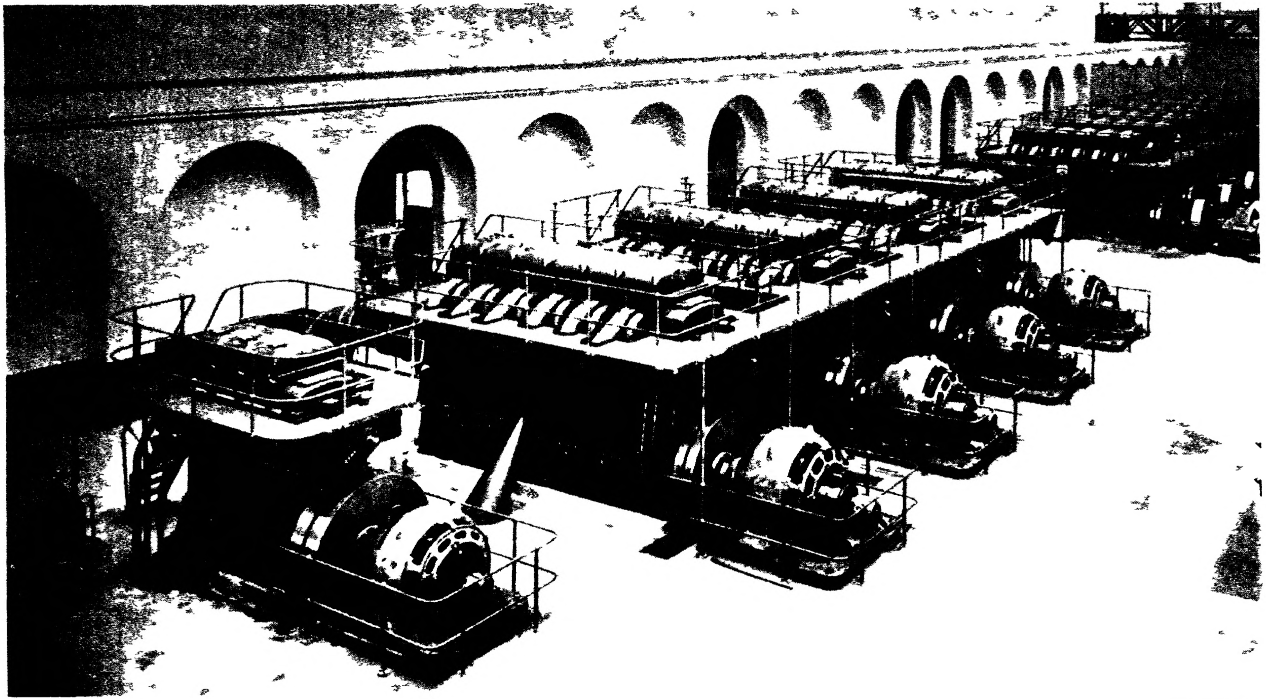
DIESEL ENGINE FUELS AND LUBRICANTS



[Frontispiece

Installation of Diesel Engines (Harland & Wolff) using Sludge Gas at the West Middlesex Sewerage Works, Mogden, Isleworth, Middlesex

DIESEL ENGINE FUELS AND LUBRICANTS

by

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PREFACE

THE events of the past twenty years have included some sweeping changes in the extent and forms of application of the Diesel principle of internal-combustion-engine operation, namely, the displacement of blast injection by airless injection; the world-wide development of the small high-speed Diesel engine for road and rail traction and other purposes; the extensive use of large double-acting two-cycle Diesel engines for marine propulsion; the gradual increase of piston speeds and mean pressures, including the use of supercharging; the development of engines using gas fuel with Diesel compression (dual fuel engines).

Concurrently with these engine developments there have been changes in the qualities of available fuels and in the organization of their distribution. Also there have been notable achievements in the technique of lubricating oil refining and blending.

These trends have influenced each other, and are matters of importance to all Diesel-engine users. There seems little reason to suppose that they have reached even a temporary halting place; nevertheless this early post-war data may be a favourable time for making a survey of the present position regarding Diesel-engine fuels and lubricants from the users' point of view.

Whilst the improvements alluded to above both of engines and of oils have been achieved with the help of all the aids which science has been able to supply, this book is not a scientific treatise. Its aim is practical—namely, to serve as a handy reference for the use of engineers and managers in charge of Diesel engines. In all such matters engineers and scientists must be prepared to meet each other half-way.

The authors have tried to include enough information on the chemistry and physics of fuels and lubricants to facilitate mutual understanding between Diesel-engine users and oil suppliers.

The authors have pleasure in acknowledging their indebtedness to a colleague, Mr. A. Hammer, Chief Tester in the Diesel Engine Department of the Belfast works of Harland & Wolff, Ltd., for reading the proofs and useful suggestions, and also to Sir Frederick Rebbeck, Chairman of this Company, for permission to make use of photographs and technical data.

E. W.
H. F. P. P.

Belfast,
July 1949.

CONTENTS

ABBREVIATIONS USED IN TEXT

A.P.I.	American Petroleum Institute.	Gal.	Gallon.
A.R.	Analytical reagent.	gm.	Gram.
A.S.T.M.	American Society for Testing Materials.	hr.	Hour.
B.E.S.A.	British Engineering Standards Association.	in.	Inch.
b.h.p.	Brake horse-power.	I.P.T.	Institute of Petroleum.
b.p.	Boiling point.	kg.	Kilogram.
B.S.I.	British Standards Institution.	KOH	Potassium hydroxide (caustic potash).
B.Th.U.	British Thermal Units.	min.	Minute.
Cal.	Calorie.	ml.	Millilitre.
c c.	Cubic centimetre.	mm.	Millimetre.
cm.	Centimetre.	R.A.E.	Royal Aircraft Establishment.
D.E.U.A.	Diesel Engine Users' Association.	r.p.m.	Revolutions per minute.
		S.A.E.	Society of Automotive Engineers.
		wt.	Weight.

ILLUSTRATIONS

CHAPTER I

INTRODUCTION

1. *Scope of the Treatment.*—The point of view considered in the following chapters is that of an engineer or manager in charge of a Diesel-engine installation, whose duties include the purchase of supplies of liquid fuel and lubricants and the supervision of their use to the best advantage. Such an engineer or manager will in many cases have a fairly wide choice of products from which to choose, and the success or otherwise of the operation of the plant under his charge may depend very much on the soundness of his judgment. Even if his choice is restricted or dictated by economics or higher authority, some knowledge of the properties of fuels and lubricants and the means by which these are controlled, will be indispensable if he is to keep a satisfactory check on the quality of supplies and get the best out of the grades available to him.

As a necessary background for the detailed considerations which follow, a brief account of the natural and industrial sources of Diesel fuels and lubricants is given in Chapter II. Subsequent chapters deal with the various Diesel fuels and lubricants in the forms in which they reach the user, their physical properties and the means by which these are ascertained or checked.

2. *Types of Diesel Engines.*—No type of prime mover is built in such a wide variety of designs, sizes and speeds as the Diesel engine. Cylinder diameters range from 2½ to 35 in.; crankshaft speeds from 80 to 4000 r.p.m.; piston speeds from 800 to 2500 ft./min. (4–12·5 m./sec.); brake mean pressures from 50 lb./in. to 180 lb./in.^{2}. In addition, we have four-stroke and two-stroke, single-acting and double-acting trunk and cross-head, vertical and horizontal, vee and radial, covered cylinders and opposed-piston engines, poppet-valve, sleeve-valve and ported engines, airless injection and air-blast injection, the latter now in a small minority but by no means negligible. These variations have their own fuel and lubrica-

tion problems. Fortunately most of them can be accounted for under the headings :

(1) Size as measured by cylinder diameter.
(2) Speed as measured for instance by the product of r.p.m. multiplied by $\sqrt{\text{bore} \times \text{stroke}}$ or r.p.m. $\times \sqrt[3]{\text{bore}^2 \times \text{stroke}}$.
(3) Temperature measured at the most exposed piston-ring groove.
(4) Effectiveness of cooling of the cylinder liner near the combustion chamber.
(5) Airless injection or air injection.

Items 1, 2 and 4 are of major importance in relation to the class of fuel which can be used with success, and item 3 is a determining factor in relation to lubrication with item 2 next in importance. There are a number of fuels which can be dealt with by air-blast engines without difficulty, which would be embarrassing to an airless-injection engine, but such fuels have tended in the last few decades to become less and less conspicuous on the fuel market. The type of injection, whether airless or air injection, has little or no influence on the type of lubricant for the main cylinders or running gear, although a compounded oil may be desirable for the compressor cylinder, to deal with condensation of water vapour. Oils compounded with vegetable or animal fats, if used in the combustion cylinders, lead to ring sticking and piston seizure.

3. *Troubles to be Avoided.*—Mechanical breakdown or excessive overhauling for the purposes of piston cleaning, valve grinding, etc., due to the use of unsuitable fuel or lubricant, is liable to result in excessive running costs out of all proportion to the saving on cheaper oils as compared with higher-priced but more suitable oils. An engine developed for the use of one type of fuel is likely to be successful with an inferior grade only if rather special arrangements are made and precautions taken. The cost of such provision should be carefully and conservatively weighed and adopted only after prolonged tests on a sufficient scale. It by no means follows that the most expensive of two lubricants is necessarily the better; it may easily be the other way round. The better of two lubricants for the purpose in

hand will usually prove cheaper in the long run even if it costs a little more per gallon.

Some account will therefore be given of the troubles which are liable to follow the use of unsuitable fuels and lubricants, and the physical tests which have been devised can assist in recognising a suitable lubricant by comparison with others. Nevertheless, it must be confessed that petroleum technologists agree that the engine itself is the final arbiter, whose verdict the laboratory cannot reverse. An experienced engineer will accumulate over the years a body of experience which no other discipline can replace, but which may with advantage be supplemented by the results of research; also he will keep an open mind with regard to new developments.

4. *Treatment of Fuels and Lubricants.*—It is one thing to have the best materials, and another to make the most advantageous use of them. In this field practical experience is of course paramount. Some notes will be given on the arrangements made in typical installations for dealing with fuel from its reception at the bunker or storage tank to its ultimate injection into the cylinder, after which its behaviour will depend on the design and state of adjustment of the engine.

With modern engines there are considerable quantities of costly lubricating oil in circulation, and it is a matter of first-rate importance that this should be kept in a satisfactory state, not only for the sake of the engine but also to avoid the expense of replacement at unnecessarily frequent intervals. The arrangements made for straining, filtration, purification, etc., depend to a large extent on the size of the installation, and even so, several variations are available for choice. Furthermore, the important questions of wear of cylinders and bearings are intimately connected with lubrication, and it is therefore appropriate that some discussion of these and other questions should be included.

CHAPTER II

SOURCES AND PREPARATION

5. *Crude Petroleum.*—Petroleum, or as the name implies, rock oil, has been known from very remote times; the fact that the "Eternal Oil Fires" of the Baku District of Russia provided the object of worship of the Parsee fire-worshippers, who made the pilgrimage from India for over a thousand years, is witness to this. In the present era, which may well be termed the "oil age", the use of petroleum and its products has assumed enormous proportions, and crude petroleum, or at least its products, may be regarded as the life-blood of the Diesel engine, both from the fuel and lubrication angles, in that it is the major source from which these oils are obtained.

With the origin of petroleum we are not concerned; suffice it to say that it has been the subject of considerable scientific controversy for many years, and while there are still adherents to the inorganic theory which postulates that petroleum is derived from metallic carbides, the organic theory is almost universally accepted today. According to this theory, petroleum has been produced from microscopic vegetable and marine-animal life through the agency of rock pressure and earth temperature operating over a very long period of time.

Crude oil is found in the earth's crust at many levels. The early wells at Baku were scooped out by hand to depths reaching 50 ft., but since the historic day in 1859 when "Colonel" Edwin Drake succeeded in drilling the first oil-bearing well, drilling into the oil-bearing strata has been the standard method. Although drilling methods have been vastly improved with the passing of the years and productive wells have been drilled to depths of 8000 ft., the principles remain more or less the same. Drilling, however, is not carried out at random, as in the early days of the industry, but in areas previously suggested by the geologist from the results of his studies of the strata.

The most important oilfields at present known are those of

Pennsylvania, California and Texas in the United States, Mexico, Venezuela, the Netherlands East Indies, Iran, Iraq, Egypt, U.S.S.R., Rumania, Poland and Japan. The output from these and other fields has now attained huge dimensions, as illustrated by the following data.

CRUDE FUELS *

Estimated Outputs

(000's tons)

	1938.†	1946.	1947.
U.S.A.	161,440	230,665	246,000
Venezuela	26,450	56,560	62,500
U.S.S.R.	29,250	22,300	25,500
Iran	10,195	19,180	19,400
Saudi Arabia	66	8,070	11,800
Mexico	5,372	6,900	7,100
Iraq	4,294	4,620	4,500
Rumania	6,504	4,116	3,600
Colombia	3,076	3,087	3,400
Argentina	2,404	2,928	3,000
Trinidad	2,418	2,843	2,850
Kuwait	—	785	2,650
British Borneo	850	285	1,800
Peru	2,062	1,635	1,670
Egypt	219	1,260	1,270
Bahrein	1,118	1,080	1,080
Canada	850	960	835
Austria	56	832	745
N.E.I.	7,157	295	685
Hungary	36	675	590
Germany	543	630	540
Ecuador	304	302	295
Others	2,480	1,130	1,270
Total	267,144	371,138	403,080

* Excluding natural gasoline.
† Actual totals.

Crude petroleum, as it flows from the wells in different parts of the world, varies in colour and viscosity, and while in the majority of cases it is a black, viscid liquid, other crudes are pale in colour and relatively mobile. It consists largely of a complex mixture of hydrocarbons (so-called because they are composed entirely of carbon and hydrogen, differing only in the manner and proportion in which these elements are bonded together) with varying small amounts of sulphur, nitrogen and oxygen.

6. *Hydrocarbons.*—These may be classified broadly into two groups.

(*a*) Aliphatics, which include the paraffin series, olefine series and acetylene series.

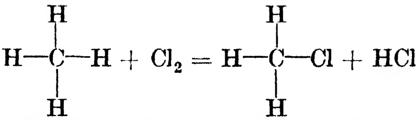
(*b*) Carbo-cyclics; this class covers the naphthenes and aromatics, the latter including the benzene and naphthalene series.

The simplest hydrocarbon is methane, which consists of a carbon atom with each of its four valencies occupied in holding a hydrogen atom. It is the first of the paraffin series, in which each member differs from the next in the series by one atom of carbon and two atoms of hydrogen. All the members of the series, therefore, can be represented by the general formula C_nH_{2n+2}, where n = number of carbon atoms. Such a series is termed homologous, and all the members of the series show a similarity in chemical properties, but as the molecular weight increases, the physical properties undergo a gradual and regular variation. Thus the simplest members of the series are gases at normal temperature, while higher up the series, from five to sixteen carbon atoms, the members are liquids, and those containing over sixteen carbon atoms are solids.

Particulars of some of the members of the paraffin series are given in the following table :

Name.	Formula.	Melting Point, ° C.	Boiling Point, ° C.	Remarks.
Methane . .	CH_4	- 184	-160 (760 mm.)	Chief constituent of natural gas and sludge gas.
Ethane . . .	C_2H_6	-172	- 93 „	Gas.
Propane . .	C_3H_8	- 45	- 44·5 „	Calor gas. Found in natural gas.
Butane . . .	C_4H_{10}	—	1 „	
Pentane . .	C_5H_{12}	—	36·3 „	Chief constituents of petrol.
Hexane . .	C_6H_{14}	—	69 „	
Heptane . .	C_7H_{16}	—	98·4 „	
Octane . . .	C_8H_{18}	—	125·6 „	Standard of anti-knock value for petrol engine.
Nonane . .	C_9H_{20}	- 51	150 „	Colourless liquids—constituents of illuminating oils, "paraffin" or kerosene.
Decane . . .	$C_{10}H_{22}$	- 31	173 „	
Undecane . .	$C_{11}H_{24}$	- 26·5	196 „	
Dodecane . .	$C_{12}H_{26}$	- 12	215 „	
Tridecane . .	$C_{13}H_{28}$	- 6	234 „	
Tetradecane . .	$C_{14}H_{30}$	4	252 „	
Pentadecane . .	$C_{15}H_{32}$	10	270 „	
Hexadecane (cetane)	$C_{16}H_{34}$	18	287·5 „	Anti-knock standard for Diesel fuels.
Eicosane . .	$C_{20}H_{42}$	37	205 (15 mm.)	Crystalline solids, e.g., paraffin wax. Many of the higher members of the series contained in Diesel fuels and lubricants.
Tetracosane . .	$C_{24}H_{50}$	51	243 „	
Pentatriacentane .	$C_{35}H_{72}$	75	331 „	
Dimyricyl . .	$C_{60}H_{122}$	102	—	

The paraffins are all characterised by great chemical stability, and only form compounds by substitution as exemplified in the equation :



$$\begin{array}{c}H\\ |\\ H-C-H\\ |\\ H\end{array} + Cl_2 = \begin{array}{c}H\\ |\\ H-C-Cl\\ |\\ H\end{array} + HCl$$

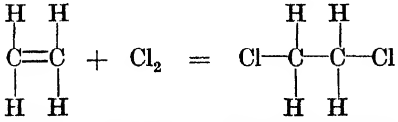
Methane. Chlorine. Methyl chloride. Hydrochloric acid.

In short, their combining capacity or valency is fully satisfied, and they are said to be saturated.

The olefines form another homologous series of the aliphatic class, having the general formula C_nH_{2n}, a few members of which are given below :

		Boiling Point, ° C.	Specific Gravity.
Ethylene	C_2H_4	Gas	—
Propylene	C_3H_6	,,	—
Butylene	C_4H_8	55	—
Amylene	C_5H_{10}	35	0·663
Hexylene	C_6H_{12}	70	0·699
Cetene	$C_{16}H_{32}$	Standard of high anti-knock value for compression-ignition engines.	

Olefines differ from the paraffins in that they are more reactive and readily form compounds by direct addition of other elements.

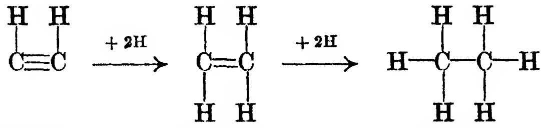


$$\begin{array}{cc}H & H\\ | & |\\ C & = C\\ | & |\\ H & H\end{array} + Cl_2 = \begin{array}{c}H \quad H\\ | \quad\; |\\ Cl-C-C-Cl\\ | \quad\; |\\ H \quad H\end{array}$$

Ethylene. Chlorine. Ethylene dichloride.

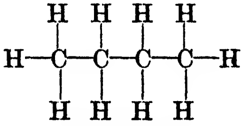
In such reactions the characteristic double linkage existing between the carbon atoms is converted into a single linkage, and the valencies or bonds thus freed attach themselves to the reacting substance. In contradistinction to the saturated paraffins, olefines are said to be unsaturated.

In the hydrocarbons of the acetylene series (C_nH_{2n-2}) the carbon atoms are united by a treble bond, indicative of the fact that they are doubly unsaturated and capable of combining with either one or two pairs of monovalent atoms, to form additive compounds. Thus acetylene may combine with two or four atoms of hydrogen, forming an olefine and a paraffin respectively.

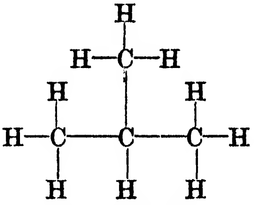

Acetylene. Ethylene. Ethane.

In the aliphatic series, many of the members occur in more than one form, i.e., the atoms are arranged differently in the molecule. For example, the atoms in the hydrocarbon butane, C_4H_{10}, can be arranged in two ways.

(*a*)

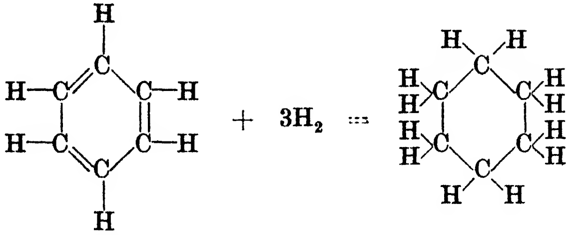

n-Butane.

(*b*)


iso-Butane.

These compounds have the same molecular weight, they contain the same percentage of carbon and hydrogen, but they have different structures, and consequently have not quite the same properties; their boiling points, for example, differ. These two molecules are said to be isomeric or to display isomerism. The greater the number of carbon atoms in the molecule, the greater the variations in structure possible, so that the number of isomers in the heavy hydrocarbons present in petroleum oils is very large.

The carbon atoms in the aliphatic series are attached to each other in the form of straight chains with or without attached branches. In the carbo-cyclic class of hydrocarbons, however, i.e., the aromatics and naphthenes, the carbon atoms in the molecule are arranged in ring form. Aromatic compounds, having double bonds, are unsaturated, and are therefore chemically reactive. Benzene, for example, combines with hydrogen, under suitable conditions, forming a hydrogenated aromatic compound of the naphthene series.



Benzene
(aromatic).

Hexahydrobenzene
(naphthene).

The naphthene series may be represented by the same general formula as the olefines, i.e., C_nH_{2n}, but in the latter the carbon and hydrogen are combined together in such a way as to give unsaturated compounds of the straight-chain type $CH_3{\cdot}CH{:}CH_2$, whereas in naphthenes the two elements are combined together in a different way, to give saturated cyclic bodies as shown above.

The diagram (Fig. 1) gives a classification of the principal hydrocarbons and their relations to the constituents of hydrocarbon liquid fuels and lubricants. This diagram is included merely to provide the layman with a rough idea of the make-up of fuels and lubricating oils, and does not purport to give a complete picture of all the homologous series which may be present, or of the chemical constituents of the oils.

Crude petroleum from the Pennsylvanian wells, the first to be exploited, has a paraffinic base, that is to say, it consists chiefly of a large number of hydrocarbons of the paraffin series, while an asphaltic base is typical of Californian and Texan crudes. Russian petroleums have an essentially naphthenic base, those of Iran a mixed base, while in the crudes of Burma and the Dutch Indies aromatic hydrocarbons predominate. Associated with the crude oil there may be a varying percentage of water and a small percentage of mineral solids or salts; some crudes contain vanadium and other metallic salts. Each crude has its own peculiar characteristics; paraffin-base crudes are rich in petrol and kerosene and usually contain relatively small amounts of asphalt and sulphur; they have a low specific gravity. Asphaltic-base crudes, as implied by the name,

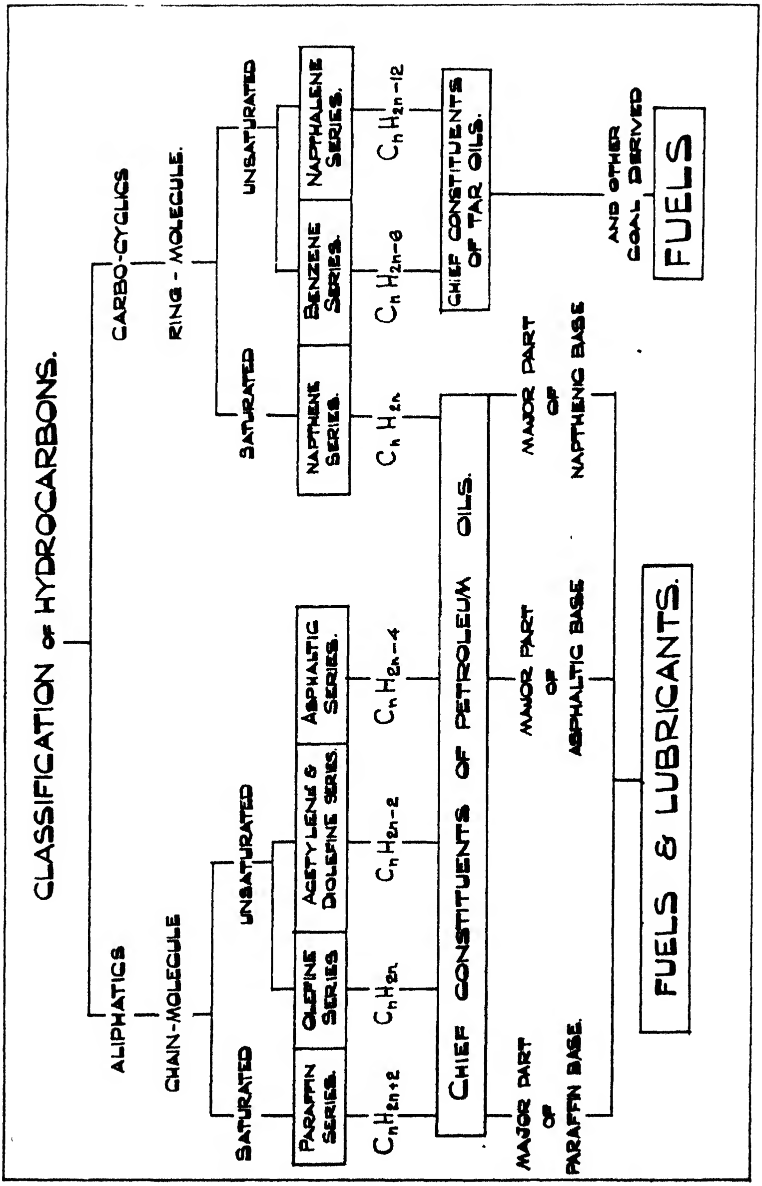


FIG. 1.—CLASSIFICATION OF HYDROCARBONS.

contain a large amount of asphalt and have a high specific gravity; they are rich in lubricating and fuel oils, but some of them contain a high sulphur content. Russian crudes, consisting essentially of naphthenes with a small percentage of acetylene hydrocarbons, are characterised by their negligible content of paraffin wax.

7. *Treatment of Crude Oil.*—The object in refining is to separate the various constituents of the mixture of hydrocarbons present in the crude, and the basis of this treatment is the difference in the boiling points of the constituents. This difference in boiling point is associated with the proportions of carbon and hydrogen present in the hydrocarbon molecule; the higher the carbon content the higher the boiling point, until eventually a solid hydrocarbon is reached, e.g., wax or pitch.

The splitting up of crude oil into the various constituents is effected by: (*a*) fractional distillation, (*b*) cracking; the latter treatment, however, is not generally applied to crude oils, but to the residues and heavier fractions obtained in straight distillation.

In a modern distillation unit, the crude oil is heated in a tubular still consisting of a series of alloy-steel pipes about 4 in. in diameter connected together so that the oil travels backwards and forwards over the fire, until it attains the highest temperature necessary to drive off all the distillates; the distillates are then cooled down gradually so that the successively cooled fractions become lighter and lighter. This is effected by passing the mixture of vapour and liquid leaving the still into the lower section of a fractionating column fitted with a number (usually fifteen) of floors or trays of a special type on which a number of mushroom-like caps or vents termed bubble caps are arranged. The point of entry of the mixture of vapour and liquid into the column is above the second or third tray, so that the liquid falls through the lower trays and meets an upward stream of super-heated steam introduced at the base, which eliminates all light products and gives a residue free from distillate.

The ascending vapours cool as they rise in the column, and a certain amount condenses on each floor until the tray is full of liquid up to the level of the overflow. This level is kept just above the holes in the bubble caps, so that all the rising vapours have to pass through condensate already in the trays and in so doing, give off that fraction of their content which distils off at the temperature obtaining at that level. That portion of vapour which is still too light for the temperature prevailing at a particular tray level bubbles through and continues to rise until it condenses. The only vapour that reaches the top of the column is the light-gasoline fraction, and this is passed through a condensing coil cooled by cold water outside the tower; part of this is pumped back into the top of the column as reflux and so assists in controlling the temperature at the top and also in giving a gasoline fraction of narrower boiling range. Other fractions of progressively higher boiling point are drawn off from the column at lower and lower levels according to the temperature desired for any particular distillate. Thus kerosene and burning oil are drawn off near the top of the column at a temperature of approximately 200–300° C., next, and lower in the column, comes gas and Diesel oil at 300–350° C., followed at a still lower level by lubricating oil at 350–500° C., or heavy fuel oil over about the same range of temperature, depending on the crude. The relative proportions of the several fractions will vary with the origin and character of the crude, and the degree of separation effected can be modified according to the market demand for one or other product of the refining. Further distillation under partial vacuum, often in the presence of steam, is generally resorted to in dealing with the higher-boiling-point and lubricating-oil fractions. The vacuum lowers the distillation temperatures and tends to minimise decomposition by cracking; steam also assisting in this direction.

A flow diagram of a modern distillation unit is given in Fig. 1(*a*).

It now remains to refine the lubricating-oil fractions which, as collected from the fractionating column, contain insoluble impurities and perhaps small percentages of unsaturated hydrocarbons. Removal of the paraffin wax may be effected by chilling and pressing, and the further treatment usually involves agitation with sulphuric acid. The sulphuric acid combines with certain bodies in the oil (which would gum or oxidise in use), forming an acid tar which is drawn off from the bottom of the agitator. After a further period of settling in another tank, clear oil is drawn off into other vessels, where it is agitated with a solution of caustic soda and subsequently washed with water; alternatively, it may be treated with fuller's earth or other active earth to which an alkali has been added and then passed through filter presses to remove all traces of earth.

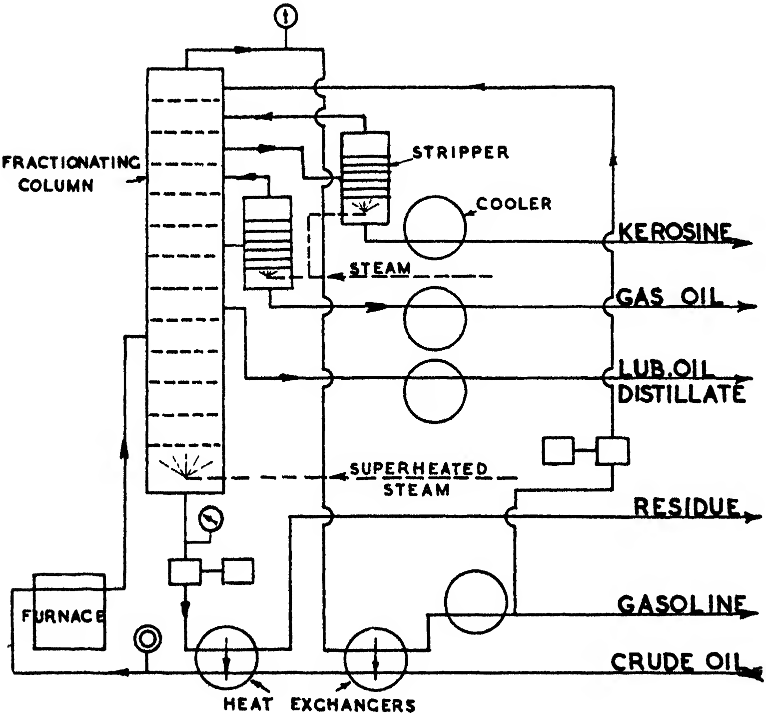


FIG. 1(*a*).—FLOW DIAGRAM OF DISTILLATION UNIT.

A more modern method of refining which has been widely applied in recent years is the Solvent Extraction Process. This is a distinct improvement on the older acid method in that all undesirable compounds are more effectively removed, and crudes which were formerly regarded as unsuitable can be treated for the extraction of lubricating oils.

Solvent extraction consists of a thorough mixing of the oil with one or more solvents such as liquid sulphur dioxide, fur-

fural, benzol, etc., at a suitably low temperature, whereby all unsaturated hydrocarbons, aromatics, resins and other unstable compounds are dissolved, leaving the desired lubricating-oil hydrocarbons unaffected. After settling, the solvent carrying the impurities, i.e., the bottom layer, is drained off, leaving only the purified oil with a little solvent dissolved in it; this is then subjected to vacuum distillation followed by filtration through fuller's earth; this ensures entire removal of all traces of solvent.

By blending various proportions of the refined lubricating-oil distillate, all types of lubricating oils are made available. All mineral oils are completely miscible with each other, and the blending of various proportions by mechanical means or agitation with air, presents no difficulty.

As distinct from straight distillation in which no molecular decomposition is brought about, cracking accomplishes decomposition or splitting up of heavy hydrocarbon molecules into simpler molecules of lower boiling range. Some of these simpler molecules differ in structure from the original, the reason being that there is not sufficient hydrogen in the complex molecules to supply the needs of the smaller cracked molecules. For example, the saturated paraffin hydrocarbon $C_{20}H_{42}$ may be cracked into another paraffin C_7H_{16} and a molecule of the unsaturated olefine $C_{13}H_{26}$ or other combination of paraffin and olefine. Cracking involves heating the heavier hydrocarbons under such conditions as promote decomposition. This may be attained by two different methods, the " liquid-phase " and " vapour-phase " cracking. In the latter, the oil is first brought into vapour form, and these vapours cracked by exposure for a short time to a very high temperature; with this method high pressure is not necessary. In the liquid-phase process which is largely used, the oil treated, known as cracking stock, may be ordinary residue, fuel oil, kerosene, or in the case of reforming, gasoline. This cracking stock is heated to a temperature of 480–530° C., while the pressure in the system may be relatively low, namely, 150–180 lb./sq. in. as in the Dubbs process, or as high as 800 lb./sq. in. as in the Cross process. Under such conditions of temperature and pressure, the so-called cracking of the heavy gas or fuel oil takes place. The oil is heated in a pipe still designed to withstand the pressure and temperature required, and to prevent local overheating a high rate of flow is maintained through the heated pipes. The heated oil passes to a reaction chamber maintained at the working pressure, and in this vessel the major portion of the oil is vaporised, leaving a residue of heavy fuel oil, generally unsuitable for use in Diesel engines. The cracked vapours then pass via a pressure-control valve into the base of a dephlegmator; in ascending, the vapours meet a countercurrent of the cracking stock falling downwards from the top, over a series of trays with which the column is fitted. The vapours are thus cooled and the cracking stock pre-heated before being pumped through the pipe still. By this treatment a sharp fractionation of the light products leaving the top of the column and the condensate collected at the bottom is effected. The condensate from the bottom is generally recycled through the plant. In this way, the yield of light constituents, mainly petrol, from a given crude can be considerably increased, but only at the expense of the yield of fuel and lubricating oils suitable for Diesel engines.

8. *Coal Tars and Tar Oils.*—Coal tar is produced mainly as a by-product in the destructive distillation of coal carried out on a large scale in the manufacture of coal gas; a relatively small amount is produced by the various low-temperature-carbonisation processes. In the former, the coal is strongly heated in iron retorts provided with air-tight doors, when the gas and other volatile products escape from the retorts through a pipe, leaving a residue of coke. The gas and volatile products are cooled by passing through a series of pipes kept cool by immersion in water, when tar and gas liquor condense, the gas being further treated in scrubbers and purifiers before passing on to the gas-holder. The coal tar is separated from the gas liquor with which it is associated, and subsequently submitted to fractional distillation. As a general rule, the yield and composition of the coal tar produced is dependent largely on the type of retort used, the temperature conditions prevailing and to a lesser degree on the type and size of the coal charged into the retorts; an average yield of crude tar is 1 cwt. per ton of coal carbonised, vertical retorts yielding a little more, and horizontal retorts rather less than this.

Vertical retorts are most frequently adopted in modern installations, producing tars which are relatively fluid and of a dark brown colour; such raw tars contain approximately 7% hydrogen and are comparatively free from inorganic matter and free carbon. On the other hand, tars produced in horizontal retorts, by reason of the high retorting temperatures employed, are viscous, black liquids and have a high specific gravity; these tars are rich in aromatic bodies and contain 20–30% of free carbon. The approximate composition of the dry tar averages carbon 91%, hydrogen 5%, oxygen, nitrogen, sulphur and inorganic matter, 4%. The high content of free carbon in tars of this type, together with the high pitch content, renders them unsuitable for Diesel fuel, and while the less viscous tars produced in vertical retorts might be used in the older air-blast Diesel engines by making suitable modifications, it is only in exceptional circumstances that this would be justified, and it is universal practice to distil the tar to separate the more suitable tar oils.

9. *Distillation of Crude Tar.*—In English practice, pot stills are largely used; these are constructed of mild-steel plates riveted together and having a capacity of 12–15 tons. The stills are vertical cylindrical vessels with concave bottoms and domed tops, their height being usually slightly greater than the diameter. They are heated directly below by a furnace, the gases from which are led through flues to heat the sides of the still. Generally the upper part of the still is covered with brickwork to minimise loss of heat.

To overcome frothing trouble arising from the presence of water in the tar and to effect economy in fuel consumption, pot-still installations are usually operated on the double-still system. The second still is situated at a higher level and is not fire-heated, but contains a coil surrounded by the next charges of crude tar for the main still. The hot vapours from the latter pass through the coil on their way to the condenser and the crude tar is sufficiently pre-heated to slowly distil off the water and light spirit. It can afterwards be rapidly distilled from the fire-heated still with safety.

The vapours which pass off are condensed in long iron or lead worms immersed in water, the liquid distillate being collected in fractions. The usual fractions collected in standard English practice are as follows :

	Temperature, ° C.	Specific Gravity.	Approx. Yield, %.
First runnings or crude naphtha	Up to 110	0·920	3·1
Light oil	110–120	0·995	1·7
Crude carbolic oil	200–240	1·015	3·5
Creosote oil	240–270	1·050	12·0
Anthracene or heavy oil	Above 270	1·095	9·7
Pitch	Residue in still.		

Each fraction contains slight amounts of the next higher and lower fraction and are themselves mixtures of oils which are generally subjected to further distillation, particularly the first two, in order to separate the benzol, toluol, xylol, etc. The fractions which are of interest as Diesel fuels are the creosote and heavy oils; these are frequently mixed and marketed as " tar oils ".

The characteristics of such a tar oil are as follows :

Specific gravity at 60° F.	1·012
Viscosity (Redwood No. 1) at 70° F.	39 sec.
,, ,, at 100° F.	35 sec.
Closed flash point	182° F.
Conradson coke value	0·81%
Sulphur	1·01%
Pour point	Fluid at 10° F.
Gross calorific value	16,400 B.Th.U./lb.
Distillation initial b.p.	184° C.
10%	211° C.
20%	219° C.
30%	225° C.
40%	234° C.
50%	241° C.
60%	250° C.
70%	266° C.
80%	291° C.
90%	331° C.
Final boiling point	350° C.

Slow-speed Diesel engines running up to say 300 r.p.m. can be readily adapted to the use of fuels of this type, and with slight modification burn tar oils satisfactorily at all loads.

In running tests made on a two-cycle Harland & Wolff engine having six cylinders of 350-mm. diameter (Fig. 2), the engine was started up on ordinary Diesel fuel and, after a few minutes running, changed over to tar oil having the characteristics detailed above. During the preliminary stages of the test there was persistent misfiring and very irregular running at all loads, but this difficulty was entirely overcome by a device consisting essentially of a variable throttle on the blower suction. The purpose of this simple air-control regulator was to ensure regular self-ignition at lighter loads by keeping the proportion of combustion air to the fuel within a controlled

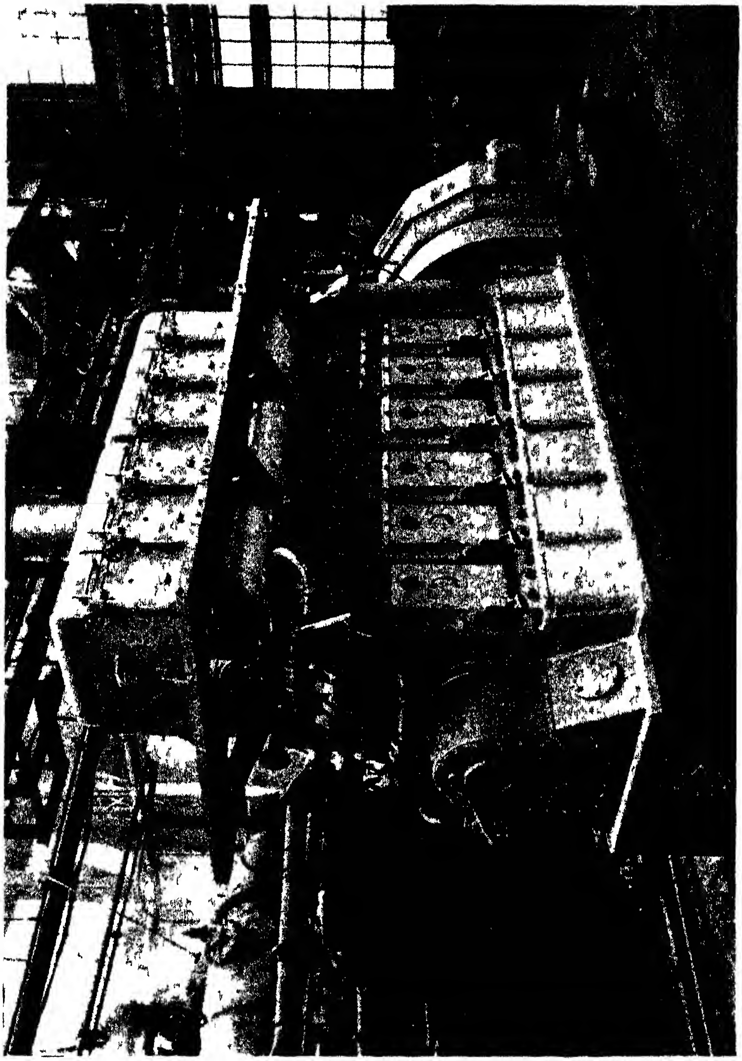


FIG 2 —UNIFLOW SCAVENGE TWO CYCLE ENGINE (HARLAND & WOLFF) TESTED ON TAR OIL value, and simultaneously to maintain a higher temperature in the cylinder than is necessary for ignition, when burning petroleum fuel oil.

In high-speed engines as used in road vehicles a report (1) dealing with home-produced fuels for Diesel engines draws the following conclusions : (*a*) straight high-temperature creosote cannot be satisfactorily used in present commercial engines; (*b*) doping this fuel improves its performance, the effect of 4% of dope being equivalent to a 40% addition of petroleum Diesel fuel; (*c*) under some conditions, low-temperature creosote may be used, and doping gives satisfactory results.

10. *Vegetable and Animal Oils.*—Vegetable and animal oils consist largely of glycerides of unsaturated fatty acids and differ from hydrocarbon oils in that they are more liable to chemical change and that they can be saponified, e.g., they can be resolved into glycerols or alcohols and fatty acids. Nevertheless, before the advent of petroleum oils, midway through the last century, vegetable and animal oils were the only source of lubricants, and today some fatty oils are still extensively used in lubricating oils; rape oil, for example, finds a place of some importance as a constituent of marine-engine oils, though not of Diesel-engine lubricants, except perhaps to a very limited extent in compounded compressor oils.

Many vegetable and animal oils could be used as Diesel-engine fuel if supplies and cost permitted, but at a period like the present when the world is suffering from a shortage of fats such a use of edible material is undesirable. Even in times of a glut of fatty oils, the use of such an oil would be justified only in small Diesel units operating in the heart of a vegetable-oil-producing district, cut off from ready access to petroleum products. The only proposal to use a vegetable oil of which the authors are cognisant concerned a Diesel engine in Equatorial Africa, the fuel proposed being palm oil having the following characteristics :

Specific gravity at 60° F.	0·922
Viscosity (Redwood No. 1) at 100° F.	55 sec.
Saponification value	19·6% KOH
Free palmitic acid	11·8%
Water	0·17%
Carbon	75·2%
Hydrogen	11·7%
Oxygen and nitrogen	13·1%
Gross calorific value	15,800 B.Th.U./lb.

Reports on research carried out in India (2) using vegetable oils as Diesel fuels disclosed that these oils in general gave outputs comparable with those obtained with mineral fuel, somewhat higher fuel consumption but rather superior thermal efficiency; the higher consumption being a consequence of lower calorific value.

Engine tests have also been made in India recently using ground-nut oil mixed with finely powdered charcoal of low ash content, the object of this being to enable vegetable oils to compete with mineral oils from an economic viewpoint; the calcium soap of ground-nut-oil fatty acid was added to the mixture (colloidal fuel) to confer stability and prevent settling down of the charcoal particles. It was found that the use of this fuel gave rise to trouble in the injection system due to abrasive action which caused the engine to stop in little more than two hours' running. Nevertheless, in view of the promise revealed by the tests with this type of fuel, in respect of stability and thermal efficiency, the originators of the idea propose carrying out further tests using still smaller charcoal particles and redesigned injection systems.

The majority of oil-producing plants thrive in tropical countries; palm in Africa, coconut in the Pacific and Indian Ocean Islands, castor in India and South America, rape in the East Indies, and so on.

Vegetable oils are usually extracted by expression of the oil from the nut or seeds by pressure, this being accomplished by passing through a series of " chill " rolls. In other cases the use of solvents is adopted. In solvent extraction the crushed seed is subjected to continual percolation with a suitable solvent such as petroleum ether, benzene, carbon tetrachloride or trichlorethylene, and the resultant oil subsequently steamed to free it from the volatile solvent, the latter being condensed for further service. Carbon tetrachloride and its derivatives have the advantage of being non-inflammable, but nevertheless petroleum ether is chiefly used and necessitates special precautions against leakage and fire risks. By the use of the solvent process less oil is left in the seed than with the pressure process.

Animal or fish oils are for the most part extracted by boiling the fatty material with water or by steam under pressure to break down the tissue, separating the oil and treating it with an alkali to neutralise the fatty acids. Finally, the oil may be clarified by filtering through fuller's earth.

SYNTHETIC SOURCES

11. *Bituminous Shales.*—Bituminous shale is found in large quantity in many parts of the world, notably Colorado, New Brunswick, New South Wales, Esthonia and Scotland; the Dorset and Norfolk deposits in England may also be mentioned. Indeed, Major W. H. Cadman of a leading oil company, in a recent review, says a survey of oil-shale deposits in twenty-one countries leads him to conclude that considerably more than one million million tons of workable oil-shale reserves have been proved. Resulting from the pioneer work of Dr. James Young of Renfrewshire, the Scottish shale industry was founded well-nigh a century ago, and since then the production of oil from these shales has been carried out in the West Lothian and Fife districts of Scotland on a fairly large scale, the annual amount of shale mined until recent years being between two and three million tons. The process developed by Young was also successfully applied to the American deposits for a number of years, until the ever-increasing production of petroleum oils in that country rendered it uneconomic.

The Esthonian deposits have been worked on a considerable scale in recent years. This shale is very different from most other oil shales in that it contains a very small proportion of nitrogen, but it is comparatively rich in oil.

The Torbanite shale of New South Wales is also rich in oil, yielding five times as much as Scottish shale, but despite this and support by government subsidies, the industry in Australia is not flourishing.

Oil shales do not contain oil as such, and therefore do not lend themselves to solvent-extraction methods for the production of oil. They consist essentially of mineral matter, usually clay, containing or combined with varying quantities of organic matter of different kinds largely derived from vegetable and, to a less extent, animal remains; when subjected to the influence of a low red heat in the absence of air, but in the presence of steam, some or all of this organic matter undergoes decomposition with the production of crude oil and ammonia.

The shales are quarried, broken up by mechanical means into pieces of suitable size and conveyed to the top of a bench of vertical retorts very similar to those used in the coal-gas industry in which destructive distillation takes place. The temperature at which the retorts operate is 900° F. in the top section, increasing to 1800° F. in the lower section, the heating of the retorts being performed by the incondensable gases produced in the process, supplemented by gas from external gas producers. A quantity of steam is introduced into each retort at the base and interacts with the carbon in the shale at the high temperature obtaining, thus producing gases of considerable heating value; at the same time the steam provides the hydrogen required to form ammonia from part of the nitrogen in the shale and also serves to prevent the decomposition of the oil vapours by diluting them and driving them rapidly up out of the lower highly heated zone, into the outlet pipe and thence into the gas mains.

A single retort of this type deals with 10 tons of shale per day, and Scottish shale yields on an average 3000 cu. ft. of gaseous products per ton. These gaseous products are passed through a series of vertical pipes in which the crude shale oil and ammoniacal liquor condense and are removed at outlets at the base; they are allowed to settle, when the oil rises to the top and is pumped off.

The yield of crude shale oil in the Scottish industry is approximately 20 gal. per ton of retorted shale, together with 3·5 gal. naphtha and 30 lb. ammonium sulphate. This crude is similar in many of its properties to crude petroleum, and refining is in principle the same in both. By repeated distillation, fractions for use as Diesel oil, motor spirit, solvent naphtha and paraffin wax are obtained, as illustrated in Fig. 3. Until recent years, a much wider range of products, including lubricating oil, was worked for, giving a yield of about 75% of refined oils and wax on the crude shale oil treated.

The Scottish shale industry when working at peak capacity dealt with approximately 3¼ million tons of shale per annum, yielding about 45 million gallons of oil products; owing to economic difficulties, however, output has fallen considerably, and in 1947 the shale output was 1¼ million tons, yielding 96,000 tons crude shale oil from which 47,000 tons of Diesel fuel were

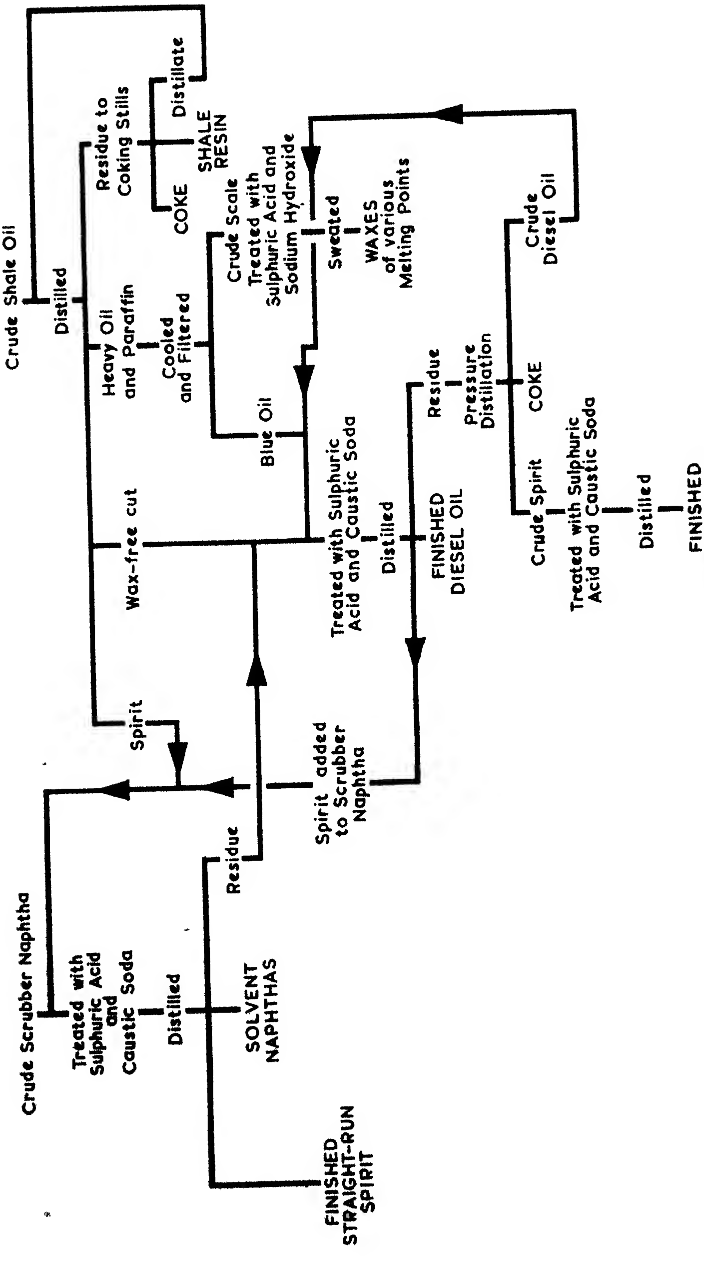


FIG. 3.—FLOW DIAGRAM OF CRUDE-SHALE-OIL REFINING.

produced; while this is a considerable output, it is extremely small compared with that of crude petroleum and, in general, the output of shale oil is not of great importance as a source of Diesel fuel and lubricating oil except locally in the producing country. Against ruling world prices of petroleum products, the cost of mining and distilling bituminous shales is not such as to make for the further exploitation of the world's bituminous shale resources; indeed, were it not for the output of sulphate of ammonia which is produced along with the crude oil, it is doubtful if the Scottish shale industry would be able to survive as an economic undertaking. This state of affairs would seem likely to persist so long as crude-petroleum production shows no sign of falling off, which is extremely unlikely in this generation, at least. At the same time the possibility is not excluded that in due course a radically new process of obtaining the oil from shale at lower cost may be evolved which will enable shale-oil products to compete with other liquid fuels.

12. *Hydrogenation of Coal, Coal Tar, Pitch or Petroleum Residuum.*—This is a comparatively modern source of Diesel fuels and lubricants, and its inception was due to the pioneer research work of the German chemist, Bergius. By this method, hydrocarbon oils are produced from carbonaceous substances of higher molecular weight, by heating them with hydrogen under high pressures, varying between 250 and 700 atmospheres, in the presence of suitable catalysts. When coal is used as raw material under these conditions, the first effect is to remove most of the combined oxygen, nitrogen and sulphur in gaseous form, leaving a residue of what is essentially a high-boiling-point hydrocarbon. Under the combined influence of heat and of hydrogen under pressure, this hydrocarbon cracks into substances of lower molecular weight, and these primary products of the cracking are saturated with hydrogen as they are formed, thus avoiding condensation to heavier products.

The process is flexible and by suitable modifications of the operating conditions varying proportions of different oil products can be produced at will. The first commercial plant was operated at Leuna in 1927, and subsequently a rapid expansion of hydrogenation plants was made throughout the Reich until a maximum annual production of 3,200,000 tons of oil products was eventually attained. These plants used as raw materials coal, coal tar, pitch or petroleum residues, the first-named being employed to the greatest extent, and produced Diesel oil, motor and aviation spirit, condensed gases and, in some cases, lubricating oil. In addition to the large tonnage of fuel and lubricating oils suitable for Diesel engines, the liquefied gases, i.e., ethane, propane and butane, can also be used as Diesel fuel with very little modification to the engine.

In brief, the process is as follows : pulverised, washed coal is made into a paste with approximately its own weight of heavy oil derived from the process or with tar or petroleum residues, and to this paste is added the powdered catalyst, usually some form of iron, and amounting to about 1% by weight of the charge. The paste is injected through a pre-heater into the convertor vessel, which is a forged, cylindrical shell of heat-resisting steel. Pre-heated hydrogen is also delivered to the convertor at the operating pressure of 250–700 atmospheres and mixed with the paste; the convertor is maintained at a temperature of about 450° C.

The products of this liquid-phase hydrogenation are : (*a*) a small proportion of liquid oil which contains the residual solids, and (*b*) a high proportion of oil vapour mixed with the excess hydrogen; the vapour is cooled and the condensed oil distilled by normal refining methods to yield crude petrol, middle and heavy oil. The middle oil and crude petrol is subsequently treated by vapour-phase hydrogenation to give a product of roughly three-fifths motor spirit and two-fifths Diesel fuel, or motor and aviation spirit and hydrocarbon gases. The yield per ton of raw material varies appreciably, but averages about 86% by weight of oil products.

In this country, a large amount of investigation work in the production of oils by hydrogenation of coal has been carried out by Imperial Chemical Industries, Ltd., and by 1938 they were producing approximately 50,000 tons of motor spirit per annum by this method. For reasons, probably economic, however, the company turned over to the hydrogenation of creosote for the production of motor and aviation spirit. So long as ample petroleum by-products are in sight it seems improbable that hydrogenation will be resorted to for the manufacture of fuel oils except those of the petrol type; the reason for this is that it is less economical to produce Diesel fuel than the higher-priced motor spirit. At the same time, in view of the rapid increase of world consumption of oils, particularly in the U.S.A., necessitating the importation of crude oil, researches on a semi-technical scale are proceeding vigorously in that country on the hydrogenation of coal.

13. *Fischer–Tropsch Synthesis Process.*—This process comprises the synthesis of liquid and solid hydrocarbons from mixtures of carbon monoxide and hydrogen. Although the first plant was not operating in Germany until 1936, the process was responsible during the war years for an annual output of more than half a million tons of oil products.

The raw material, generally coke, is treated with steam in a water-gas generator giving a gas containing hydrogen and carbon monoxide in ratio of approximately 5 : 4, a proportion of which, after removal of sulphur, is treated with a further quantity of steam at 500° C. over an iron catalyst. The resultant hydrogen-rich gas, blended with the remainder of the converted water gas, gives a gas suitable for synthesis; this is effected by the passage of the prepared gas over a catalyst of cobalt and thorium, dispersed in kieselguhr, at a temperature of 200° C., in a sheet-steel reaction vessel containing a large number of cooler tubes. Under these conditions the reaction which occurs can be represented as follows :

$$n(2H_2 + CO) \longrightarrow (CH_2)_n + n(H_2O)$$

The reaction is exothermic, and most of this heat has to be withdrawn by passing water through the cooler tubes, otherwise the catalyst becomes ineffective. The process can be worked either at normal or medium pressure. In the former process the hot gases leaving the reaction vessel are cooled in packed towers where the fraction boiling above 150° C. is condensed. The cooled gases and vapours then pass through an active charcoal absorption plant where the low-boiling-point liquid hydrocarbons and the bulk of the gaseous hydrocarbons are removed and subsequently recovered by steaming. These liquid products recovered by condensation and steaming are fractionally distilled, and the fractions washed with alkali solution to remove fatty acids.

The products are : (*a*) condensable gases, ethane and butane, which are marketed in the liquefied form, (*b*) low-grade petrol, (*c*) middle oil boiling at 165–230° C., with a cetane number of 78, used as a high-grade Diesel fuel oil component; generally, this high-grade oil is blended with an equal volume of coal-tar middle oil and provides a very good Diesel oil. Alternatively, the complete fraction boiling between 170° and 320° C. may be used alone as Diesel fuel. The process gives an average yield of 70% of the theoretical, and the annual rate of production in Germany, until bombing put many of the plants out of commission, was 135,000 tons of Diesel oil and 20,000 tons of lubricating oil, together with a larger yield of petrol, oils and waxes.

The wax produced by this process, and also that from lignite distillation, provides a source of synthetic lubricating oil. By cracking at about 470° C., followed by polymerisation by heating with aluminium chloride in order to convert the unsaturated hydrocarbons to saturated, and subsequent vacuum distillation of the product, a yield of finished lubricating oils of about 55% of the wax charged is obtained, plus 7% of Diesel fuel.

In the United States, two large plants for oil synthesis by a modification of the Fischer–Tropsch process are in course of construction. In these plants it is proposed to utilise natural gas, i.e., methane, for the manufacture of the synthesis gas by the controlled combustion of the methane with oxygen, under a pressure of 20 atmospheres. The annual output anticipated from one of these plants alone is approximately 230,000 tons of petrol, 50,000 tons of Diesel oil and 10,000 tons of mixed alcohols.

The technology of the Fischer–Tropsch process has been described in detail by Weil and Lane (29).

14. *Methane Gas.*—This gas occurs in large quantities in oil-bearing regions and in coal deposits and may also be produced synthetically. Another interesting source of supply which is capable of very substantial expansion is the biological treatment of sewage, termed the Activated Sludge Process, which is being adopted by an increasing number of authorities both in Great Britain and abroad. In brief the process is as follows:

After removal of the grit and solid matter from the sewage by screening and sedimentation, the liquid containing the dissolved and colloidal organic matter is passed to aeration tanks, where it is treated with the requisite volume of activated sludge; it is then passed along channels in which air under pressure is discharged from the bottom. Thence the liquid passes to the final separating tanks for recovery of the activated sludge, the clear effluent being discharged. The crude sludge from the sedimentation tanks is transferred to sludge-digestion tanks, which are furnished with gas holders, and during a digestion period of three to four weeks, 80% of the available gas is given off. The approximate composition of this gas is 70% methane, 29% carbon dioxide and 1% other gases, mainly hydrogen; hydrogen sulphide is present to the order of 0·03%. Sludge gas of this composition provides a very suitable fuel for Diesel engines, and in most cases is so used without further treatment. An example is the Mogden Works of the West Middlesex Drainage Board, where the daily production of such gas is 1,350,000 cu. ft., the bulk of which is used in Diesel engines driving centrifugal air blowers for the process described above and also Diesel-driven electric generators for providing power for ancillary plant. On the basis of the Mogden yield, Lawrie (3) estimates that if all the sewage works in England and Wales operated the digestion process, sufficient methane could be produced to generate 3,750,000 h.p. hours daily. This equivalent in terms of Diesel fuel would be roughly 500,000 tons per annum.

The frontispiece is taken from a photograph of the Mogden installation of ten Harland & Wolff four-stroke oil-gas engines, eight of which normally run on sludge gas.

CHAPTER III

THE FUEL-OIL SYSTEM

15. *Storage and Transfer.*—In a small installation using liquid fuel, the storage tank may consist simply of a drum in which the oil is received and from which it is pumped to an elevated " ready-use " tank by means of a semi-rotary hand-pump. In one such system, deliberately sabotaged by the insertion of sand into the ready-use tank, the fuel valves and fuel pumps were saved from ruin by an efficient type of cloth filter on the suction side of the fuel-pumps. It is wise to take precautions at all stages against the entry of dirt or dust into the fuel system.

In a large land installation, the storage tank usually takes the form of a cylindrical steel vessel capable of holding anything from a week's to some months' supply, depending on local facilities for supply by tank wagon. The storage tank may be arranged at some distance from the engine-room to reduce fire risk.

In marine installations, the storage reservoir generally takes the form of a deep rectangular tank or tanks, built into the ship's structure above the double bottom. Provision is made for sounding, ventilation, drainage and cleaning.

In large installations, liquid fuel is transferred from the storage tank to the elevated ready-use tanks by electrically driven pumps of the positive-displacement or centrifugal types, but unless the fuel has been specially filtered or purified before delivery, it is advisable to include arrangements for doing this (see Section 16) en route to the ready-use tanks. In stationary installations, one ready-use service tank holding enough fuel for, say, 8 hr. running, may be allotted to each engine. It is convenient to calibrate each tank with a level device as a check on fuel consumption. For marine installations, it is usual to provide two ready-use or settling tanks, one in use and one in reserve, each holding enough fuel for 12 hr. running of the whole installation.

16. *The Fuel-feed System.*—From the ready-use service tank the fuel passes to the engine filter by gravity, except in those installations in which head is not available, e.g., road vehicles and locomotives, etc. If the engine is provided with a fuel-booster pump, the head between tank and pump may be the bare minimum to give adequate flow at all loads. If there is no booster pump, it is advisable to arrange the ready-use tank at such a level that the pressure head at the suction side of the injection pumps is not less than about 8 lb./sq. in. after allowing for fluid resistance. The suctions of the fuel-pumps are, in general, intermittent, and if the pressure head is less than about 8 lb./sq. in., there is a possibility of negative pressures in the supply pipe, leading to the drawing in of air, or the evolution of dissolved air or vapour, and these may cause irregular operation of fuel-pumps, loss of power and possible stoppage. This point was strongly emphasised by Le Mesurier and Stansfield (4), who pointed out the importance of making the fuel-feed piping sufficiently large in diameter to reduce fluid resistance to a harmless amount in relation to the available head. The flow is usually streamline, and the drop of pressure p in a length l of pipe of diameter d with a flow Q is such that

$$p \propto \frac{\lambda Q l}{d^4}$$

in which λ is the viscosity. If $l = 100$ ft., $d = 1$ in., $Q = 100$ gal./hr., $\lambda = 1$ poise, then $p = 5{\cdot}5$ lb./sq. in. Any other case with other values for l, d, etc., can easily be worked out on the slide rule by the above formula; for example, if $l = 37$ ft., $d = 1\frac{1}{2}$ in., $Q = 73$ gal./hr., $\lambda = 2{\cdot}6$ poises, then

$$p = 5{\cdot}5 \times 2{\cdot}6 \times \frac{37}{100} \times \frac{73}{100} \times \left(\frac{1}{1{\cdot}5}\right)^4 = 0{\cdot}77 \text{ lb./sq. in.}$$

The fuel filter at the engine may be of the edge or fine-gauze type capable of stopping particles exceeding 2/1000 to 4/1000 in. in diameter. This would be suitable for engines running up to about 500 r.p.m. For small engines running faster than this, a filter of the fabric, felt or similar types would be preferred. The material should be such that there is no shedding of hairs or threads leading to clogging of nozzle holes or sticking of valves. Fabric filters can arrest all particles exceeding a very small size of the order of 1/20,000 in. The resistance is, in general, a fraction of a lb./sq. in. with low-viscosity fuels usual with high-speed engines, on account of the small flow involved.

If a recalcitrant fuel is used it may be necessary to provide an alternative ready-use tank or tanks for starting or stopping the engine on a normal fuel or for a change-over in case of emergency. For example, with certain crude fuels the filters may become choked with wax with little or no warning. With tar oil it may be necessary to run the engine on normal fuel oil for some time on load until the compression temperature has reached a value sufficiently high to cope with the higher ignition temperature of the tar oil.

Certain good-quality boiler oils of low viscosity can be used on large- or medium-sized engines with no other precautions than treatment in a centrifugal purifier and heating to about 120° F. on the way to the engine filter. One type of heater consists of a coiled tube for the fuel, immersed in a vessel of water heated to the desired temperature by circulation of the water through another coiled tube exposed to the flow of exhaust gas.

By utilising the more elaborate treatment described by Lamb (5), heavier types of furnace oil having viscosities up to 1400 Redwood No. 1 at 100° F. have been used in marine Diesel engines running at about 100 r.p.m. The oil is heated to 170° F. and passed through two centrifugal machines, one an ordinary purifier and the other, known as a clarifier, a similar machine arranged for the separation of finer particles. Whilst the whole process is simple in principle, the arrangements for dealing with the fuel are necessarily more elaborate and costly than those in use for normal fuel. It is estimated that the additional cost would be wiped out in about six to twelve months by saving in the cost of fuel.

17. *Airless-injection System.*—Whilst there is much variation in detail, practically all airless-injection systems involve individual or grouped fuel-pumps with cam-operated and spring-returned fuel-pump plungers closely lapped into their guides, and spring-loaded fuel-valves also lapped into their guide sleeves, and lifted by oil pressure. The successful operation of such gear requires the almost complete absence of dirt or grit from the working surfaces in order to avoid sticking or

scoring of plungers, sticking of delivery valves and fuel-valve spindles, and the choking of the fine holes through which fuel is injected into the combustion space. Hence the wisdom of taking precautions at all stages against the ingress of dirt or grit, and the necessity for adequate filters. Each fuel-valve is usually provided with a final filter to stop all particles capable of choking the injection holes.

The fluid mechanics of airless injection is a special study. The basic conception is that of dynamic pressure generated by impulsive velocity given to the fuel in the pipe between the pump and the injection valve. The fundamental quantities on which the action depends are :

(1) Engine revolutions per minute.
(2) Plunger diameter.
(3) Rate of cam rise (in. or mm. per degree of crankshaft rotation).
(4) Diameter and length of pipe between pump and valve.
(5) Area of fuel-valve holes.
(6) Lifting pressure of fuel valves.
(7) The point at which the plunger begins to deliver.

Item 7 is not always easy to measure, and it is convenient to substitute with " lift of plunger at top dead point ". This is the only item (apart possibly from 6) which the user can modify without replacing parts. Whilst item 5 determines the rate of entry of the fuel into the combustion space under given conditions of pressure, established by the motion of the pump plunger, the number, diameter, length and directions of the holes are vital for the correct distribution of fuel in the combustion chamber.

In cleaning and overhauling fuel-valves the user will be guided by the maker's instruction book. The work is best carried out in a small room free of dust and dirt, with a zinc- or lead-lined bench and sink. The parts are cleaned with a brush and paraffin or gas oil; waste or rags should not be used.

18. *Air-blast Injection.*—Few air-blast engines are now built, but many remain in service. The fuel-pumps and valves are careful pieces of work, but not of the same degree of precision as airless-injection equipment. The fuel-pumps are merely required to meter correct quantities of fuel against a blast

pressure of 600–1000 lb./sq. in., delivering to the fuel-valves during the idle periods. The fuel-valves are lifted mechanically by cam-operated levers, and a mixture of blast air and fuel enters the cylinder in a highly mixed and turbulent state. The holes through which the air and fuel enter the cylinder are comparatively coarse, so that special precautions against dirt or grit are not so essential; nevertheless, a small piece of grit may be enough to " cut out " a cylinder by hanging up a fuel-pump suction or delivery valve.

Fuels of widely varying viscosities can be dealt with on the air-blast system without difficulty. Heating of very viscous fuels may be necessary. The use of very thin fuels may necessitate adjustments if the engine has been tuned to a different fuel; several adjustments can be made :

(1) Advancing or retarding the fuel-valve cam.
(2) Increasing or decreasing the fuel-valve lift.
(3) Increasing or decreasing the number of pulverising rings.
(4) Increasing or decreasing the number and size of holes in the pulveriser rings.
(5) Increasing or decreasing the number and size of holes in the pulveriser cone.
(6) Modifying the flame-plate hole or holes in diameter or length.

In experienced hands this wide range of adjustment gives great flexibility for dealing with variations of fuel quality.

19. *Combustion.*—The high turbulence obtained with air-blast injection is a great help in obtaining complete combustion; in this respect it has something in common with airless-injection systems of the pre-combustion-chamber type, and those making use of high rotary swirl, as, for example, in two-cycle engines of the uniflow type with two fuel-valves injecting tangentially from the periphery. With all three types it is comparatively easy to obtain a clear exhaust, but this does not always mean good combustion in the best sense; it may be accompanied by too much burning late in the stroke and the deposition of oxidation products on the walls. It is therefore necessary to take account of other symptoms, viz., fuel-consumption rate, exhaust temperature, shape of draw cards, thickness of toe of

normal indicator diagrams, appearance of the piston top, comparing good examples with bad, and so on. A slight advance of the ignition of some cylinders may be enough to effect a marked improvement in performance by eliminating recurrent troubles due to ring sticking.

The power which a given cylinder can develop, with satisfactory behaviour in service with a given compression pressure and maximum pressure, depends primarily on :

(1) The volumetric efficiency.*
(2) The percentage of the combustion-chamber volume which is accessible to the fuel sprays (live air ratio).
(3) The evenness of the distribution of the fuel over the accessible region.
(4) The motion of the air in the chamber during the injection period.

(Note : in connection with 2 the inaccessible volume is known as " dead air " or " parasitic volume ".)

The above items are urgent questions for design and test development; they concern the user to the extent of doing his utmost to maintain the engine in service as far as possible in the condition in which it gave its best performance on the test bed. For example, the regular cleaning of air filters, air and exhaust ports and passages, the maintenance of valve tightness and timings, all influence volumetric efficiency. Similarly, the cleaning and adjusting of fuel-valves influence the subsequent distribution of fuel in the combustion space.

If the service fuel differs materially from that for which the engine was tuned, adjustments may be necessary. Viscous fuel may require pre-heating; some form of fuel-valve cooling by fuel or water may be beneficial in preventing the formation of carbon cones on the nozzles; alternatively, a blast chamber surrounding the fuel-valve end, and designed to blow carbon formations off the nozzles, may be more effective in this respect. In many cases of high-speed, heavily loaded, high-duty engines in which the flux of heat to the fuel-valve end is exceptionally high, the best type of fuel-valve may be one in which the

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* The volumetric efficiency depends on the density of the charge at the beginning of compression and the thoroughness with which the exhaust gases have been expelled. These in turn are influenced by the air-supply ratio.

spindle guide is located farther than usual from the combustion face. In other instances of a change of fuel, benefit may be obtained by altering the combination of size and number of fuel-valve holes.

20. *Ignition Delay.*—The ignition of a fuel spray on entering the combustion space is conditional on the compression temperature being above the " ignition temperature " of the fuel. Even so, the ignition is not immediate. The delay can be measured by suitable indicator diagrams showing the opening of the fuel-valve and the subsequent rise of pressure due to combustion. If the delay is too much, a large fraction of the fuel may be injected before burning begins, and then combustion, when it occurs, is liable to proceed with an accelerated intensity resulting in a very rapid rise of pressure and the symptom known as " Diesel-knock ". The delay may be anything from about ½ to 10 millisec. (1/1000 sec.). The delay is diminished by temperature as might be expected from the general speeding up of chemical reactions at the rate of about 100% for every 10° C. rise. It is also diminished by increase of compression pressure, a circumstance which is very favourable to supercharging. The effect is attributed to the increase of concentration of oxygen. The delay is also influenced by other factors, such as turbulence, which are not so amenable to direct measurement. Moderate turbulence seems to reduce delay.

At 100 r.p.m. a delay of 1 microsec. corresponds to 0·6 crankshaft degrees, and is not important; at 2000 r.p.m., the same delay corresponds to 12 degrees, which is very appreciable. In certain circumstances, the effect of increased turbulence at increased revolutions may be such that the delay may be constant in terms of crankshaft degrees over a wide range. A delay of the above order is about that experienced with Diesel bus engines operating on the high-grade fuel in common use for such engines.

" Ignition quality " is the term used to cover the combination of properties which determine the behaviour of an engine in respect of smooth or rough running as influenced by combustion delay and rate of pressure rise. It is clearly a concept having most relevance to high-speed engines. In fact, the " cetane number ", which is the accepted measure of ignition quality, is determined and defined with reference to the performance of a small high-speed engine developed for the purpose. The cetane number, since it is clearly related to the properties of the constituent molecules, can be approximately ascertained in other ways (see Sections 81 and 82).

One of the problems before designers is to increase the range of cetane numbers of fuels which can satisfactorily be used in high-speed engines. Meanwhile, users have to accept the position that the cetane numbers of suitable fuels are related to revolutions approximately in accordance with the following table.

Range of r.p.m.	Cetane Number.
0– 100	15–30
100– 200	15–40
200– 400	30–45
400– 800	35–50
800–1500	45–55
1500–3000	50–60

In a recent address, Ricardo (28) has given particulars of tests which he has carried out on an engine running at 1500–2000 r.p.m. With a pressure boost of half an atmosphere, the engine ran smoothly on a fuel having a cetane number as low as 18.

The use of fuels of high cetane number in Diesel engines running at about 100 r.p.m. has sometimes resulted in stuck and carbonised fuel-valves and subsequent poor combustion and high exhaust temperature. The low lubricating value of such thin fuels has been adduced as a possible explanation of sluggish fuel-valve operation. It seems not improbable that the low delay may be a disadvantage in such slow-running engines by promoting too intense combustion in the proximity of the fuel-valve.

21. *Carbonisation.*—Sticking of piston-rings and choking of ports is usually caused by oxidation of lubricating oil, but it can be accentuated by the use of fuel which the engine is not able to consume effectively. It may not always be easy to determine whether augmented carbonisation or sludging is primarily due to oxidation products from the fuel or due to increased oxidation of lubricating oil brought about by an increase of piston temperature caused by late burning of fuel.

One special type of carbonisation, viz., the formation of crusts or cones on the end of the fuel-valve, is due to fuel only. This trouble can be caused by fuel dribble with any fuel, but tends to be specially acute with crude fuels containing a large fraction of light constituents, e.g., petrols. It is significant that petrols have higher ignition temperatures than the heavier fractions. There may be other causes connected with the distillation range (see Section 41). The formation of cones is combated by fuel- or water-cooling of the fuel valves or by means of blast chambers.

A grey exhaust at full or part loads is no necessary indication of the formation of deleterious oxidation products, neither is it incompatible with a high degree of economy. Conversely, a clear exhaust is no certain indication that such products are not being formed in the combustion chamber by the cracking of the fuel in the early stages of combustion.

22. *Fuel Consumption.*—The gross calorific value (see Section 39) of petroleum Diesel fuel averages about 19,300 B.Th.U./lb. The difference between the gross and nett values varies from 1100 to 1250, averaging 1200. The average nett value is therefore about 18,100 B.Th.U./lb. With such fuel the full-load consumption of practically all existing Diesel engines lies between the limits 0·35 and 0·45 lb./b.h.p. hr. The vast majority lie between the narrower limits 0·38 and 0·42, depending on size, type and revolutions.

When tested on fuels of different calorific value but not unsuitable for the revolutions, an engine will frequently yield consumptions which vary, if at all, by less than the percentage differences in calorific value. The effect is perhaps due to differences in viscosity; increased viscosity tends to advance the ignition by reducing fuel-pump leakage, and the fuels of lower calorific value are not infrequently those of higher viscosity. Other things being equal, the fuel consumption tends to be in inverse ratio to the calorific value, but much depends on ignition quality, and in extreme cases the result may go either way.

For a given engine, a curve of fuel used per hour, plotted against b.h.p. shows by its upward curvature at high loads the relatively inefficient utilisation of the fuel burnt during the later stages of combustion. A graph strictly proportional to the above, and useful for comparing the performances of different engines, is obtained by plotting the product of fuel consumption per b.h.p. hr. × brake mean pressure, against brake mean pressure as a base. It is easily shown that the above product is proportional to the fuel consumed per unit of swept volume. For example, with a brake mean pressure of 75 lb./in.^{2} and a consumption of 0·38 lb./b.h.p. hr., the product is 28·5. For a supercharged engine developing a brake mean pressure of 120 lb./in.^{2} with the same fuel consumption per b.h.p. hr. the product is 45·0, and so on.

With a given compression ratio, the fuel consumption decreases with increase of maximum pressure, and this is the main reason for the low fuel consumptions given by many small high-speed engines in spite of relatively high figures for lost mean pressure due to mechanical friction and pumping losses as compared with slower speed engines. Nevertheless, it seldom pays to allow the maximum pressure to exceed about 1·6 times the compression pressure.

With a fixed maximum pressure, the efficiency theoretically increases with increase of compression pressure. In practice the gain obtainable in this way is limited by the adverse effect of dead air or parasitic volume, which nullifies an increasing percentage of the combustion volume as the compression ratio is increased. The optimum compression ratio lies in general between 13 and 18, the latter figure being only admissible when the parasitic volume is a very small percentage of the stroke volume.

The progress of combustion can be roughly divided into three stages of diminishing efficiency.

(1) Combustion at constant volume.
(2) Combustion at constant pressure.
(3) Combustion at constant temperature.

Beyond a rather moderate mean pressure, increase of load is mainly obtained by extension of stage (3).

23. *Exhaust Analysis.*—The analysis of a typical liquid fuel for Diesel engines is represented approximately by $C = 87\%$, $H_2 = 13\%$, that of air being $N_2 = 77\%$, $O_2 = 23\%$. Assuming that all the carbon is burnt to CO_2 and all the hydrogen to H_2O, it can readily be shown that the percentage by volume of CO_2 in the resulting exhaust gas is related to the percentage

of air "burnt", i.e., denuded of oxygen, by the following table:

Percentage of air burnt .	100	90	80	70	60	50	40	30	20	10	0
Percentage of CO_2 .	15·4	13·8	12·2	10·6	9·0	7·4	5·9	4·4	2·9	1·5	0

Then, assuming complete combustion, the air-supply ratio of the engine is given by the relation,

$$\text{Air-Supply Ratio}^{*} = \frac{\underset{(\text{lb./sq. in.})}{\text{Brake Mean Pressure}} \times \underset{(\text{lb./b.h.p. hr.})}{\text{Fuel Consumption}}}{0{\cdot}72 \times \%\ \text{of air ``burnt''}}$$

The determination of the CO_2 percentage by the Orsat or similar apparatus requires certain precautions as under:

(1) Samples should be collected at or after a silencer or other mixing chamber, since inequalities of composition persist in the exhaust manifold and outlet pipe.
(2) Leakage of air into, or exhaust out of, the exhaust system must be prevented.
(3) Any leakage at the instrument must be avoided.
(4) Reasonably fresh reagents should be used, otherwise the processes of absorption are liable to be slow, and premature readings may result.
(5) Several readings should be taken at each load, and "wild" readings rejected; repeated samples to be taken until four or five concordant readings are obtained; it is worth while spending time on repeated readings, since alternative methods of finding volumetric efficiency are, in general, very costly.

24. *Gaseous Fuel Systems.*—Earlier experimenters with the gas engine found that pre-ignition and rough or bumpy running occurred if the compression ratio exceeded about 7 or 8. It has since been found that if the compression ratio is carried up to,

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* Air-supply ratio = Volume of air supplied per cylinder per cycle (referred to ambient conditions of temperature and pressure) – swept volume of cylinder.

say, 13, the engine being strong enough for this to be done with safety, regular quiet running with spark ignition can be obtained up to a considerable fraction of full load. For example, town gas can be used in a 20-in. bore Diesel engine with spark ignition, up to a brake mean pressure of about 60 lb./sq. in. before bumping begins. In smaller cylinders the mean pressure may be carried much higher. If ignition is effected in the 20-in. cylinder by a pilot spray of liquid fuel, bumping is inhibited and a brake mean pressure of about 80 lb./in.^{2} can be carried without undue rate of pressure rise or excessive maximum pressure. Such engines are now built as "dual-fuel" engines which can be turned over from full oil operation to gas operation with 5–15% of the calorific value of the charge provided by the pilot injection of liquid fuel, without stopping the engine or varying the load. A number of the Harland & Wolff engines shown on the frontispiece are dual-fuel engines of 650 b.h.p. each with Diesel compression.

The above notes refer to four-stroke engines; two-stroke Diesel engines can be arranged for operation on gaseous fuel by injecting gas under pressure during the compression stroke or just before the top dead centre.

The following table gives properties of typical gases which have been used as fuel on engines with Diesel compression :

Gas.	CO.	H_2.	CH_4.	C_nH_m.	O_2.	CO_2.	N_2.	Density lb. per cu. ft.*	Net Calorific Value, B.Th.U. per cu. ft.*	Ratio $\frac{\text{vols. air}}{\text{vols. gas}}$ †	Cal. Value of Mixture, B.Th.U. per cu. ft.*
Methane	—	—	100	—	—	—	—	0·0425	910	9·5	87
Natural gas	0·4	1·5	98·1	—	—	—	—	0·042	897	9·4	87
Sludge gas .	—	—	67·0	—	—	32·0	1·0	0·067	610	6·4	82
Coal gas .	18·0	49·4	20·0	2·0	0·4	4·0	6·2	0·036	426	4·05	84
Producer gas	19·8	18·7	1·3	—	1·2	9·6	49·4	0·074	127	1·04	63

* At 60° F. and at pressure.
† For complete combustion.

Fuel gases of all these types (except sludge gas) are found with rather wide variations of composition. In particular, natural gas may contain appreciable percentages of ethane, propane, etc., as shown in the table on p. 41.

Constituent.	% by vol. "Wet" Gas.	% by vol. "Dry" Gas.
Methane	86·5	90·6
Ethane	4·6	4·6
Propane	4·4	3·8
I-Butane	1·9	0·5
N-Butane	1·1	0·3
Pentanes	1 5	0·2
Gasoline content, Imp. gals./1000 ft.^{3} at 60° F. and 30 min. Hg	0·6	—

For operation in Diesel engines the "dry" gas is preferred, but "wet" gas has been used successfully. The gas is passed to large containers in which any gasoline in liquid form settles out and is drained away.

At full load the efficiencies of such engines are about the same as with oil fuel, but at low loads the efficiency may be considerably less than with oil, since throttling of the air is generally necessary for steady running, and this reduces the mechanical efficiency, and furthermore, a certain amount of fuel seems to escape unburnt at light loads.

The lowest spontaneous-ignition temperatures of various gases are approximately as under:

	° C.
Hydrogen	530
Carbon Monoxide	610
Methane	645
Ethane	530
Propane	510
Butane	490
Ethylene	540
Propylene	455
Butene	445
Acetylene	335
Town gas	510

CHAPTER IV

THE LUBRICATING-OIL SYSTEM

25. *Forced Lubrication.*—The earliest commercial Diesel engines were of the four-stroke trunk type having cylinders from about 8 in. to 22 in. in diameter and running at piston speeds from 600 to 900 ft./min. They were provided with long ring-lubricated main bearings and wide big-ends lubricated with drip-fed " banjo " fittings. The cylinders were lubricated as now with pressure-fed quills, and the top-ends often received oil from the surface of the cylinder liner. These arrangements worked well on the whole without excessive wear of bearings. They survive today in many designs of single- and twin-cylinder horizontal engines.

As speeds were raised and the number of cylinders per engine increased, forced lubrication became practically universal for vertical engines. The system consists essentially of an engine-driven or separately driven lubricating-oil pump, drawing from a crankcase sump or drain tank, and delivering to a bus-main of generous diameter, with branches of smaller diameter to the main and subsidiary bearings. The big-ends generally receive their supply through holes drilled in the crankshaft, and the top-ends by way of a drilled connecting-rod or by splash. The suction of the lubricating-oil pump is protected by a strum box or gauze, and it is advantageous if the sump or drain tank is so arranged that there is a chance of sludge settling out of circulation. A generous volume of drain tank is indicated. A strainer or filter (or both) are interposed between the pump discharge and the bus-main, together with an oil cooler (except in small sizes). Apart from piston cooling, to be discussed later, the oil circulation has two functions to perform :

(1) To supply each bearing with enough oil for the maintenance of a full hydrodynamic film.

(2) To carry away the heat generated at the main journals, big-ends and top-ends.

The quantity of oil supplied is much in excess of what is required for lubrication; the successful operation of the early ring-lubricated and drip-fed bearings is ample proof of this. The amount of heat generated in the engine bearings does not usually exceed about 2 or 3% of the total heat content of the fuel used, but some margin is necessary, and the oil cooler (with no piston cooling) will usually be proportioned to deal with 3–5% of the total heat, since the oil flow can pick up heat in other ways, such as by conduction from the cylinder liners and piston-skirts. The oil temperature will usually average about 120° F. when plenty of cooling water is available at a temperature not exceeding 90° F. In less favourable circumstances it may not be feasible to keep the oil temperature below 140° F. or even higher. If the viscosity of the oil under working conditions is too low, the film separating the journal and the bearing will be too thin, and the bearing may suffer undue wear or wiping. The use of a thicker oil to maintain the desired viscosity at a high temperature involves a disadvantage, viz., that thick oils have, in general, high "carbon"-forming propensities which are to be avoided. It follows that the practical range of viscosities of oils suitable for Diesel-engine lubrication is fairly narrow, viz., from about 150 to 250 Redwood No. 1 at the standard temperature of 140° F. as under:

Small engines of bus engine size . . .	150–175
Medium-sized industrial and ship auxiliary engines	175–200
Large marine and industrial engines . . .	175–250

26. *Piston Cooling.*—Most four-stroke engines above 15 in. in diameter and two-cycle above 10 in. in diameter require fluid cooling of pistons. In some engines water is used for piston cooling, but oil-cooling is more prevalent. Even small pistons if subject to high duty may benefit by oil-cooling. This may take the form of a feed or squirt from the top-end bearing, but in medium- and large-sized engines a full-flow system is used. Piston cooling puts a further demand on the quality of the lubricating oil if carbonisation of the piston-cooling space is to be avoided. Fortunately, the range of viscosity which gives good results for lubrication is suitable also for piston cooling, so that separate circuits are not required. Low figures

for carbonisation tests, such as the Conradson and the Ramsbottom, and also baking and oxidation tests are indicated.

The permissible piston-cooling oil-outlet temperature ranges up to about 150° F. when ample water at a temperature not exceeding 90° F. is available. In special circumstances where water cannot be used for oil cooling, or the water temperature is unavoidably above 90° F., a higher piston-outlet temperature up to, say, 160° F. may be tolerated.

27. *Cylinder Lubrication.*—In small engines the cylinders are lubricated by splash or mist from the crankcase. It is therefore important that the oil in circulation should be of a quality that will not lead to trouble with resinous deposits on the piston-skirts or unduly rapid sticking of the piston-rings.

The cylinders of medium and large marine and industrial engines are lubricated by means of the traditional quill fittings, fed by sight-feed lubricators of specialist make. In general, the timing of cylinder lubricators for trunk engines is random, but with large double-acting two-cycle engines, correct timing of the cylinder lubricators in accordance with the builders' recommendations may be an important factor in securing proper distribution of an adequate oil supply, without an undue excess which might give trouble by carbonisation of ports and passages. In the interest of economy and to reduce the possibility of excessive cylinder wear, timing of the cylinder lubricators is advisable in all types of cross-head engines whether single- or double-acting, of two-cycle or four-stroke types.

Earlier practice favoured high-viscosity oils for cylinder lubrication—up to 300–400 Redwood No. 1 at 140° F. Such thick oils are useful for the early life of the engine up to, say, 1000–2000 hr., but for normal service an oil with a viscosity of about 250 Redwood No. 1 at 140° F. seems to be satisfactory and beneficial in minimising deposits.

For medium-size industrial and marine engines, the cylinder lubricant is generally the same as the crankcase oil. Engines of high duty may benefit by a special cylinder oil, and the use for this purpose of oils having special additives in aid of detergency and anti-oxidation properties, is a field for further research.

28. *Cooling of Lubricating Oil.*—If oil is used for piston cooling, a heat exchanger is required capable of transferring

about 7–15% of the total heat content of the fuel; 10% is a fair average. The temperature drop will usually be 10–20° F. depending on the rate of circulation. The temperature drop is little affected by the effectiveness of the cooler, this being inversely proportional to the difference between the mean temperature of oil and water. For purposes of calculation it is near enough in most cases to assume a specific heat of 0·5 for the oil.

Large oil coolers are usually of the condenser type with water flowing through the tubes and oil outside. In time the effectiveness of the cooler becomes seriously reduced by viscous sludge, and cleaning is carried out by means of detergent fluid. If the tube stack is removable it may be immersed in a bath of trichlorethylene, and cleaning is facilitated by scraping between the tubes. If the stack is not removable, cleaning is carried out by continuous pressure spraying with detergent fluid which is pumped out of the bottom of the cooler as fast as it falls. In difficult cases it may be necessary to resort to boiling with alkaline fluid such as sodium metasilicate or caustic soda. These processes point again to the advantages of oils having low tendency to the formation of carbonaceous sludges, particularly those of an adherent kind.

In some situations, e.g., on Diesel locomotives, cold water is not available for cooling oil, and radiators of the gilled-tube or similar type have to be used. The easy removal of elements and accessibility for cleaning are points of importance.

29. *Filtration and Cleaning.*—All Diesel engines are provided with some form of strainer on the suction and discharge sides of the lubricating-oil pump. In engines up to a few hundred b.h.p. the discharge strainer may well take the form of a filter of the fabric or other type capable of arresting all particles exceeding about 0·0002 in. in diameter. If such filters are arranged in duplicate with a change-over valve, there is less chance of the relief valve, usually provided, coming into action and allowing unfiltered oil to reach the engine bearings. For large engines such filters arranged for full flow are hardly practicable, and strainers are used, permitting the passage of particles up to about five to eight thousandths of an inch. They may be of the plate-edge or similar type or built with elements of gauze mesh which has the advantage of arresting

hairs or threads which would pass through filters of the edge type. Batteries of filters of the fabric type, capable of dealing with the full oil flow of comparatively large engines, can be used to advantage on the test bed for the trapping of unavoidable dust and grit. Magnetic filters can perform a useful function by removing ferrous particles from circulation.

The removal of detritus and other solid matter from the oil-circulation system is accomplished by one of two methods :

(1) Continuous purification.
(2) Batch purification.

On the continuous system a special pump draws a small flow of oil continuously from the engine sump or drain tank, and passes it either to a centrifugal purifier or through a filter capable of removing all solids; it is returned thence to the engine sump.

On the batch system the whole of the oil in the system is removed for treatment and replaced with new oil, until the renovated oil is ready to resume duty. With a large installation either system will include an elevated tank into which the dirty oil is pumped and from which it gravitates to the purifiers or filters; also another tank into which the clean oil is pumped and stored ready for return to one of the engine sumps.

With either system the rate of wear of, say, 12-in. crank-pins of trunk engines with crankcase exposed to cylinder detritus may amount to less than ½/1000 in. per year of 5000 hr. running time, and ovality less than half this amount. The wear of main journals is commonly less than half that of the crank-pins.

Filters are of many types, and if reliance is placed on oil " additives ", care must be taken that the filters used are not of a sort which remove the additives from circulation.

30. *Lubricating-oil Consumption* may be expressed in various ways such as pints/hr., gal./24 hr., etc. For comparative purposes useful modes are :

(1) Grams per rated b.h.p. hr. (1 gal. = 4000 gm.).
(2) Rated b.h.p. hr. per gal.
(3) Percentage of fuel used.
(4) Percentage of full load fuel.

Large marine engines use about ¼ gm. of oil for cylinder lubrication per b.h.p. hr.; the total consumption for all purposes is usually between ⅓ and ¾ gm. per b.h.p. hr.

Industrial trunk engines are expected to operate with oil consumptions of about 1–2 gm. per b.h.p. hr., but the last figure is often doubled as the time approaches for piston overhaul. The consumption may return to normal after the replacement of one or more worn piston rings and/or the clearing of choked vent holes, at or below the scraper rings.

Excessive lubricating-oil consumption is always a matter of concern, apart from cost, since it is a symptom that the engine is in need of adjustment, perhaps at one of the most vital points, viz., the pressure rings, and also because the excess oil may easily make matters worse by clogging piston-rings and ports, thereby promoting blow-by of hot gases, clogging of ports, raising the exhaust temperature and ultimately setting up a vicious circle leading to breakdown or loss of potential power.

The estimation of lubricating-oil consumptions over short periods such as 24 hr. requires much care to ensure that conditions are the same as far as possible at the beginning and end of the period. Corrections may be necessary for differences of density due to differences of temperature. Checks should be put on the possibility of water accumulating at the bottom of the drain tank or the oil gaining volume by access of fuel.

31. *Dilution with Fuel.*—Fuel may gain access to the crankcase by direct leakage from the fuel-pumps, but the design of the engine should make this a remote possibility. With direct injection of fuel into the body of the combustion chamber, a small amount of fuel reaches the cylinder wall, particularly at light load, and percolates past the piston to the crankcase. This source of dilution will be aggravated by any maladjustment of fuel valves tending towards over-penetration. Dilution is not usually serious, being kept within limits by topping up with fresh lubricating oil. A dilution of up to 8% is tolerated; 10% would call for treatment. Much more than this has been experienced without serious consequences. The extent of dilution is estimated by:

(1) Observing the drop in viscosity.

(2) Observing the drop in flash point.

The second method is mainly qualitative; very little dilution reduces the flash point very materially. The drop in viscosity may be masked by thickening due to sludging and polymerisation if these are considerable. Usually, a rough but sufficient approximation to the extent of dilution can be obtained by making a viscosity determination at 140° F. and using Fig. 4 provided the original viscosity is known (see also Fig. 5).

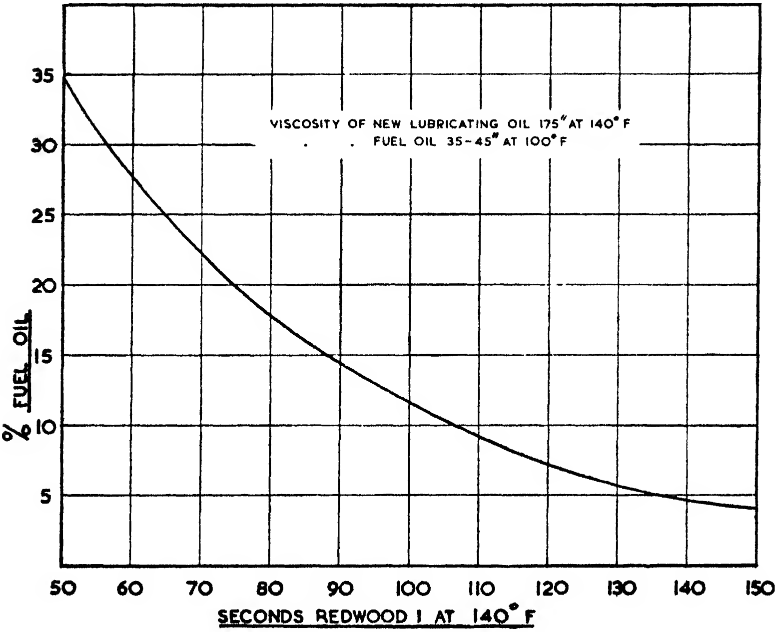

FIG. 4.—RELATION BETWEEN FUEL-OIL CONTENT AND VISCOSITY OF LUBRICATING OIL.

Fuel oil cannot be removed from lubricating oil by centrifugal machines or filters. Separation can only be effected by a distillation process in a refining plant. The desirability of having the oil examined periodically for fuel will therefore be obvious.

32. *Contamination with Water.*—Water also may accumulate in the circulating-oil system, and by reason of the presence of colloidal carbonaceous matter and other finely divided impurities, give rise to emulsification. However, by making use of settling tanks, drawing off the water and sludge which

separate out, and subsequently passing the oil through a centrifugal separator, the circulating oil can be maintained free from water and solid impurities, other than colloidal matter. Land installations lend themselves to more elaborate methods of purification, involving the use of chemicals such as trisodium phosphate or sodium silicate to assist coalescence of the impurities before filtering.

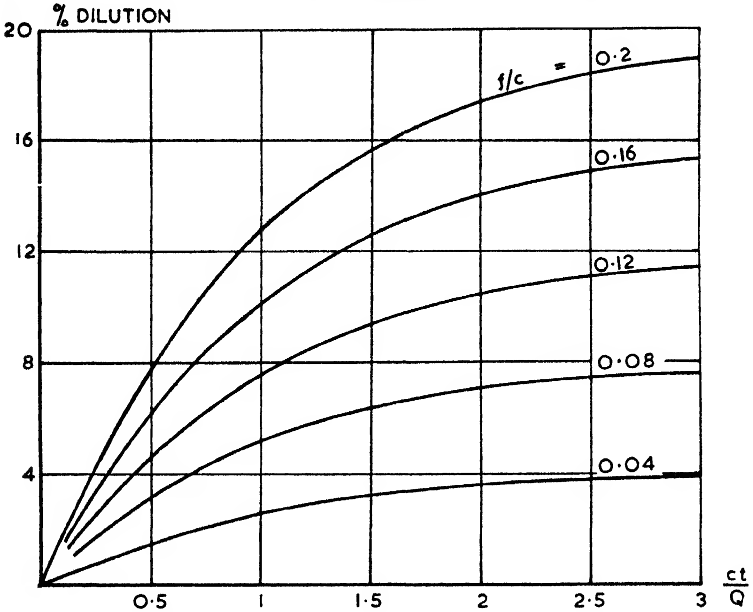

FIG. 5.—CRANKCASE LUBRICATING OIL: DILUTION WITH FUEL OIL.

Let, Q_l = Volume of lubricating oil in sump, gallons.
Q_f = Volume of fuel oil in sump gallons.
$Q = Q_l + Q_f$.
f = Rate of access of fuel to sump, gallons/hr.
l = Rate of addition of lubricating oil to maintain level, gallons/hr.
$c = f + l$ = Rate of consumption of sump contents.
t = Time in hours since putting clean oil in sump.

$$\frac{dQ_f}{dt} = f - c\left(\frac{Q_f}{Q}\right)$$

$$100\frac{Q_f}{Q} = \frac{100f}{c}\left(1 - e^{\frac{-ct}{Q}}\right) = \text{percentage dilution.}$$

33. *Carbonisation.*—This term is loosely applied to the formation of black oxidation products mixed with soot or

colloidal carbon. These products when dry may take the forms of

(1) Fluffy or powdery deposits.
(2) Deposits of rubbery consistency.
(3) Hard, shiny, enamel-like layers.

These oxidation products are brought about primarily by high temperature, but the rate of their production may be accelerated by crankcase turbulence forming a mist of oil having a very large surface in relation to volume; also by the presence of finely divided particles of cylinder and bearing detritus, which may promote oxidation by catalytic action. One of the objects of " doping " lubricating oils with " additives " is to reduce the rate of oxidation by means of " anti-oxidation " inhibitors. Up to a point the formation of black oxidation products in the body of the oil does little if any harm. The viscosity of the oil is somewhat increased, but this may perhaps be beneficial. Much of the oxidation products may be deposited as thick adhesive sludge in the base of the crankcase or drain tank, whence it is removed during the periodical overhauls.

If, however, sludge formation is too copious and of an adherent type, it may become a menace by clogging oil-ways in bearings and crankshaft drillings, thus bringing about excessive wear or complete failure of bearings by oil starvation.

With uncooled cast-iron pistons, the underside of the crown is shielded from oil mist or splash by means of an oil-tight diaphragm, to prevent excessive carbonisation at this hottest spot inside the crankcase. If the pistons are of aluminium alloy the surface temperature of the underside of the crown may, in the case of small pistons, be sufficiently low to make this precaution unnecessary. Oil-cooled pistons, whether of aluminium or cast iron, seem to have little effect in promoting the formation of oxidation products in the body of the oil, but detrimental deposits may be formed in the piston-cooling space if the piston temperature is excessive or if the oil is of unsuitable quality. Excessive deposit may lead to further overheating of the piston followed by burning or cracking.

One would expect the carbon-forming propensities of the oil to be related to the values obtained with the Conradson, Ramsbottom, baking or oxidation tests, and up to a point this is found to be so; the tests are useful in eliminating oils likely or certain to be unsatisfactory in service. They are not, however, completely and finally discriminating; the ultimate test is that of experience under operating conditions.

34. *Ring Sticking.*—The sticking of piston-rings in their grooves by the adhesive action of oxidation products is a special instance of the general phenomenon of "carbonisation", and merits separate discussion by reason of the serious results which may follow in extreme cases. A piston-ring partially stuck in its groove is ineffective as a gas seal, it tends to scuff itself and the cylinder liner, thus producing detritus for further wear and deterioration of the remaining rings, as well as their grooves and the cylinder liner. When fully stuck all round, a piston-ring is perhaps harmless, except in so far as it has abandoned its proper function as a gas seal; it has at least ceased to cause cylinder wear. Meanwhile the onus of duty has been passed on to the remaining rings, and if they behave in the same way it is only a matter of time before "blow-past" develops, oil is burnt off the lower rings, scuffing develops apace, and finally the rubbing surfaces of the piston are dried by the passage of hot gas and the piston seizes.

To avoid this sequence, it is necessary so to space the regular intervals for removal of pistons for cleaning, that the trouble never gets a hold. The length of time between piston overhauls depends on

(1) Type, design and rating of the engine.
(2) The revolutions per minute.
(3) The properties of the lubricant in use.
(4) The load factor of the engine.

As a very rough rule the time between piston overhauls may be estimated by dividing 1 million hr. by the r.p.m. and the load factor of the engine expressed as a fraction of the 12-hr. rating of the engine. The pistons of large marine engines may run for two years between overhauls. Ships' auxiliaries are generally overhauled once a year. Industrial engines running 6000 hr. a year may require their pistons to be cleaned twice a year if the fuel is crude or otherwise not of the best. Locomotive engines running at about 1000 r.p.m. may run 5000 hr. between piston overhauls, if engaged on shunting work with a load factor of 10–15%. The same engine on passenger service might require to have the pistons removed every 1500 hr. In many cases the piston overhaul will be required for the cleaning of vent holes in the interest of lubricating-oil consumption, and the piston-rings will be cleaned at the same time.

The sticking of rings is promoted by anything which raises the temperature of the piston crown; after-burning due to late injection may be a potent cause; nevertheless, it is perhaps fair to say that in most cases of ring sticking, it is the lubricant and not the fuel which provides the bulk of the adhesive medium.

The high-duty high-speed engine for traction on road and rail, also for submarine or other severe naval services, has provided the incentive for the production and widespread use of "high duty" (H.D.) oils. Oils of naphthenic origin are naturally detergent in comparison with those of paraffinic base; this means that they have to some extent the useful property of washing away their own oxidation products. The expression "H.D." is commonly used to denote oils which by the inclusion of special additives have been rendered more detergent than they would otherwise be. These additives act by keeping in circulation oxidation products which would otherwise be deposited about the engine; by washing away deposits which would otherwise cake between the piston-rings and their grooves. The use of such lubricating oils may increase the period between necessary piston overhauls by 100% or more with certain types of engine in which it is difficult to prevent the metal around the piston-ring grooves from approaching the critical temperature (200–250° C.) at which "carbonisation" proceeds rather rapidly. The use of such doped oils demands certain precautions. Some types of effective filters remove the additive on which the H.D. property depends. Some additives attack anti-friction metal containing cadmium. High-detergent oils should not be added to the sumps of engines running on normal oils, since the accumulated deposits of oxidation products may be suddenly floated into circulation and cause clogging of oil holes and destruction of bearings. Before changing over to H.D. oil the engine must be completely cleaned of all such deposits. H.D. oils were extensively used during the war on high-speed engines for military purposes and fully justified their use in the circumstances. Without additives, much of the available stocks of lubricants would have caused havoc among the high-duty engines required by war service.

If for any reason the top piston-ring operates at a temperature approaching 200° C., say 390° F. or more (and it appears that this is not easily avoided in certain highly rated engines), the user has a choice of two types of lubricant : (1) a naturally detergent oil (that is, one with a steep viscosity curve) doped with an inhibitor to minimise oxidation; (2) an oil with a comparatively flat viscosity curve (usually an oil of paraffinic base) doped with a detergent.

Either choice has its advocates.

Choice (1) has many successes to its credit in cases in which the use of a straight paraffinic oil of the highest quality would be disastrous.

Choice (2) holds out the inducement of higher viscosity and lubricating value of the oil at the high temperature prevailing in the ring belt, with the possibility of less wear of piston-rings and cylinder-liners than with choice (1). There seems to be some evidence that choice (2) is the right one for the more extreme cases of thermal loading of the pistons of small high-speed engines.

The situation may perhaps be summed up by the advice—never use a double-purpose crankcase and cylinder oil of the artificially detergent type if the engine will run satisfactorily (without requiring excessive piston overhauling) on :

(*a*) a straight oil;
(*b*) an oil inhibited against oxidation.

In the present stage of knowledge the artificially detergent oil is the last resort—" claret for boys, port for men, brandy for heroes ".*

35. *Corrosion.*—If water (fresh or salt), or products of combustion, or both, enter the crankcase of a Diesel engine, a slightly corrosive condition of the oil, of sufficient severity to attack crankshaft journals and crank-pins, may result. In the authors' experience, such corrosive conditions are more frequently caused by combustion products than by water.

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* Dr. Samuel Johnson.

In a trunk engine leakage of gas past worn or stuck rings may be the primary cause. A small proportion of any sulphur dioxide in the combustion products is converted to sulphur trioxide, which in combination with condensed water vapour, also present in the combustion products, forms sulphuric acid. The higher the sulphur content of the fuel the higher will be the concentration of sulphur dioxide in the exhaust gases, and the greater will be the risk of some traces of sulphuric acid reaching the crankcase oil.

Crankcase oil may acquire small percentages of fresh or salt water, as the case may be, from cylinder-jacket leakages. In the presence of finely divided carbon and other impurities this water may form persistent emulsions with the oil in the circulating system. Acidity in emulsified oil is difficult to wash out with a centrifugal separator, and when an engine has been idle for a few days, contact of such oil with the crankshaft may give rise to serious corrosion. In several cases of corroded crankpins and journals which have come to the authors' notice, the lubricating oil was heavily contaminated with fresh water and contained free mineral acidity to the extent of 0·005% sulphuric acid. Sludge present in the crankcase, however, a typical analysis of which follows, contained 0·05% free sulphuric acid.

Analysis of Sludge

	Percentage.
Oil	43·8
Water	32·2
Carbonaceous matter	14·69
Tin and antimony oxides	1·70
Iron oxide	5·46
Copper oxide	0·22
Total sulphate (SO_4)	1·07
Sulphate soluble in water	0·14
Silica	0·79
Sulphuric acid	0·056

In another instance, in which minute amounts of sulphuric acid were present, it was concluded that the acid in the crankcase had been derived from ferric sulphate present in the sludge found in the trays beneath the pistons of the four-stroke crosshead engine with piston-rods passing through lantern pieces and stuffing-boxes. Water had been leaking from a defective waterpipe into this material and thence to the crankcase. The importance of keeping the crankcase free from combustion products and water will therefore be apparent.

35a. *Wear of Cylinder Liners.*—The earlier view on this subject, expressed by P. H. Smith in the early nineties, ascribed cylinder-liner wear to the abrasive action of detritus worn in the first place from the piston-rings and later from the cylinder-liner; this action being accentuated by gas pressure behind the piston-rings forcing them against the surface of the liner. This explanation satisfactorily accounted for the concentration of maximum wear towards the inner end of the travel of the piston-ring nearest the combustion chamber and the axial scratches observed at this place.

A later view, which first came into prominence as the result of experiments by Williams, regards corrosion as the main agency of cylinder-liner wear. This view is discussed further in Section 46.

It can hardly be doubted that wear would take place even if chemical action were entirely absent. On either theory effective lubrication of the piston-rings is a necessary condition for minimum wear. There is some evidence that cylinder wear is reduced by the use of oils inhibited against oxidation.

In general, a fully stuck piston-ring ceases to cause cylinder-liner wear. On removing a piston and finding all the rings stuck, it is sometimes noticed that the cylinder-liner is brown all round the upper part, showing that wear has been absent for some time. On the other hand, a half-stuck ring probably acts as a scraper causing greatly accelerated wear. This explains why, with a multi-cylinder engine, liable to ring sticking, there is often a wide scatter in the amounts of wear of the several cylinders, some cylinders showing very little and some very much wear. If the rings are working freely there is much less percentage variation from the mean in the wear of the various cylinders.

CHAPTER V

PROPERTIES OF DIESEL FUELS

36. *Classes of Diesel Fuels.*—By reason of the enormous output from the crude-oil wells, the fuels mainly used in Diesel engines are of petroleum origin; they are often of the wholly distillate type or a blend of distillate and residual oils, but residual oils solely are used to some extent, and there is a definite trend towards an increase in their use. Shale oils, tar oils, vegetable oils, natural gas and sludge gas may also be used with success. To these may be added fuel oil derived from the hydrogenation of coal, and from the Fischer–Tropsch synthesis process.

It is the exception rather than the rule for crudes to be used in Diesel engines, inasmuch as it is not economic or advisable to do so except in special circumstances. However, in the case of the Kirkup to Haifa pipeline, Iraq crude has been used with success during the past twelve years in the series of Diesel engines employed on pumping the same crude oil along from the oilfields to the port (Fig. 6). Crude is also expected to be used on the further series of engines built for the duplication of the line.

The characteristics of Iraq crude are as follows :

Specific gravity at 60° F.	0·856
Viscosity (Redwood No. 1) at 70° F.	52 sec.
„ „ 100° F.	41 sec.
Hard asphalt	1·50%
Conradson coke value	4·01
Sediment	0·19%
Aniline number	75° C.
Ash	0·026%
Diesel index	56

The extremely low flash point of crudes puts them out of court for marine and most ordinary industrial services, and their use in generating-station engines might be attended with too great a fire risk to warrant consideration of their possible use in this service.

The large bulk of Diesel fuels are obtained from crudes by straight distillation or cracking as described in Chapter II; it should be mentioned, however, that in some cases crudes are merely "topped", that is, the petrol and kerosene fractions are removed and the residual oil marketed as Diesel fuel; the better classes of fuel are obtained by further distillation, and such grades are essential for small high-speed engines, as at present constructed. The topping of crudes has been stimulated in recent years by the ever-increasing demand for low-boiling-point aviation and road-traffic fuels which provide a

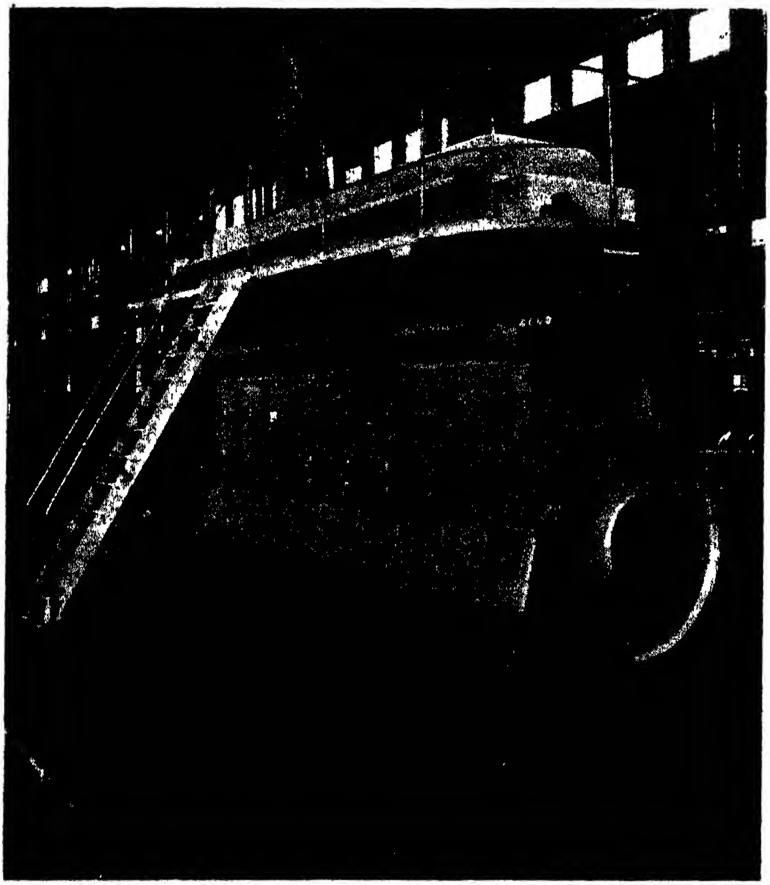
FIG. 6.—1250 B.H.P. PRESSURE-CHARGED FOUR-STROKE DIESEL ENGINE (HARLAND & WOLFF) FOR THE IRAQ PETROLEUM CO., LTD., FOR PIPELINE PUMPING.

higher margin of profit than the production of Diesel fuels; the inevitable consequence will be a tendency to restrict, in due course, the oils available for Diesel use to the heavier residues of the oil refineries.

The chemical composition of an average Diesel fuel is approximately as follows, the chief variable being sulphur.

	Percentage.
Carbon	86 –87
Hydrogen	11 –13·5
Sulphur	0·5– 2·0
Oxygen and nitrogen	0·5– 1·0

Beyond providing some indication of the calorific value, the ultimate composition alone is of little value in assessing the suitability of a Diesel fuel, for which purpose a consideration of the characteristics discussed in the following sections is necessary; of these, viscosity and ignition quality are generally considered to be the most important items.

37. *Specific Gravity.*—In the days before the adoption of Standard Pool Marine Diesel Fuel, specific gravity varied widely and provided a rough indication of the origin and general type of the fuel. Non-asphaltic-base oils have, in general, lower specific gravities than the asphaltic type and may range between 0·83 and 0·89, while the latter are of the order of 0·89–0·95.

In a given homologous series, e.g., the paraffins, the space occupied by a molecule increases with the molecular weight but not in the same ratio, so that the specific gravity of the constituents is an increasing function of molecular weight. The viscosity also increases with molecular weight, so there is a correlation between specific gravity and viscosity. For the aggregates of mixed molecules which make up Diesel fuels, the correlation is somewhat loose, and is roughly indicated in the following table, which excludes furnace oils.

Specific Gravity.	Viscosity, Redwood No. 1 at 100° F. (sec.).		
	Minimum.	Maximum.	Mean.
0·83–0·84	32	35	33
0·84–0·86	35	42	37
0·86–0·88	35	50	40
0·88–0·90	42	76	48
0·90–0·92	42	107	50
0·92–0·94	237	462	370
0·94–0·96	270	710	414

Similarly, there is loose correlation between specific gravity (coupled with viscosity) and ignition quality as measured by Cetane number, roughly as under :

Specific Gravity.	Range of Cetane Numbers.
0·85	59–63
0·875	50–56
0·90	47–52
0·925	44–47
0·95	36–38

Dicksee (6) tested sixteen fuels of varying specific gravity in an engine running at 1000–2000 r.p.m. and classified the fuels as "very good", "poor", "bad" and "very bad". All the fuels of specific gravity below 0·85 were recorded as "very good" and all those above 0·9 as "very bad". It should be emphasised, however, that these results refer only to certain small high-speed engines and are not applicable to larger slow-running marine engines; for the latter, fuel oils having a specific gravity in the range of 0·89–0·91 are likely to give better results than those having a specific gravity of the order of 0·85 unless special adjustments are made to injection rates, timing and nozzle-hole areas to suit the lighter fuels.

Although specific gravity alone is never conclusive it often enables a rough estimate to be made of the probable ranges within which lie the values of the viscosity and Cetane number for supplies from a given source. Undue reliance, however, should not be placed on gravity alone, since fuels of identical gravity from different sources may differ appreciably both in viscosity and Cetane number. Specific gravity is also useful when test data are not available, as an approximate guide to the calorific value of normal fuel oils, as illustrated in Fig. 7, which is based on a large number of determinations made by one of the authors; see also Fig. 8, by Cloud and Blackwood. Further, it enables the engineer to convert volume to weight for consumption purposes, and since specific gravity varies with the temperature at which it is determined, it is necessary to take temperature into account. It is usual practice to record the specific gravity at 60° F., and if temperatures deviate from this a correction must be applied (see Section 66). The specific gravity of the bulk of Diesel fuels used on large marine engines is around 0·90, and the designer arranges the fuel-pump diameter and cam rate to suit fuel of this grade. Should the fuel supply be changed to one of appreciably lower specific gravity, it is necessary, for a given load on the engine, to inject into the cylinders at each stroke a greater volume of the lighter oil, and of necessity, the injection period will be increased accordingly. This, of course, will slightly reduce the expansion ratio of the burning gases with detrimental effect on the overall efficiency. For this reason, the somewhat higher heating value which generally accompanies a lighter fuel, as compared with the normal 0·9 gravity fuel, is largely neutralised, and the lower consumption which might be anticipated from a changeover to a low-gravity oil does not materialise in practice.

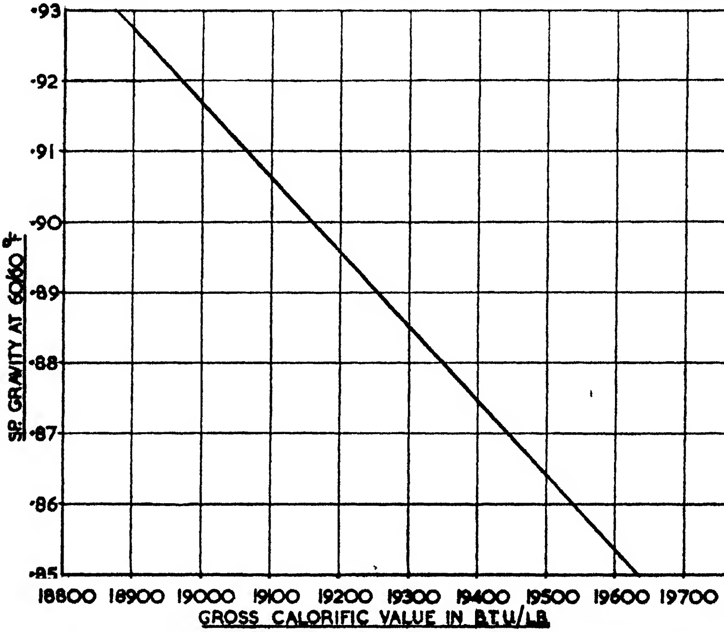

Fig. 7.—Relation between Specific Gravity and Calorific Value of Diesel Fuel Oil.

38. *Viscosity.*—This physical property is a measure of the resistance of a fluid to streamline (i.e., non-turbulent) flow. In scientific measure the unit of viscosity is the dyne sec./sq. cm. or poise; 1 lb./sq. in. = 69,000 dynes/sq. cm. Viscosity divided by density is known as kinematic viscosity for which

the unit is the sq. cm./sec. or stoke. The laboratory instrument for the direct determination of viscosity is known as an "absolute viscometer" and consists essentially of a long capillary tube through which the fluid is forced by pressure. In technical and commercial practice, types of viscometer are used which measure the kinematic viscosity by empirical calibration against an absolute viscometer. For commercial and comparative purposes the readings are quoted directly in seconds of time required for the efflux of a specified volume of fluid, or some function thereof. Three types of viscometer are in general use, viz., Redwood (Great Britain), Saybolt (U.S.A.), Engler (Continent of Europe). The relationship between the kinematic viscosity V of an oil and its viscosity as measured by Redwood No. 1, Saybolt and Engler viscometers is expressed approximately by the following formulæ. (V = stokes.)

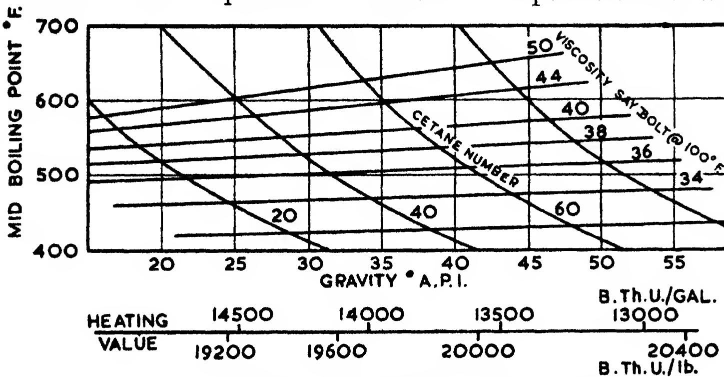

FIG. 8.—RELATED PROPERTIES OF DIESEL FUELS.

$$V = 0{\cdot}0026T - \frac{1{\cdot}79}{T} \text{ where } T = \text{Redwood sec. from 34 to 100.}$$

$$= 0{\cdot}00247T - \frac{0{\cdot}5}{T} \text{ where } T = \text{Redwood sec. above 100.}$$

$$= 0{\cdot}00226T - \frac{1{\cdot}95}{T} \text{ where } T = \text{Saybolt U. sec. less than 100.}$$

$$= 0{\cdot}00220T - \frac{1{\cdot}35}{T} \text{ where } T = \text{Saybolt U. sec. above 100.}$$

$$= 0{\cdot}08E^\circ - \frac{0{\cdot}0864}{E^\circ} \text{ where } E^\circ = \text{Engler}\ ^\circ \text{ from } 1{\cdot}35 \text{ to } 3{\cdot}2.$$

$$= 0{\cdot}076E^\circ - \frac{0{\cdot}04}{E^\circ} \text{ where } E^\circ = \text{Engler}\ ^\circ \text{ above } 3{\cdot}2.$$

Engler viscosity in degrees is obtained from the efflux time in seconds by dividing by the time for the outflow of an equal volume of water at 20° C.

Appendix I gives a comparison of the several viscometer readings and interpretation in centistokes, e.g., 0·01 stokes; to convert stokes to poises multiply by the density in gm./cc. which is numerically the same as the specific gravity. For example, 100 sec Redwood No. 1 = 115 Saybolt = 3·3° Engler = 0·243 stokes.

If the specific gravity is 0·865, the viscosity in poises = 0·243 × 0·865 = 0·210 poise.

The viscosity of an oil decreases rapidly with increase of temperature and it is usual to record viscosities at 70°, 100° and 180° F. The viscosity at the standard temperature of 100° F. is commonly accepted as a measure of the general viscidity of the fuel. For lubricants the temperature of reference is 140° F.

Fig. 9 shows the viscosity-temperature relations for some representative fuels.

The viscidity of a liquid hydrocarbon influences its suitability as a Diesel-engine fuel in several distinct ways.

(1) High viscosity increases difficulties of transfer and delivery by gravity or pumping; this is most serious in small high-speed engines. For bus and other high-speed engines a fuel viscosity at 100° F. of not more than about 36 sec. Redwood No. 1 is preferred. For medium-sized engines running at, say, 500 r.p.m., viscosities up to 100 sec. Redwood No. 1 may offer no difficulty. In large installations of slow-running engines, fuels having viscosities up to 1250 sec. Redwood at 100° F. may be dealt with by heating up to 180° F., thereby reducing the viscosity at the filters, purifiers and pumps to about 150 sec. Redwood No. 1. A marked change in the viscosity of the fuel used may necessitate a modification to the size of the fuel-valve nozzle in order to obtain satisfactory combustion.

(2) High viscosity tends to reduce atomisation and increase penetration of the fuel on injection and thereby cause incomplete combustion; this also is most serious with small high-speed engines.

(3) Dirt and grit remain longer in suspension in viscous

fuels, whereas they may have some chance of settling through more fluid fuels.

(4) High viscosity is commonly associated with low ignition quality (see Section 42). This may be due, as suggested by

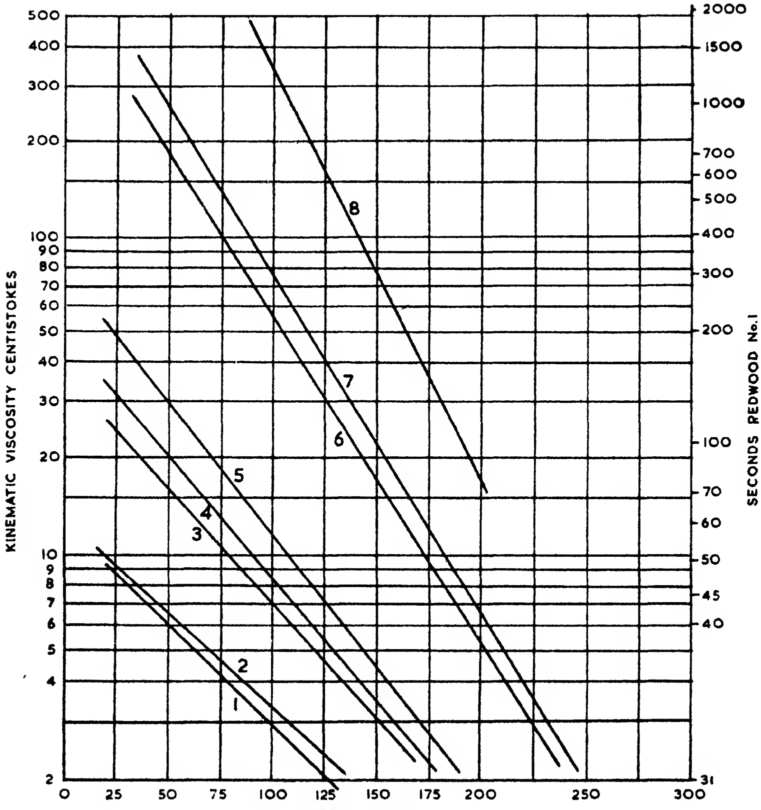

FIG. 9.

1 and 2, Gas Oil. 3, 4 and 5, Typical Diesel Fuels. 6, Air Blast Engine Fuel. 7, Recommended Viscosity Limit for Airless-injection Engine Fuel without Preheating. 8, Boiler Oil used at 180° F.

Dicksee (6), to a small difference between the ignition temperature and the final distillation temperature.

It will be noted that objections 1, 2 and 3 may be overcome by pre-heating at some expense in complication (Lamb, *loc. cit.*). Item 4 is more fundamental; much research has been carried out with a view to widening the range of fuels usable in high-speed engines; (*a*) by doping the fuel with ignition accelerators, (*b*) by improvement in design, in particular by increasing turbulence, (*c*) by supercharging.

Very low-viscosity fuels are deficient in lubricating properties which may give rise to wear on fuel pump and injector parts; a tendency for the fuel to leak in the pumps and atomisers also accompanies very low viscosity.

39. *Calorific Value.*—The calorific value of a fuel oil, which is expressed in B.Th.U./lb. or kg. calories/kg., is the amount of heat given by combustion. As ascertained by use of the usual bomb calorimeter, the calorific value includes the latent heat of the water vapour formed by the combustion of the hydrogen content. The value so obtained is the gross calorific value. The value obtained after subtracting the latent heat of the water vapour is the nett calorific value. The difference between the gross and nett values depends on the percentage of hydrogen present in the oil, and in normal Diesel fuels usually varies between 1100 and 1250 B.Th.U./lb. The calorific values of Diesel fuels, particularly those from the same source, do not in general vary widely, and the gross values are usually in the range of 19,000–19,300; for gas oils, 19,300–19,600, and for boiler-type oils sometimes used in Diesel engines, 18,600–18,800 B.Th.U./lb. For general purposes, the approximate calorific value can be obtained by the use of the curves given in Figs. 7 and 8, or from the following equation, which is based on the A.P.I. gravity of the fuel.

Gross Calorific Value, B.Th.U./lb. $= 17{,}687 + (57{\cdot}9 \times \text{A.P.I. gravity})$ (for definition of A.P.I. gravity see Section 68). For thermal efficiency calculations, however, it is necessary to have an accurate figure, generally obtained by means of the bomb calorimeter.

From the gross value so determined, the nett value may be obtained, when the hydrogen content of the fuel is not available, by using the following formula:

$$\text{Nett B.Th.U./lb.} = 4525 + (0{\cdot}7070 \times \text{Gross B.Th.U./lb.}).$$

40. *Ignition Temperature.*—This is the minimum temperature at which an oil will ignite in air or oxygen without the application of a spark, and is of some importance in judging the

suitability of oils of unknown origin for use in internal-combustion engines. Since a Diesel engine depends for ignition upon the temperature attained in the cylinder at the end of the compression stroke, it is clear that the oil used must have a spontaneous-ignition temperature considerably less than this compression temperature in order to obtain easy and regular firing. The apparatus devised by Moore for determining spontaneous ignition temperature is probably the best known, and the results obtained thereby are generally expressed as the number of degrees Centigrade, in air, at atmospheric pressure. These conditions differ from those under which actual ignition takes place in the engine cylinder, and there is no definite correlation between the spontaneous-ignition temperature of the fuel under these different conditions. However, for a given compression the maximum permissible ignition temperature of a fuel can be computed with sufficient accuracy for all practical purposes. Thus the temperature of a gas under adiabatic compression can be derived from the formula :

$$T_2 = T_1\left(\frac{P_2}{P_1}\right)^{\frac{n-1}{n}}$$

where T_1 and T_2 are the initial and final temperatures of compression and P_1 and P_2 the corresponding pressure (both absolute). Under adiabatic conditions the value of $n = 1{\cdot}40$, but under the conditions existing in a Diesel-engine cylinder the formula can be applied by adopting a value of $n = 1{\cdot}35$. From the adiabatic curve shown in Fig. 10, the upper limiting value for ignition point for any given compression within the range generally used can be assessed. For example, a compression pressure of 500 lb./sq. in. is shown to require an ignition point of the fuel in oxygen not exceeding 350° C. to ensure easy starting and regular firing.

Most fuels of petroleum origin have spontaneous ignition temperatures in air within a fairly narrow range, e.g., 350–450° C., which is well within the above compression temperatures. Tar oils and fuels derived from highly aromatic-base crudes have high ignition points, and unless a higher compression ratio be used or a throttled-blower suction be adopted (Section 9), ignition difficulties will be encountered.

41. *Distillation Range.*—In the early days of the Diesel

engine it was the practice to assess the ease or otherwise of the evaporation or volatility of a fuel by estimating the percentage of residue left after heating a known weight of the oil to 325° C. in an open vessel; in the company with which the authors are associated a fuel giving a residue not greater than 30% was considered suitable. This method gave rather erratic results and has been superseded by a determination of the distillation range, which, in addition to furnishing the amount of residue left after distilling to 350° C., gives the boiling points of the constituents making up the mixture of hydrocarbons in the oil together with their percentage. When the volume distilled is plotted against temperature, a distillation curve (Fig. 11) is

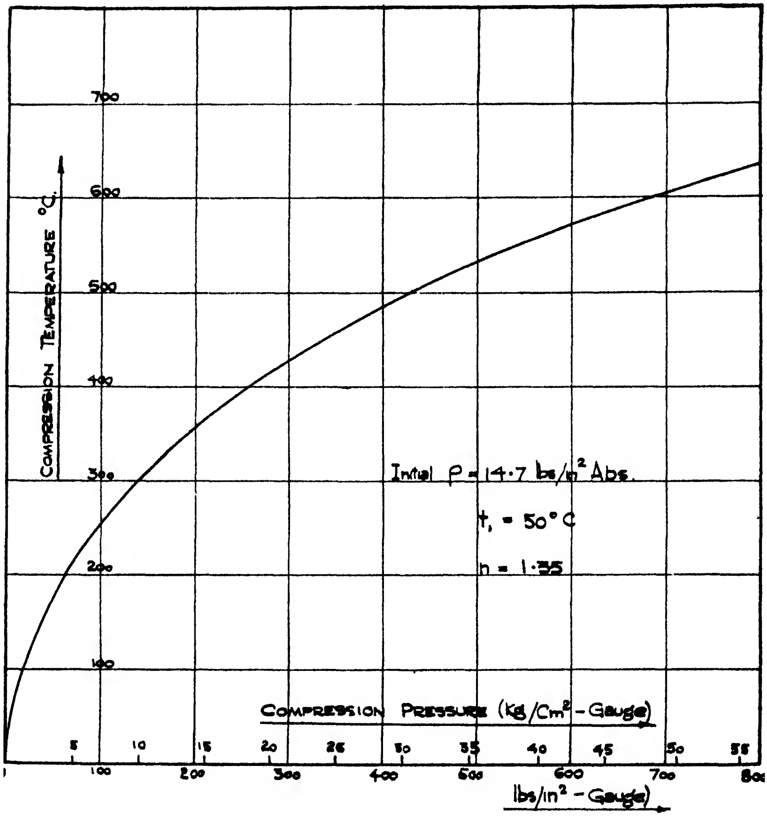

FIG. 10.—COMPRESSION TEMPERATURES.

obtained, and this curve is of some importance in assessing the suitability of a fuel oil, at least for high-speed Diesel-engine use. In fact, Dicksee (6) regards distillation curve and ignition point as the two properties of a fuel having the greatest influence upon the suitability of an oil for such engines, and suggests that a fuel which has a low-temperature distillation range or a high spontaneous ignition point has a greater tendency towards knocking than one of a somewhat higher distillation range and a lower ignition point. From engine-test results he concluded that fuels having a relatively flat distillation curve with a low residue above 350° C. and which have a comparatively small temperature difference between the final boiling point and the ignition temperature, were the best high-speed fuels.

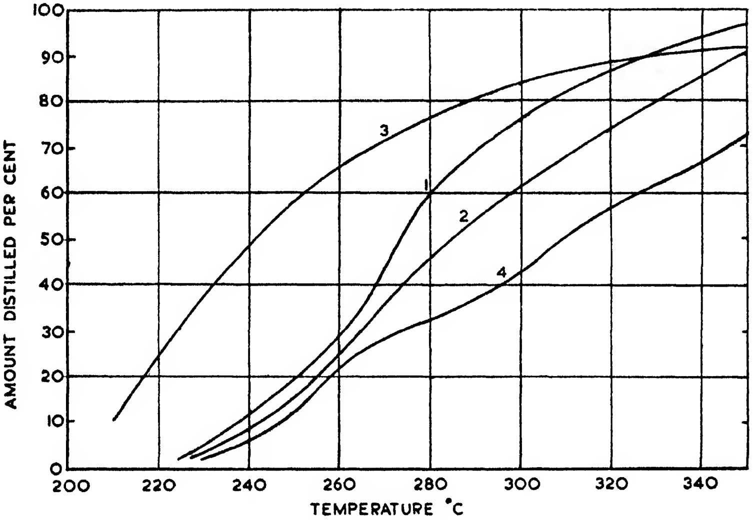

FIG. 11.—DISTILLATION CURVES OF TYPICAL FUELS.
1, Scottish Shale Oil; 2, Gas Oil; 3, Tar Oil; 4, Blended Diesel Oil.

At the same time it was realised that whereas distillation ranges are obtained under normal atmospheric conditions, in an engine cylinder the fuel is subjected to a pressure of several hundreds of pounds per square inch during the period when vaporisation may be expected to take place. The effect of operating pressure is to increase the distillation temperature and to decrease the ignition temperature; hence, fuels which under atmospheric pressure have an ignition point not much above that of their final boiling point may, under engine conditions, have an ignition point which occurs quite early in the distillation range, or possibly at a temperature even lower than that of the initial boiling point. Under such conditions it would be impossible for vapour to collect in sufficient quantities to form an explosive mixture, and smooth engine operation would result.

For the distillate fuels, almost universally used in high-speed engines, Broeze and Hinze (7) have shown that there is a strong correlation between volatility (65% point of A.S.T.M. distillation) and viscosity. The B.S.I. Specification No. 209 for fuels for such engines requires that 85% by volume shall be recoverable at 350° C. For heavier classes of fuel oil, the standard distillation range is not of much value in assessing suitability, because only the lighter constituents of normal fuel oils are indicated thereby, and it is not practicable to distil beyond 350° C. because cracking of the oil starts at about this temperature. By distilling under reduced pressure, however, it is possible to remove some of the less volatile constituents and still keep within the maximum range of 350° C. without cracking. Hence in the authors' practice, distillation range is invariably carried out under reduced pressure of 120 mm. mercury, and is applied not only to distillate fuels but also to ordinary quality fuel oils.

42. *Ignition Quality.*—In recent years much research has been carried out in developing tests with which to assess this rather elusive property of ignition quality, which is now generally accepted to be one of the most important characteristics of Diesel fuels from the aspect of satisfactory engine operation. Ignition quality may be defined as a measure of the time required for combustion to start after the commencement of ignition; the shorter the time, the higher is the ignition quality. High ignition quality indicates ease of starting from cold at slow speeds and smoothness of running. Ignition quality may be indicated by the cetane number or the Diesel index. Cetane number is measured in a specified engine running under certain conditions and is the percentage by volume of cetane ($C_{16}H_{34}$) in a mixture of this compound and *a*-methyl-naphthalene, which has the same ignition delay as any particular fuel or, in other words, is equivalent in ignition quality to the fuel. The

higher the cetane number of a fuel the shorter the period of time between injection of the fuel and commencement of rapid pressure rise. Köhler (8) investigated a method of classifying Diesel fuels on the basis of their cetane numbers, the work being carried out on the I.G. Diesel test engine. Cetane numbers were determined in a range of 0–100, by changing the compression ratio on the engine between 7 and 30, to give a constant ignition lag. It appeared that a definite relation existed between the cetane number and the compression ratio. Köhler concluded that the ignitability of hydrocarbons rises with molecular weight, exceptions being the purely or predominantly aromatic fuels; branching of paraffin hydrocarbons lowers the ignitability.

The cetane numbers of Diesel fuels of petroleum origin range between 25 and 60. For high-speed engines fuels having a cetane number of 45–50 are generally found satisfactory up to about 1000 r.p.m.; engines running at 1500–2000 r.p.m. are usually supplied with fuel having a cetane number of 50–60. In medium-speed engines, 35 may be regarded as the minimum, while for slow-speed engines cetane numbers from 25 upwards will be satisfactory. Since the specially equipped engines necessary for determining cetane numbers are not available in most laboratories an approximation is sometimes obtained without an engine test, using the method of Section 81, but it is more usual to employ the Diesel index, which for all practical purposes affords as satisfactory an indication of ignition quality as cetane number for most petroleum oils. Diesel index is derived from the aniline point and the A.P.I. gravity by using the following formula :

$$\text{Diesel Index Number} = \frac{(\text{A.P.I. Gravity at } 60^\circ \text{ F.}) \times (\text{Aniline Pt. } ^\circ \text{ F.})}{100}$$

in which A.P.I. gravity (American Petroleum Institute) is within the relevant gravity range, practically coincident with Beaumé gravity (see Section 68). Aniline point is the lowest temperature at which equal parts (by volume) of freshly distilled aniline and the fuel oil under test are completely miscible. Light distillates suitable for high-speed engines will generally be found to have aniline points above 60° C., while normal

Diesel grades should not be less than 45° C. A high aniline point is indicative of a fuel having a paraffin base, while a low aniline point indicates an unsaturated, naphthenic or aromatic hydrocarbon-base oil; in general, it has been found that the higher the paraffinicity the better the ignition quality of the fuel oil. Having regard to the relationship between the aniline value and the Diesel index, it is reasonable to expect that the higher the Diesel index the more satisfactory will be the ignition quality of the oil, and for high-speed engines should be about 50. For medium-speed engines and normal marine solid-injection engines, Diesel index averages about 35 and should not be less than 25.

43. *Flash Point.*—This may be defined as the temperature at which an oil gives off sufficient inflammable vapour from its surface to ignite in the presence of a small flame. Both closed and open flash point are often quoted for Diesel fuels, and the closed is of some importance in that a minimum of 150° F. is required by government regulations for marine fuel oil. The open flash point of a normal oil is 25–30° F. higher than the closed, due to the fact that the vapours given off by an oil under heat escape more readily from an open vessel than from a closed one. The fire point, i.e., the temperature at which sufficient inflammable vapour is given off to maintain a continuous flame, is also related to both closed and open flash point and is usually 30–40° F. higher than the open flash point.

The flash points are measures of the risk of fire encountered when storing the oil, and afford no indication of the behaviour of the oil in an engine.

44. *Hard and Soft Asphalt.*—Most Diesel fuels of petroleum origin, excepting the light distillates as used on high-speed engines, contain asphaltic bodies: (*a*) asphaltenes commonly termed hard asphalt, which is that portion of the oil insoluble in petroleum ether, (*b*) soft asphalt, the residue insoluble in ether–alcohol mixture. Both these constituents have a very low volatility, from which it is reasonable to assume that the portion of the oil represented by these two bodies is burnt whilst in the state of finely divided liquid particles. In general, a high asphalt content induces slower combustion of the oil, which in turn gives rise to higher exhaust-gas temperatures, thus affecting the service life of exhaust valves; moreover, high-

asphalt oils tend to carbonise and form deposits on piston heads and around fuel-valve nozzles. Despite this, oils containing as much as 6% of hard asphalt have, under conditions of good combustion, been used with success in Diesel engines, although the usual limit in large slow-running engines is 2%. It not infrequently happens, however, that high asphalt content in oils is associated with higher water content (probably due to the mainly colloidal nature of the asphaltenes) which aggravates the adverse effects of the asphalt. In the absence of water in the oil very little trouble is likely to be experienced in low-speed engines, provided the asphalt is not above 6%, but for high-speed engines a low asphalt content is essential, preferably below 0·1%; this is due to the limited combustion-chamber volume and the very short time available for burning the fuel charge.

45. *Coke Value.* The coke value is some measure of the carbon-forming propensity of an oil, and is the percentage residue remaining after the oil has been heated until all the volatile constituents have been burnt off. Since asphaltic bodies have negligible volatility it follows that as the asphalt increases in an oil, the coke value also increases, with very similar effects on engine efficiency; in other words, coke value is inter-related with the total asphalt content, and in this connection Broeze and Hinze (7) have shown that the Conradson coke value is a more reliable guide to the carbonising tendency of an oil in an engine than the hard-asphalt content. Further, Kneule (9) has found that the Conradson coke value is a good indication of the tendency of a fuel to deposit carbon on the fuel-injection nozzles.

46. *Sulphur Content.*—The sulphur content of fuel oils has no influence on the combustion of the oil in a Diesel engine. On burning, however, the sulphur forms sulphur dioxide, together with a proportion of the trioxide, and when the temperature of the combustion gases falls below the dew point, the sulphur oxides dissolve in the condensed water arising from the combustion of hydrogen, forming sulphur acids. Corrosion effects are therefore liable to be experienced in silencers and exhaust pipes and turbo blowers when cold, and a certain amount of corrosion is possible in combustion spaces, under low cylinder jacket temperatures, this liability being increased with

increasing sulphur content of the fuel used. The presence of sulphur oxides in the combustion gases leads also to an increased rate of engine fouling, and the higher the sulphur in the fuel the greater is the tendency to fouling; this gives rise to contamination of the crankcase oil with a slightly acidic sludge, and if the oil contains a little water, as is not uncommon, corrosion may possibly result.

How far corrosion due to sulphur in the fuel is responsible in service for cylinder-liner wear is a matter on which there are two divergent views : (*a*) that sulphur content has little or no bearing on liner wear under normal running conditions, and (*b*) that corrosion arising from sulphur products is the main agency of liner wear, assisted by the action of abrasion in removing the corrosion products and exposing fresh surfaces to chemical action. Representative of view (*a*) is the finding of Le Mesurier and Stansfield (*loc. cit.*), who, from a consideration of liner-wear data in marine main engines running on various fuels, concluded that the effect of corrosion is generally negligible in comparison with that of other causes which lead to liner wear and that a sulphur content up to 2% has no measurable effect in practice. Melkumov (10) supports this view. According to his report, tests conducted with fuels of sulphur content as high as 2% showed that the operation of the engine remained unaffected, nor could it be established that the presence of sulphur in combination with water was harmful either to liners or combustion chambers.

The contrary view, first suggested by the experiments of Williams (25), has more recently found support in the results of a series of tests carried out on high-speed automotive engines by Cloud and Blackwood (26). They found that as the sulphur content of a fuel was increased, the cylinder-liner and piston-ring wear was also increased and that the higher the sulphur content of a fuel then the greater was the amount of engine fouling. There are other published test results which point in the same direction. However, in order to accelerate results, such tests have sometimes been carried out under extreme conditions in regard to coolant temperatures, and more data is required before a clear conclusion can be drawn on the influence of sulphur under normal operating conditions or as to what percentage of sulphur is permissible in the various types of Diesel engine. It can be stated, however, that for all sizes of engines it is almost certainly advantageous to keep the upper part of the cylinder at a temperature above the dew point. With large engines this does not involve high water temperatures, since there is a considerable gradient through the cylinder-liner wall. With small engines having thin liners, thermostatic control of cooling-water temperatures may be desirable.

Service experience seems to indicate that sulphur content up to 3% is not a matter of great concern with engines of large or medium size. With engines of small size having cylinders, say, 4 or 5 in. in diameter, a lower content, not exceeding 1·5% is preferable, but it is possible that higher percentages may be tolerable if thermostatic control of cylinder-cooling-water temperature is adopted or if special materials (e.g., chromium-plating of the top part of the cylinder surfaces) are employed; a further expedient is the use of lubricating oil containing an additive which neutralises or inhibits the action of the corrosive sulphur products.

Whatever further research may reveal, it is unlikely that sulphur content will rule out the use of any otherwise suitable petroleum fuel.

47. *Ash Content.*—The ash content is a measure of the inorganic impurities present in the oil. It consists usually of iron oxide, sand and sundry metallic salts the composition of which varies with the origin of the oil; for example, some fuel oils contain the sodium salt of vanadium, others nickel salts. In general, ash is a highly undesirable constituent in Diesel fuel, and the composition of the ash is probably of greater importance than the actual amount, provided the latter is within certain limits. Some oils leave an ash which is soft and relatively harmless, but usually the ash is hard and gritty, and consequently abrasive. A proportion, probably the greater part of the ash, is ejected from the cylinder with the exhaust gases, but some portion is held by the cylinder lubricating oil, causing wear of the liner and piston-rings. Particles of ash may be deposited under the exhaust valves, where these are fitted, giving rise to pitting of the valve faces; this trouble can also be caused by incompletely burnt carbonaceous particles. Ash content is therefore one of the important factors to be considered in evaluating a Diesel fuel and should never exceed

0·05% in the slowest-speed engines. Oils used for high-speed Diesels should not contain more than the merest trace of ash.

Centrifugal treatment of Diesel oils can often be adopted with beneficial effects on the ash content; an example is quoted below; oils of boiler quality have by such treatment in the preheated condition been rendered suitably low in ash content for successful use in Diesel engines.

	Before Purification, percentage	After Purification, percentage
Ash . .	0·043	0·026 *
Hard asphalt	0·38	0·20
Sediment	0·29	0·18

* Reduction 40%.

48. *Water Content.*—The water content of Diesel fuel should be as low as possible, never exceeding 1%, as it can prove a source of trouble in engine operation. This arises from the fact that water is insoluble in oils of petroleum origin and is not usually in a homogeneous state of suspension in the oil but tends to separate in small pockets. The result is that when using an oil containing appreciable water, the fuel-pump may occasionally draw a charge consisting mainly of water, causing misfiring of the engine, subsequent spattering of unburnt oil on combustion-space surfaces and resulting carbonisation. A further adverse effect is the contamination of the lubricating oil with unburned and partially burnt fuel.

49. *Sediment.*—Somewhat related to ash content is the "sediment", a term applied to mechanical impurities present in the oil, which are insoluble in benzole. In light distillates, such impurities are rarely found, but in higher-viscosity petroleum-base oils a small percentage is usually found, and, as a rule, an appreciable proportion of this sediment is in the form of particles of carbonaceous matter; the remainder is incombustible matter such as sand, and the amount is determined in the ash content. Coal-tar distillates are relatively free from mechanical impurities, but not infrequently contain the crystalline solid naphthalene, which is liable to separate out and choke the fuel system unless such oils are kept at a suitable temperature throughout the fuel system.

49a. *Summary and Diesel Fuel Outlook.*—From the foregoing considerations it will be observed that a rough assessment of the suitability of a Diesel fuel may be deduced from the specific gravity and viscosity. It is desirable, however, particularly for fuels intended for high-speed engines, to take into consideration the more fundamentally important characteristics of ignition quality (as indicated by cetane number or Diesel index) and the distillation range, or at least the amount of residue remaining beyond the final boiling point. The latter, together with the Conradson value, provide an indication of the amount of heavy hydrocarbons present which do not burn readily and lead to the formation of carbonaceous residues. Such residues, together with the incombustibles, i.e., the ash, are the main factors leading to increased wear on liners and rings.

At the present time there is a shortage of gas oils throughout the world. This has been brought about mainly by the large increase in the number of Diesel engines in operation, particularly of the small high-speed type, and by the use of gas oils as cracking stocks by the refiner in order to meet the ever-increasing demands for petroleum and aviation spirits. Both these demands are likely to be intensified rather than eased as time goes on, and it seems inevitable that the amount of gas oils and other light-petroleum distillates available for use as Diesel fuel will be gradually diminished. Many authorities feel, therefore, that Diesel-engine users will be forced by the operation of the law of supply and demand to turn to supplies in the light and heavy residual class, at least for main marine propulsion engines.

There is no doubt that at the present time there are numerous large slow-speed marine engines operating on light distillate fuels which would run equally well and more economically on a heavier grade oil. In this connection, the pioneer work of Lamb (*loc. cit.*) in The Anglo-Saxon Petroleum Company's m.v. *Auricula* has demonstrated that the use of a boiler-fuel oil suitably preheated and purified is not only practicable but economical, and that maintenance costs are not appreciably increased.

Filippini (27) records similar experiences in Fiat Diesel engines using boiler fuel oils, and further evidence in the same direction has been afforded by the results obtained in m.v.

British Strength, the first ship of the British Tanker Co. to be fitted out for burning boiler-grade fuel in her four-cycle under-piston-supercharged main Diesel engine. Without any alterations to the normal standard Harland & Wolff fuel-injection equipment for burning Diesel-grade fuels, the shop tests proved that when changing over to twice-purified " Haifa " furnace fuel, maintained at a final temperature of 125° F. at the fuel pumps, the fuel-consumption records at full load (3300 b.h.p. at 115 r.p.m.) actually improved about 1 %. The gross calorific value of the Diesel fuel was 19,250 B.Th.U.s with a specific gravity of 0·887. The corresponding figures of the Haifa furnace fuel before purification were 18,650 B.Th.U.s and 0·947 specific gravity, the viscosity at 100° F. being 1150 sec. Redwood 1. (During purification the temperature of the furnace oil was kept at 180° F.) The better fuel consumption figures with the furnace oil were no doubt partly due to a slight increase in the maximum firing pressures and partly to a possible reduction in irrecoverable fuel-oil leakages. After the main engine was installed in the ship, the first dock trial and the sea trials were carried out from beginning to end on the furnace oil, no Diesel-grade fuel being used for starting up or shutting down the engine. The heated furnace oil was being circulated through the fuel system while the engine was stopped.

The properties desired in Diesel fuels by various authorities are summarised in the British and American specifications given in the following tables. Typical analyses of Diesel fuels from different sources are also tabulated.

BRITISH DIESEL-FUEL-OIL SPECIFICATIONS

	British Admiralty Diesel Oil.	Pool Gas Oil No. 21. 1942.	D.E.U. Assn. for High-speed Engines. 1937.	B.S.I.		Engine Builders' Specification.‡	
				Class A.	Class B.	Medium Speed.	Low Speed
Type	Distillate	Distillate	Distillate				
Viscosity, Redwood No. 1 at 100° F.	45 sec. max.	32–40 sec.	30–45 sec.	31–45 sec.	100 sec.	75 sec. max.	250 sec. max.
Centistokes at 100° F.	7·5 max.	3–6·1	2·1–7·5	2·5–7·5	24 max.	17 max.	64 max.
Closed flash, ° F.	175 min.	150 min.	150 min.	150 min.	150 min.	150	150
Sulphur, %	1·5 max.	1·0 max	1·0 max.	1·5 max.	2·0 max.	—	—
Conradson coke, %	0·2 max.	0·05 max.	0·2 max.	0.1 max.	2·0 max.	2·0 max.	3·0
Ash, %	0·01 max.	0·01 max.	0·01 max.	0·01 max.	0·03 max.	0·01	0·05
Water, %	0·1 max.	0·05 max.	0·05 max.	0·1 max.	0·25 max.	0·5 †	1·0
Mineral acidity	Nil	Nil	Nil	Nil	Nil	—	—
Hard asphalt, %	0·1 max.	—	0·1 max.	—	—	1·0	2·0
Pour point, ° F.	20 max.	—	—	—	—	20	35
% Distilling at 350° C.	85 min.	85 min.	85 min.	85 min.	—	—	—
Cetane number	50 min.	45 min.	50 min. (Cetene) *	45 min.	23 min.	40 min.	30 min.
Diesel index	53 min.	48 min.	—	48 min.	23 min.	41 min.	30 min.
Gross calorific value B.Th.U.	19,000 min.	—	—	19,000 min.	18,500 min.	—	—
Aniline no.			60° C.				

* Cetane numbers are about 15% lower than cetene numbers.
† Water and sediment.
‡ Harland & Wolff, Limited.

TABLE 12-5 *

(American) Fuel Requirements for Diesel Engines (a)

Grade of Diesel Fuel Oil.(b)	Flash Point F,(c) min.	Pour Point, F.(d)	Water and Sediment, % by Volume, max.	Carbon Residue, % by Weight, max.	Ash, % by Weight, max.	Distillation Temperatures, F.		Viscosity at 100° F.			Sulphur, % by Weight, max.(g)	Corrosion.	Alkali and Mineral Acid.	Cetane Number, min.
								Kinematic, centistokes.		Saybolt Universal, sec., max.				
						90% Point, max.	End Point, max.	Min.	Max.					
No. 1-D	100 or Legal	—	0·05	0·05 (e)	0·01	550 (f)	—	—	—	—	0·5	Pass	None	40
No. 2-D	140	—	0·05	0·25 (e)	0·01	650	700	2·0	6·0	45·5	1·0	Pass	None	45
No. 3-D	140	—	0·10	0·25	0·02	—	—	—	12	65	1·5	—	None	35
No. 4-D	140	—	0·50	2·00	0·10	—	—	—	—	140	2·0	—	None	30

(*a*) With the exception of the changes in the estimation of Conradson carbon, pour point, ash, 90% point, and cetane number, these requirements are the same as those listed in the Diesel Fuel Oil Classification published in the *Proceedings of the American Society for Testing Materials*, Vol. 41, 1941.

(*b*) No. 1-D Diesel fuel is a distillate fuel of high volatility for use in high-speed engines (speed range above 1200 r.p.m.): No. 2-D is a distillate fuel of medium volatility for high-speed engines (speed range above 1200 r.p.m.); No. 3-D is a distillate fuel of low volatility for medium-speed engines (speed range between 500 and 1200 r.p.m.): and No. 4-D is a viscous fuel for low-speed engines (speed range below 500 r.p.m.).

(*c*) The flash point has no bearing on performance of a fuel in an engine. However, it is required for storage, or for legal limits.

(*d*) To avoid flow restrictions in cold weather, the pour point of a Diesel fuel must be specified at least 10° F. below the lowest fuel temperature reached in service.

(*e*) On 10% residuum.

(*f*) Set to assure a light fuel for critical service, where smoking on heavier stock might be objectionable.

(*g*) Although the information regarding the absolute maximum limits for sulphur is still inconclusive, recent evidence indicates that the sulphur permissible in these recommendations may be excessive.

* *S.A.E. Journal*, March 1945.

ANALYSIS OF TYPICAL DIESEL FUELS

	High-speed Engine Fuels.						Air-blast Engine Fuels.			
	Shell Diesoline.	Shell Diesoleum.	Scottish Shale Oil.	Argentine Gas Oil.	Standesol Grade "A."	Pool Gas Oil.	Grosny Fuel Oil.	Mexican Fuel Oil.	Californian Fuel Oil.	Origin Unknown.
Specific gravity at 60° F. .	0·834	0·844	0·833	0·868	0·842	0·850	0·905	0·897	0·937	0·902
Viscosity, Redwood No. 1 at 70° F. (sec.)	38	41	35	59	35	43	606	474	1601	566
Viscosity, Redwood No. 1 at 100° F. (sec.)	33	35	32	42	33	36	272	242	625	222
Closed flash point, ° F. .	176	208	182	163	213	165	188	204	218	198
Open flash point, ° F. .	194	230	—	193	—	198	210	220	238	226
Fire point, ° F.	226	258	-	228	-	—	241	—	270	—
Ash, % . .	Nil	Nil	0·003	0·008	Nil	—	0·03	0·03	0·08	0·03
Conradson coke, % .	0·56	0·64	0·01	0·86	—	0·06	—	—	4·50	6·02
Hard asphalt, %	0·10	0·10	Nil	0·08	Nil	Trace	2·63	0·10	6·09	2·24
Sediment, % .	Trace	Trace	0·007	0·01	Trace	Trace	0·07	0·46	0·21	0·18
Sulphur, % .	0·55	0·71	0·54	0·24	0·75	0·86	0·12	—	1·00	1·85
Gross calorific value, B.Th.U.	19,600	19,475	19,600	19,520	19,650	19,640	19,200	19,250	18,740	18,750
Cetane number.	—	—		—	53	57	—		--	—
Diesel index .	—	-	—	—	62	55	—	—	—	—

	Medium- and Low-speed (Airless-injection) Diesel-engine Fuels.									
	B.P. Persoleum.	Californian Diesel Fuel.	Iranian Marine Diesel Fuel.	Venezuelan Diesel Fuel.	Balik Papen Diesel Fuel.	Mexican Diesel Fuel.	Borneo Diesel Fuel	Stanvac Diesel Fuel.	Pool Marine Diesel Fuel.	Shell Diesel Fuel.
Specific gravity at 60° F. .	0·914	0·910	0·870	0·889	0·903	0·882	0·923	0·859	0·895	0·863
Viscosity, Redwood No. 1 at 70° F. (sec).	222	72	66	65	63	65	81	52	52	46
Viscosity, Redwood No. 1 at 100° F. (sec.)	107	51	48	47	46	45	50	37	41	39
Closed flash point, ° F. .	172	167	176	176	203	194	190	198	167	189
Open flash point, ° F. .	208	196	201	214	223	215	208	215	185	210
Fire point, ° F. .	—	225	234	237	255	239	239	248	219	—
Ash, % . .	0·007	0·03	0·01	Trace	0·01	0·01	0·01	0·005	0·003	Trace
Conradson coke, % . .	3·59	2·27	1·90	1·75	1·46	1·50	1·24	0·70	0·50	1·26
Hard asphalt, %	3·79	2·16	0·81	0·74	0·12	0·50	0·20	0·01	0·05	0·22
Sediment, % .	Trace	0·05	0·01	0·28	0·17	0·26	0·07	Trace	Trace	0·03
Sulphur, % .	—	0·69	1·04	0·78	0·23	0·88	0·20	0·50	0·65	0·42
Gross calorific value, B.Th.U.	—	18,950	19,320	19,200	19,150	19,300	19,120	19,550	19,300	19,440
Cetane number.	—	—	—	--	—	—	—	—	46	—
Diesel index .	—	—	—	—	—	—	—	—	44	—

CHAPTER VI

PROPERTIES OF DIESEL LUBRICATING OILS

50. *Composition and Constitution.*—Mineral oils compounded with a certain amount of vegetable oil are sometimes preferred for use in air compressors. Apart from this application, straight hydrocarbon oils obtained from the heavy constituents of petroleum crude oils are used almost exclusively in modern Diesel-engine practice. Such hydrocarbon oils are mixtures of homologous series varying with the country of origin of the crude oil from which they are obtained (see Chapter II). It should be pointed out, however, that while most crude oils contain hydrocarbons of the lubricating-oil viscosity range, all hydrocarbons of suitable viscosity do not necessarily possess the other properties desirable for good lubricants.

Lubricating oils derived from the crudes of Pennsylvania and Ohio consist mainly of paraffins (C_nH_{2n+2}), with smaller amounts of olefines (C_nH_{2n}) and acetylenes (C_nH_{2n-2}). It is only in lubricating oils of low viscosity, however, that the paraffins predominate; the heavier-bodied oils are largely composed of the C_nH_{2n} series from $C_{12}H_{24}$ to $C_{18}H_{36}$, and of the acetylene series C_nH_{2n-2}, from $C_{19}H_{36}$ to $C_{22}H_{42}$. They usually contain a certain amount of paraffin wax and therefore tend to have high pour points.

Oils obtained from asphaltic-base crudes consist mainly of the olefines (C_nH_{2n}) and asphaltic hydrocarbons of type C_nH_{2n-4}; such lubricating oils cover a wide range of viscosity and have relatively low pour points.

Lubricating oils from Russian crudes are composed almost entirely of naphthenes (C_nH_{2n}). They contain practically no paraffin wax. Their specific gravity is relatively high, and the viscosity index is low (see Section 51). These statements apply also to oils of asphaltic base, in contrast to oils of paraffinic base which are characterised by low gravity and high viscosity index.

At one period there was a widespread preference for paraffinic-base lubricating oils for Diesel-engine lubrication; latterly there has been a tendency to attach less importance to the high viscosity index of paraffinic oils and more importance to the naturally detergent properties of naphthenic oils, which are valuable for the avoidance of piston-ring sticking and choking of ports. Paraffin-base oils give, as a rule, hard, tenacious carbonaceous deposits, whereas oils of naphthenic base leave deposits of a soft, non-adherent consistency. In recent years the natural " hard-carbon "-forming propensities of paraffinic-base lubricating oils have been mitigated by means of additives (see Chapter VII).

LUBRICATING OILS

	Base.		
	Paraffinic.	Naphthenic.	Asphaltic.
Geographical sources	Pennsylvania Ohio	Russia	Texas California Mexico Venezuela
Homologous series	Paraffins Olefines Acetylenes	Naphthenes	Olefines Asphaltic
Specific gravity	Low	High	High
Pour point	High	Low	Low
Viscosity index	High	Moderate	Low
Natural detergency	Low	High	Moderate
Carbon deposits	Hard, tenacious	Soft, non-adherent	Soft, non-adherent
Chemical stability	Good	Good	Poor

51. *Viscosity.*—This may be described as the " body " of an oil or its resistance to flow; it is a measure of the inherent fluid friction of an oil and is an important factor in its capacity to withstand high pressure in service. Viscosity is one of the two properties of an oil which render hydrodynamic lubrication possible; the other property is that of adhesion to solid surfaces (see Sections 54 and 60). The internal friction of viscous or heavy-bodied oils is greater than that of lighter oils, and since

friction causes heat it is manifest that an oil having as low a viscosity as will maintain an adequate lubricating film between the wearing surfaces under the operating pressure and temperature, is desirable; this is emphasised by the fact that the bearing oil is also used for piston cooling in many cases, and, as a coolant solely, a still lower viscosity would be advantageous. Too low a viscosity of the bearing oil would jeopardise the oil film, with disastrous results in the way of wiped or worn bearings.

An oil of higher viscosity is generally desirable in large engines for power-cylinder lubrication, particularly during the "running-in" period, in order to maintain the lubricating film between the piston-rings and the cylinder; but too viscous an oil is to be avoided. In the first place, such an oil may not spread freely over the cylinder walls from the points of injection spaced around the cylinder, and secondly, any solid impurities in the combustion gas will be held by the oil, thus tending to build up undesirable deposits. Moreover, an unduly viscous oil and/or over-lubrication has been found to result in the deposition of excessive amounts of carbonaceous matter near exhaust ports and in exhaust manifolds. Deposits in exhaust ports may restrict the area of exhaust, while in air manifolds it not infrequently happens that the deposit ultimately ignites, causing a scavenge fire.

The viscosities of all oils decrease with increase of temperature; in other words, the oil loses "body" and flows more easily. By plotting the viscosity of an oil against temperature a curve is obtained, the slope of which represents the rate of fall of viscosity with increased temperature. An oil which falls off rapidly in viscosity with rise of temperature is said to have a steep viscosity curve or a high-temperature coefficient of viscosity. On the other hand, an oil the viscosity of which falls off relatively slowly with temperature increase is said to have a flat viscosity curve or a low-temperature coefficient of viscosity. Typical curves are shown in Fig. 12.

A method of expressing numerically the viscosity–temperature coefficient is afforded by the viscosity-index system of Dean and Davis (11) which is widely used in the oil industry and often appears in modern specifications. The flatter the temperature–viscosity curve, the higher the viscosity index of the oil, and vice versa. To obtain the viscosity index according to this system the viscosities of the oil at 100° F. and 210° F. in Saybolt seconds or centistokes, preferably the latter, are first determined. Reference is then made to tables (see Appendix III) which give the viscosities at 100° F. of two series of oils, one having a very flat viscosity–temperature curve (*H* series) and the other a very steep curve (*L* series), but both having the same viscosity at 210° F. The oils of the *H* series are assigned a viscosity index of 100, and those of the *L* series a viscosity index of 0. The viscosities at 100° F. of oils of the *L* and *H* series having the same viscosity at 210° F. as the oil in question are obtained from the table.

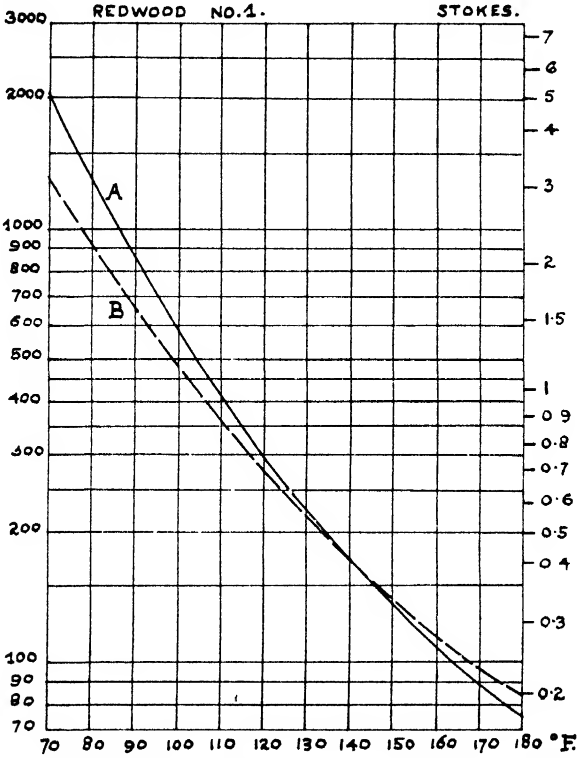

FIG. 12.—VARIATION OF VISCOSITIES OF LUBRICATING OILS WITH TEMPERATURE.
A, Naphthenic-base Oil; B, Paraffin-base Oil.

Then,

$$\text{Viscosity Index} = \frac{L - U}{L - H} \times 100$$

in which L = Viscosity at 100° F. of 0 viscosity-index oil; H = Viscosity at 100° F. of 100 viscosity-index oil; U = Viscosity at 100° F. of the sample under examination.

To improve the viscosity index of lubricating oils, additives are sometimes used in modern practice, but this development finds a greater application in oils for aero-engines which operate at temperatures in excess of those customary in Diesel-engine practice.

Although viscosity is most accurately measured by an absolute viscometer of the capillary-tube type (Chapter VIII), it is usually determined in commercial practice by measuring the time in seconds for a given volume of oil to flow through a standard aperture. The standard dimensions of the apertures of the viscometers most widely used and the relevant oil volumes are as follows :

Viscometer.	Aperture Dimensions in mm.	Volume of Oil Discharged.	Oil Volume in Viscometer.
Redwood . .	1·5 dia. × 10 long	50	130
Saybolt . .	1·8 dia. × 13 long	60	70
Engler . .	2·9 top 2·8 btm. × 20 long	200	240

Viscosity should be specified at two or three temperatures to cover, as far as possible, crankcase, bearing and cylinder-liner temperatures. Redwood viscosity is usually specified at 70° F., 140° F. and 200° F., Engler at 50° C. and 100° C., Saybolt at 100° F. and 210° F. For conversion from one scale to another see Appendix I.

Viscosity increases with pressure, the relationship depending on the grade of oil and the temperature; typical figures are tabulated under :

Pressure, lb./sq. in.	Viscosity ÷ Viscosity at 14·7 lb./sq. in.	
	Castor Oil.	Mineral Oil.
14·7	1	1
2,000	1·1	1·2
4,000	1·3	1·8
6,000	1·8	2·5
8,000	2·5	3·4
10,000	3·4	5·2

Lubricating oils are often classified according to their viscosity, as exemplified in the S.A.E. scheme appended.

S.A.E. STANDARDS OF VISCOSITY RANGE

S.A.E. No.	Saybolt, sec.		Redwood No. 1, sec.		Absolute Viscosity, Centipoises.	
	At 130° F., 54° C.	At 210° F., 99° C.	At 130° F., 54° C.	At 210° F., 99° C.	At 130° F., 54° C.	At 210° F., 99° C.
10	90–120	-	76–103	-	16 –22½	—
20	120–185	- -	103–160	—	22½–35	
30	185–255	—	160–220	–	35 –50	-
40	255–	–	220–	—	50 –	–
50	—	75–105	—	65– 88	-	13–19
60	—	105–125	—	88–110		19–24
70	-	125–150	–	110–130	–	24–28½

The lubricating-oil requirements of Diesel engines, in respect of viscosity, are fully covered by Nos. 30 and 40 in the above standards.

52. *Resistance to Oxidation.*—This covers resistance to the formation of sludge and carbonaceous deposits and also the development of undue organic acidity. In the crankcase system of Diesel engines the lubricating oil is continually churned up with air at temperatures ranging from 120° to 140° C. or more, conditions which are conducive to oxidation of the hydrocarbons, and this tendency is aggravated by contact of the hot oil with the surfaces of copper alloys in the system and also iron dust, which act as catalysts or accelerators. The first evidence of oxidation having taken place is the gradual darkening of the oil, accompanied by some development of organic acidity and a slight thickening of the oil as the period of service lengthens. This is an indication that oxidation products have been formed, and in the early stages these products are held in solution in the oil. As the oxidation progresses, the viscosity increases further, and, arising from polymerisation (i.e., the combination of similar hydrocarbon molecules), bodies of high molecular weight are formed, which are insoluble in the oil; these are deposited in the form of sludge. This sludge settles on cooler tube and other metallic surfaces and in the presence of any water in the oil forms emulsions which tend to hold any extraneous matter present. In this way, appreciable deposits may build up in the rather limited spaces between oil-cooler tubes and seriously

affect the cooling efficiency. Sludge also tends to collect in the oil grooves of the bearings through which the oil passes in the system, thus restricting the oil passages. A further stage in the oxidation of the oil produces asphaltic matter, and if taken to finality, carbon, but such complete breakdown rarely occurs and only takes place under high-temperature conditions.

Resistance to oxidation is thus associated with resistance of the oil to decomposition by heat. The bearing oil in circulation in Diesel engines is frequently used for piston cooling, and an oil which is already oxidised is less resistant to decomposition by the hot surface of the piston crowns and yields an excessive amount of carbon. The building up of carbon in the piston head seriously reduces the cooling effect of the oil and is liable to lead to cracked pistons.

The increase in organic acidity resulting from the oxidation of the oil is not disadvantageous provided it does not reach a point at which it becomes corrosive to metals; this rarely happens. On the contrary, small contents of organic acidity increase the " oiliness " and the lubricating value of the oil.

Some measure of the resistance of an oil to oxidation is obtained by the change in viscosity and coke value or by the quantity of sludge formed on passing air or oxygen through a heated sample of oil. In the Michie sludging test a specified volume of the oil is heated at a fixed temperature for a given time, during which air is bubbled through the oil at a constant rate. The oxidation products so formed are then extracted and weighed. An oil for crankcase use should have a Michie sludge value not exceeding 0·5%.

The British Air Ministry test is very similar, but the temperature of heating the oil is lower, and the oxidation products are not estimated. The viscosity and coke value of the oil are measured before and after heating. Preference should be given to the oil, particularly for small high-speed Diesel engines, which shows the least increase in viscosity or coke value, and in no case should the ratio of the final viscosity to the original viscosity exceed 2·5 for a bearing oil.

53. *Carbon Residue.*—The carbon-forming propensities of an oil are of importance in cylinder lubricants, particularly for high-speed engines, not only in respect of the amount but also the character of the carbonaceous residue. Some of the oil

which passes the piston is decomposed by heat, leaving carbonaceous residues in the combustion space which tend to collect on the oil on the cylinder wall and ultimately work down below the piston into the crankcase. Conradson's or Ramsbottom's coke test gives some indication of this carbon-forming tendency, and both measure the coke residue remaining when an oil is strongly heated in the absence of excess air under prescribed conditions (see Chapter VIII), so as to drive off the oil as vapour. The Conradson value of a dual-purpose crankcase and cylinder oil should preferably not exceed 0·25%. The coke value generally increases with the viscosity of the oil, which is another reason why oils with as low a viscosity as is consistent with the maintenance of the oil film should be used.

The results afforded by these tests do not always correspond with the behaviour of the oil in service, and the authors have found a "baking" test to be a more reliable guide; this is essentially an evaporative test carried out by heating a given weight of the oil in a shallow platinum receptacle of specified diameter, at a temperature of 270–280° C., which is higher than that expected at the top piston-ring. The amount and character of the residue remaining after all volatiles have been driven off at this temperature is noted. Oils giving a high percentage of carbonaceous residue of a hard, adherent type are apt to give rise to piston-ring sticking after a short period of service, whereas those leaving a low percentage of residue, less than 7%, have generally been found to give satisfactory running over long periods of service. As shown by the undernoted data, there is some correlation between the results of this test and the Conradson values, but the latter do not bring out the difference so strikingly or disclose the character of the residue to be expected in the piston grooves.

Oil.	Specific Gravity.	% Residue by Baking Test.	Conradson Coke Value.
A	0·916	3·4	0·14
B	0·937	4·3	0·11
C	0·915	7·4	0·15
D	0·898	7·9	0·13
E	0·892	12·1	0·27
F	0·895	15·3	0·66
G	0·884	20·3	0·72

Viscosity of above oils at 140° F. = 170–180 sec. Redwood No. 1.

The feature of these results is that, in general, oils of paraffin base having a low specific gravity and high viscosity index give the highest residues, while higher gravity oils of mixed or naphthenic base give low residues usually of a non-adherent type.

54. *Oiliness.*—This rather vague term is applied to the property in oils of molecular adhesion to metallic surfaces whereby static friction is reduced. In fluid-film lubrication there is a continuous film of oil between the moving parts, and oiliness does not come into play, but when pressure or temperature is increased to a high degree, so-called boundary lubrication may result; under such conditions it is the oiliness of the oil that is important. Full hydrodynamic lubrication is essential for any bearing subjected to any considerable peripheral speed. With boundary lubrication the coefficient of friction would be impossibly high for continuous operation. The property of oiliness enables a bearing to run for a short time under conditions of boundary lubrication; the consequent rise of temperature makes the oil more fluid and perhaps facilitates the re-establishment of full hydrodynamic lubrication. In any case, boundary lubrication exists in any bearing for a few seconds at starting and stopping. So far as is known, oiliness bears no relation to the physical properties of an oil, but has been identified with the stability of very thin films on metallic surfaces. Oiliness is somewhat greater in high-viscosity oils than in low-viscosity oils of the same type, yet two oils may have the same viscosity and the oiliness be greater in one than in the other. A high degree of refining may reduce oiliness by removing some of the polar constituents which contribute to oiliness. For example, a highly refined oil product such as medicinal paraffin has less oiliness than a normally refined oil of the same viscosity; again, a high degree of refining, as often practised to lower pour points, can adversely affect oxidation resistance because constituents which act as oxidation inhibitors are removed in the process.

55. *Pour and Setting Points.*—When lubricating oils are cooled they gradually become more and more viscous until they finally congeal or set; the temperature at which this occurs is called the setting point, and is measured by cooling the oil by a freezing mixture in a standard apparatus and noting the temperature at which, under slight pressure, the oil remains

stationary. The lowest temperature at which the oil just flows is called the pour point, and this is usually about 5° F. above the setting point. It should be mentioned that the pour point of an oil may be affected by the previous thermal treatment it has received; for example, if an oil is heated to a temperature of, say, 200° F. immediately before testing, its pour point may, according to the base of the oil, be higher or lower than it would be if the previous heating had not taken place. In order to standardise the conditions in this respect, the oil should be heated to 115° F. immediately before the pour point is determined. The pour point of a mineral oil is largely associated with the paraffin-wax content, and hence it comes about that Russian and other non-paraffinic-base oils have appreciably lower pour and setting points than have paraffin-base oils. From a practical point of view, the pour point of an oil leaves something to be desired in that it affords no information on the behaviour of the oil under agitation or pressure by which the wax structure tends to become broken up. However, the admissible pour point for service depends on the facilities (if any) which are available for keeping the oil warm under service conditions.

56. *Demulsibility.*—Owing to the risk of contact with water derived possibly from leaky jacket joints or oil-cooler tubes, Diesel-engine crankcase oil should have a low emulsification tendency with water. While hydrocarbon lubricating oils generally have a low affinity for water, this affinity differs appreciably with different oils, the difference being attributed to the presence of very small percentages of unstable hydrocarbons and of impurities such as sulphur derivatives, mercaptans and thio-ethers. Apart from this inherent difference the not-infrequent presence in crank-chamber oil, after a short period of service, of colloidal carbonaceous matter and finely divided iron oxide and metallic iron, leads to the development of emulsifying tendencies in the oil, and often promotes the formation of emulsions with water which separate very slowly. The desirability of the removal of water from an oil by systematic treatment in centrifugal purifiers before emulsion troubles arise and of the selection of an oil with strong demulsifying properties will therefore be apparent; the latter may be determined by shaking definite quantities of oil and water and measuring the

rate of separation and the amount of scum remaining, or other tests on the same lines.

57. *Flash Point.*—This is the lowest temperature at which an oil, when heated at a controlled rate, gives off sufficient vapour to ignite or flash upon the application of a test flame. The closed flash point, being that obtained under conditions which prevent escape of the vapours, is always lower than the open flash point, which is determined in a vessel open to the atmosphere. The closed flash point is on an average 25–30° F. lower than the open for Diesel crankcase oils, and 30–40° F. for cylinder oils.

A reasonably high flash point simply affords some indication of a well-refined oil and freedom from low-volatile constituents. On the other hand, a low flash point gives an indication of the presence of volatile constituents, and an oil containing an undue proportion of these lower hydrocarbons may result in a high oil consumption. At the same time it is not a measure of the volatility of an oil. Flash point is not correlated in any way with the lubricating properties of an oil, and a high flash point does not afford any measure of the ability of an oil to resist decomposition by heat and carbonising tendencies, as is sometimes supposed; oils with very high flash point generally contain a high proportion of residual cylinder oil, and the small portion which passes the piston-rings and enters the combustion space is slowly baked rather than burnt, leaving a deposit of carbon.

58. *Specific Gravity.*—This is the weight of unit volume of the oil compared with that of unit volume of water at the same temperature, the standard being 60° F. It is most readily determined by means of a graduated hydrometer or more accurately by the weighing method which involves the use of an accurate chemical balance. Specific gravity may afford some indication of the base and natural source of a lubricating oil, in view of the appreciable difference existing in this characteristic between paraffinic- and non-paraffinic-base crudes. When an oil has been treated by a solvent-refining process, however, such clues as to the base oil are largely removed, since this process of refining appreciably lowers the specific gravity irrespective of the base. As a general rule, oils of low specific gravity possess viscosities which are not affected by temperature to so great an extent as oils of higher specific gravity, but,

on the other hand, low-gravity oils generally leave higher coke residues. Specific gravity cannot be said to bear any direct relation to the lubricating properties of an oil, and it is only really useful as an identification test of a particular oil or in connection with weight-to-volume relationships. The specific gravity of most oils, vegetable and mineral, decreases with temperature at the rate of about 7% per 100° C.

59. *Specific Heat.*—The specific heat of a lubricating oil is the quantity of heat required to raise the temperature of any weight of the oil 1° C. as compared with the quantity of heat required to heat the same amount of water 1° C.; this definition is not strict, but is near enough for practical purposes. In view of the widespread use of crankcase oil for piston-cooling purposes, the specific heat of the oil used is required for thermal calculations.

Early investigations by Mabery and Goldstein (12) indicated that the specific heats of the paraffin series of hydrocarbons are higher than those of the naphthenes and other hydrocarbon series containing a lower percentage of hydrogen than the paraffins; other workers have shown that the freer an oil is from asphalt the higher is the specific heat, and further, that the specific heat of all hydrocarbon oils increases as the temperature of the oil increases.

According to the U.S.A. Bureau of Standards (13) the specific heat of lubricating oils in the liquid state at different temperatures is closely related to their specific gravities at corresponding temperatures. From this it follows that the specific heats of oils of differing origins can be calculated at varying temperatures. The formula, which is approximately correct to ± $2\frac{1}{2}$%, is as follows:

$$c = \frac{1}{\sqrt{d}}(0{\cdot}388 + 0{\cdot}00045t),$$

where c = specific heat in B.Th.U's per lb. per ° F. or calories per gm. per ° C.; d = specific gravity at 60°/60° F.; t = temperature in ° F.

Specifications for Diesel-engine lubricating oils issued by (1) Diesel Engine Users' Association, (2) British Admiralty, (3) U.S. Army, and (4) An Engine Builder (Harland & Wolff, Ltd.) are given in the following tables:

DIESEL ENGINE USERS' ASSOCIATION

Specification for Lubricating Oils for Use on Heavy Oil Engines

	"L. 1."	"M. 1."	"H. 1."
Specific gravity at 60° F.	Not exceeding 0·882	Not exceeding 0·885	Not exceeding 0·888
Closed flash point	Not below 400° F.	Not below 400° F.	Not below 400° F.
Viscosity Redwood No. 1 sec.:			
at 70° F.	Not exceeding 700.	Not exceeding 1250.	Not exceeding 1800.
at 200° F.	Not less than 50.	Not less than 56.	Not less than 68.
Cold test or pour point	Not higher than 35° F.	Not higher than 35° F.	Not higher than 35° F.
Colour (by transmitted light) *	Clear red or yellow.	Clear red or yellow.	Clear red or yellow.
Demulsibility †	2 minutes.	3 minutes.	4 minutes.
Total sulphur	Not exceeding 0·5%.	Not exceeding 0·5%.	Not exceeding 0·5%.

	"L. 2."	"M. 2."	"H.C."
Specific gravity at 60° F.	Not exceeding 0·915.	Not exceeding 0·918.	Not exceeding 0·920.
Closed flash point	Not below 375° F.	Not below 375° F.	Not below 375° F.
Viscosity Redwood No. 1 sec.:			
at 70° F.	Not exceeding 1300.	—	—
at 140° F.	—	Not exceeding 190.	Not exceeding 230.
at 200° F.	Not less than 52.	Not less than 60.	Not less than 68.
Cold test or pour point	Not higher than 35° F.	Not higher than 35° F.	Not higher than 35° F.
Colour (by transmitted light) *	Clear red or yellow.	Clear red or yellow.	Clear red or yellow.
Demulsibility †	4 minutes.	6 minutes.	8 minutes.
Total sulphur	Not exceeding 0·8%.	Not exceeding 0·8%.	Not exceeding 0·8%.

The oil shall be a STRAIGHT MINERAL OIL.

Method of testing: Institution of Petroleum Technologists. No tolerances allowed.

* Where engines are likely to be exposed to abnormally low temperatures a low cold test should be specified.

† Where oils are required for engines in which there is a liability for water to become mixed with the oil in the crankcase. i s advisable for buyers to make the above stipulation regarding the demulsibility test of oils supplied, otherwise the abov lemulsification clause can be omitted from the specification.

The specification covers oils which are suitable for all purposes on a heavy oil engine, excepting that for some air compressor t is desirable to use a slightly compounded oil.

ADMIRALTY SPECIFICATION FOR LUBRICATING OIL FOR INTERNAL COMBUSTION ENGINES

Shall conform to the following characteristics :

(1) Specific gravity at 60° F.—Not exceeding 0·910.
(2) Closed flash point—Not less than 395° F.
(3) Viscosity (Redwood No. 1) at 70° F.—1500 sec. maximum.
,, ,, at 140° F.— 145–175 sec.
,, ,, at 200° F.— 60 sec. minimum.
(4) Acidity (expressed as mgm. KOH per gm. oil) :
(*a*) Inorganic acidity—Nil.
(*b*) Organic acidity—Not exceeding 0·1.
(5) Sulphur—Oil to be free from deleterious sulphur compounds.
(6) Ash—not exceeding 0·01%.
(7) Carbon residue—Ramsbottom I.P.T. 0·7% maximum.
(8) Pour point—not exceeding 25° F.

U.S. ARMY SPECIFICATION NO. 2-104B, MAY 6TH, 1943, FOR LUBRICATING OIL FOR INTERNAL COMBUSTION ENGINES

Test.	Test Limits.		
	Grade S.A.E. 10.	Grade S.A.E. 30.	Grade S.A.E. 50.
Viscosity, Saybolt Universal :			
sec. at 130° F.	90 to less than 120	185 to less than 255	—
sec. at 210° F.	—	—	95 to less than 105
Viscosity index, minimum . .	85	55	75
Pour point, ° F. maximum . .	−10	0	15
Pour point after dilution with 20% precipitation naphtha, ° F. maximum	−40	−40	—
Flash point, ° F., minimum . .	360	390	400 *

* The minimum flash point before the addition of any additive shall be 450° F.

BUILDER'S SPECIFICATION FOR LUBRICATING OILS

	A. Crank-case Oil.	B. Cylinder and Crank-case Oil.	C. Cylinder Oil.	D. Cylinder Oil for "Running-in" Purposes.	E. Compressor Oil.
Viscosity (Redwood No. 1) secs.:					
at 70° F.	700 min.	1300 min.		-	700 min.
at 140° F.	95–160	160–200	200–270	350–500	95–160
at 180° F.	55–75	75–100	95–125	150–220	55–75
at 200° F.	50 min.	60 min.	70 min.	105 min.	50 min.
Acidity (mgm. KOH/100 gm. oil):					
Inorganic	Nil	Nil	Nil	Nil	Nil
Organic	10 max.	10 max.	10 max.	10 max.	500 approx.
Conradson coke value	0·50% max.	0·50% max.	0·75% max.	0·75% max.	0·50% max.
Cold test or pour point	To be below 32° F.	To be below 32° F.	To be below 35° F.	To be below 35° F.	To be below 32° F.
Michie sludge value	1·0% max.	1·0% max.	—	—	—
Closed flash point	400° F. min.	400° F. min.	400° F. min.	400° F. min.	400° F. min.

Oils "A", "B", "C" and "D" to be pure mineral oils; oil "E" to be approximately 3–5% compounded.

As a general rule, oil "B" is used for main-engine crankcase lubrication in D.A. or S.A. 2C and 4C engines, and oil "C" for cylinder lubrication after the running-in period.

In generator engines, oil "B" is often used as a dual-purpose oil. For high-speed or high-temperature conditions, oil "C" can also be used as a dual-purpose oil.

KEY TO GRADES OF LUBRICATING OILS

	Four-cycle.				
	Double Acting.	Single Acting.			
		Cross-head.		Trunk.	
		Norm. I.	Press. I.	Piston Speed up to 4 m./sec.	Piston Speed 4–7 m./sec.
Cylinder .	D or C	B	B or C	B	B or C
Crankcase .	B	A or B	B	A or B	B or C

	Two-cycle.			
	Double Acting.	Single Acting.		
		Piston Speed up to 4 m./sec.	Piston Speed 4–7 m./sec.	Piston Speed 7–9 m./sec.
Cylinder .	D, C or B	B	B or C	B or C
Crankcase	B or C	A or B	B or C	B or C
Exhaust piston .	D, C or B	B	B or C	B or C

CHAPTER VII

DOPED OILS

60. *Improved Lubricants.*—The more severe operating conditions resulting from higher power output per cylinder, particularly in Diesel engines of the high-speed type, have led to a demand for improved lubricating oils. To keep pace with these demands, refining methods have been improved and solvent-extraction methods have made a notable step forward, but there is a limit to what can be accomplished in this direction; over-refining defeats the objective sought because of the removal of some of the polar constituents on which the lubricating properties depend and also of oxidation-inhibiting constituents. In recent years, therefore, there has been a definite trend towards the use of lubricating oils in which small percentages of additives, or " dopes " as they are called, have been incorporated. A very large number of these additives have been developed with the object of improving one or more characteristics of the oil. Such additives can be classified according to the function they are designed to fulfil, and, so far as Diesel lubricants are concerned, can be conveniently considered under four headings: (*a*) Oiliness and film-strength improvers, (*b*) Oxidation inhibitors, (*c*) Detergents and (*d*) Pour-point depressants.

61. *Oiliness and Film-strength Improvers.*—In general, all hydrocarbon oils may be considered as possessing oiliness and film strength of about the same order. Maag (14) has demonstrated that the film strength of straight mineral oils is directly related to viscosity. E. A. Evans (15) and J. H. Evans (16) respectively using different machines have investigated the effect of the addition of metallic soaps and esters on the film strength of mineral oils, and have shown that the esters have a greater beneficial effect on film strengths than metallic soaps. Further, according to E. A. Evans (*loc. cit.*) the film strengths of all mineral oils lie between 4000 and 5000 lb./sq. in. whereas fatty oils give much higher values, as following:

	lb./sq. in.
Rape oil	15,000
Blown rape oil	11,000
Seal oil	10,000
Olive oil	9,000
Castor oil	9,000
Lard oil	9,000
Sperm oil	8,000

At the same time, fatty oils possess a higher oiliness value as indicated by static friction tests.

Early locomotive and marine steam engines, as well as industrial engines of the same period, were lubricated with fatty oils of animal and vegetable origin such as tallow oil, lard oil, rape oil, etc.; the high degree of oiliness and film strength of these oils were no doubt very valuable in view of the meagre lubrication by drip or wick feed and the low standards of dimensional accuracy of these early engines.

With the advent of cheap mineral oils, the virtues of the fatty oils were retained, at least in part, by compounding mineral oils with a fractional amount (5–25%) of animal or vegetable oil. Such oils are still used for railway rolling-stock and reciprocating marine steam engines; also, in some cases, for the cylinder lubrication of the air-blast compressors of Diesel engines. The fatty oil is claimed to prevent the washing of oil off the cylinder surfaces by water of condensation. There is some experimental basis for this claim, Southcombe and Wells (17) having shown that the presence of free fatty acids in fixed oils lowers the interfacial tension between oil and water. In the authors' experience, an oil compounded to the extent of 3–5% is preferable for air-compressor-cylinder lubrication.

Some at least of the virtues of fatty oils appear to be concentrated in the fatty acids which they contain. Oiliness is characterised by the aptitude of an oil to form a strong adherent film on metallic surfaces, and this aptitude has been shown by several workers to be enhanced by the addition of fatty acids. Langmuir (18) and his colleagues demonstrated that a layer of a long-chain fatty acid such as oleic acid, only one molecule thick, considerably reduced static friction. The later experiments of Hardy (19) showed that each lubricant when tested in a special instrument gave a determinate value for the static coefficient of friction, which, however, depended to some extent on the metals concerned. The fatty oils gave low values as compared with mineral oils, and hopes were entertained that the hitherto elusive property of oiliness had been tracked to its source and was amenable to exact measurement. Later researches have not entirely supported these conclusions, although the importance of these pioneer experiments is widely recognised. It is not surprising to find, therefore, that oleic acid was probably the most widely used oiliness improver until recent times and provided the basis of the well-known "Germ Lubricants" of Southcombe and Wells; the amount of free fatty acid in these lubricants is of the order of 1%. Amongst later additives claimed to possess the property of improving oiliness may be mentioned mildly oxidised vegetable oils, esters of organic acids and halogenated derivatives of organic acids.

Finally, mention should be made of the use of oils to which colloidal graphite has been added. In view of the efforts made to minimise "carbon" formation, it seems at first sight superfluous to propose adding carbon in the form of graphite; but graphite is carbon in a very special form. It may be regarded as a crystalline substance with one plane of cleavage offering very little resistance to shear and conducing to the formation of thin, flat flakes. It may be that such flakes when surrounded with oil behave somewhat after the manner of self-adjusting Michel pads. In any case, it seems to be established that colloidal graphite when added to lubricating oil can perform a useful function during the "running-in" period of engine testing. It is easy to see how the presence of a powder offering great resistance to pressure but very little to shear may obviate or mitigate metallic contact between a piston and its cylinder liner, and enable the piston-rings to bed themselves to the liner in a slow and gentle manner, avoiding undue development of heat and subsequent seizing and scuffing. Apart from the "running-in" of replacement parts, there appears to be no object in using graphite in normal service.

62. *Anti-oxidants.*—The importance of any additive which will increase the oxidation stability of an oil requires no further emphasis (see Chapter IV). Unfortunately, this stability depends not only on that of the hydrocarbons themselves but also on the influence of oxidation catalysts, particularly copper and iron surfaces. Evans and Kelmore (20) showed that tin

and chromium oleates had a decided inhibitory effect on the oxidation of oils and that when using an oil containing 0·1% tin oleate and 0·8% chromium oleate, the amount of deposit produced in a series of engine tests was only 58% of that obtained with the undoped oil. Other substances which have been proposed and tested as oxidation inhibitors are easily oxidisable substances such as derivatives of phenols and naphthols, naphthylamines, organo-metallic compounds of phosphorus, arsenic, selenium and tellurium. Whether anti-oxidants function by reducing the oxidation-promoting tendency of the iron and copper surfaces or by inhibiting the oxidation of the oil itself, is in many cases an open question. Evans (*loc. cit.*) suggests the first of these two theories to explain the inhibitor effect of tin and chromium oleates.

Of all types of lubricating-oil additives, the anti-oxidants are perhaps the most generally useful and have come into fairly widespread service.

The views of the authors are that lubricating oils containing an oxidation inhibitor are to be preferred for crankcases of all types of Diesel engines, whether single-acting or double-acting, four-stroke or two-cycle, cross-head or trunk. Oils of this class can also be usefully employed as dual-purpose oils for crankcase and cylinder lubrication of trunk and cross-head engines.

63. *Detergents.*—The noun " detergent " means a cleansing agent. A detergent lubricating oil has one or both of the following properties :

(*a*) ability to wash away carbon deposits;
(*b*) ability to keep finely divided oxidation products in suspension instead of precipitating them on solid surfaces.

A " naturally detergent " oil possesses property (*a*) but not (*b*) in any marked degree. An oil rendered highly detergent (H.D.)* by means of additives, possesses both properties in a high degree and prevents the coagulation of the sludge which originates as finely divided colloidal particles. Many complex chemical compounds have been patented as detergent additives, but in the main, those in use are metallic soaps in some form or

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* (H.D.) is a contraction for " high duty." It is applied to lubricants (of high viscosity index) containing additives to increase detergency.

other; the amount of such a detergent usually incorporated in an oil is about 1%. Calcium phenyl stearate is an example of an effective detergent which also possesses the ability to break up large sludge particles into smaller ones, or, in other words, it is a good peptising agent. It is known that with oil as the liquid medium, peptising agents, to be effective, must consist of large organic molecules containing polar groups, and it is thought that these molecules are adsorbed to the particles by means of the polar groups, thus surrounding and protecting them.

Some additives which confer detergent properties on an oil may adversely affect the oil in other directions. For example, diphenyl stearates are very good detergents, but readily hydrolyse at high temperatures, thereby imparting acidity to the oil and rendering it corrosive. Metallic phenates, on the other hand, are good detergents and, on hydrolysis, form non-corrosive bodies, i.e., phenols, which have anti-oxidation properties.

Detergent oils should not be used indiscriminately, and there are certain precautions which should be observed when changing over from straight mineral to this type of doped oil.

(*a*) Filters or purifiers of adequate capacity must be provided to deal with the greater quantities of carbonaceous particles which may be expected to accumulate in the forced lubricating-oil system.

(*b*) Chemically active filters should not be used, otherwise the additive will be removed.

(*c*) Liquid sight-feed lubricators should be filled with distilled water, as the mineral salts present in tap water will form an emulsion with the additive and rapidly cloud the sight glasses, necessitating frequent cleaning.

(*d*) Copper–lead bearing metals should be avoided, as such metals are liable to corrosion attack by doped detergent oils; this effect may, however, be avoided by the incorporation in the H.D. oil of an anti-corrosive additive.

The changeover in large engines may conveniently be brought about gradually by topping up with the H.D. oil. In small auxiliary engines of low sump capacity, however, the old oil should be completely drained off while the engine is still warm, recharged with detergent oil, and the engine then run for a period of not less than 24 hr. The oil should then be again drained off, the sump and crankcase cleaned out, the filters cleaned and the sump refilled with new detergent oil.

Generally H.D. oils have a greater tendency to foam than undoped oils, and foaming will also be more marked in a dirty system than in one which is clean; the remedy for this is to prevent the admixture of air with the oil as far as is practicable.

Detergent additives are expensive and consequently "H.D." oils are appreciably higher priced than the best-quality straight mineral oils. The use of H.D. oils is only justified, therefore, in special circumstances such as with small engines of high output peculiarly prone to lacquering and piston-ring sticking, or where the extra expenditure involved is covered by the reduced maintenance costs consequent on the longer service periods between overhauls accruing from the use of the detergent oil. In the opinion of the authors, the use of oils containing detergent additives is not necessary for crankcase lubrication except for the smaller types of high-speed engines outside the usual marine or industrial range. Such oils, however, may be used to advantage as cylinder lubricants in cross-head types of engines, both two-cycle and four-stroke, in which the cylinder oil cannot become mixed with the crankcase oil. In trunk engines, in which a different grade of lubricating oil is used in the crankcase, the use of detergent oils is not recommended.

64. *Pour-point Depressants.*—In ships or stationary engines which have to operate in very cold climates, the low temperatures prevailing may give rise to trouble by the separation of small amounts of residual wax from both lubricating and fuel oil, thus preventing the oils from flowing freely. To meet such conditions, oils doped with a pour-point depressant are available. Alkyl naphthalenes in a concentration of between 0·1 and 1 % are representative of the additives used for this purpose, and by their use the pour point of an oil can be lowered to temperatures of 0° F. and less, provided the oil treated has a reasonably low pour point originally. One explanation of the action of additives of this type is that they prevent the crystallisation of wax by reason of their colloidal nature. In general, the effectiveness of pour-point depressants decreases as the viscosity of the oil increases.

65. *Doped Fuels.*—The incorporation of small percentages of additives in fuel oil with the object of improving ignition quality has also been tried. For this purpose, chemical compounds such as ethyl nitrate, amyl nitrate and organic polysulphides have been used; these dopes have the effect of materially reducing the ignition point of the fuel and have a smoothing effect upon the combustion. Broeze and Hinze (21) have shown that by adding 1–1½% of ethyl nitrate or acetone peroxide to mixed-base fuel oils an improvement in the cetane number of 23–29% was effected. Bogen and Wilson (22) also investigated the effect of ethyl nitrate, *iso*-amyl nitrate, commercial amyl nitrate and acetone peroxide when added to typical Diesel fuels, and found that apart from the improvement in ignition quality, flash point was the physical property most affected by the addition of these compounds. Their investigations also showed that these ignition accelerators when incorporated in either straight-run or cracked Diesel fuels do not promote combustion deposits and concluded that amyl nitrate is the ignition accelerator most likely to be used in the future, because of its commercial availability. However, to improve the ignition quality of a poor fuel sufficiently to make it satisfactory in a sensitive engine may require the addition of 3% or more of dope, and because of the prohibitive cost of such amounts, doped fuels have not found much commercial application; their use, at the most, seems likely to be limited to very high-speed engines.

CHAPTER VIII

ANALYSIS OF DIESEL FUELS AND LUBRICATING OILS

Many of the tests commonly applied in assessing the suitability of fuel oils are also applicable to lubricating oils and these are dealt with in Section A

SECTION A

66. *Sampling.*—No useful purpose is served by an engineer incurring the expense of a chemical analysis of an oil if the sample submitted is not truly representative of the bulk consignment; in taking samples, the first essential is that the sample container should be clean and dry and fitted with a suitable stopper. In sampling storage tanks, samples should be taken from the top, middle and bottom levels; if water be present to any appreciable extent it will be shown in the sample from the bottom to the greatest extent, in which case it is preferable to make separate analyses, at least so far as water is concerned. In the absence of water, however, and generally whenever possible, the three samples should be mixed and an average sample taken therefrom.

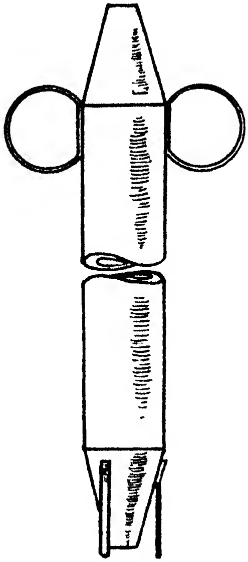


FIG. 13.—THIEF FOR SAMPLING DRUMS.

For sampling storage tanks a suitable device consists of a weighted metal cage which carries the sample bottle, the stopper of which is attached to a release cord. Before being lowered into the oil the bottle is loosely closed by the stopper, and when the bottle has been lowered to the position desired in the tank, the stopper is removed by jerking the cord.

Samples from barrels or drums can be conveniently drawn by means of a sampling " thief ". Such a thief may be a stout-walled glass tube of about 1 in. bore drawn out at the top and bottom and provided with lifting handles. Alternatively, it may be of tinned iron 36 in. long, $1\frac{1}{4}$ in. in diameter, tapering to a $\frac{3}{8}$ in. diameter at each end. Three legs equally spaced at the lower end give a clearance of $\frac{1}{8}$ in. from the bottom of the drum or barrel; two rings soldered on opposite sides of the tube at the upper end serve for holding the thief by slipping two fingers through them, leaving the thumb free to close the opening (Fig. 13).

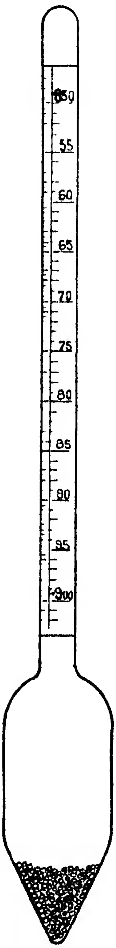


Fig. 14.—Hydrometer.

67. *Specific Gravity.*—Although specific gravity has largely lost its one-time significance as regards lubricating oils, and is, therefore, often omitted in present-day specifications, it is sometimes required by the engineer in charge to convert volume to weight, particularly in connection with fuel oil. Specific gravity may be determined by use of a hydrometer, or more accurately by a weighing method involving the use of a specific-gravity bottle or pyknometer and a chemical balance. The first-named method is most convenient to an engineer without a laboratory and, with due precautions, provides results sufficiently accurate for most purposes.

The hydrometer (Fig. 14) is a glass or metal float with a narrow stem and so weighted that when placed into an oil having a specific gravity between certain limits, only the stem projects from the oil; the stem is provided with a graduated scale, and the number on the scale which coincides with the meniscus of the oil indicates the specific gravity at the temperature of the oil. The range of specific gravity of all oils normally used for Diesel engines is covered by two of the series of standard hydrometers, viz., B and C, having limits of accuracy recognised by the Institute of Petroleum Technology.

In using a hydrometer the oil to be tested is poured into a clean, dry hydrometer jar which must be deep and wide enough to allow the instrument to float freely without touching the bottom and sides. The hydrometer is then carefully placed in the oil and allowed to sink by its own weight, after which it should be pressed slightly downwards and again allowed to come to rest in order to facilitate the formation of a uniform meniscus around the stem. The reading is then taken, placing the eye in the same horizontal plane as the meniscus; the temperature of the oil should immediately be taken, and the necessary correction made therefrom as indicated later.

68. *Specific-gravity Bottle Method.*—Bottles, consisting of a small glass vessel provided with a ground-glass stopper which is pierced with a small-diameter hole, can be purchased to contain a specified weight of water, usually 25 or 50 gm. at 60° F. Such a bottle, duly cleaned and dried, is first weighed and then filled almost to the top with the oil under test. The bottle is then allowed to stand for about half an hour to allow the escape of any trapped air and to attain temperature equilibrium. The stopper is then inserted and the bottle wiped clean on the outside from excess oil displaced in inserting the stopper, and carefully weighed. The temperature of the oil in the bottle is then taken immediately. By subtracting the weight of the empty bottle from that of the bottle of oil the weight of the oil contained in the bottle is obtained, and this weight divided by the weight of the water which the bottle is calibrated to hold at 60° F. gives the specific gravity at the temperature of the determination. Any deviation from 60° F. involves a small error, temperatures above 60° F. giving low values and conversely. The correction, which should be added for temperatures above 60° F. and subtracted when the temperature is below 60° F., averages 0·00035 for every 1° F. difference, or on the Centigrade scale, 0·00063 for every 1° C. For example, an oil having a specific gravity of 0·895 at 67° F. determined by either method would require correction to the extent of plus (7 × 0·00035), so that the specific gravity at 60° F. would be 0·8974.

A.P.I. gravity (American Petroleum Institute), which is largely used in the United States, is measured by a hydrometer and can be converted to specific gravity by applying the following formula :

$$\text{Specific Gravity } 60/60^\circ \text{ F.} = \frac{141{\cdot}5}{\text{Degrees A.P.I.} + 131{\cdot}5}$$

Twaddell's hydrometers are sometimes used for coal-tar products, and readings on this scale may be converted to specific gravity by use of the formula :

$$\text{Specific Gravity} = \frac{1000 + (5 \times \text{degrees Twaddell})}{1000}$$

69. *Flash Point.*—In this country the Gray and the Pensky-Martens apparatus are generally used for making the closed test, the latter being that specified by the B.E.S.A. for Diesel-engine fuels. The Pensky-Martens apparatus (Fig. 15) consists of a brass cup fitting loosely in a cast-iron body, by which it is supported on the top rim but not touching on either the sides or bottom. The cup is closed at the top with a cover fitted with a perforated slide, and a spring lever is provided which, when turned, rotates the cover. The cover also carries a stirrer and a thermometer so fixed as not to foul the stirrer. The oil to be tested is placed in the cup in such quantity as to just touch the prescribed mark on the inside of the cup; the cover is then fitted into position on the cup and heating of the apparatus by means of a suitable Bunsen burner commenced. During heating, the oil must be constantly stirred and the heating so adjusted as to give a temperature rise of the oil at the time of flashing of 7–8° F. per minute. As the oil approaches the temperature of flashing, the injector burner is lighted and injected into the oil container at 12-sec. intervals until a distinct flash is observed within the container. This gives the closed flash point.

The open flash point can conveniently be determined as part of the same operation, by removing the cover of the apparatus immediately the closed test has been completed and then continuing the heating, using a thermometer suspended from the arm of a retort stand and immersed in the oil as stirrer. The vapours emitted are tested with a small flame every half minute until flash occurs—i.e., the open flash. By still further continuation of the heating, the fire point can also be determined by observing the temperature at which the oil just begins to burn continuously.

70. *Viscosity.*—As indicated in Chapter V, viscosity for commercial purposes is usually determined in Great Britain by the Redwood viscometer, in the U.S.A. by the Saybolt and in Europe by the Engler. All these are similar in principle, and

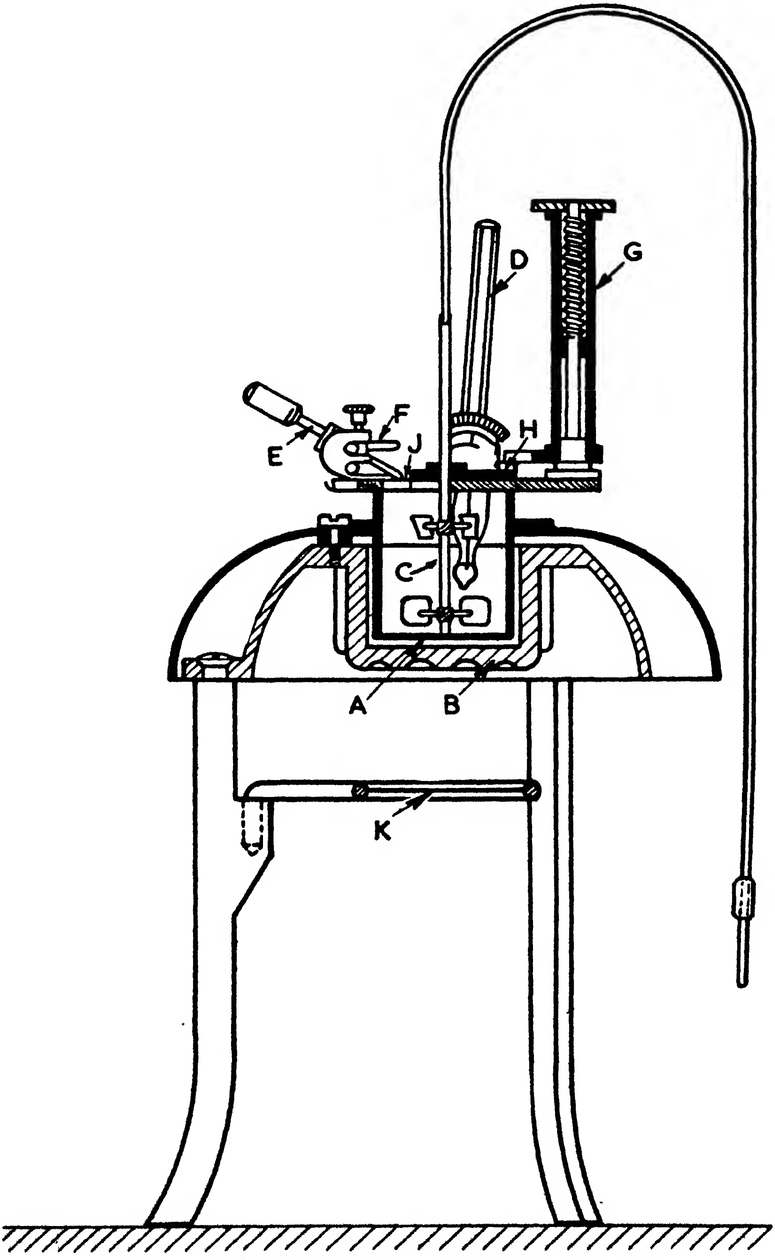


FIG. 15.—PENSKY-MARTENS FLASH-POINT APPARATUS.

A, Oil Cup; B, Heating Vessel; C, Stirrer; D, Thermometer; E, Ignition Burners; F, Pilot Burner; G, Spring Handle; H, Revolving Shutter; J, Orifice; K, Gauze Disc.

differ only in the volume of oil held in the container, the size of the aperture and the volume of oil, the efflux time of which is measured.

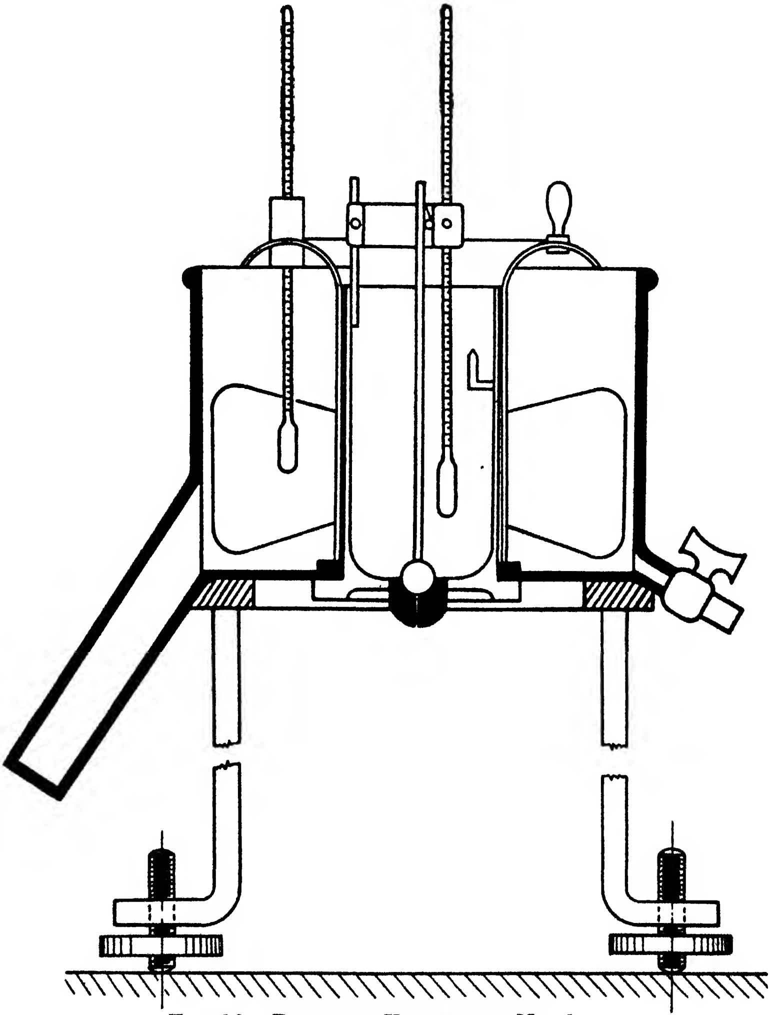
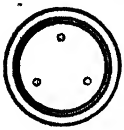


FIG. 16.—REDWOOD VISCOMETER NO. 1.

The Redwood viscometer (Fig. 16) consists of a cylindrical copper vessel silvered internally and provided with an agate jet of specified dimensions in the bottom, which is closed with a spherical plug attached to a wire. Inside the oil cylinder and at a short distance from the top is screwed a small bracket terminating in a point which serves as a gauge of the height of the oil level. A copper bath surrounds the oil cylinder and is furnished with a copper tube closed at the lower end, projecting at an angle of about 45° from the side of the bath near the bottom, which provides a means of heating the bath liquid; by use of a revolving agitator the heated liquid rising from the copper tube can be uniformly mixed throughout the bath. The agitator carries a thermometer to indicate the temperature of the bath. A short standard attached to the oil cylinder carries a clip to hold a thermometer in the oil. The instrument is supported on a tripod, and before using must be levelled by means of screws in the legs and a level provided for this purpose.

The sample of oil to be tested is placed in the oil cylinder up to the point of the gauge and the temperature adjusted to that required by regulating the temperature of the surrounding bath; the thermometer dipping into the oil cylinder is generally used as a stirrer. When the oil is at the required temperature the plug is lifted and simultaneously a stop-watch started and the time in seconds noted for 50 c.c. to flow into a graduated receiving flask. To obtain accurate results in the Redwood viscometer the instrument must be level, the oil cylinder and orifice must be perfectly clean and the bulb of the oil-cylinder thermometer must be sufficiently low in the cylinder to enable it to record the true temperature, but not so low as to impede the flow of oil through the aperture. It should also be noted that accurate results are only obtained for times of outflow ranging between 30 and 2000 sec.; for efflux times exceeding 2000 sec. the No. 2 viscometer should be used, which gives readings convertible into No. 1 scale by multiplying by ten.

Michell's workshop viscometer (Fig. 17) provides a means of making quick approximate measurements of the viscosity of moderately viscous lubricating oils. This viscometer consists of a steel ball about $\frac{3}{4}$ in. in diameter, which fits into a cup attached to a hollow handle into which a thermometer can be placed to register the temperature of the cup. Equally spaced on the face of the cup are three slight projections standing out 1/1000 in. from the surface; these determine the thickness of the oil film when the ball is pressed into position. It is essential that both ball and cup be perfectly clean and free from rust and that they are free from magnetisation.



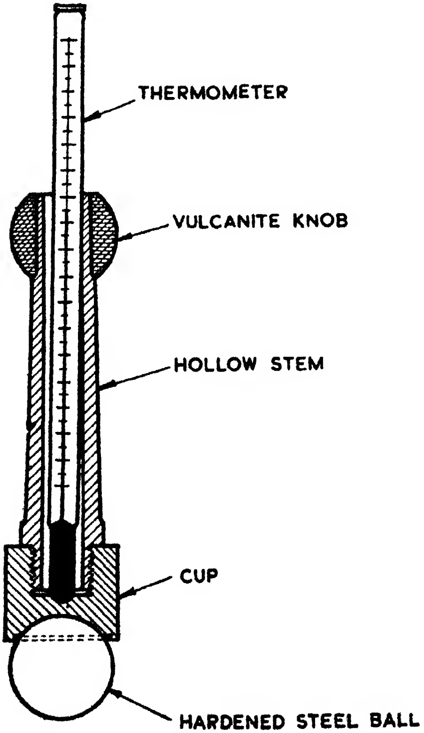


Fig. 17.—Michell Viscometer.

To make a viscosity determination of a sample of oil, the cup is held by its stem with the hollow surface of the cup upwards, and a few drops of the oil are placed therein. The ball is then placed in the cup and pressed firmly for 5–10 sec., a pressure of 5–6 lb. being sufficient. The instrument is then inverted, and the time for the ball to drop clear of the cup recorded in seconds by means of a stop-watch; the temperature of the cup is noted at the same time. The ball should be allowed to fall on a clean surface of wood or similar material to avoid disfigurement of the surface, and a further precaution to be taken is that the quantity of oil placed in the cup is sufficient to fill the small groove around the edge of the cup when the ball is in position; the oil retained in this groove is drawn upon to feed the film between the ball and the cup until the film breaks and the ball drops.

The time of fall of the ball in seconds divided by the constant provided with the instrument gives the absolute viscosity of the oil in poises. The corresponding viscosity on the Redwood scale can then be obtained by reference to the formula given in Section 38.

The instrument gives reasonably accurate results provided that the apparatus is all at the same temperature as the oil film, but it is advisable to take the mean of three or four determinations.

Viscosity is most accurately determined by modifications of Poiseuille's method of measuring the rate of flow of the oil through a capillary tube.

Full details of the several types of capillary instruments used are described in B.S.I. Specification No. 209–1947, for Fuels for Oil Engines. One of these, the U-tube viscometer shown in Fig. 18, consists of a fine capillary tube approximately 10 cm. long and of a bore suitable for the oil to be examined, ranging from 0·06 to 0·38 cm. in three stages.

The small-bore instrument is used for testing low-viscosity products such as light fuel oils, and those with the larger capillary diameter for heavier fuels and the usual range of lubricating oils.

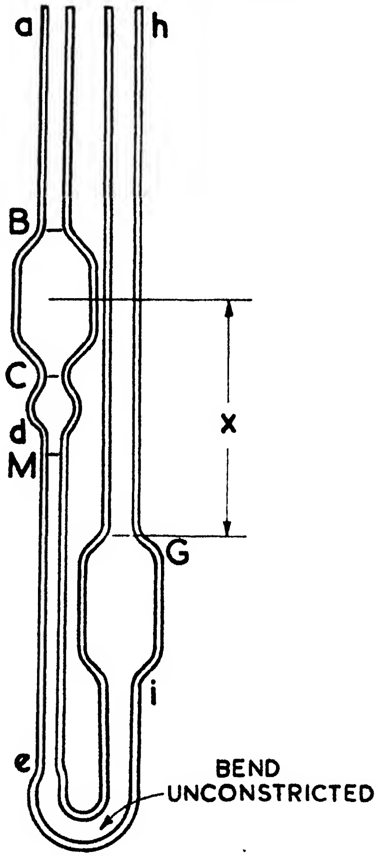


FIG. 18.—U-TUBE VISCOMETER.

In making a viscosity determination, the viscometer is immersed in a suitable constant-temperature bath so that mark *B* is at least 2 cm. below the surface of the bath liquid, and the viscometer should not deviate from the vertical by more than 1°. The oil sample, after filtering through a 200-mesh filter to ensure freedom from suspended matter, is introduced into the tube *hG* of the viscometer by means of a pipette so that the level in this arm is within 0·2 mm. of the mark *G* when the specified temperature has been attained; if tests are made with one filling at different temperatures, it is necessary to readjust the volume for each temperature. To ensure temperature equilibrium the viscometer should remain in the bath a minimum of 30 min. for the 210° F. bath and 20 min. for the lower temperatures. After the sample has attained bath temperature it is sucked up to a point 1 cm. above the mark B, and the time occupied by the oil in flowing back through the capillary tube while the level falls from B to C is noted in seconds. If the time of flow is less than 120 sec. the operation should be repeated in the next smaller-bore viscometer.

The kinematic viscosity in centistokes is then calculated from the following equation:

$$V = Ct - \frac{c}{t}$$

where V = kinematic viscosity in centistokes; C = the determined calibration constant for the instrument; t = the time of flow in seconds; c = a constant determined by the design of the viscometer having values of 2·4 for the three smaller bore viscometers. For viscosities of 20 centistokes and above, the abbreviated formula $V = Ct$ is sufficiently close for all practical purposes.

71. *Acidity or Neutralisation Value.*—(*a*) The total acidity which covers both organic acids and free mineral acid, if present, is determined by weighing out approximately 10 gm. of the oil into a conical flask and adding 50 ml. of rectified spirit which has previously been neutralised with KOH solution. The mixture is then heated to boiling point on a water-bath and well shaken to complete the solution of the acids in the alcohol. The mixture is then cooled to about 40° C. and titrated with decinormal caustic potash using 1 ml. of 0·5% solution of phenol phthalein as indicator. The results are expressed in milligrams of KOH necessary to neutralise the acidity of 1 gm. of the sample.

(*b*) Inorganic (free mineral) acidity is estimated by vigorously shaking a known weight of the oil, approximately 100 gm., in a separating funnel with an equal volume of warm, distilled water for one minute. After standing for a few minutes to allow separation of the water, the water layer is run off into a flask, cooled if necessary and titrated against $N/10$ potassium hydroxide using 0·1 ml. (2 drops) of a 0·1% solution of methyl orange as indicator, this being unaffected by weak organic acids. If mineral acid is present, which is very rarely so, the results should be expressed as for total acidity.

(*c*) Organic acidity is obtained by subtracting the value for (*b*) from that of (*a*).

72. *Water Content.*—For this determination the standard Dean and Stark apparatus is used (see Fig. 19). This consists of a 500-ml. round-bottomed flask *A*, which is connected through a graduated trap receiver *C* to a reflux condenser *B*. The amount of the sample used for the test will depend on the water content of the oil, and must never be more than will completely fill with water the graduated trap receiver. For fresh lubricating and fuel supplies, however, 100 ml. is a suitable amount, and the sample should be thoroughly shaken before measuring out the volume for test in a graduated cylinder. The measured volume is poured into the flask, to which has been added a few pieces of broken pumice stone or porcelain. The oil adhering to the measuring cylinder is washed into the flask with two 50-ml. portions of xylene or standard petroleum spirit boiling between 90° and 160° C. The graduated receiver with the reflux condenser is then assembled on the flask, the connections generally being made with tightly fitting corks; alternatively, apparatus provided with ground-glass joints may be used. Heat is then applied to the

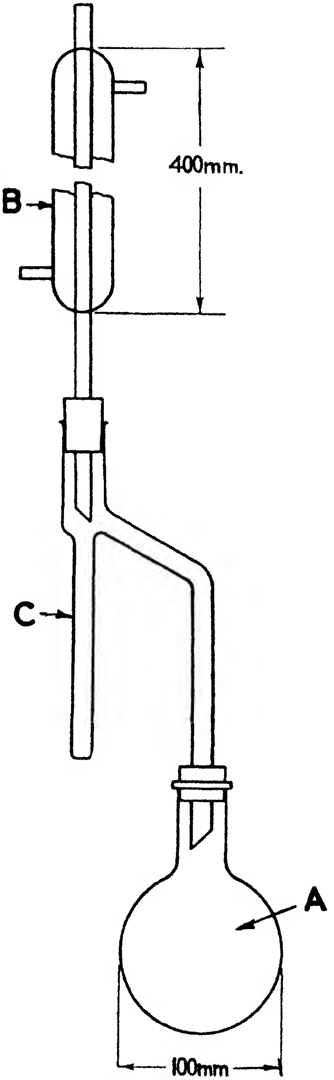


FIG. 19.—DEAN AND STARK APPARATUS.

flask, and the distillation of the xylene carries over any water present, which is condensed and trapped in the graduated receiver; the heating is continued until the volume of the water in the receiver remains constant for 5 min., after which the receiver and contents are allowed to cool to room temperature and the total volume of water noted. The results are expressed as percentage by volume.

An approximate method suitable for use on board ship is as follows:

(1) The oil is shaken up in the container and 50 ml. are poured into a 250-ml. dry measuring cylinder. 50 ml. benzol is added, and the mixture is thoroughly shaken. After leaving it to settle for about 3 hr., a light-brown layer may have collected at the bottom. The quantity in millilitres thus separated out, multiplied by two, will give the percentage of water which is now emulsified, but normally is combined or contained in the fuel oil. If this is more than 1% the oil should be heated in order to effect the separation of the water before the oil is used in the engine.

(2) Another sample of the oil is shaken up in the same measuring glass with 10% of water added. If, after having been left to settle for 1 hr., less than 10% has separated out again, then the oil has a tendency to absorb water, and in that case it will be necessary to make sure that all storage tanks are absolutely dry before the oil is taken on board.

73. *Hard Asphalt.*—The quantity of sample required for test varies with the quality of the fuel, but for the lighter distillates about 8 gm. is a suitable weight and for heavier fuels 3–4 gm. A weighed quantity of the fuel contained in a 100-c.c. conical flask is thoroughly mixed with 25 ml. of petroleum ether, boiling point 40–60° C., and allowed to stand for 24 hr. in the dark, the flask being corked. The solvent is then decanted through a weighed Gooch crucible containing a prepared pad of asbestos fibre fitted into a filter flask connected to a filter pump. The residue is then washed by decantation with successive quantities of petroleum ether and finally transferred to the Gooch crucible, where it is washed with petroleum ether until the washings are free from oil. The crucible is then transferred to a drying oven maintained at 105° C. for a suitable period, subsequently cooled and finally weighed. As a routine method the above is

sufficiently accurate for all practical purposes, but for referee work the I.P.T. method, Serial Designation FO. 12, should be followed.

74. *Coke Content—Conradson Method.*—The coke content of an oil is the percentage of carbon residue remaining after controlled evaporation of the oil in an enclosed space. The weight of oil used for the test varies with the type of oil, and is such that the residue of coke does not exceed 0·4 gm. For Diesel fuels and lubricants, 3 gm. is a suitable amount; this is weighed in a tared porcelain or silica crucible, *A* (Fig. 20), containing two glass beads about 0·1 in. in diameter, and the capacity of the crucible used should be 29–31 ml. with a rim diameter of 1·81–1·93 in. This crucible is placed in the centre of a Skidmore iron crucible, *B*, flanged and ringed, 65–82 ml.

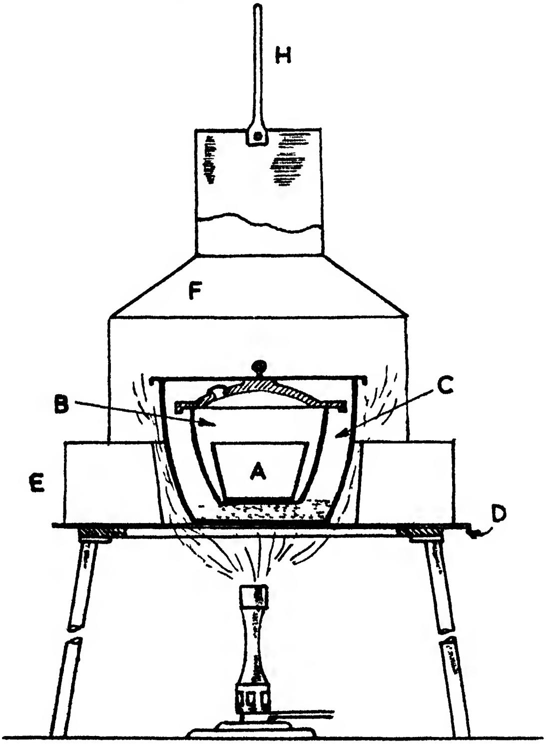


FIG. 20.—CONRADSON CARBON TEST APPARATUS.

capacity, provided with a cover, this in turn is placed on a layer of sand in the centre of a larger sheet-iron crucible, *C*, also provided with a cover, the latter being loosely fitting to allow free exit to the vapours as formed. A triangle of nichrome wire, *D*, is placed on a suitable ring, and on it a hollow sheet-metal box, *E*, 6–7 in. in diameter provided with a metal-lined cone-shaped opening through the centre 3¼ in. in diameter at bottom and 3½ in. in diameter at top. The sheet-iron crucible is centred in the block with its bottom resting on top of the triangle, and the whole covered with a circular sheet-iron hood.

Heat is applied by a high flame from a Meker-type gas burner so regulated that the pre-ignition period will be 10 min. ± 1½ min. When smoke appears above the chimney the burner is moved or tilted so that the gas plays on the side of the burner, thus igniting the vapours. Then temporarily remove the burner and before replacing adjust the flame so that the ignited vapours burn uniformly with the flame above the chimney. The heat may be increased if necessary when the flame does not show above the chimney. The period of burning the vapours should be 13 min. ± 1 min.

When the vapours cease to burn and no further blue smoke can be observed, readjust the burner and hold the heat as at the beginning so as to make the bottom and lower part of the iron crucible a cherry red and maintain for exactly 7 min. The total period of heating should be 30 min. ± 2 min.

Take away the burner and allow the apparatus to cool and then remove the cover of the Skidmore crucible. Lift the porcelain or silica crucible with heated tongs, place in a desiccator and cool and weigh. Calculate the percentage of carbon residue on the original sample.

75. *Ramsbottom Method.*—While similar in principle to the Conradson method, the results given by the two methods are not comparable, the Ramsbottom being lower, and the test is not generally applied to residual fuel oils; it is, however, coming more and more into favour for lubricating oils. The evaporation of the oil (about 4 gm.) is carried out in a weighed glass bulb of fixed shape and dimensions. The glass bulb is enclosed in an iron sheath, closed at one end, which is immersed in a bath of molten lead maintained at a temperature of 550° C.

until all vapours have ceased to be evolved, after which the bulb is cooled and weighed.

The dimensions of the sheath are 3 in. long, 1 in. internal diameter and $\frac{3}{64}$ in. wall thickness. The coking bulb is made from glass tubing of 1 in. external diameter and 1 mm. wall thickness. One end is rounded, and the other drawn out to a capillary of $\frac{1}{16}$ in. diameter and $\frac{3}{8}$ in. long; the length of the bulb from the base of the shoulder is $1\frac{1}{2}$ in., and from the base to the tip of the capillary $2\frac{1}{4}$ in.

76. *Ash.*—The ash is determined by evaporating a suitable quantity of the oil in a weighed platinum or silica dish and finally burning off all traces of carbon by heating the dish to redness, subsequently cooling in a desiccator and reweighing. About 50 gm. of oil is a suitable weight to take for the determination.

77. *Pour Point (I.P.T. Method).*—This value is determined by slowly cooling a sample of the oil in a test jar of standard dimensions filled to a height of not less than 51 mm. nor more than 57 mm., immersed in a cooling liquid. Beginning at a temperature about 20° F. above the expected pour point, the tube is removed at 5° F. intervals and held on its side for 5 sec. The pour point is taken as 5° F. above the temperature at which the oil ceases to flow. It is necessary, for correct results, to avoid disturbance of the oil or movement of the thermometer in the oil, when the oil has cooled enough to allow the formation of paraffin-wax crystals.

Details of apparatus : The clear-glass cylindrical test jar *A* (see Fig. 21) having a flat bottom, is approximately 30 mm. inside diameter and 115–125 mm. high and is fitted with a cork, *C*, bored centrally to carry the test thermometer. Enclosing the test jar is a jacket *D* of cylindrical form about 115 mm. deep with inside diameter about 12 mm. greater than the outside diameter of the test jar. A disc of cork or felt, *E*, fits in the bottom of the jacket, and a ring gasket, *F*, also of cork or felt, fits around the outside of the test jar and inside the jacket to prevent the test jar from touching the jacket. The jacket is held in a vertical position in a cooling bath *G* by means of a cork ring of dimensions to suit the bath and the jacket. The required bath temperature may be attained by suitable freezing mixtures, those commonly used being :

For temperatures down to 50° F. .	Ice and water.
,, ,, ,, 10° F. .	Crushed ice and salt.
,, ,, ,, – 15° F. .	Crushed ice and calcium chloride.

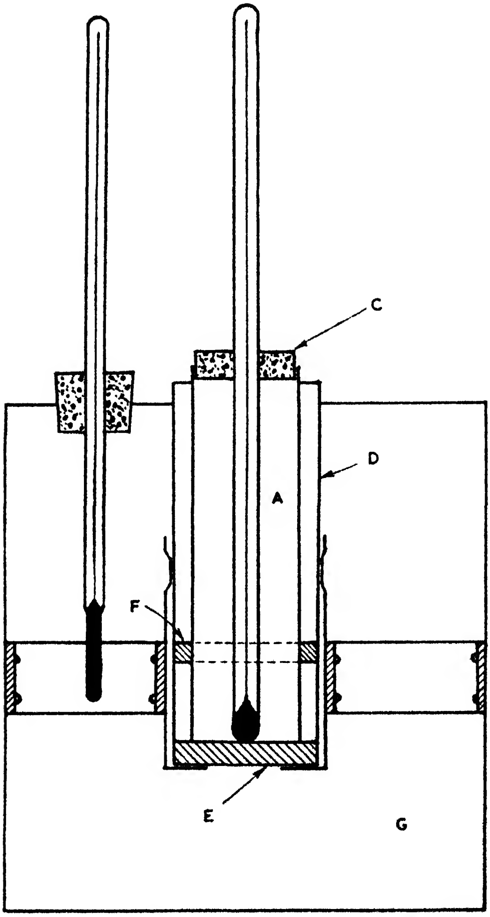


Fig. 21.—Cloud and Pour-point Apparatus.

Section B.—Tests Applied to Fuel Oils only

78. *Calorific Value.*—Apparatus : This determination is made by means of a bomb calorimeter in which a weighed quantity of the oil, contained in a small crucible, is burnt, the heat

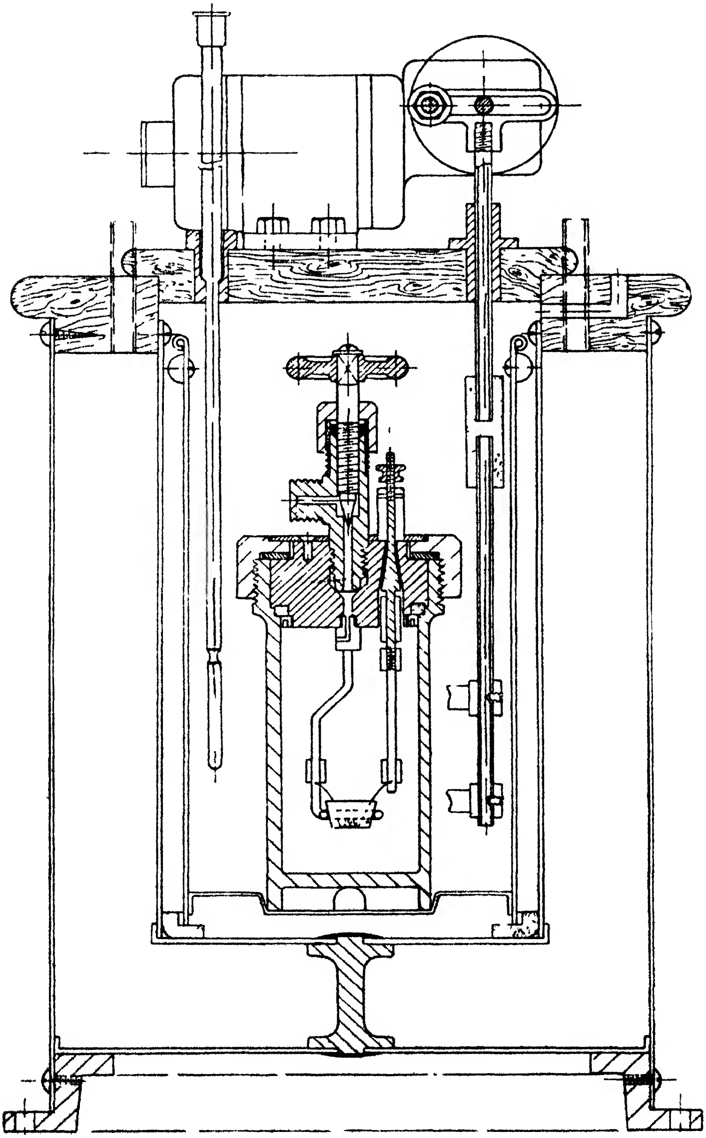


Fig. 22.—Mahler-Cook Standard Bomb Calorimeter.

liberated being measured. The Mahler-Cook (Fig. 22) is the one most generally used and consists of a stainless-steel vessel about 2½ in. in internal diameter and 5¼ in. depth and of suitable thickness to withstand 200 atmospheres pressure. The bottom of the bomb is bored up and slotted across to allow of water circulating under the bomb, and to provide a means of holding it in a cast-iron plate with cross-bar when screwing down the cover with which the bomb is provided. A gas-tight joint between the cover and bomb is effected by means of a rubber fabric ring. The cover contains a passage leading to the inside of the bomb, controlled by a conical-seated valve and also carries two insulated electric terminals. These terminals conduct an electric current employed to fuse inside the bomb a 0·0035 in. diameter platinum wire which in turn ignites the oil. The bomb is enclosed in a light copper calorimeter vessel of about 3 litres capacity, which during the experiment contains a known volume of water, usually 2500 ml. A water-jacket of sheet copper encloses the calorimeter vessel, which fits into an ebonite ring at the bottom so arranged as to form an air space underneath and all round. A polished teak-wood ring joining the two vessels forming the water-jacket carries on the top surface an electric plug switch for connecting the electro motor to the mains and two insulated terminals for connecting to the bomb terminals for ignition. The enclosure formed by the water-jacket is covered by a polished teak lid which fits the teak-wood ring of the water-jacket and carries on its upper surface the motor and stirrer circulator, an ebonite sleeve for the thermometer and two metal lifting rings.

Before making a calorific determination it is necessary to know the water equivalent of the bomb and calorimeter together with the stirrer and thermometer, as not only is the water in the calorimeter heated during the determination but the metal of the bomb and all other accessories in contact with the water, and it is essential to know the amount of heat absorbed by them to raise their temperature 1° C. This is ascertained by burning a known weight of benzoic acid having a known calorific value, viz., 6330 cal./gm., and proceeding exactly as in the determination of the calorific value of a fuel oil, as described on p. 121, and using the standard formula :

Calorific Value =

$$\frac{\text{Wt. of water} + \text{water equivalent} \times \text{rise of temperature}}{\text{Wt. of oil used}}$$

$$\therefore \text{Total Water Equivalent} = \frac{6330 \times \text{Wt. of benzoic acid}}{\text{Rise of temperature}}$$

Water equivalent of bomb, thermometer, etc. = Total water equivalent — wt. of water in calorimeter.

Method.—About 1 gm. of oil is weighed out in the crucible, and the crucible placed in position in the fitting provided in the bomb with platinum ignition wire partly immersed in the oil. 10 ml. of distilled water are placed in the bottom of the bomb. The bomb cover is placed on the bomb, and the nut screwed down tightly by hand, using the hand spanner subsequently if necessary. The bomb is then connected to an oxygen cylinder by copper tube and unions, the pin valve opened and a steady flow of oxygen allowed to enter the bomb until a pressure of 25 atmospheres is attained. The valves are then closed in the following order: (1) oxygen cylinder, (2) pin valve in bomb. The bomb is then detached and placed in the calorimeter vessel containing 2500 ml. of water. The teak-wood calorimeter cover to which the electro motor and reciprocating water-circulator is fixed is then placed in position, and the Beckman thermometer placed in the ebonite sleeve provided for the purpose. The water-circulator motor is now started, and the temperature of the water noted at intervals of a minute, this being continued for 5–10 min. in order to enable the bomb to acquire the temperature of the water and to determine the rate of increase, if the temperature of the water initially is below room temperature. The terminals on the bomb are then connected to the battery supply (10 volts approximately is required for 0·004 in. diameter platinum wire) and the oil ignited. The temperature is noted at 1-min. intervals until a maximum is reached, and then for a further similar period in order to determine the rate of heat loss; the stirring of the water is regularly maintained throughout. When the test is completed the bomb is removed from the calorimeter and the pin valve opened very cautiously so as to allow the gases to escape without any carry-over of water. *Example.*—Weight of fuel oil taken, 1·0016 gm.

Time, min.	Temperature, °C.	Time.	Temperature, °C.
0	0·18	1 min. after firing	2·40
1	0·175	2 ,, ,, ,,	3·09
2	0·17	3 ,, ,, ,,	3·44
3	0·17	4 ,, ,, ,,	3·54
4	0·17	5 ,, ,, ,,	3·56
5	0·17	5·5 ,, ,, ,,	3·565
Oil fired		6·0 ,, ,, ,,	3·575
		6·5 ,, ,, ,,	3·575
		7·0 ,, ,, ,,	3·575
		8·0 ,, ,, ,,	3·575
		10·0 ,, ,, ,,	3·565
		13·0 ,, ,, ,,	3·56
		16·0 ,, ,, ,,	3·555

$$\text{Temperature rise} = 3{\cdot}575 - 0{\cdot}17 = 3{\cdot}405^\circ\ \text{C.}$$

$$\text{Corrected rise} = 3{\cdot}405 + \frac{(3{\cdot}575 - 3{\cdot}555) \times 6}{10} = 3{\cdot}417^\circ\ \text{C.}$$

$$\text{Calorific value} = \frac{(\text{Weight of water} + \text{water equiv.}) \times \text{Rise}}{\text{Weight of Oil.}}$$

$$= \frac{2500 + 676 \times 3{\cdot}417}{1{\cdot}0016} = 10{,}835 \text{ calories}$$

$$10{,}835 \text{ calories} \times 1{\cdot}8 = 19{,}503 \text{ B.Th.U's.}$$

79. *Total Sulphur.*—This estimation is best made on the liquid remaining in the bomb calorimeter after completion of a calorific-value determination. To obtain accuracy it is necessary that the internal surface of the bomb shall be of material resistant to the products of combustion and that the gaskets and insulating materials are similarly not affected. 10 ml. of distilled water are placed in the bomb, and after completion of the calorific-value determination the excess oxygen and remaining products of combustion should be allowed to escape very cautiously, to prevent carry-over of water.

The water in the bomb is then emptied into a beaker, and the interior, including the cover and all internal parts, washed out thoroughly with distilled water. With stainless-steel bombs the washings are generally clean, but with porcelain-lined bombs small particles of lining may be anticipated, in which case the washings should be filtered and the filter paper thoroughly washed with hot distilled water.

To the washings 5 ml. of concentrated hydrochloric acid are added and a few drops of A.R. Bromine to oxidise any sulphurous to sulphuric acid; the solution is then boiled until all bromine is expelled. While still boiling 10 ml. of 10% barium-chloride solution are added and boiling continued for at least

15 min., after which the solution is left on the steam-bath or the side of the hot plate for not less than 4 hr. and preferably overnight. The precipitate of barium sulphate is then filtered through a tared, sintered glass Gooch crucible, well washed with hot water, dried and reweighed. Alternatively, it may be filtered through an ashless filter paper, the precipitate and paper being washed with water until free from traces of chlorides. The paper and precipitate are then transferred to a weighed crucible, dried, ignited and finally weighed. The weight of barium sulphate × 0·1373 gives the weight of the sulphur in the amount of oil taken for test.

As such a test cannot be made with any degree of accuracy except in a laboratory, a method whereby it is possible to estimate the sulphur content on board ship within certain limits is now described.

Using a millilitre pipette, graduated in 1/10th mls., exactly 1 ml. of the oil is measured into a small porcelain crucible. Three paper-thick slices of sodium are added. The crucible covered with its lid is placed on about 3 mm. of sand in the bottom of a sand bath. More sand is filled in at the sides until it reaches near the top of the crucible. A tin lid or asbestos sheet is placed on top of the sand bath, and using a spirit lamp the whole receptacle is heated up for about 1 hr., slowly at first, but later by the full flame until no more vapour rises when the lid is eased. The lamp is then extinguished and the crucible left to cool. When cold it is placed in a porcelain basin and a little water poured in to dissolve the sodium sulphide which has formed. With the help of a glass rod, a knife or the like, care should be taken to remove every particle of the black substance from the crucible into the basin and to get it crushed finely. When this is done the content is poured into a glass beaker. Exactly 4 c.c. of a solution of $N/10$ iodine is now added (take twice 2 c.c. with the pipette). Next acetic acid is added drop by drop while the mixture is stirred, the glass rod being periodically dipped into the mixture and drawn across a piece of blue litmus paper until it changes its colour to red. When this occurs add some starch solution.

Should the liquid immediately show a strong green or blue colour the oil contains less than 1% sulphur. Should the colour remain unaltered, i.e., yellow, light brown or brown, 2 c.c.

more of iodine solution is added at once. If the colour now turns green or blue it indicates that the sulphur content of the oil is about 1 %. Should the liquid be dark and not transparent a little can be poured into a test tube and diluted with water; the colour will then easily show up. Additions of 3 c.c. extra of $N/10$ iodine are necessary for each additional ½ % of sulphur present in the oil.

80. *Spontaneous-ignition Temperature.*—This is the temperature at which a fuel ignites without the assistance of a flame or spark; it has no connection with flash point or burning point. In this country the determination is generally made by Moore's or the more recent R.A.E. apparatus.

Moore's Apparatus (Fig. 23): The instrument consists of a heat diffusion block of 4 in. diameter mild steel, 3¼ in. deep, the base of which is recessed in order to provide a greater heating surface. The top face of the bar is bored out centrally, so that the hole exactly fits a platinum crucible of dimensions, upper diameter 35 mm., height 37 mm. and base diameter 22 mm.

A thermometer or pyrometer socket is also provided in the top portion, sloping towards the axis and of approximately the same depth as the crucible so that the pyrometer junction fits as close as practicable to the base of the crucible.

A screwed-on cover provided with two holes, one for air or oxygen inlet and one for oil inlet, also serves to protect the upper end of the crucible from draughts. The air or oxygen used is pre-heated to the temperature of the experiment by passing through a thin copper coil located in a chamber inside the block.

In carrying out a test, the block is heated to a given temperature and oxygen or air passed through the apparatus at a rate of three bubbles a second in case of oxygen, observed by passing through a wash bottle containing sulphuric acid which also serves as a drying agent. When the temperature of the block is constant at a desired temperature, one drop of the fuel under examination is allowed to fall through the hole in the centre of the cover of the instrument. If the temperature is much higher than the ignition point a sharp explosion will occur almost immediately, but if below the ignition point no explosion occurs. When only slightly above the ignition temperature, the explosion follows some 10–12 sec. after the introduction of the oil. By repeating the experiments, the lowest temperature at which ignition takes place is ultimately determined. This temperature is the temperature of spontaneous ignition.

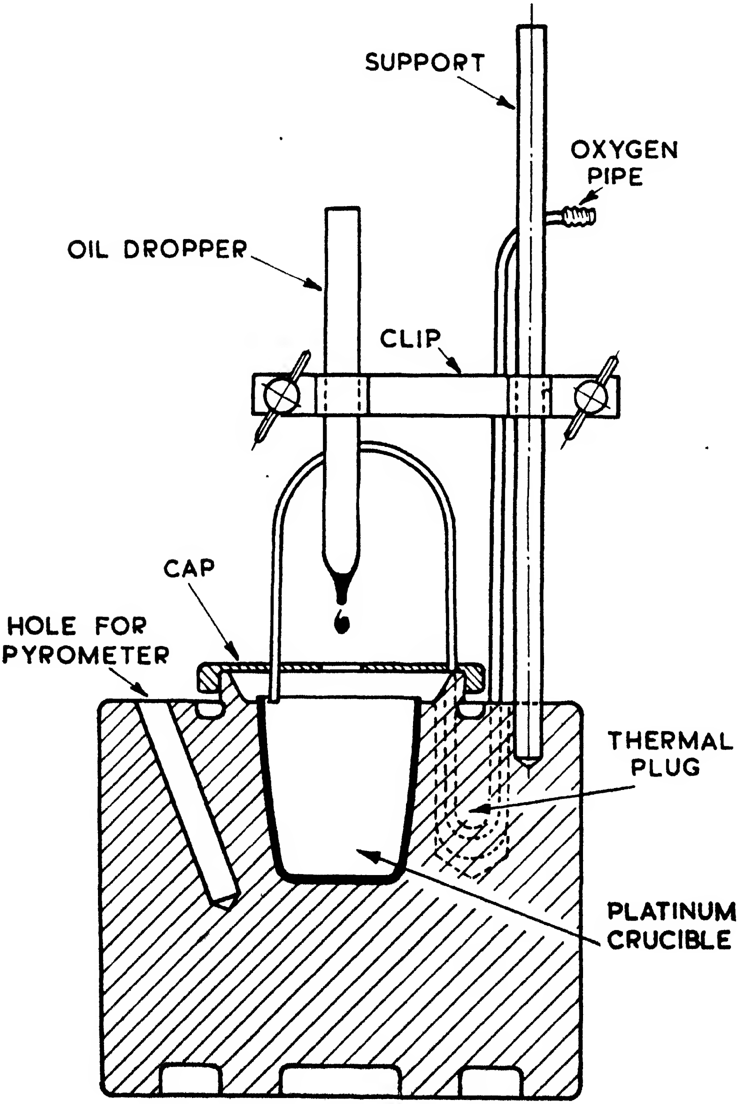


FIG. 23.—MOORE IGNITION-POINT APPARATUS.

When air is used instead of oxygen, the temperature of ignition is considerably higher, and in this case the explosion is much less violent and always follows about 1 sec. after the introduction of the oil.

The R.A.E. (Royal Aircraft Establishment) Apparatus: This apparatus is a distinct advance on the older instrument designed by Moore, in that it more nearly simulates actual working conditions. It consists of an electrically heated explosion vessel furnished with a fuel-injection system, a timing mechanism for recording the instants at which injection and explosion occur and a thermocouple for temperature measurements.

The explosion vessel consists of a wrought-iron cylinder 6 in. in diameter and 18 in. long, the sides of which are electrically heated and lagged. The top end of the cylinder is formed of layers of steel and asbestos, and carries a fuel-injection valve of the Bosch pintle type, a thermocouple, a vent and an air tube and also a connection for the explosion time recorded. The fuel-injection valve and explosion vessel are so arranged as to give a fuel spray having an angle less than the cone angle subtended by the perimeter of the bottom end of the vessel with the point of entry of the fuel into the vessel; so as to prevent the fuel spray from striking the heated sides of the vessel. The bottom end of the cylinder is of the inverted-cone shape, unlagged and insulated from the body part by an asbestos joint ring, so as to ensure that any fuel from the jet which may impinge on the bottom does so on a relatively cool surface.

The fuel-injection system consists of a standard Bosch outfit, and the pump is operated by a falling weight pivoted on the pump base, which ensures that the rate of injection of the charge is constant for each test.

The timing mechanism for recording the instant of fuel injection comprises a pair of contacts in an electrical circuit which are closed when the fuel-valve opens, by means of a tappet pin; the moment of explosion is timed by means of a disc valve fitted into the top end of the explosion vessel, which lifts when the explosion occurs, thereby opening a pair of contacts. A time record is obtained by means of a calibrated electrical tuning-fork which traces a record on a moving tape, on which are also recorded the instants of injection and explosion.

In making a test, the temperature of the explosion vessel is raised to a point considerably higher than the ignition point, the current then switched off and time allowed for temperature conditions to stabilise. Air is then drawn into the cylinder and the apparatus again allowed to stand for a few minutes until the air temperature begins to fall from the maximum attained. The fuel is then injected by the injector nozzle, and the time lag between injection and ignition recorded. The products of combustion are then drawn out of the cylinder, a fresh charge of air introduced and the operation repeated at a lower temperature. Following the same procedure a series of readings is taken 20° or 30° C. lower in each case, until finally a temperature is reached at which no explosion occurs after an indefinite delay. The results so obtained can be subsequently expressed in the form of a curve in which ignition delay is plotted against temperature. It has been shown by several investigators that results obtained by the use of this apparatus are of definite value in indicating the ease of engine starting with various Diesel fuels.

81. *Aniline Point of Diesel Fuel—I.P.T. Method.*—The aniline point is affected by the presence of water, and the determination must be carried out after the water, if any, has been removed; to ensure this, the test sample must be dried over two-fifths its weight of calcium chloride in a dry, wide-mouthed, stoppered glass bottle, which, after well shaking, is stood in a vessel of water, the level of the water being up to about one-third of the height of the oil in the bottle. The water is next raised to a temperature of 50° C. and is maintained at this temperature for a period of 7 hr., the bottle and its contents being well shaken up at intervals of about an hour. At the end of this treatment the bottle and its contents are allowed to cool to atmospheric temperature; the bottle is then opened, and sufficient of the oil for test filtered through paper on a Buchner funnel. The apparatus used must be thoroughly dried in an air oven. 5 ml. of the dried sample and 5 ml. of A.R. aniline, previously dried over KOH and redistilled, are introduced into a 25 mm. × 50 mm. test tube provided with a cork carrying a thermometer and a wire stirrer. This tube is placed inside a further test tube 38 mm. × 150 mm., being supported concentrically by a cork, so that the gap between the bottom of the tubes is 20 mm.

The outer jacket is very gently warmed by intermittently applying a naked gas flame, the mixture being stirred. As soon as miscibility occurs the source of heat is removed and the apparatus allowed to cool, stirring being continued. The temperature at which cloudiness appears is noted as the approximate aniline point. A repeat test is then carried out on fresh portions of the sample and of the aniline, and the temperature at which cloudiness reappears when the warm mixture is allowed to cool with stirring is taken as the aniline point.

Dark oils present difficulties in ascertaining the point at which cloudiness appears, and modifications of the above method have been investigated. Williams and Dean (23) claim to have obtained good results by using a U-tube, the bridge of which is flattened to give a film of oil 2 mm. in thickness; one limb of the U-tube carries the stirrer, the other the thermometer.

82. *Cetane Value.*—A method of determining cetane value without having resort to an engine test has been evolved by Schmitt (24) and requires only a determination of the specific gravity and the mean boiling temperature; the latter is obtained by observing the temperature after the distillation of 5 ml. and each successive 10 ml. up to 105 ml., taking the sum of these temperatures and dividing by ten. Reference is then made to the chart, Fig. 24, giving the cetane number of fuel oil in relation to specific gravity and the mean boiling temperature. The authors have used this method as a routine test and have found good correlation between the cetane value so obtained and Diesel index derived from the aniline point and A.P.I. gravity. Unfortunately this method of determining ignition quality is not applicable to doped fuels, and tends to give unreliable results on coal-tar oils and shale oils, which it generally rates too low.

A somewhat similar method makes use of A.P.I. gravity together with the mid boiling point, i.e., the temperature at which 50% of the oil distils, and the following formula :

$$\text{Cetane No.} = 175{\cdot}4 \text{ Log (Mid Boiling Pt. } {}^\circ\text{F.)} + 1{\cdot}98 \text{ (A.P.I. Gravity)} - 496.$$

This was found by a Panel appointed by the Institute of Petroleum to give the most accurate results of all the formulæ investigated.

83. *Distillate Test or Boiling Range.*—In the I.P.T. standard

method, 200 ml. of fuel oil is measured into a distillation flask of 250 ml. capacity conforming to B.S. Spec. 571—1934. A thermometer, 400° C. range, provided with a cork, is fitted tightly into the neck of the flask so that it lies in the middle of the neck with the bulb opposite the vapour-exit tube. The charged flask is placed over a $2\frac{3}{4}$-in.-diameter hole in a hard asbestos board, placed over a ring support of the ordinary laboratory type. The vapour outlet of the flask is inserted about 1 in. into the tube of a condenser, consisting of $\frac{9}{16}$ in. outside diameter No. 18 I.W.G. seamless brass tube, 22 in. in

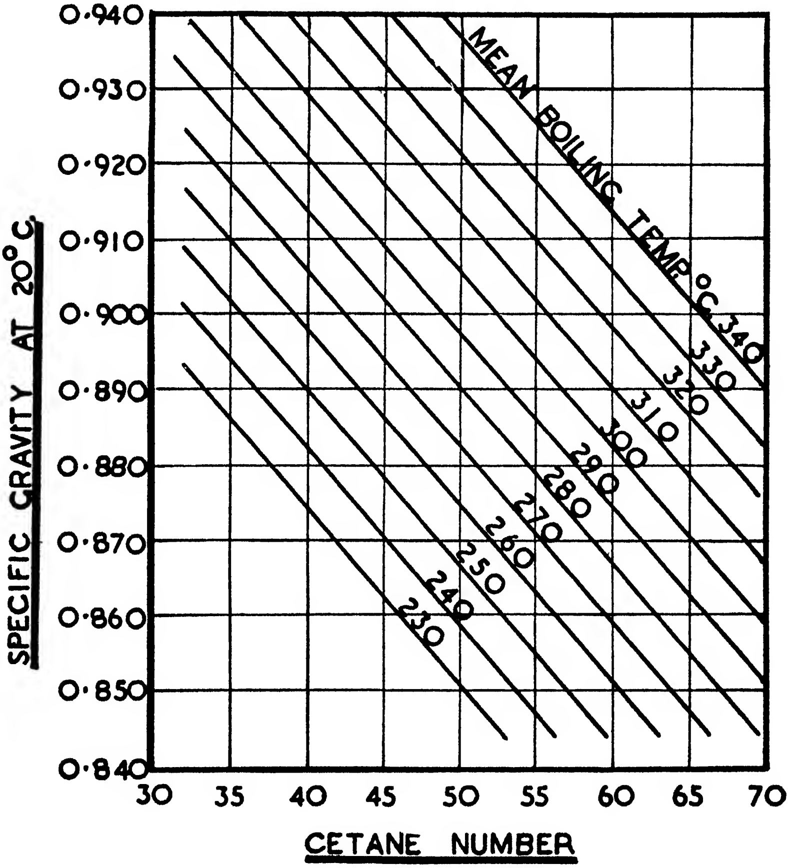


Fig. 24.—Chart Giving the Cetane Number of Diesel Fuel Oil in relation to the Specific Gravity and the Mean Boiling Temperature.

length. A sheet-metal shield of dimensions indicated in sketch (Fig. 25) is placed around the distillation flask, and a dry, graduated cylinder placed at the outlet of the condenser tube. Heat is then applied to the contents of the flask by means of a suitable Bunsen burner, so regulated that the first drop of condensate falls from the condenser in 10–15 min. The temperature at which the first drop falls from the end of the condenser is noted and recorded as the Initial Boiling Point. The heat is then regulated so that distillation proceeds at a uniform rate of between 8 and 10 ml. per minute. The volume of distillate collected in the cylinder is observed to the nearest millilitre and reported as a percentage when the thermometer reaches each point that is a multiple of 10° C. The distillation is continued until a vapour temperature of 350° C. is reached, or if lower, until the maximum temperature point is reached.

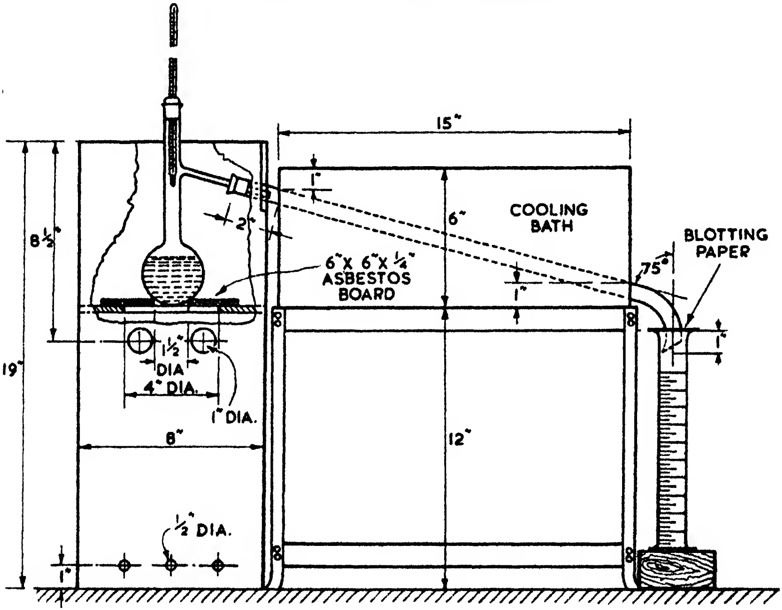


Fig. 25.—Distillation Apparatus.

Alternatively, distillation under reduced pressure, viz., 120 mm. of mercury, is often adopted in the authors' practice when dealing with fuels other than gas oils. This necessitates the provision of a pressure-relief tube in the stopper carrying the thermometer which is fitted in the neck of the distillation flask; also the fitting of a further distillation flask on the arm of the distillation flask proper, in which to collect the distillate; the arm of the second flask is connected to a Geryk pump by pressure tubing, via a Woulff's bottle, carrying a suitable vacuum gauge. 100 ml. of oil together with a few pieces of broken porcelain are placed in the distillation flask, the stoppers and connections made, and after ascertaining that all joints are pressure tight the distillation flask is immersed in a suitable oil bath placed over a gas ring. The pressure is maintained at 120 mm. mercury, and the temperature of the bath gradually increased until the initial drop of distillate appears, when the temperature is noted. Fractions are then taken off at approximately every 30° C. up to 300° C., transferred to tared glass dishes and weighed.

SECTION C—TESTS APPLIED TO LUBRICATING OILS ONLY

84. *Oxidation Tests.*—The Michie and the British Air Ministry tests are generally used in this country, and are designed to measure the resistance of the oil to decomposition by air when heated. In both tests a known weight of the oil contained in a tube or flask is heated in an oil bath maintained at a fixed temperature, whilst a measured volume of air is bubbled through the oil in the flask for a standard time.

British Air Ministry Test: 40 ml. of the oil is heated in a glass boiling tube immersed in a suitable oil bath for two periods of 6 hr. on consecutive days at 200° C. during which 15 litres of air is bubbled through the sample. The viscosity of the oil at 100° F. is determined before and after the oxidation and expressed as the ratio of final to original viscosity. The Ramsbottom Carbon Residue Test of the oil is also determined on the original and oxidised sample and similarly expressed as a ratio of final to original figures.

Details of apparatus (Fig. 26): The boiling tube is approximately 250 mm. long by 25 mm. internal diameter fitted with a cork slotted to allow escape of air from the tube and carrying an inlet tube 5 mm. internal diameter which clears the bottom of the tube by 6 mm. The tube is fixed vertically in a cradle support in the oil bath, the temperature of which can be maintained at 200° C. ± 1° C. The walls of the bath project approximately 6 in. higher than the lid to protect the thermometer and tube from draughts.

The air supply is delivered from a suitable blower and passed via a cotton-wool or glass-wool filter into a pressure stabiliser, and thence by way of a screw-down needle valve, or other sensitive control, and a capillary tube, into the tube containing the oil under test. The rate of flow of air is measured by means of a previously calibrated manometer and may be varied by adjustment of the needle valve. To ensure sufficient sensitivity, the difference in level of the liquid in the two limbs of the manometer should be considerable—about 80 mm. is suitable.

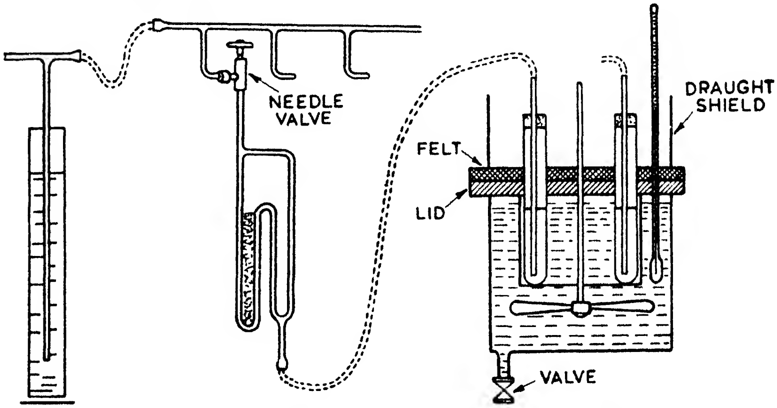


Fig. 26.—Apparatus for Oxidation Test for Lubricating Oil.

85. *Michie Test.*—In this test, the temperature to which the oil is heated is 150° C. and the time of heating 45 hr.; a catalyst in the form of a strip of copper foil 2 in. × 1·25 in. × 0·004 in. thick rolled into a cylinder 1·25 in. high is immersed in the oil while a current of purified air maintained at a rate of 2 litres per hour is bubbled through the heated oil. After this treatment the oil sample is allowed to cool and transferred to a beaker, any traces of deposit adhering to the flask being removed by petroleum ether. A further quantity of petroleum ether is then added until the total amount of spirit is 450 ml. The whole is then stirred and allowed to stand in the dark for between 16 and 24 hr. to facilitate separation of the sludge. The clear liquid is then decanted through a tared 12·5-cm. filter, the sludge washed by decantation, and then washed into

the filter paper by means of petroleum ether. The deposit on the filter paper is washed with petroleum ether until free from oil, and the filter paper then dried until constant in weight. The increase in weight represents the weight of the sludge and is expressed as a percentage.

The apparatus is arranged as shown in Fig. 27, and details of same specified in the I.P.T. test T.O.21 are as under.

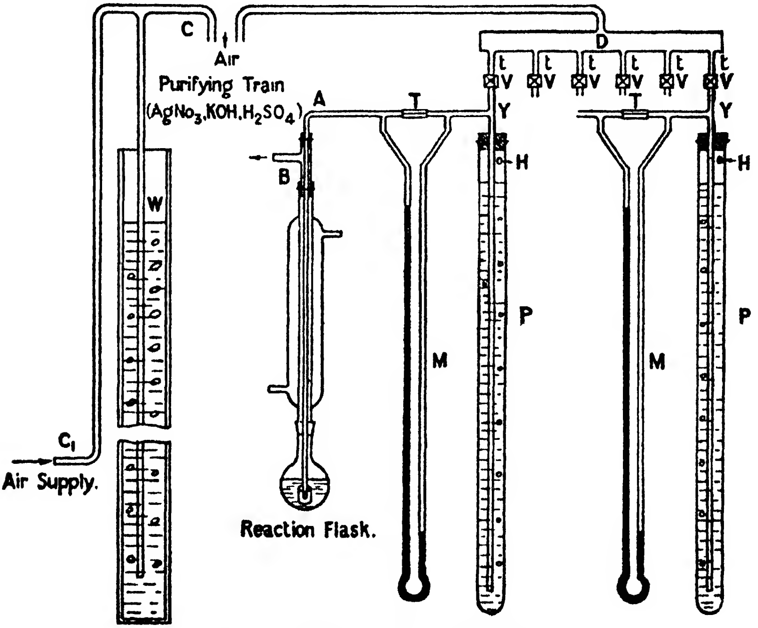


FIG. 27.—MICHIE TEST APPARATUS.

The flask in which the oil is heated should have a bulb 76 mm. in diameter and neck 70 mm. long with 25 mm. diameter which can be fitted to a straight glass condenser by means of a ground-in joint. The oil bath, provided with a cover, should be of such dimensions that the whole of the bulb can be immersed. A glass condenser, the upper portion of which is provided with a one-hole cork to carry a glass T-piece, *B*, which in turn carries a glass inlet tube, *A*. The internal diameter of the T-piece shall be 10 mm. and the internal diameter of the inlet tube 4 mm. The inlet tube shall reach to within 3 mm. of the bottom of the flask and shall pass axially through the cylinder of copper.

The rate of air flow through the oil shall be indicated by means of a calibrated capillary flow meter or a mechanical gas meter inserted between the air-purifying train and the reaction flask.

Before entering the reaction flask this air shall be purified and dried by passing through a series of three Woulff's bottles containing not less than 80 ml. of 10% aqueous potassium-hydroxide solution and not less than 150 ml. of 98–99% sulphuric acid, respectively, followed by a U-tube containing glass wool.

86. *Baking Test.*—1 gm. of the oil under test is weighed into a shallow platinum receptacle, 35 mm. diameter and 5 mm. deep; platinum crucible lids serve the purpose quite well.

This receptacle fits into one of a series of circular recesses 5 mm. deep machined in the top face of a piece of sheet aluminium alloy, 6 mm. thick; this plate also carries a horizontal hole in one side to allow the insertion of a thermo-electric pyrometer couple. The plate carrying the receptacle is then placed on a gas-heated hot plate and the temperature brought up to 270–280° C. at which it is maintained until any vapours cease to be evolved. The receptacle containing the residue is cooled and subsequently weighed, the nature of the residue also being noted.

87. *Diesel Fuel Diluent in Crankcase Lubricating Oil.*—Provided the viscosity of the lubricating oil as supplied and that of the fuel oil in use is known, an approximation of the fuel content can be obtained by use of a graph referred to in Section. 31. This graph is obtained from viscosity data determined on a series of mixtures of definite volumes of the lubricating oil concerned and an average grade of Diesel fuel. The method is not applicable, however, when the Diesel fuel is of the heavy residual type.

When the grade of crankcase oil is not known, distillation under reduced pressure or steam distillation is the most suitable and at the same time probably the most accurate method to adopt. In the I.P.T. tentative standard method, steam distillation is used. About 100 ml. of the crankcase oil is measured into a round-bottomed, long-necked flask of 1 litre capacity, fitted with a cork carrying a steam inlet tube, suitably bent, reaching to within 1 cm. of the bottom of the flask and a steam outlet which terminates just below the bottom of the cork, the other end being suitably bent and connected through another cork to a glass-tube-type condenser. Steam from a suitable boiler is connected to the steam inlet tube of the flask,

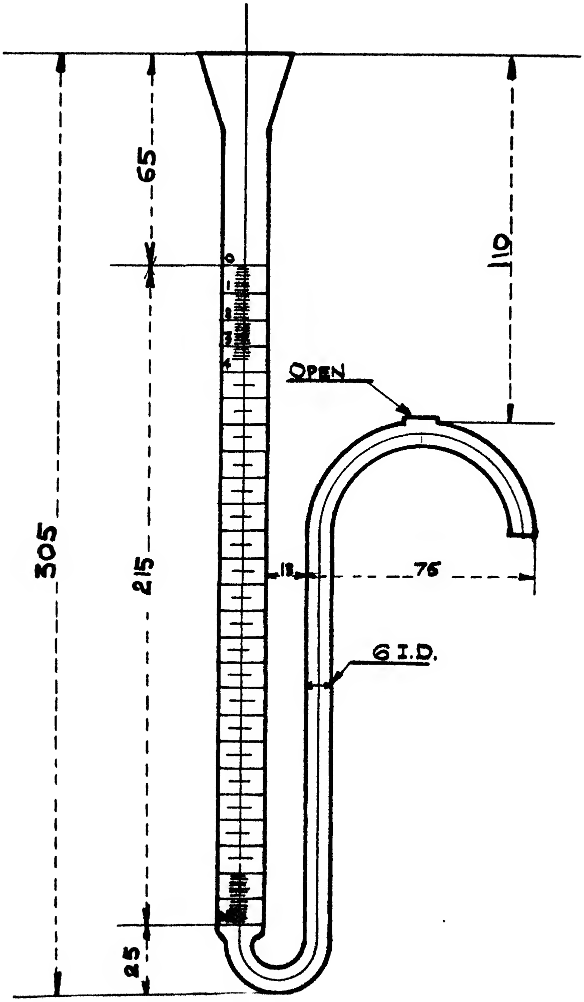


FIG. 28.—GLASS TRAP FOR THE COLLECTION OF WATER CONDENSATE, AND DILUENT, DISTILLED FROM OIL SAMPLES.

which is then immersed at an angle of approximately 45° to the vertical, in an oil bath maintained at 140° C. Steam is passed into the oil in the flask at such a rate that about 10 ml.

of water condensate forms per minute. The water condensate and the diluent, distilled from the oil samples, is collected in a glass trap of the form and dimensions shown in Fig. 28, which allows the water collected to siphon away at a constant level, leaving the diluent in the graduated portion of the trap. The distillation is continued until the diluent distilling over with 50 ml. of water is not greater than 0·1 ml. The result is reported as a percentage by volume to the nearest 1%.

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APPENDIX I

VISCOSITY CONVERSION TABLE

Redwood Sec.	Saybolt Universal Sec.	Engler Units.	Kinematic Viscosity in Centistokes.	Redwood Sec.	Saybolt Universal Sec.	Engler Units.	Kinematic Viscosity in Centistokes.
30	33·6	1·09	2·08	140	165·2	4·55	35·20
32	36·0	1·16	2·96	145	171·1	4·71	36·55
34	38·4	1·23	3·68	150	177·0	4·87	37·86
36	40·8	1·29	4·60	155	182·9	5·03	39·20
38	43·3	1·35	5·37	160	188·8	5·19	40·54
40	45·6	1·40	6·12	165	194·7	5·35	41·87
42	48·2	1·46	6·84	170	200·6	5·52	43·19
44	50·6	1·55	7·55	175	206·5	5·68	44·52
46	53·0	1·60	8·23	180	212·4	5·84	45·85
48	55·4	1·66	8·91	185	218·3	6·00	47·18
50	57·8	1·72	9·59	190	224·2	6·17	48·50
52	60·2	1·78	10·23	195	230·1	6·33	49·82
54	62·6	1·84	10·85	200	236·0	6·49	51·15
56	65·0	1·90	11·48	210	247·8	6·82	53·79
58	67·3	1·97	12·11	220	259·6	7·15	56·42
60	69·6	2·03	12·74	230	271·4	7·47	59·05
62	71·9	2·09	13·35	240	283·2	7·80	61·69
64	74·5	2·16	13·95	250	295·0	8·12	64·32
66	77·1	2·22	14·55	260	306·8	8·45	66·90
68	79·6	2·28	15·15	270	318·6	8·77	69·60
70	81·9	2·33	15·75	280	330·4	9·05	72·20
72	84·2	2·39	16·33	290	342·2	9·42	74·80
74	86·6	2·45	16·93	300	354·0	9·75	77·43
76	88·9	2·52	17·51	325	383·5	10·56	83·98
78	91·3	2·58	18·09	350	413·0	11·37	90·51
80	93·6	2·65	18·66	375	442·5	12·15	97·04
82	95·9	2·70	19·23	400	472·0	13·00	103·57
84	98·3	2·76	19·79	425	501·5	13·77	110·10
86	100·6	2·82	20·35	450	531·0	14·58	116·55
88	103·0	2·88	20·92	475	560·5	15·39	123·50
90	105·3	2·93	21·49	500	590·0	16·20	129·66
92	107·6	3·00	22·06	525	619·5	17·01	136·22
94	110·0	3·06	22·62	550	649·0	17·82	143·00
96	112·3	3·12	23·18	575	678·5	18·63	149·50
98	114·7	3·19	23·74	600	708·0	19·44	156·00
100	117·0	3·27	24·30	625	737·5	20·25	162·20
105	123·4	3·41	25·67	650	767·0	21·06	168·70
110	129·8	3·55	27·06	675	796·5	21·87	175·50
115	135·7	3·73	28·42	700	826·0	22·68	181·80
120	141·6	3·90	29·78	725	855·5	23·49	188·50
125	147·5	4·06	31·13	750	885·0	24·30	195·00
130	153·4	4·22	32·48	775	914·5	25·11	201·30
135	159·3	4·38	33·84	800	944·0	25·92	207·80

APPENDIX I—*continued*

Red-wood Sec.	Saybolt Univer-sal Sec.	Engler Units.	Kine-matic Viscosity in Centi-stokes.	Red-wood Sec.	Saybolt Univer-sal Sec.	Engler Units.	Kine-matic Viscosity in Centi-stokes.
825	973·5	26·73	214·0	1375	1622·5	44·55	357·3
850	1003·0	27·54	221·0	1400	1652·0	45·36	364·0
875	1032·5	28·35	228·0	1425	1681·5	46·17	370·5
900	1062·0	29·16	234·0	1450	1711·0	46·98	377·0
925	1091·5	39·97	240·5	1475	1740·5	47·79	383·5
950	1121·0	30·78	247·9	1500	1770·0	48·60	390·0
975	1150·5	31·59	253·3	1550	1829·0	50·22	403·0
1000	1180·0	34·50	259·8	1600	1888·0	51·84	416·0
1025	1209·5	33·21	266·1	1650	1947·0	53·66	429·0
1050	1239·0	34·02	273·0	1700	2006·0	55·08	442·0
1075	1268·5	34·83	279·3	1750	2065·0	56·70	455·0
1100	1298·0	35·64	285·7	1800	2124·0	58·32	468·0
1125	1327·5	36·45	292·3	1850	2183·0	59·94	481·0
1150	1357·0	37·26	299·0	1900	2242·0	61·56	494·0
1175	1386·5	38·07	305·3	1950	2301·0	63·18	507·0
1200	1416·0	38·88	311·9	2000	2360·0	64·80	520·0
1225	1445·5	39·69	318·3	2050	2419·0	66·42	533·0
1250	1475·0	40·50	324·9	2100	2478·0	68·04	546·0
1275	1504·5	41·31	331·3	2200	2596·0	71·28	572·0
1300	1534·0	42·12	337·9	2300	2714·0	74·52	598·0
1325	1563·5	42·93	344·3	2400	2832·0	77·76	624·0
1350	1593·0	43·74	350·8	2500	2950·0	81·00	650·0

APPENDIX II

COMPARISON OF TEMPERATURE SCALES

Centigrade to Fahrenheit

° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.
−40	−40	− 5	+23	30	86	65	149
−39	−38·2	− 4	+24·8	31	87·8	66	150·8
−38	−36·4	− 3	+26·6	32	89·6	67	152·6
−37	−34·6	− 2	+28·4	33	91·4	68	154·4
−36	−32·8	− 1	+30·2	34	93·2	69	156·2
−35	−31	*0	32*	35	95	70	158
−34	−29·2	1	33·8	36	96·8	71	159·8
−33	−27·4	2	35·6	37	98·6	72	161·6
−32	−25·6	3	37·4	38	100·4	73	163·4
−31	−23·8	4	39·2	39	102·2	74	165·2
−30	−22	5	41	40	104	75	167
−29	−20·2	6	42·8	41	105·8	76	168·8
−28	−18·4	7	44·6	42	107·6	77	170·6
−27	−16·6	8	46·4	43	109·4	78	172·4
−26	−14·8	9	48·2	44	111·2	79	174·2
−25	−13	10	50	45	113	80	176
−24	−11·2	11	51·8	46	114·8	81	177·8
−23	− 9·4	12	53·6	47	116·6	82	179·6
−22	− 7·6	13	55·4	48	118·4	83	181·4
−21	− 5·8	14	57·2	49	120·2	84	183·2
−20	− 4	15	59	50	122	85	185
−19	− 2	16	60·8	51	123·8	86	186·8
−18	− 0·4	17	62·6	52	125·6	87	188·6
−17	+ 1·4	18	64·4	53	127·4	88	180·4
−16	+ 3·2	19	66·2	54	129·2	89	192·2
- 15	+ 5	20	68	55	131	90	194
−14	+ 6·8	21	69·8	56	132·8	91	195·8
−13	+ 8·6	22	71·6	57	134·6	92	197·6
−12	+10·4	23	73·4	58	136·4	93	199·4
−11	+12·2	24	75·2	59	138·2	94	201·2
−10	+14	25	77	60	140	95	203
− 9	+15·8	26	78·8	61	141·8	96	204·8
− 8	+17·6	27	80·6	62	143·6	97	206·6
− 7	+19·4	28	82·4	63	145·4	98	208·4
− 6	+21·2	29	84·2	64	147·2	99	210·2

Formulæ : $\frac{°\text{C.} \times 9}{5} + 32 = °\text{F.}$ $\frac{(°\text{F.} - 32) \times 5}{9} = °\text{C.}$

APPENDIX II—*continued*

° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.
†100	212†	145	293	190	374	235	455
101	213·8	146	294·8	191	375·8	236	456·8
102	215·6	147	296·6	192	377·6	237	458·6
103	217·4	148	298·4	193	379·4	238	460·4
104	219·2	149	300·2	194	381·2	239	462·2
105	221	150	302	195	383	240	464
106	222·8	151	303·8	196	384·8	241	465·8
107	224·6	152	305·6	197	386·6	242	467·6
108	226·4	153	307·4	198	388·4	243	469·4
109	228·2	154	309·2	199	390·2	244	471·2
110	230	155	311	200	392	245	473
111	231·8	156	312·8	201	393·8	246	474·8
112	233·6	157	314·6	202	395·6	247	476·6
113	235·4	158	316·4	203	397·4	248	478·4
114	237·2	159	318·2	204	399·2	249	480·2
115	239	160	320	205	401	250	482
116	240·8	161	321·8	206	402·8	251	483·8
117	242·6	162	323·6	207	404·6	252	485·6
118	244·4	163	325·4	208	406·4	253	487·4
119	246·2	164	327·2	209	408·2	254	489·2
120	248	165	329	210	410	255	491
121	249·8	166	330·8	211	411·8	256	492·8
122	251·6	167	332·6	212	413·6	257	494·6
123	253·4	168	334·4	213	415·4	258	496·4
124	255·2	169	336·2	214	417·2	259	498·2
125	257	170	338	215	419	260	500
126	258·8	171	339·8	216	420·8	261	501·8
127	260·6	172	341·6	217	422·6	262	503·6
128	262·4	173	343·4	218	424·4	263	505·4
129	264·2	174	345·2	219	426·2	264	507·2
130	266	175	347	220	428	265	509
131	267·8	176	348·8	221	429·8	266	510·8
132	269·6	177	350·6	222	431·6	267	512·6
133	271·4	178	352·4	223	433·4	268	514·4
134	273·2	179	354·2	224	435·2	269	516·2
135	275	180	356	225	437	270	518
136	276·8	181	357·8	226	438·8	271	519·8
137	278·6	182	359·6	227	440·6	272	521·6
138	280·4	183	361·4	228	442·4	273	523·3
139	282·2	184	363·2	229	444·2	274	525·2
140	284	185	365	230	446	275	527
141	285·8	186	366·8	231	447·8	276	528·8
142	287·6	187	368·6	232	449·6	277	530·6
143	289·4	188	370·4	233	451·4	278	532·4
144	291·2	189	372·2	234	453·2	279	534·2

APPENDIX II—*continued*

° C.	° F.	° C.	° F.	° C.	° F.	° C.	° F.
280	536	300	572	320	608	340	644
281	537·8	301	573·8	321	609·8	341	645·8
282	539·6	302	575·6	322	611·6	342	647·6
283	541·4	303	577·4	323	613·4	343	649·4
284	543·2	304	579·2	324	615·2	344	651·2
285	545	305	581	325	617	345	653
286	546·8	306	582·8	326	618·8	346	654·8
287	548·6	307	584·6	327	620·6	347	656·6
288	550·4	308	586·4	328	622·4	348	658·4
289	552·2	309	588·2	329	624·2	348	660·2
290	554	310	590	330	626	350	662
291	555·8	311	591·8	331	627·8	351	663·8
292	557·6	312	593·6	332	629·6	352	665·6
293	559·4	313	595·4	333	631·4	353	667·4
294	561·2	314	597·2	334	633·2	354	669·2
295	563	315	599	335	635	355	671
296	564·8	316	600·8	336	636·8	356	672·8
297	566·6	317	602·6	337	638·6	357	674·6
298	568·4	318	604·4	338	640·4	358	676·4
299	570·2	319	606·2	339	642·2	359	678·2

APPENDIX III *

VALUES OF H, L, AND D FOR KINEMATIC VISCOSITY IN CENTISTOKES AT 210° F.

H = Viscosity at 100° F. of an oil of 100 viscosity index.
L = Viscosity at 100° F. of an oil of 0 viscosity index.

Kinematic Viscosity at 210° F., Centistokes.	H.	L.	D $(L - H)$.	Kinematic Viscosity at 210° F., Centistokes.	H.	L.	D $(L - H)$.
2·00	6·620	8·360	1·740	5·00	30·040	42·570	12·530
2·10	7·143	9·043	1·900	5·10	31·090	44·500	13·410
2·20	7·684	9·752	2·068	5·20	32·150	46·460	14·310
2·30	8·243	10·485	2·242	5·30	33·210	48·440	15·230
2·40	8·821	11·244	2·423	5·40	34·270	50·430	16·160
2·50	9·417	12·028	2·611	5·50	35·330	52·430	17·100
2·60	10·031	12·838	2·807	5·60	36·390	54·430	18·040
2·70	10·664	13·672	3·008	5·70	37·450	56·430	18·980
2·80	11·315	14·532	3·217	5·80	38·510	58·430	19·920
2·90	11·984	15·417	3·433	5·90	39·570	60·430	20·860
3·00	12·671	16·328	3·657	6·00	40·630	62·430	21·800
3·10	13·377	17·263	3·886	6·10	41·690	64·430	22·740
3·20	14·101	18·224	4·123	6·20	42·750	66·430	23·680
3·30	14·843	19·210	4·367	6·30	43·810	68·430	24·620
3·40	15·603	20·222	4·619	6·40	44·880	70·430	25·550
3·50	16·382	21·258	4·876	6·50	45·970	72·460	26·490
3·60	17·179	22·320	5·141	6·60	47·080	74·550	27·470
3·70	17·994	23·407	5·413	6·70	48·220	76·740	28·520
3·80	18·828	24·520	5·692	6·80	49·390	79·040	29·650
3·90	19·680	25·657	5·977	6·90	50·590	81·440	30·850
4·00	20·550	26·820	6·270	7·00	51·820	83·920	32·100
4·10	21·400	28·060	6·660	7·10	52·980	86·460	33·480
4·20	22·280	29·360	7·080	7·20	54·150	89·040	34·890
4·30	23·180	30·730	7·550	7·30	55·273	91·660	36·387
4·40	24·100	32·180	8·080	7·40	56·473	94·095	37·622
4·50	25·040	33·720	8·680	7·50	57·669	96·528	38·859
4·60	26·000	35·350	9·350	7·60	58·873	98·958	40·085
4·70	26·980	37·060	10·080	7·70	60·063	101·398	41·335
4·80	27·980	38·840	10·860	7·80	61·305	103·925	42·620
4·90	29·000	40·680	11·680	7·90	62·513	106·388	43·875

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* **Taken from I.P. Standards, "Standard Methods for Testing Petroleum and its Products", 1947.**

APPENDIX III—*continued*

Kinematic Viscosity at 210° F., Centistokes.	*H.*	*L.*	*D* (*L* − *H*).	Kinematic Viscosity at 210° F., Centistokes.	*H.*	*L.*	*D* (*L* − *H*).
8·00	63·723	108·859	45·136	12·50	123·781	239·713	115·932
8·10	64·969	111·419	46·450	12·60	125·274	243·136	117·862
8·20	66·251	114·067	47·816	12·70	126·730	246·482	119·752
8·30	67·501	116·650	49·149	12·80	128·189	249·842	121·653
8·40	68·753	119·306	50·553	12·90	129·689	253·305	123·616
8·50	70·041	121·926	51·885	13·00	131·153	256·690	125·537
8·60	71·296	124·528	53·232	13·10	132·658	260·180	127·522
8·70	72·542	127·153	54·611	13·20	134·166	263·684	129·518
8·80	73·793	129·786	55·993	13·30	135·716	267·293	131·577
8·90	75·089	132·515	57·426	13·40	137·230	270·824	133·594
9·00	76·352	135·176	58·824	13·50	138·745	274·369	135·624
9·10	77·617	137·841	60·224	13·60	140·270	277·964	137·694
9·20	78·880	140·517	61·637	13·70	141·784	281·498	139·714
9·30	80·184	143·284	63·100	13·80	143·348	285·177	141·829
9·40	81·448	145·989	64·541	13·90	144·874	288·776	143·902
9·50	82·714	148·695	65·981	14·00	146·402	292·388	145·986
9·60	83·986	151·411	67·425	14·10	147·933	296·014	148·081
9·70	85·262	154·147	68·885	14·20	149·507	299·749	150·242
9·80	86·575	156·982	70·407	14·30	151·043	303·402	152·359
9·90	87·856	159·722	71·866	14·40	152·582	307·069	154·487
10·00	89·178	162·494	73·316	14·50	154·124	310·749	156·625
10·10	90·458	165·361	74·903	14·60	155·708	314·540	158·832
10·20	91·814	168·303	76·489	14·70	157·255	318·247	160·992
10·30	93·128	171·194	78·066	14·80	158·804	321·968	163·164
10·40	94·461	174·075	79·614	14·90	160·396	325·801	165·405
10·50	95·825	177·068	81·243	15·00	161·950	329·549	167·599
10·60	97·152	179·980	82·828	15·10	163·548	333·410	169·862
10·70	98·492	182·907	84·415	15·20	165·190	337·385	172·195
10·80	99·818	185·849	86·031	15·30	166·793	341·275	174·482
10·90	101·206	188·873	87·667	15·40	168·399	345·179	176·780
11·00	102·537	191·848	89·311	15·50	170·007	348·881	178·874
11·10	103·909	194·899	90·990	15·60	171·660	353·131	181·471
11·20	105·305	197·966	92·661	15·70	173·274	357·078	183·804
11·30	106·721	201·150	94·429	15·80	174·891	361·039	186·148
11·40	108·100	204·238	96·138	15·90	176·552	365·117	188·565
11·50	109·493	207·339	97·846	16·00	178·174	369·107	190·933
11·60	110·887	210·468	99·581	16·10	179·841	373·214	193·373
11·70	112·273	213·601	101·328	16·20	181·552	377·439	195·887
11·80	113·711	216·829	103·118	16·30	183·224	381·577	198·353
11·90	115·114	219·981	104·867	16·40	184·942	385·729	200·787
12·00	116·507	223·145	106·638	16·50	186·577	389·897	203·320
12·10	117·948	226·412	108·464	16·60	188·300	394·184	205·884
12·20	119·438	229·784	110·346	16·70	189·983	398·381	208·398
12·30	120·883	233·078	112·195	16·80	191·670	402·594	210·924
12·40	122·330	236·392	114·062	16·90	193·401	406·929	213·528

APPENDIX III—*continued*

Kinematic Viscosity at 210° F., Centistokes.	*H.*	*L.*	*D* (*L* − *H*).	Kinematic Viscosity at 210° F., Centistokes.	*H.*	*L.*	*D* (*L* − *H*).
17·00	195·094	411·172	216·078	23·00	308·34	711·24	402·90
17·10	196·831	415·537	218·706	23·20	312·09	721·67	409·58
17·20	198·571	419·917	221·346	23·40	316·32	733·47	417·15
17·30	200·357	424·421	224·064	23·60	320·57	745·35	424·78
17·40	202·104	428·832	226·728	23·80	324·36	755·98	431·62
17·50	203·853	433·260	229·407	24·00	328·63	768·00	439·37
17·60	205·605	437·704	232·099	24·20	332·45	778·76	446·31
17·70	207·361	442·161	234·800	24·40	336·75	790·92	454·17
17·80	209·162	446·745	237·583	24·60	341·05	803·17	462·12
17·90	210·923	451·237	240·314	24·80	345·40	815·49	470·09
18·00	212·687	455·743	243·056	25·00	349·3	826·5	477·2
18·10	214·350	460·266	245·916	25·20	353·6	839·0	485·4
18·20	216·268	464·915	248·647	25·40	358·0	851·5	493·5
18·30	218·042	469·469	251·427	25·60	362·4	864·1	501·7
18·40	219·818	474·039	254·221	25·80	366·8	876·8	510·0
18·50	221·597	478·625	257·028	26·00	371·2	889·6	518·4
18·60	223·423	483·339	259·916	26·20	375·1	901·0	525·9
18·70	225·208	487·956	262·748	26·40	379·6	913·9	534·3
18·80	226·996	492·590	265·594	26·60	384·0	926·9	542·9
18·90	228·831	497·352	268·521	26·80	388·5	939·9	551·4
19·00	230·625	502·017	271·392	27·00	393·0	953·1	560·1
19·10	232·466	506·812	274·346	27·20	397·5	966·3	568·8
19·20	234·354	511·739	277·385	27·40	402·0	979·6	577·6
19·30	236·201	516·568	280·367	27·60	406·0	991·4	585·4
19·40	238·052	521·413	283·361	27·80	410·6	1004·9	594·3
19·50	239·906	526·274	286·368	28·00	415·1	1018·4	603·3
19·60	241·806	531·247	289·441	28·20	419·7	1032·0	612·3
19·70	243·666	536·164	292·498	28·40	424·3	1045·6	621·3
19·80	245·529	541·075	295·546	28·60	428·9	1059·4	630·5
19·90	247·440	546·120	298·680	28·80	433·5	1073·2	639·7
20·00	249·31	551·07	301·76	29·00	438·1	1087·0	648·9
20·20	253·10	561·12	308·02	29·20	442·8	1101·0	658·2
20·40	256·86	571·13	314·27	29·40	446·9	1113·5	666·6
20·60	260·59	581·08	320·49	29·60	451·6	1127·6	676·0
20·80	264·64	591·94	327·30	29·80	456·2	1141·8	685·6
21·00	268·26	601·66	333·40	30·0	460·9	1156·0	695·1
21·20	272·35	612·67	340·32	30·5	472·8	1192·0	719·2
21·40	275·99	622·52	346·53	31·0	484·1	1226·8	742·7
21·60	280·10	633·67	353·57	31·5	496·1	1263·7	767·6
21·80	284·22	644·89	360·67	32·0	508·2	1301·1	792·9
22·00	287·90	654·94	367·04	32·5	520·4	1338·9	818·5
22·20	292·05	666·30	374·25	33·0	532·6	1377·2	844·6
22·40	296·22	677·75	381·53	33·5	544·9	1416·0	871·1
22·60	299·96	687·98	388·02	34·0	557·3	1455·3	898·0
22·80	304·13	699·57	395·44	34·5	569·9	1495·0	925·1

APPENDIX III—*continued*

Kinematic Viscosity at 210° F., Centistokes.	*H.*	*L.*	*D* (*L* – *H*).
35·0	582·4	1535·2	952·8
35·5	595·8	1577·7	981·9
36·0	608·5	1618·9	1010·4
36·5	621·4	1660·6	1039·2
37·0	634·3	1702·7	1068·4
37·5	647·4	1745·3	1097·9
38·0	660·5	1788·3	1127·8
38·5	674·4	1833·9	1159·5
39·0	687·7	1877·9	1190·2
39·5	701·1	1922·4	1221·3
40·0	714·6	1967·4	1252·8
40·5	728·3	2013·1	1284·8
41·0	741·9	2058·7	1316·8
41·5	756·1	2106·4	1350·3
42·0	770·2	2154·1	1383·9
42·5	784·2	2201·7	1417·5
43·0	798·2	2249·3	1451·1
43·5	812·7	2299·0	1486·3
44·0	827·2	2348·6	1521·4
44·5	842·2	2400·4	1558·2
45·0	857·2	2452·1	1594·9
45·5	872·1	2503·8	1631·7
46·0	886·9	2555·4	1668·5
46·5	902·0	2608·1	1706·1
47·0	917·1	2660·7	1743·6
47·5	932·7	2715·5	1782·8
48·0	948·2	2770·3	1822·1
48·5	963·7	2825·0	1861·3
49·0	979·1	2879·6	1900·5
49·5	994·8	2935·2	1940·4
50·0	1010·4	2990·8	1980·4
50·5	1026·2	3047·4	2021·1
51·0	1042·0	3104·0	2062·0
51·5	1058·4	3162·9	2104·5
52·0	1074·7	3221·8	2147·1
52·5	1090·9	3280·4	2189·5
53·0	1107·1	3339·0	2231·9
53·5	1123·9	3399·9	2276·0
54·0	1140·6	3460·8	2320·2
54·5	1157·2	3521·4	2364·2
55·0	1173·7	3582·0	2408·3
55·5	1190·5	3643·6	2453·1
56·0	1207·2	3705·2	2498·0
56·5	1224·2	3767·8	2543·6
57·0	1241·1	3830·4	2589·3
57·5	1258·6	3895·4	2636·8
58·0	1276·1	3960·4	2684·3
58·5	1293·5	4025·0	2731·5
59·0	1310·8	4089·6	2778·8
59·5	1328·3	4155·2	2826·9
60·0	1345·8	4220·7	2874·9
60·5	1363·9	4288·8	2924·9
61·0	1382·0	4356·8	2974·8
61·5	1399·9	4424·4	3024·5
62·0	1417·7	4492·0	3074·3
62·5	1435·8	4560·6	3124·8
63·0	1453·9	4629·1	3175·2
63·5	1472·6	4700·2	3227·6
64·0	1491·2	4771·3	3280·1
64·5	1509·7	4841·9	3332·2
65·0	1528·1	4912·4	3384·3
65·5	1546·8	4984·0	3427·2
66·0	1565·4	5055·5	3490·1
66·5	1584·7	5129·7	3545·0
67·0	1603·9	5203·8	3599·9
67·5	1622·9	5277·4	3654·5
68·0	1641·9	5350·9	3709·0
68·5	1661·1	5425·5	3764·4
69·0	1680·3	5500·0	3819·7
69·5	1700·1	5577·2	3877·1
70·0	1719·9	5654·4	3934·5
70·5	1739·5	5731·0	3991·5
71·0	1759·1	5807·5	4048·4
71·5	1779·3	5886·8	4107·5
72·0	1799·5	5966·0	4166·5
72·5	1819·5	6044·6	4225·1
73·0	1839·4	6123·1	4283·7
73·5	1860·0	6204·4	4344·4
74·0	1880·6	6285·6	4405·0
74·5	1901·0	6366·2	4465·2
75·0	1921·3	6446·7	4525·4

APPENDIX IV

CONVERSION TABLE FOR A.P.I. GRAVITY TO SPECIFIC GRAVITY, GALLONS PER TON AND CUBIC FT. PER TON

A.P.I. Gravity.	Specific Gravity.	Imp. Gal. per ton (2240 lb.).	Cubic Feet per ton (2240 lb.).	A.P.I. Gravity.	Specific Gravity.	Imp. Gal. per ton (2240 lb.).	Cubic Feet per ton (2240 lb.).
10	1·0000	223·98	35·96	24	0·9100	246·13	39·51
10·5	0·9965	224·67	36·08	24·5	0·9071	246·93	39·64
11	0·9930	225·53	36·21				
11·5	0·9895	226·26	36·33	25	0·9042	247·73	39·77
12	0·9861	227·13	36·46	25·5	0·9013	248·53	39·90
				26	0·8984	249·33	40·03
12·5	0·9826	227·87	36·59	26·5	0·8955	250·11	40·15
13	0·9792	228·71	36·72	27	0·8927	250·90	40·28
13·5	0·9758	229·51	36·85				
14	0·9725	230·31	36·98	27·5	0·8899	251·70	40·41
14·5	0·9692	231·09	37·10	28	0·8871	252·50	40·54
				28·5	0·8843	253·29	40·66
15	0·9659	231·88	37·23	29	0·8816	254·08	40·79
15·5	0·9626	232·68	37·36	29·5	0·8789	254·87	40·92
16	0·9593	233·48	37·48				
16·5	0·9561	234·28	37·61	30	0·8762	255·65	41·04
17	0·9529	235·07	37·74	30·5	0·8735	256·44	41·17
				31	0·8708	257·23	41·30
17·5	0·9497	235·85	37·86	31·5	0·8681	258·03	41·43
18	0·9465	236·64	37·99	32	0·8654	258·83	41·56
18·5	0·9433	237·43	38·12				
19	0·9402	238·22	38·24	32·5	0·8628	259·62	41·69
19·5	0·9370	239·01	38·37	33	0·8602	260·40	41·81
				33·5	0·8576	261·15	41·94
20	0·9340	239·80	38·50	34	0·8550	261·90	42·07
20·5	0·9310	240·59	38·62	34·5	0·8524	262·74	42·20
21	0·9279	241·38	38·75				
21·5	0·9248	242·19	38·88	35	0·8498	263·59	42·32
22	0·9218	243·00	39·01	35·5	0·8473	264·38	42·44
				36	0·8448	265·18	42·57
22·5	0·9188	243·77	39·13	36·5	0·8423	265·96	42·70
23	0·9159	244·54	39·26	37	0·8398	266·73	42·82
23·5	0·9129	245·33	39·38				

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