in Architecture," Lux, *E.T.Z.*, 40, pp. 285–289, June 12, 1919.
" Railway Lighting and Maintenance," A. Cunnington, *Ill. Eng.*, 12, pp. 59–88, March 1919.
" The Determination of Shadow," K. Norden, *E.T.Z.*, 40, p. 376, July 31, 1919.
" The Sheringham Daylight Lamp," *Electrical Review*, 85, p. 741, Dec. 12, 1919.
" The Maintenance of Lighting Systems," W. Harrison and J. R. Colville, *Electr. World*, 75, pp. 204–208, Jan. 24, 1920.
" Industrial Lighting as an Element in Mass Production," L. Gaster, *Electrician*, 84, pp. 485–487, April 30, 1920.
" Colour Matching by Natural and Artificial Light," L. C. Martin, *Ill. Eng.*, 13, pp. 31–59, Feb. 1920.
" Electric Lighting of Railroad Signals," L. C. Porter and F. S. Stallknecht, *Am. Ill. Eng. Soc. Trans.*, 15, pp. 223–242, June 10, 1920.
" Output by Natural and Artificial Light in the Silk Industry," *Ill. Eng.*, 13, pp. 245–248, Sept. 1920.
" Improved Methods of Lighting Kinema Theatres " L. A. Jones, *Am. Ill. Eng. Soc. Trans.*, 15, pp. 645–673, Dec. 1920.
" Flashing Speeds of Incandescent Signalling Lamps," A. G. Worthing, *Journal Franklin Institute*, pp. 231–257, Feb. 1921.
" Simplification of the Design of Lighting Installations," E. A. Anderson, *Electr. World*, 77, pp. 416–422, Feb. 19, 1921.
" Gas-filled Lamps for Street Lighting," G. H. Stickney, *G.E.R.*, 24, pp. 734–739, Aug. 1921.
" Charts and Data for Industrial Lighting," P. A. Powers, *Electrical Review*, Chicago, 79, pp. 231–234, Aug. 13, 1921.

" Ship Lighting in Relation to Safety, Comfort, and Efficiency," W. J. Jones, *Ill. Eng.*, 14, pp. 116–131, May 1921.
" Alternating-Current Series Street-Lighting Circuits," H. E. Butler, *G.E.R.*, 24, pp. 763–769, Aug. 1921.
" Railway Carriage Lighting," G. E. Hulse, *Am. Ill. Eng. Soc. Trans.*, 16, pp. 99–110, July 1921.
" Artificial Light as an Aid to Games and Sports," J. S. Dow, *Ill. Eng.*, 14, pp. 149–157, June 1921.
" Report on Lighting Legislation," *Am. Ill. Eng. Soc. Trans.*, 16, pp. 359–389, Nov. 20, 1921.
" The Use of Light as an Aid to Aerial Navigation," L. F. Blandy, *Ill. Eng.*, 15, pp. 42–58, Feb. 1922.
" Electric Lighting's Part in the Electrical Industry," G. S. Merrill, *G.E.R.*, pp. 340–345, June 1922.
" Illumination Fundamentals for the User of Light," J. R. Colville, *G.E.R.*, pp. 373–378, June 1922.
" Highway Lighting," H. E. Butler, *G.E.R.*, pp. 465–476, Aug. 1922.
" The Use of Light in Hospitals," J. Darch, *Ill. Eng.*, 15, pp. 165–180, June 1922.
" Third Report of the Home Office Departmental Committee on Lighting in Factories and Workshops," *Ill. Eng.*, 15, pp. 197–202, July 1922.
" Calculation of Illumination Due to Diffuse Reflection," R. Ulbricht, *E.T.Z.*, 43, pp. 1262–1265, Oct. 12, 1922.
" Lighting in the Food Industries," W. H. Rademacher, *Am. Ill. Eng. Soc. Trans.*, 17, pp. 548–576, Oct. 1922.
" Cotton-Mill Lighting," J. M. Ketch, *Am. Ill. Eng. Soc. Trans.*, 17, pp. 577–599, Oct. 1922.
" Principles of School Lighting," H. B. Dates, *Am. Ill. Eng. Soc. Trans.*, 17, pp. 642–662, Nov. 1922.
" Electrical Equipment of the London County Hall," *Electr. Review*, 91, pp. 151–153, 186–189, Aug. 11, 1922.
" Development, Position, and Problems of Electric Lighting," H. Lux. *E.T.Z.*, 43, pp. 1401–1405, Nov. 23, and pp. 1451–1454, Dec. 7, 1922.
" A Comparison of Direct and Indirect Lighting," W. Kunerth, *Electr. World*, 80, pp. 1268–1269, Dec. 9, 1922.
" Kinema Studio Lighting," F. S. Mills, *Am. Ill. Eng. Soc. Trans.*, 18, pp. 143–150, Feb. 1923.
" Stage Lighting," *Electr. Review*, 92, pp. 406–409, March 16, and pp. 447–449, March 23, 1923.
" Illuminating Flares," G. J. Schladt, *Am. Ill. Eng. Soc. Trans.*, 18, pp. 366–381, April 1923.
" Safety Illumination in Theatres and Factories," S. Baumann, *E.T.Z.*, 44, pp. 182–183, Feb. 22, 1923.
" Street Lighting Requirements," H. T. Harrison, *Ill. Eng.*, 16, pp. 6–11, Jan. 1923.
" Influence of Paint on Interior Illumination," R. L. Hallett, *Am. Ill. Eng. Soc. Trans.*, 18, pp. 338–347, April 1923.
" Lighting Effects on the Stage," L. Hartmann, *Am. Ill. Eng. Soc. Trans.*, 18, pp. 419–433, May 1923.
" Æsthetic Aspects of Fixture Design," E. G. Perrot, *Am. Ill. Eng. Soc. Trans.*, 18, pp. 525–539, July 1923.
" Co-operation with the Architect in Lighting Problems," A. D. Curtis and J. L. Stair, *Am. Ill. Eng. Soc. Trans.*, 19, pp. 43–54, 65–86, Jan. 1924.

" Depreciation of Lighting Equipment due to Dust and Dirt," E. A. Anderson and J. M. Ketch, *Am. Ill. Eng. Soc. Trans.*, 19, pp. 55–86, Jan. 1924.
" Street Lighting," J. Schaer, *E.T.Z.*, 45, pp. 641–646, June 19, and pp. 684–688, June 26, 1924.
" Artificial Daylight," L. C. Martin, *Nature*, 114, pp. 53–55, July 12, 1924.
" Street Lighting," P. S. Millar, *Am. I.E.E.J.*, 43, pp. 495–503, June 1924.
" Present Practice in Motor-Bus Lighting," L. C. Porter and A. C. Roy, *Am. Ill. Eng. Soc. Trans.*, 19, pp. 456–474, May 1924.
" Traction Lighting by Electricity," J. F. Caine and E. A. Marx, *Ill. Eng.*, 17, pp. 19–28, Jan.-March 1924.
" Progress in Illuminating Engineering," *Ill. Eng.*, 68, pp. 5–7, Jan. 1925.

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