BIBL

THE INSTITUTE OF PETROLEUM AND THE ROYAL AERONAUTICAL SOCIETY.

A JOINT meeting of the Institute of Petroleum and the Royal Aeronautical Society was held at Manson House, 26 Portland Place, London, W.1, on Wednesday, February 12, 1947.

SIR ANDREW AGNEW (President of the Institute of Petroleum) opened the proceedings and welcomed the members of the Royal Aeronautical Society. He said : Having regard to the subject of the paper to be presented we are fortunate in having with us Air-Commodore Banks who has had a lifelong experience in the petrol engine field for both aircraft and motor cars. The paper is on fuels and lubricants for aero gas turbines and Air Commodore Banks is well qualified to handle a discussion on that subject. It is a development of a major character and it is only right that there should be a paper giving full technical consideration to it. I, therefore, ask Air Commodore Banks to take the Chair and introduce the author of the paper.

AIR COMMODORE F. R. BANKS : I have known Dr C. G. Williams, the author of the paper, for some fifteen years. He was a graduate in engineering at the Manchester University and became a Doctor of Science in that University in 1941. He was, up to 1940, Director of Research in the Institution of Automobile Engineers Research Department, where he was responsible for a lot of good work on cylinder bore wear and valve wear on ordinary petrol engines. Then he became Director of Research at the Shell Aeronautical Laboratory, which in 1942 was turned over for Government work lock, stock, and barrel. I was at the time Director of Development at the Ministry of Aircraft Production and when this laboratory was offered we took it with both hands. The work done there by Dr Williams and his staff was absolutely first class and all sorts of awkward questions were referred to him. The following paper was then read :

FUELS AND LUBRICANTS FOR AERO GAS TURBINES.

By C. G. WILLIAMS,* D.Sc., M.I.Mech.E., F.R.Ae.S. (Fellow).

INTRODUCTION.

THE subject of fuels and lubricants for aero gas turbines is a comparatively new one, and the author has been faced with certain difficulties in his choice of material for the present paper. Extensive experimental work is being carried out on various aspects of combustion and lubrication at a number of laboratories, very little of which has been published in the general technical press. The author did not feel justified, therefore, in drawing on this information except in a very generalized manner. The

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laboratory with which he is associated, the "Shell" Aero Engine Laboratory at Thornton, Cheshire, has been engaged on lubrication studies for the aero gas turbine since 1943, and began fuel and combustion studies in 1944. This work has been undertaken with some knowledge of the practical problems which have been experienced in engine development and operation, and it was therefore decided to base the following paper on this general knowledge with illustrations and experimental data drawn, whenever possible, from the work of the Thornton laboratory.

It is clear, therefore, that the following treatment does not do full justice to the activities of other laboratories, many of which have made extremely valuable contributions. It may, however, provide a general introduction to the subject and stimulate others to pass comment on the data and opinions submitted by the author.

PART I.—FUELS.

In the early days of its development there was a comparatively widespread impression that the aero gas turbine was congenitally omnivorous. It was recognized that this early development had been carried out largely on kerosine, but it was conjectured that in a very short time aero gas turbines would be operating on almost any liquid fuel.

This early optimism has since given way to a realization of the influence of quite a number of fuel factors. The performance of the gas turbine, as of any other prime mover, is determined by a combination of fuel characteristics and engine design and during its evolution the relative emphasis on fuel characteristics and on engine design may change. Since, in the present stage of the art, combustion in gas turbines is, to a large extent, influenced by mechanical or aerodynamic factors, it would be anticipated that, as development proceeds, increasing knowledge of mechanical design will result in reduced importance being attached to fuel properties. In other words, the trend is possibly in the direction of that hoped for by the early pioneers, but we are a good way from complete realization of that ideal.

On the other hand, there is always the possibility that efforts to achieve higher efficiency and better performance may emphasize certain fuel properties and make the aero gas turbine more discriminating in its taste for fuels.

The author has attempted in the following to discuss the inter-relation between fuel characteristics and engine performance only as the subject appears at the present time.

A gas turbine fuel should have the following main qualities :---

(a) "Pumpability", *i.e.*, flow of fuel to the engine must occur under all operating conditions;

(b) Starting must be quick, down to the lowest possible starting temperatures;

(c) Combustion must be efficient and stable under all conditions;

(d) The calorific value should be as high as possible;

(e) The combustion zone should be as small as possible;

(f) The combustion products should have no harmful effects on any engine components, particularly flame tubes and turbine blades;

- (g) If possible, it should have "safety" characteristics;
- (h) It should be available in adequate quantities.

The influence of fuel properties on some of the above requirements will now be discussed.

Fuel Flow to Engine.

In the aero gas turbine it is necessary to ensure a flow of fuel to the engine which may range from 50 to 500 gallons per hour, the corresponding range of pressure being of the order of 20 to 780 p.s.i. It is essential that the fuel should not have any deletereous effects on the pumping system and that the required flow of fuel should be maintained down to the lowest temperature which may occur under starting conditions or in flight. In this connexion, the gas turbine emphasizes low temperature requirements because of (a) its inherent capacity for quick starting which will encourage users to dispense with the "nursing" given to piston engines in the form of protection from low temperatures, (b) the extremely high altitudes which will be characteristic of turbined aircraft, (c) the requirement on certain multi-engined aircraft of a shut-down of some engines under cruising conditions.

In so far as the maintenance of fuel flow is concerned, difficulties may arise through (a) water in the fuel which may either cause corrosion or icing, (b) freezing of the fuel at low temperatures, (c) viscosity effects on pumpability, etc.

Water Content. The water content of fuels may give rise to corrosion troubles in fuel pumps, or to filter clogging due to ice formation. Reference will be made in the first place to corrosion difficulties.

In the early days of the aero gas turbine the kerosine then used was obtained from many sources, and was intended mainly for illuminating purposes or for other industrial applications which did not require the high degree of cleanliness required for aviation use and considerable troubles were experienced due to impurities.

Precautions are now taken in the storage and distribution of aviation turbine fuels which have alleviated serious troubles due to water and dirt. These include a filtration before distribution using a 180-mesh metal gauze filter, while there is customarily a final filtration through a felt filter when re-fuelling aircraft.

As will be shown later, all fuels normally contain water in solution which cannot easily be removed and this water may give rise to difficulties when the temperature of the fuel is reduced.

Until recently, the fuel system used on British engines was somewhat sensitive to the presence of moisture which tended to cause rusting and sticking of sliding parts, more especially those whose movement was only small and occasional. This corrosion was avoided by adding 1 per cent of lubricating oil to the fuel, the oil functioning mainly as a corrosion inhibitor.

Recent improvements in the fuel system, whereby sliding parts liable to cause trouble have been eliminated, have enabled this addition of oil to the fuel to be discontinued in the case of kerosine and the only sliding parts left are the pump plungers, which are no more likely to stick than the plungers of a diesel pump.

The problem is more difficult for fuels of appreciably lower viscosity than that of kerosine, *e.g.* gasoline. Where the fuel delivery pressure is relatively low it is possible to design a gear type pump for gasoline which will function satisfactorily. This apparently is the case in the U.S. where certain turbine engines operate on gasoline without the addition of oil to the fuel.

Where the delivery pressure is high and piston pumps are used, as on British engines, it is necessary to lubricate such parts as cams and the ends of plungers when gasoline is being pumped. This can be done by



TEMPERATURE, °C.

FIG. 1.

SOLUBILITY OF WATER IN PETROLEUM FRACTIONS.

adding lubricant to the fuel, or by providing a feed of lubricant to certain parts of the pump. The latter method, which is clearly preferable, has, in fact, been recently applied to pumps for gasoline. Where the fuel contains heavy fractions with lubricating properties it may be possible to dispense with this separate lubrication.

It can therefore be stated with some certainty that, in the near future, fuels for gas turbines—whether gasolines or kerosine—will not require the addition of a lubricant.

The other difficulty which may arise from the presence of water in the fuel is that of filter-clogging due to freezing of the water. In this connexion, hydrocarbon fuels are normally saturated with water and Figs 1 and 2

show the water solubility of a number of fuels and hydrocarbons plottted against temperature.

The most important feature to note in these graphs is the very large effect of temperature on solubility. A kerosine saturated with moisture at normal atmospheric temperature contains about 0.005 per cent by weight of water. Chilling of the fuel to -10° C or below results in the precipitation of most of this moisture which may remain in suspension or be deposited depending on conditions. The quantity of water involved is of the order of 0.04 gallon per hour with a fuel consumption of 1000 gallons per hour. If conditions are such that the fuel is subjected to low temperatures for a



SOLUBILITY OF WATER IN GASOLINE.

prolonged period, the moisture may tend to be deposited at the bottom of the fuel container where it may do little or no harm. Under conditions of more rapid chilling, the moisture will remain in suspension and be carried along to the engine.

The solubility of water in a fuel depends on the composition of the fuel. In the first place, it would be anticipated on physico-chemical grounds that the water solubility of fuels of a given molecular type would increase with decreasing molecular weight of the fuel. This is illustrated in Fig 1 where it is clear that the water solubility of the gasolines is, in general, higher than that of kerosines. In the same way, the water solubility of "heavier" fuels, such as gas oil, will be lower than that of kerosine. Fig 2 suggests that the water solubility may increase appreciably with aromatic content; thus the addition of 30 per cent of toluene to a gasoline doubled its water solubility while benzene has a solubility ten times that of gasoline. In Table I the water solubility at 18° C is given for a number of fuels, for which the aromatic contents are also given. It is evident that for these fuels there is no clear connexion between water solubility and aromatic content. Two kerosines of high aromatic content (20.5 and 22 per cent)

TABLE I.

	Filter	Clog	gging	Tender	ncy	v.	Water	Solubility.		
Fuels	satura	ated	with	water	at s	tors	age ter	mperature	(10-15°	C)

Fuel.	Sp. gr. (60/60).	Boiling range (° C).	Cloud point (°C).	Aro- matics (% w).	Solubility of water in fuel saturation value 18° C (% w).	Tempe (° C) at flow d by 20%.	erature t which ropped
100/130 Grade Base	0.735	44-171	<-60	22.2	0.007(0)	-22	-26
Naphtha TL 604	0.784	156 - 220	< -60	15.2	0.005(7)		
Naphtha 206 (JP 2							
type fuel) .	0.707	88 - 231	< -60	10.6	0.004(9)	40	43
Kerosine SR 312	0.806	158 - 276	-43	8.6	0.006(0)	25	-29
Kerosine 201	0.804	143 - 262	< -60	21.9	0.008(5)	-22	-25
Kerosine 203	0.834	186 - 279	-49	20.5	0.004(3)	*	*
Kerosine 205 .	0.878	188-309	-37	23.0	0.005(4)		
Kero-gas oil TL 255B	0.827	100 - 284	-45	16.3	0.004(6)	31	38
Hydrogenated gas							
oil	0.825	184-297	< -60	4.4	0.003(6)	-39	-42
Gas oil 363B .	0.848	204-378	_°7	22.6	0.004(2)		_

* Clogging occurred at -50° C; this was partly due to solid hydrocarbon separation (cloud point -49° C), there being no appreciable difference between wet and dry fuel (see Table II).

have water solubilities of 0.0043 and 0.0085, respectively, whereas a fuel of low aromatic content (8.6 per cent) has an intermediate water solubility of 0.006 per cent. It may be conjectured that the type of aromatic and its molecular weight may have a considerable influence on water solubility.

Apart from the corrosion difficulties mentioned above this water may give rise to filter clogging due to ice accumulation on cloth-type filters. This question has been studied at Thornton on the apparatus shown in Fig 3, in which fuel is pumped round a closed circuit, passing in turn through a cooling coil and a filter element across which the pressure drop is measured. The flow rate through the $\frac{3}{4}$ -sq. in. filter was 5 to 8 gallons per hour, corresponding to a flow rate of 1000 gallons per hour through a full-size filter. Flow measurements, together with pressure and temperature readings, were made for every 5 to 10° C drop in temperature. The temperatures at which the flow dropped by 20 and 50 per cent compared with the dry fuel at the same temperature are shown in Table I.

It will be noted that filter-clogging occurs at temperatures which in many cases are well above the cloud points of these fuels. Fig 4, plotted from the data in Table I, shows that there is a rough relationship between the clogging tendency and the water solubility. The lower the water solubility the lower the temperature at which filter-clogging, due to ice formation, takes place.



FIG. 3.





EFFECT OF WATER SOLUBILITY ON FILTER CLOGGING.

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The experimental conditions of this test apparatus are obviously severe since they allow practically no opportunity for the deposition of water, *i.e.*, all the water is retained in suspension.

A few experiments were carried out at Thornton to ascertain whether filter-clogging due to ice could be alleviated by (a) preliminary filtration in the engine with a gauze filter, and (b) the addition of an "anti-freeze" to the fuel.

It was found that filter clogging of a cloth filter could be delayed by a preceding filtration with a 100-mesh gauze filter—a coarser mesh allowed ice to pass through, while a finer mesh clogged.

Filter clogging due to ice was entirely eliminated by the addition of 0.5 to 1 per cent of *iso* propyl alcohol to the fuel. This acted as an anti-freeze, sufficient of it being precipitated with the water to depress the freezing point to -50° C or below.

If filter clogging due to ice formation can be avoided, it will occur at a still lower temperature due to wax formation. The apparatus shown in Fig 3 was used for studying the relation between filter clogging and the conventionally determined cloud point for fuels which had been dried with phosphorus pentoxide. The results are summarized in Table II, from which it is obvious that there is an approximate connexion between the cloud point of the fuels and the temperature at which flow through the filter drops by 20 per cent.

Fuel.	Cloud point, °C (±1°C).	Pour point, °C (±1°C).	Temp. at which flow dropped by 20% of value calculated from extrapolated viscosity (° C).	Temp. at which flow dropped by 50% of value calculated from extrapolated viscosity (° C).	
Gas oil 363B Kero-gas oil TL. 255B Kerosine SR. 312 . Kerosine 203 Kerosine 206 Hydrogenated gas oil	$\begin{array}{r} - 7 \\ -43 \\ -43 \\ -49 \\ < -60 \\ < -60 \\ < -60 \\ < -60 \end{array}$	$-12 \\ -46 \\ -54 \\ -54 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60 \\ <-60$	$\begin{array}{c c} - & 6 \\ -43 \\ -46 \\ -52 \\ < -60 \\ < -60 \\ < -60 \end{array}$	$-10 \\ -44 \\ -47 \\ -53 \\ < -60 \\ < -60 \\ < -60$	

TABLE II.

Filter Clogging Tendency v. Cloud Point for Dry Fuels.

These results, therefore, indicate that the conventional cloud point may be used to indicate the temperature at which serious interference with fuel flow is likely to occur owing to deposition from the fuel itself.

There is a considerable difference between the cloud points required by American and British specifications, viz. -60° C and -40° C respectively. The American figure is apparently an inheritance from the gasoline specification; if a figure of -50° C was warranted for gasoline it might be assumed that at least a similar limit on the cloud point should be specified for a gas turbine fuel. Early British fuels for gas turbines were supplied to a -60° C cloud point, but the availability of such kerosines was limited and the specification limit was raised to -40° C.

Experience under service conditions will presumably indicate whether the cloud point should be -40° C or -60° C or some other figure. A good deal will depend on whether fuel lines are exposed. In addition, it should be recalled that there is a temperature rise due to the forward velocity of the aircraft which at 600 m.p.h., amounts to a possible 36° C, so that, with an ambient temperature of -60° C, the leading surfaces of the aircraft will be at approximately -30° C.

It would be appropriate to mention here the influence of aromatic content on freezing point. A particular batch of vaporizing oil was segregated a few years ago for gas turbine work because it had a cloud point of -65° C. It also had an aromatic content of 22 per cent, but because considerable troubles were experienced on certain engines due to carbon deposition its use was discontinued and the aromatic content of subsequent fuels was limited to 12 per cent. This immediately raised difficulties with regard to the cloud point since a reduction in the aromatic content tends to raise the cloud point. Thus, an illuminating kerosine which has been used for a period as a standard reference kerosine has an aromatic content of 8.6 per cent and a cloud point of -43° C.

It will therefore be noted that an advantage of an aromatic-type kerosine is its lower initial freezing or cloud point. Naphthenes have even lower freezing points, so that a naphthenic-type kerosine would have the lowest cloud point.

Some mention should be made here of heavier fuels such as gas oil. Such fuels have pour points ranging from -40° C or below, to 0° C, so that many of them could not be used for aero gas turbines without some provision for heating. Here again, there is a general tendency for the aromatic rich gas oils to have the lowest cloud points. The use of pour point depressants in gas oils has not been particularly successful since such materials are only effective with large molecules.

It is also possible from gas oil to produce fuels which, by the process of cracking followed by distillation, are roughly within the kerosine range of volatility and have a cloud point of -60° C or below. Such fuels might be used to supplement the supply of kerosine.

Combustion Efficiency.

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In considering alternative fuels for gas turbines, it would be expected that some fuels would be more difficult to burn than others and that this might result in incomplete combustion and in a general lowering in the overall engine efficiency. Conversely, it may be necessary, in order to get the best out of a given fuel, to modify combustion chamber design in order that the heat content of the fuel may be fully released.

Combustion efficiency can be defined as the actual heat released from a given quantity of fuel expressed as a percentage of the theoretical heat release which would be obtained if the fuel were completely burned. In this connexion it is necessary to limit combustion to the combustion chamber itself, since any burning which takes place beyond the turbine is detrimental to the life of the turbine blades and, to a large extent, wasted.

There are four principal methods of measuring combustion efficiency: (a) from temperature measurements; (b) by gas analysis; (c) by calorimetric methods; (d) by thrust measurements.

For the accurate application of the first method it is necessary to know the approximate composition and specific heats of the products of combustion, the heat of combustion of the fuel and the air and fuel flow. In addition, there are considerable difficulties in measuring high "stagnation" temperatures (*i.e.* including adiabatic temperature rise due to gas velocity). This can be done by using shielded couples intended to eliminate radiation losses; alternatively, it is possible to apply correction factors to unshielded couples to allow for radiation effects. The possibility that errors may arise due to surface combustion on the thermocouple and conduction along the leads must also be borne in mind.

It is usually considered necessary to measure combustion efficiency in the plane of the turbine nozzles, where temperatures and velocities are not uniform, so that a laborious temperature and velocity traverse has to be made, with subsequent averaging. In one laboratory a number of couples suitably located are arranged in parallel and connected to a potentiometer, so that an average temperature reading is obtained. A way of evading the difficulty associated with a temperature traverse is to mix the combustion products by means of baffles, so as to equalize the temperatures, but this method does not satisfy the above requirement that combustion efficiency should be measured in the plane of the turbine nozzles.

The estimation of combustion efficiency from temperature measurements is simplified, with the introduction of slight inaccuracy, by defining it as the actual temperature rise obtained between the combustion chamber entry and the turbine blades, expressed as a percentage of the actual rise which would occur if the fuel were completely burned.

The method of gas analysis has been less widely used than that employing temperature measurements, but it has certain marked advantages. It does not require a knowledge of the heat of combustion of the fuel, or of the air and fuel flows, and it avoids difficulties associated with temperature measurements. It does necessitate, however, a gas sampler to give a representative sample and an accurate method of gas analysis. To obtain an accurate value of the percentage thermal loss from gas analysis, it is necessary to carry out a complete analysis for all combustible gases, *i.e.*, unburnt fuel and hydrocarbons, methane, carbon monoxide, and hydrogen.

A useful expression is the "CO, per cent loss," defined as :---

" CO_{2} per cent loss " =

 $100 \times \frac{\text{CO}_2 \text{ which would result from burning any}}{\text{CO}_2 \text{ resulting from complete combustion of fuel}}$

This expression is not necessarily identical with the thermal loss, but it gives a fairly close approximation in most cases, particularly for comparative purposes. It follows that if a means of estimating the CO_2 from unburnt gas is available, a fairly close estimate of the combustion efficiency can be arrived at.

The calorimetric method does not appear to have been used to any appreciable extent. In one laboratory, however, a measured quantity of water is introduced into the products of combustion and the final temperature of the products determined, from which an estimate is obtained of the

combustion efficiency. The thrust method has been used in Germany and elsewhere on single combustion chambers.

Gas Analysis.

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A 16-point gas sampler has been developed at Thornton. The flow from each sampling point can be measured and although separate samples can be taken from each point, the gases are normally fed into a mixing manifold from which a representative sample can be taken.

In regard to gas analysis, special problems arise because of the very high air-fuel ratios which imply that the products for analysis are only present in small proportions, and also because of the possible presence of unburnt vaporized hydrocarbons. It is the considered view of the Thornton laboratory that these problems cannot be solved by the use of the conventional absorption type of apparatus.

Baldwin and Bamford described the vacuum method in the Journal of the Chemical Society, 1941, and since then Baldwin has worked on the development of this method at the Thornton laboratory. In this method, each constituent is estimated directly by fractional condensation and fractional combustion instead of by the indirect method of absorption and the measurement of the difference between two large quantities. To illustrate the principle of the method, carbon dioxide is measured by circulating the sample through a trap cooled in liquid air. The carbon dioxide condenses and after the uncondensed gas has been pumped away, the quantity can be estimated directly by measurement of the pressure developed in a given volume. The present apparatus used at Thornton gives an accuracy of 0.005 per cent for each gas containing carbon, and enables combustion losses of 0.2 per cent to be detected.

While the vacuum method is a reliable basic method, particularly for research, there was an obvious need to develop something approaching a continuous recording apparatus. A method developed at Thornton employs the principle that if a gas containing CO₂ is bubbled through a dilute solution of sodium bicarbonate, the solution acquires a definite pH which is determined by the partial pressure of the CO₂ in the gas. Thus, by reading a pH meter it is possible to measure the CO₂ content, and other gases which can be converted to CO_2 by oxidation. An accuracy of 2 per cent of the CO₂ concentration is possible over the whole range. For determinations of combustion efficiency the CO₂ is first removed with an absorbent and all unburnt gases are then oxidized on copper oxide at 1000° C and the CO₂ produced from oxidation is estimated by the pH meter. Using this method a "CO₂ combustion efficiency" evaluation can be obtained in 10 to 20 minutes, compared with about 3 hours by the vacuum method described above. If a closer approximation to the thermal efficiency is required, carbon monoxide can be estimated separately after low-temperature oxidation using a second bicarbonate solution, without lengthening the time of 10 to 20 minutes for the estimation.

Combustion Efficiency with Different Fuels.

Little work has as yet been carried out in comparing different fuels in regard to combustion efficiency. Fig 5 is given for the purpose of illustration and shows combustion efficiency plotted against engine speed for (a)

ideal conditions where the atomization is adjusted to give optimum results; (b) a more typical engine curve obtained with kerosine; (c) the sort of combustion efficiency curve which may be obtained with a fuel giving inferior combustion. In such instances, experimental studies are obviously required in order to ascertain in what ways the combustion efficiency can be improved by design modifications.

Fig 5 illustrates the effect of engine speed on combustion efficiency; the



TYPICAL COMBUSTION EFFICIENCY CURVES.

improvement with increased speed is attributable to increased turbulence and improved atomization. An increase in turbulence usually results in a higher pressure drop through the chamber which, in itself, produces a detrimental effect on overall engine efficiency.

Little is known regarding the mechanism of combustion loss. Work carried out at Thornton using small-scale combustion chambers intended to simulate combustion in the primary zone of a full-scale chamber, but using vaporized fuel, suggests that loss at weak mixtures is not experienced until the air-fuel ratio exceeds 30:1 and increases almost linearly with increasing air-fuel ratio until the weak limit blow-out occurs This loss

occurs mainly as carbon monoxide, an interesting observation which, when interpreted, may help to explain the mechanism of combustion loss.

In considering the influence of fuel properties on combustion in the gas turbine it is logical to begin with the process of atomization. While a good deal has been learned regarding atomizer design, notably through the wax droplet method of Joyce of the Shell Petroleum Co. Ltd., and through the efforts of Messrs. Joseph Lucas Ltd., very little work has been done to investigate the influence of fuel properties. The fuel properties which are relevant are the viscosity, surface tension and density, and, in the absence of experimental data, dimensional analysis suggests that the particle size is proportional to the 0.45 power of the viscosity, and that surface tension has a negligible influence. The influence of particle size on combustion has been studied in various laboratories in relation to combustion efficiency, blowout, etc. Its influence on cold-starting will shortly be discussed.

Atomization is followed by heating and evaporation of the fuel particles. The rapidity of the evaporation will depend on the volatility and latent heat of the fuel, which will clearly constitute important factors.

The above factors are all physical as distinct from chemical. The factors controlling ignition and rapidity of combustion would also appear to be very largely physical in nature, as they are mainly controlled by mixing conditions, in particular, the physical recirculation of hot gases and of "chain carriers." It can therefore be deduced that under most conditions combustion in the gas turbine is controlled by physical rather than chemical factors though there may be exceptions which, in the further development of the gas turbine, may assume some importance.

The study of the effect of fuel properties on combustion can be carried out on full-scale combustion chambers and work of this kind is now being done. Useful fundamental data can also be obtained by special methods, e.g. the work of Lloyd at the National Gas Turbine Establishment where the ignition lag of a fuel is measured in an igniting stream of hot air. Considerable work has been carried out at Thornton on reduced scale combustion chambers, which have the advantage of economy in the amount of air and fuel required. On such apparatus phenomena such as combustion loss, carbon deposition, flame length, flame colour, etc., can be studied on pure hydrocarbons, the physical and chemical properties of which are well known or determinable. In addition, such experiments can be carried out on vaporized fuels to eliminate the complications and uncertainties involved in the atomization process, while a comparison of such results with combustion under atomized conditions will help to elucidate the importance of the atomization and vaporization processes. Other types of apparatus can be used for the measurement of ignition limits, flame speeds, ignition temperatures and the effects of temperature and pressure on these properties. For example, flame propagation at low pressures has been studied at Thornton in a glass reaction vessel, using homogeneous mixtures. This work has shown that there exists a critical pressure below which flame propagation is impossible and which is almost the same for all the hydrocarbon fuels investigated.

Certain important practical considerations will now be discussed, viz., flame blow-out, combustion efficiency, combustion intensity and flame length, detonation, and carbon deposition.

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Flame Blow-Out.

Considerable troubles have been experienced due to flame extinction, more especially at altitude under varying load conditions. When the pressure and temperature of the air and fuel pressure are all low, atomization and mixing are poor and, under such conditions, a rapid change of load may produce abnormally weak or rich zones, which may cause flame extinction.

Air is usually fed, in part, to the primary zone through swirler vanes which cause reversal of air flow upstream along the centre of the flame tube (see Fig 6). It is generally accepted that this reversal zone, which



FIG. 6.

AIR FLOW AND FUEL DISTRIBUTION PATTERN FOR TYPICAL COMBUSTION CHAMBER.

conveys hot gases back to the incoming fuel, is responsible for maintaining a stable flame. It may be conjectured that under certain conditions the re-circulated gas may not be hot enough to cause ignition, which may be due to weak mixture strength or to incomplete combustion resulting from insufficient time for completion. The fact that insufficient time is available may arise from too low an evaporation or combustion rate. If the incoming fuel/air mixture is outside ignition limits, or if the ignition temperature is too high, extinction will occur.

A good deal of effort is being devoted to a study of the factors affecting flame extinction, and studies are being made at various laboratories of the separate effects of air pressure and temperature and of atomization. In the meantime some simple experiments have been carried out at Thornton to study the differences between fuels in regard to their weak mixture blowout. In this connexion, it is understood that while flame extinction at weak

mixtures may occur on engines with separate combustion chambers, certain engines with annular combustion chambers are inclined to suffer from rich blow-out.

A method of expressing stability limits over a range of air flows is shown in Fig 7 in which air flow is plotted against air-fuel ratio for a given set of conditions. Such a curve is obtained by varying the air-fuel ratio at a given air flow and determining the rich and weak mixtures at which flame extinction occurs. Combustion is thus stable within this curve.

In general, it was not found possible to investigate rich mixture blow-out on the full-scale combustion chamber because of the danger of over heating, and attention was therefore concentrated on weak mixture blow-out, *i.e.* on the right-hand portion ABC of the curve. Such a curve, showing a continued extension of the weak limit as the air flow is reduced, is obtained with a gaseous fuel, such as butane or vaporized kerosine. With an atomized fuel, however, the curve bends back as illustrated in Fig 7 approximately



TYPICAL BLOW-OUT CURVE.

along a line of constant fuel flow B'C'. It would appear that over the portion AB the air velocities, fuel flow and fuel pressures are all sufficiently high to produce reasonably good atomization. As point B is approached, however, fuel flow at blow-out becomes progressively less until a flow is reached below which the atomization is too poor to allow combustion to continue. When this state of affairs is reached, the blow-out curve follows approximately a line of constant fuel flow, B'C'.

These phenomena are illustrated in Fig 8 which presents blow-out results for a number of fuels obtained on a full-scale combustion chamber under ground atmospheric conditions with an air inlet temperature of about 30° C at the lower air flows.

The results can be taken as illustrating the general effect of fuel characteristics on blow-out.

At the higher air flows there are differences between the various fuels for which, at the present time, no explanation is offered. The results certainly are not in the order of volatility or viscosity of the fuel. It is of interest that aviation kerosine under these relatively high air flow conditions has a

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better weak mixture blow-out limit than the *iso*paraffinic fuels, *iso*octane and "safety fuels." Further studies are obviously necessary to ascertain whether any chemical factors affect weak mixture blow-out under these conditions.

The order of merit of the fuels at low air flows, where poor atomization takes control, is, however, easier to explain. Under these conditions an improvement in volatility would be expected to extend the weak mixture blow-out limit since, as shown by Fig 8, a very considerable extension was



OVERALL AIR-FUEL RATIO.

FIG. 8.

WEAK LIMITS OF COMBUSTION IN SINGLE-COMBUSTION CHAMBER.

obtained with a completely vaporized fuel. The minimum critical fuel flow for each of the fuels treated is plotted against the 10 per cent distillation temperature of the fuels in Fig 9 and it is seen that there is reasonable correlation.

It can, therefore, be deduced that under conditions where poor atomization takes control, an improvement in volatility is beneficial. For example, gasoline would give a weaker blow-out limit than kerosine, and kerosine would be better than gas oil.

It should be emphasized, however, that design factors can exercise a

predominant effect in extending a weak mixture blow-out at low air flows, *e.g.*, by improved atomization.



EFFECT OF FUEL VOLATILITY ON BLOW-OUT.

Carbon Deposition.

Carbon formation in combustion chambers is an indication that combustion conditions are imperfect though it does not necessarily imply low combustion efficiency. There are three possible consequences of carbon deposition, all of which may be serious, viz. (a) local over-heating and buckling of flame tubes; (b) erosion of the turbine blades, caused by lumps of carbon which break loose from the flame tube and pass through the engine; (c) blockage of turbine nozzles by lumps of carbon.

It is widely recognized that there is a tendency for carbon deposition to increase with increasing aromatic content of the fuel. The same discovery was made many years ago in relation to illuminating kerosines which, in general, have to be of low aromatic content.

Reference has already been made to carbon deposition troubles which were experienced on a particular batch of aviation kerosine containing 22 per cent of aromatics. These troubles were serious on one design of engine, while on other designs no particular difficulties were experienced with this fuel, thus emphasizing at the outset that carbon deposition troubles with highly aromatic fuels are by no means inevitable and are associated with engine design. In fact, there is reason to believe that most, if not all, current designs of British turbine engines are relatively insensitive to carbon deposition troubles with highly aromatic fuels; such troubles may, however, still arise under conditions of maladjustment or misuse.

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In addition, there is reason to believe that carbon formation increases with combustion pressure so that with a future trend towards increased pressures, troubles due to carbon may be accentuated. It is, therefore, still necessary to assess the carbon-depositing propensities of a fuel and this can be conveniently carried out on a full-scale single combustion chamber.

Experiments have been carried out at Thornton on a full-scale chamber under conditions intended to aggravate carbon deposition, viz., an air flow of 0.5 lb/second, an air-fuel ratio of 50:1, the duration of the test being 1 hour. In Fig 10 the carbon deposited is plotted against aromatic content



EFFECT OF AROMATIC CONTENT ON CARBON DEPOSITION.

for four aviation turbine fuels (see Table I for further details) and the expected trend is evident, the carbon deposition for the two kerosines containing over 20 per cent aromatics being nearly twice that with the kerosine containing just under 10 per cent of aromatics.

The fuels 201, 203, and SR312 had similar distillation characteristics, while 206 had a low initial boiling point of 87° C compared with the initial boiling points of the other fuels, which ranged from 145 to 185° C. The low carbon deposition with 206 suggests that carbon deposition may be decreased by lowering the initial boiling point of the fuel—a conclusion supported by results obtained at the "Shell" Emeryville laboratories.

The Emeryville experiments were carried out on a reduced-scale gas turbine combustion chamber and covered a wide range of fuels. It was found that for one hydrocarbon type carbon deposition increased with a

reduction in volatility and that paraffins were better than naphthenes which, in turn, were better than aromatics. Similarly, aromatics with paraffinic side-chains were better than aromatics without side-chains. The following formula was developed expressing the relation between carbon deposition, C : H ratio, and the 10 per cent temperature T

$$ext{Carbon deposit} = \log_{10} rac{(ext{C}: ext{H} - ext{C}_1)}{ ext{C}_2} + rac{T}{ ext{C}_3} - ext{C}_4$$

where C₁, C₂, C₃, and C₄ are constants.

This formula shows how carbon deposition tends to increase with the C: H ratio (*i.e.*, with aromatic fuels) and that a reduction in the 10 per cent temperature reduces carbon deposition.

In so far as the sulphur content is concerned, the general evidence suggests that, within normal limits, its effect on carbon deposition is very much less than that of the aromatic content.

It should be emphasized that, since a limit on the aromatic content of kerosines entails a limitation of supply, it would be of advantage to develop combustion chambers which are not sensitive to the aromatic content.

Flame Tube Temperatures.

Considerable efforts have been devoted towards increasing the life of flame tubes. It seems to be generally agreed that buckling and cracking of flame tubes is attributable, in the main, to the combined effects of overheating, resulting from localized over-rich mixtures and of unsymmetrical air flow around the outside of the flame tube, resulting in under-cooling of the same areas. It is important to consider whether the fuel is likely to have any effect in this connexion, and the most obvious factor to investigate is the aromatic content since it is known from piston engine experience that highly aromatic fuels burn with a slightly higher flame temperature and result in a slightly increased cyclinder head temperature. A few experiments have been carried out at Thornton in order to compare two fuels of different aromatic content with regard to flame tube temperature.

Sixteen thermocouples were fitted in the wall of a flame tube and a comparsion of the temperatures attained under identical conditions of operation on two fuels, viz. SR.312 (aromatic content 8.6 per cent) and on aviation kerosine 201 (aromatic content 22 per cent).

In Fig 11 are shown the cross-sections A, B, C, D, E, and F at which temperatures were measured. Three or four temperatures were taken at each cross-section and they differed appreciably, but in the graph of Fig 11 the average reading at each section is plotted for the two fuels. This graph illustrates the rise in temperature along the flame tube until the tertiary air holes are reached where the temperature drops due to cooling of the products of combustion by dilution with air.

It will be noted from Fig 11 that there was little difference between the two fuels, of 8.6 and 22 per cent aromatic content, under these particular conditions.

Some experiments were carried out on the same two fuels in which the overall air-fuel ratio was varied by altering the fuel flow, and the results are shown in Fig 12. This graph emphasizes the great influence of mixture strength, or heat input, on flame tube temperature and shows that, at the

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teristica te initial C. The may be neluxion rices. sale gas It was with a richer mixtures, there was little difference between the fuels, as already noted. At the weaker mixtures, the 22 per cent of aromatic fuel gave higher temperatures, e.g., 100° C higher at an air-fuel ratio of 80:1. Since,



COMPARISON OF FLAME TUBE TEMPERATURES WITH DIFFERENT FUELS.

however, this difference occurs at air-fuel ratios where the temperatures are relatively low, it is possible that it is not of practical importance.

The above experiments were carried out with a clean combustion chamber. The effect of a coating of carbon was investigated by operating the combustion chamber for a preliminary period under conditions producing

a coating of carbon while carrying out a temperature survey. It was found that there was a progressive decrease in temperature in the region of the flame tube where the carbon was being formed, *e.g.*, one thermocouple showed a drop in temperature from 640° C to 340° C. This decrease in wall temperature, brought about by the poor thermal conductivity of carbon, may tend to produce local stresses due to excessive heat gradient between areas which are coated with carbon and those which are not. In fact, during the progress of these tests buckling of the flame tube occurred around the area where carbon had been deposited.



FIG. 12.



Combustion Intensity and Flame Length.

The rate of heat release influences directly the size of the combustion chamber, which should be a minimum in order to reduce engine size and weight. The problem is, therefore, that of achieving high combustion intensity with a minimum turbulence and combustion loss. At the present time there is very little information available on the effect of different fuels and fuel properties on flame dimensions, though such work is in hand.

Flame length and colour are largely influenced by mixture strength, but here again, there are reasons to believe that in so far as flame length is concerned, the influence of mixture strength is physical rather than chemical.

It may be recorded here that work in America has suggested that luminosity is not necessarily an indication that combustion is taking place

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and, therefore, that visual observations of flame length can be misleading. A technique for ascertaining where combustion really terminates has been developed by the use of a "water probe," water being sprayed across the combustion chamber from the end of a probe which can be adjusted longitudinally. When the water is sprayed into "inert" products of combustion, there is a fixed drop in temperature, irrespective of the position of the probe, due to the cooling effect of the water. When the probe enters the zone where combustion is occurring, there is an abrupt chilling effect, due to the quenching of combustion.

Noise and Detonation.

It has been generally observed that under certain conditions very considerable noise, with fluctuations in pressure, can arise in gas turbine combustion chambers. The evidence suggests that this influence may arise from operation under critical mixture strength conditions which are not stable, with the result that there is a rapid fluctuation between two widely differing flame lengths producing considerable noise. It is not known to what extent this problem is affected by the use of different fuels; it might be anticipated that to a large extent it is determined by physical rather than chemical factors.

It is conceivable that another form of explosive combustion might be produced by the self-ignition of pockets of recirculated combustible mixture under certain pressure and temperature conditions. Such an occurrence would be analogous to detonation in a reciprocating engine where a pocket of "end-gas" is heated by compression and auto-ignition results. Such a phenomenon would be influenced by chemical factors, *e.g.*, by knock inhibitors. That detonation can, in fact, occur in gas turbine combustion has still to be established.

Calorific Value.

The gas turbine, during the early years of its development, has suffered the disability of a high fuel consumption which has emphasized the importance of the calorific value of the fuel. In this connexion, it is necessary to distinguish between calorific value on a volumetric basis, and calorific value on a weight basis. Where the limiting factor is the fuel tankage capacity, as on fighter aircraft, it is the calorific value by volume which is important, and, in this case, an increase in the volumetric calorific value will bring a corresponding increase in range, up to some all-up weight limitation due to the accompanying increase in weight. On the other hand, if the more normal requirement of fuel weight in relation to payload is the decisive factor then calorific value per pound of fuel is the criterion. In this case some improvement in payload can be achieved. For example, in a hypothetical long range axial flow propeller turbine aircraft, cruising at 425 m.p.h. over a stage of about 2000 miles, an improvement in calorific value of 10 per cent by weight can give an increase in payload of up to 25 per cent under favourable conditions, provided that the necessary tankage capacity is available.

The calorific value of hydrocarbon fuels is related to their specific gravity and, in general, as the specific gravity increases there is a reduction in

calorific value per pound and an increase in calorific value per gallon. The following equation, due to Cragoe, enables the gross calorific value to be calculated with sufficient acuracy for most purposes.

Gross calorific value = $22,320 - 3780d^2$ B.Th.U/lb where $d = \text{sp.gr } 60^{\circ}/60^{\circ}$ F

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Gross calorific value = $223,200d - 37,800d^3$ B.Th.U/gal.

These equations which are applicable to both pure and mixed hydrocarbon fuels demonstrate the relationships expressed above, the second equation being a cubic with a maximum at approximately d = 1.4. It should be noted, however, that aromatics generally have calorific values some 5 per cent lower than those given by the above equations, both by volume and by weight.

Table III illustrates the same trends for practical fuels. The calorific values are not only expressed in terms of B.Th.U. per pound and per gallon, but also as a ratio of the corresponding values for fuel meeting RDE/F/Ker specification. The heaviest fuel, viz., the cracked fuel oil, with specific gravity of 1.08, has a calorific value 15.8 per cent greater than RDE/F/Ker fuel on a volumetric basis and 13.0 per cent less on a weight basis. At the other extreme 100/130-grade gasoline has a calorific value 9.2 per cent less on a volumetric basis and 2.1 per cent greater on a weight basis.

It will be evident that some of the heavier fuels given in the table may be excluded from aero gas turbine use because of their high pour point.

Fuel.	Sp. gr.	Cal. val	ue (net).	Ratio to RDE/F/KER Specification fuel.	
		B.Th.U/ lb.	B.Th.U/ gal.	Per lb.	Per I.G.
100/130 grade aviation gaso- line	0.720 0.740 0.771 0.810 0.848 0.850 0.870 0.910 0.924 0.970 0.949 0.973	18,940 18,890 18,740 18,560 18,710 18,260 18,050 17,980 17,740 17,740 17,760 17,760	136,580 139,900 144,460 150,390 158,800 155,230 157,040 163,630 164,000 168,600 168,600 168,600 173,160	1.021 1.019 1.009 1 1.008 0.9836 0.9722 0.9684 0.9560 0.9380 0.9570 0.9585	0-9081 0-9290 0-9605 1 1-054 1-032 1-044 1-088 1-090 1-121 1-120 1-1514
California Cracked fuel oil, West Texas.	$1.013 \\ 1.080$	16,910 16,110	171,300 174,000	$0.9120 \\ 0.870$	$1.140 \\ 1.1580$

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Cold Starting.

The ease of ignition of a spray of atomized fuel will depend on a number of factors, notably: (a) the degree of atomization; (b) the fuel volatility; (c) the location of the igniting source in relation to the spray; (d) the nature of the igniting source; (e) the temperature conditions; (f) the primary airfuel ratio; (g) the air velocity.

Fuel characteristics obviously influence (a) and (b) directly, while the other factors may also affect the relative cold starting performance of different



FIG. 13.

fuels. For example, the influence of volatility and atomization might be very much less with "torch" ignition than with spark ignition. The few experiments which have been carried out at Thornton on the starting characteristics of fuels relate to a conventional combustion chamber with spark ignition, which may tend to accentuate the differences between fuel qualities in this respect.

In these experiments the ease of starting was assessed by the fuel pressure necessary to initiate ignition over a range of air flows The results obtained are summarized in Fig 13 in which the minimum fuel pressure necessary for ignition at a given air mass flow and starting temperature is plotted against the 10 per cent recovery temperature for the fuel.

EFFECT OF FUEL VOLATILITY ON STARTING CHARACTERISTICS.

It will be noted that there is an approximately linear relation, the lower the 10 per cent temperature the less the fuel pressure required to start, viz. the easier the starting.

There is a general relationship between viscosity and volatility of hydrocarbons, *i.e.*, the greater the volatility the lower the viscosity, so that it is sometimes difficult to differentiate between the respective influences of these two factors in regard to their effect on ignitability and combustion. In the



present instance there is reason to believe that the influence of viscosity was relatively small and that the effect illustrated in Fig 13 is largely attributable to volatility.

Reference to Fig 14, in which the viscosity of a number of fuels is plotted against temperature, will show that at 30° C the viscosity of aviation kerosines is of the order of 1.5 cs. With swirl-type atomizers there is a loss of pressure in the swirl chamber which will obviously increase with fuel viscosity, so that there will be a tendency for atomization to deteriorate with increasing viscosity. This deterioration seems to begin in the region

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of 10 cs so that it might be necessary to place an upper limit of 15 cs on the fuel viscosity, but such a limit would obviously depend upon atomizer design and might become less stringent with developments in this direction.

Fig 14 shows that if a viscosity of 15 cs be assumed to be the maximum permissible, the gas oil would not give satisfactory atomization below about -7° C, while the aviation kerosine SR. 312 would be satisfactory down to -40° C. The aviation kerosine 201 will be satisfactory down to an even lower temperature of about -60° C.

It will be obvious that, in general, the gasolines have such a low viscosity that satisfactory atomization should be possible at any temperature.

Fire Hazard.

One of the main attractions of the gas turbine in its present form is that it is capable of using a low vapour pressure fuel which might be described



IGNITION LAG V. SURFACE TEMPERATURE.

as a "safety fuel." This advantage has, with one or two exceptions, been confirmed in service.

In considering the relative safety of different fuels it is necessary, at the outset, to distinguish between fires originating from three different causes, as follows :---

(a) the ignition, by an adjacent spark, flame, or incandescent filament, of fuel vapour from spilled fuel;

(b) ignition arising from fuel impinging on a surface sufficiently hot to cause spontaneous ignition;

(c) ignition in a fuel tank arising from the existence of an inflammable fuel-air vapour, ignited either by incendiary bullet or by "static" discharge.

In considering the first form of ignition, which may occur most commonly in the event of a crash when large quantities of fuel are spilled on the ground





CORRELATION BETWEEN VOLATILITY (VAPOUR PRESSURE) AND INFLAMMABILITY (FLASH POINT).

or on the wing surfaces, it would appear that fuel volatility is the deciding factor. Work has been carried out at Thornton using a simple apparatus in which a definite quantity of fuel is spilled on to a flat surface maintained at a given temperature. Ignition can occur from an adjacent electricallyheated filament, and the time lag between the spilling of the fuel and ignition is measured. Results obtained on a number of fuels are shown plotted in Fig 15, in which the time for ignition to occur is plotted against the "surface" temperature.

It is clear from Fig 15 that the "surface" temperature has a very important effect on the time lag before ignition occurs. In fact, below a

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certain temperature ignition fails to occur with the less volatile fuels, *e.g.*, kerosine and "safety fuel." Such a difference might mean a good deal to passengers and crew in the event of a crash.

The order of merit of the fuels in Fig. 15 is approximately that of their volatility, as shown in Fig 17. This would be anticipated since ignition would occur when the fuel vapour pressure in the neighbourhood of the igniting source has reached the lower limit of inflammability. The same is true of the conventional flash-point test, which is virtually a measure of the temperature at which a fuel reaches a vapour pressure which gives an inflammable mixture; this vapour pressure is of the order of 7 to 10 mm Hg.



FIG. 17.

VAPOUR PRESSURE V. IGNITION TEMPERATURE.

Correlation between the vapour pressure and flash point of fuels would, therefore, be expected and is indicated in Fig 16.

It is also of interest to record that there is some correlation between the 10 per cent temperature of the fuel and the flash point, as shown in Fig 18.

The above data therefore suggest that the flash point, the vapour pressure, or the 10 per cent temperature, can be used as a measure of the relative inflammability of fuels under conditions described in (a) above.

It must be emphasized, however, that it is impossible to describe one fuel as "safe" and another as "unsafe" since any fuel can be made to ignite if it falls on a surface sufficiently hot to increase its vapour pressure and thereby provide an inflammable mixture of vapour and air. There exist simply *DIFFERENCES* in inflammability.

A subject related to the above is the speed at which flame propagation occurs once ignition has taken place and, in this respect, the higher the vapour pressure the more rapidly will flame propagation occur.

The form of ignition referred to in (b) above might occur in a piston engine when fuel or oil is splashed on to an exhaust manifold, and it is conceivable that it might take place if fuel or oil were brought into contact with the turbine blades of a gas turbine aircraft. This form of ignition was



CORRELATION BETWEEN VOLATILITY (VAPOUE PRESSURE) AND INFLAMMABILITY (FLASH POINT).

studied at Thornton by allowing drops of fuel to impinge on an electrically heated hot plate, the temperature of which could be adjusted. The following table gives the self-ignition temperature of a number of fuels and oils of interest :---

Fuel or oil.						
-		355				
		430				
		595				
		630				
		650				
		725				
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The above table shows the general tendency for the ignition temperature to be lower the higher the molecular weight and the lower the vapour pressure. In other words, the order of merit of fuels discussed above is, in general, reversed when considering the present form of ignition. Kerosine has a somewhat lower ignition temperature than gasoline, while lubricants have considerably lower ignition temperatures. In the latter connexion, it is well known that many piston engine fires have originated with the lubricating oil.

It would appear from the above figures that the self-ignition temperature of aviation kerosine might be within the range of current turbine blade temperatures, whereas that of gasoline would probably be above.

In connexion with the hazard of an explosion in the fuel tank, the risk of an explosive mixture being in the fuel tank is much greater in hot weather with kerosine than with gasoline. In mild weather the risks are about equal, while in very cold weather (ground temperature 0° C or lower) there is no risk with kerosine, whereas with gasoline the risk is considerable. This risk can be eliminated by the method of blanketing with inert gas.

It may be concluded that the "safety" characteristics of a fuel have to be considered in relation to the nature of the fire hazard. Kerosine is "safer" than gasoline for hazard (a) above, but less safe for hazards (b)and (c). In general, hazard (a) is considered to be the most serious and therefore emphasizes the advantage of fuels of low volatility.

Availability of Turbine Fuels.

Kerosine was used in the early Whittle experiments and has subsequently been accepted very widely as a fuel for aviation gas turbines because of its suitability in regard to low tempertaure properties, low cost, high heat content per gallon, and relative safety in relation to gasoline. There has been a tendency to assume that unlimited quantities of kerosine would be available, but this is far from being the case.

Kerosine is, of course, a distillate from crude oil, intermediate between gasoline and the next distillate fraction, known as gas oil. From the total output of crude oil, only 5 to 6 per cent of kerosine is produced as compared with 40 to 50 per cent of gasoline. Gas oil, the next distillate, is also produced in relatively small quantities, something of the order of 10 per cent (excluding, for the moment, cracked gas oils, of which only a small proportion is suitable for aviation gas turbines) so it will be seen that the total distillate, other than gasoline, is a relatively small percentage of crude.

Already there are well-established demands for both kerosine and gas oil. For example, kerosine is used in many parts of the world for lighting, heating, and cooking where there is no alternative, and gas oil is in demand for use in high-speed diesel engines, central heating plants, and, in the modern refinery, as a source of raw material for catalytic cracking to produce high octane motor fuels. It seems advisable, therefore, that the designer of the gas turbine should look to a fuel which does not make too serious inroads in these demands and one which can be made available in the required quantities.

Such requirements would be met by a distillate fuel of fairly wide boiling range (e.g., 65° C to 300° C), in fact, a sort of naphtha. This fuel could be prepared with low pour point, and cold starting and flame stability charac-

teristics would be good. Calorific value on a weight basis (which is of importance for long range aircraft) will be high. Whilst in some circumstances the fire hazard of this fuel might be considered to be greater than that of kerosine, it does present an improvement over gasoline.

In the section on "fire hazard" it was pointed out that the vapour pressure of a fuel was a measure of its inflammability under certain conditions of ignition. In this connexion, the vapour pressures (in mm Hg at 20° C) of a typical kerosine, a $65-300^{\circ}$ C distillate, and a gasoline are of the order of 2, 25, and 180, respectively, so that the $65-300^{\circ}$ C distillate does represent an improvement over gasoline in this respect.

A further increase in supply would be possible either by extending the distillation range, for example, by raising the end point to 350° C, or by the use of cracked fuels in the same distillation range as and when they are found to be satisfactory for gas turbines. There is little doubt that modern refinery technique could achieve this with little additional cost.

PART II.—LUBRICANTS.

Lubrication System.

The components requiring lubrication in the gas turbine used for jet propulsion are the compressor and turbine bearings and the various bearings and gears of the gear box and auxiliary drives. In the propeller turbine engine, the lubrication of the reduction gears has also to be provided for.

Fig 19 shows diagrammatically the lubrication system of a representative engine. The compressor bearing, which is normally at the front of the engine and, therefore, adjacent to the gear box which drives the auxiliaries, is supplied with oil from a pump in the gearbox, to which the oil drains back. The turbine bearing, normally situated at the rear, may also be lubricated by circulatory system with an oil flow of, say, 15 gallons per hour. Alternatively, the turbine bearing may be lubricated by an air-atomized oil spray on the total loss system, in which case the oil feed may be as low as 0.25 pint per hour. The gears in the gearbox are normally lubricated by a jet of oil supplied from the pump.

On early engines the atomized oil feed was generally used for lubricating the turbine bearings, but the tendency now is to employ the dry sump circulatory system for lubricating the turbine bearing. This system has the advantage of providing some cooling for the turbine bearing by enabling a comparatively high rate of oil circulation to be used in conjunction with a cooler.

Bearings.

Early engines were fitted with ball bearings, but there was subsequently a tendency to use plain bearings, followed by a reversion to ball bearings. One advantage of ball bearings is the very much lower starting torque required. A piston engine can be made to start at, say, 20 r.p.m., whereas a turbine engine has to be motored at 1500 r.p.m. or more during starting so that anything which can be done to reduce frictional torque will permit an appreciable reduction in the size and weight of starter equipment. Under operating conditions, the amount of frictional heat generated with plain

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bearings necessitates an oil cooler. In addition, while plain bearings can be designed to carry heavier loads than ball bearings, there are problems which arise at high speeds, *e.g.*, "oil whip," which is a shaft vibration having a frequency approximately half engine speed and which may result in bearing



failure. Also, traces of dirt in the lubricant may more readily cause bearing failure with a high-speed plain bearing than with a ball bearing. One argument is, however, adduced in favour of the plain bearing, viz. that in the event of a bearing failure the turbine shaft is still located when a plain bearing is used, so that a complete engine break-up is less likely to result.

Of the components requiring lubrication, the turbine bearing operates at the highest temperature, and normally the outer race temperature lies between 125° and 150° C. When the engine is stopped, heat may flow inwards from the turbine disc and result in a higher temperature of up to 200° C for a short period until the engine cools. It appears to be generally agreed that if the running temperature rises above 150° C, provision should be made for an oil cooler. On the other hand, an oil cooler is looked upon as a component which has obvious disadvantages, particularly in producing increased drag, and it will certainly be omitted if satisfactory bearing life can be achieved without it. This implies the need for the mechanical and metallurgical development of bearings to give adequate durability at high temperatures and the provision of lubricants which will give satisfactory service at these elevated temperatures. There is a further reason which is now advanced for deliberately increasing the operating temperature of turbine bearings, viz. that the higher the bearing temperature the lower the temperature gradient across the turbine disc and therefore the lower the stress. In this connexion, possible bearing temperatures of 300° C are being discussed. There is every reason to believe that very considerable development in ball bearing manufacture will have to take place before operating temperatures of this magnitude will be possible. In any case, this method of reducing stresses may well imply that other methods of reducing turbine disc stresses have not been fully investigated.

Low Temperature Requirements.

The low temperature requirements of a lubricant for gas turbines depend both on the design of the engine and on the conditions of operation. On early engines the turbine bearing at the rear was lubricated through a "capillary" tube exposed to the air stream, and a pour point of -60° C was therefore proposed. By avoiding such unnecessary exposure it has been possible to alleviate this requirement so that at the present time a pour point of -40° C is considered adequate in British engines.

Low temperatures may be experienced either in starting up or in flight, and in the case of military aircraft it may be necessary to make provision for cold starting at a temperature of -40° C, or even lower, without the aid of ground heaters, etc. In addition, the ability of the gas turbine to permit rapid attainment of full power should not be restricted by inadequate low temperature properties of the lubricant.

There appears to be little data available as yet regarding oil tempertures which may be experienced in flight, more especially during prolonged shutdown of an engine. As far as the author knows, oil temperatures lower than -30° C have not, as yet, been measured. A good deal would appear to depend on whether the engine is allowed to "windmill" during a shutdown; if it is, then oil circulation will continue and a certain amount of frictional heat will be generated which will retard congealing of the oil.

It has already been pointed out that an important consideration is the frictional torque required to motor an engine during starting. Fig 20 gives some engine starting torque curves plottted against cranking speed, for various temperatures ranging from $+13^{\circ}$ C to -35° C. These curves emphasize the important influence of temperature on cranking torque, and the dotted curve shows the effect of reducing the oil viscosity at the

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TYPICAL ENGINE CRANKING TORQUE CURVES.

Obtained with oil of viscosity 5.8 cs at 210° F., engine fitted with auxiliaries.



FIG. 21.

temperature of -20° C. It may thus be necessary to specify a maximum viscosity at low temperatures in order to permit easy starting without the provision of heavy starting equipment.

The gears used to drive the auxiliaries are lubricated by a jet of oil and possible failure of this jet, due to too high a viscosity at low temperatures, may impose a limit. Thus Fig 21 gives the viscosity-temperature relation for a number of lubricants. If flow through the oil jet should be restricted when the viscosity exceeds, say, 2500 cs, it is clear that the lowest safe operating temperature for the various lubricants will be : 7° C for 2472B, -35° C for 44D, and -45° C for the oil "SR.1358."

D.T.D. 44D specification hydraulic oils have been most widely used for turbine lubrication and have been considered so far to have adequate low temperature properties. The specification requires that these oils shall flow in the Air Ministry cold test at -45° C; the corresponding pour point would be about -40° C. There is a tendency at the present time to consider that these low temperature requirements might be alleviated if this would result in an oil of higher viscosity at normal operating temperatures.

The requirement of a low pour point for turbine lubricants would, of course, be removed if some provision for preheating the oil were used, but this solution is not likely to be popular with the designer. Another alternative is the use of a system analogous to the Worth dilution system which would provide for the dilution of the lubricant with, say, gasoline, before shut-down, thus enabling an oil of higher viscosity and higher pour point to be used. It would, however, be necessary to ensure that the loadcarrying capacity of the diluted oil is adequate for satisfactory reduction gear lubrication.

High Temperature Requirements.

It has already been pointed out that the normal turbine bearing temperature is 125° to 150° C and that there is a possibility that such operating temperatures will rise in the future. Engines at the present time seem to be divided into two categories, viz. those with bearings which do not appear to be viscosity-sensitive, and those which are. There appear to be two reasons why a certain degree of viscosity may be necessary for the lubrication of high-speed ball bearings.

First, the Hertz stresses between ball and track may be reduced by a film of oil which tends to distribute the contact pressure between ball and race over a larger area; the magnitude of this "cushioning" would tend to increase with oil viscosity. This effect is somewhat conjectural and further experiments are required in order to establish its significance. It would be expected that its importance would increase with the loading on the bearing.

Secondly, a certain level of viscosity may be required for fluid film lubrication between the balls and the cage, where rubbing occurs. The severity of the conditions existing between balls and cage depends on cage material and on the method of location. On early engines aluminium alloy cages were used, which gave rise to considerable troubles, which, to a large extent, were removed by the general adoption of bronze cages. So far as method of location is concerned, there is some reason to believe that race-located cages make less demand on the lubrication of the bearings than

ball-located cages. The actual viscosity required under working conditions is, therefore, very much dependent on current engine design and is liable to be modified with further developments. In any case, it is possible that the viscosity requirements will be determined by the load-carrying capacity of transmission gears discussed later in this paper.

The resistance to oxidation of the lubricant and its method of assessment will depend on whether or not the oil contains an additive. For undoped oils the general principles governing oil oxidation stability are well understood and the development of a suitable laboratory test should be relatively simple compared with the complications of predicting the performance of lubricants for piston engines. Perhaps the most undesirable oxidation products are those which increase the oil viscosity and give rise to oil insoluble gums and lacquers, particularly on the hot turbine disc. Oils containing heavy components are known to cause trouble in this respect and, if possible, a gas turbine oil should be a relatively narrow petroleum cut. Probably a simple form of evaporation-oxidation test to assess the residue left by evaporation in air at temperatures of 200° C and above might be adequate for undoped oils.

Lubrication of Reduction Gears.

Where a gas turbine is used to drive a propeller it is necessary to provide for the lubrication of heavily loaded reduction gears and at the present time tooth loadings approaching 40,000 lb per inch are being considered. Quite apart from propeller reduction gears it is quite possible that the gears used to drive the auxiliaries may require attention.

Failure of transmission gears can occur in three general ways :---

(a) Breakage of the tooth at the root. This is a form of fatigue failure which is probably quite unconnected with the lubricant;

(b) Pitting of the surface of the gears in the neighbourhood of the pitch line. This is usually attributed to a form of fatigue cracking originating just below the surface where the Hertz stresses are highest. Such fatigue cracks may spread to the surface and pieces of material be thereby removed. This form of failure would appear to be primarily mechanical, though the possibility that a lubricant may reduce the Hertz stresses by providing a cushioning film which distributes the load over a bigger area should not be lost sight of. Further work is required to establish what influence, if any, the lubricant has in relation to pitting;

(c) Scuffing of the tooth profile. This is definitely a lubrication failure, and scuffing is attributed to the consequent momentary welding together of the rubbing surfaces. The effect of various oil factors on this form of failure will now be discussed.

A machine which is extensively used in the U.K. for the study of lubrication in relation to gear scuffing is the I.A.E. machine, which is a "foursquare" machine, *i.e.*, it employs the power circulation principle with two pairs of gears connected with two parallel shafts. One of these machines, modified in certain important respects, has been used at Thornton for the evaluation of turbine lubricants. At the outset, however, it should be emphasized that this machine has certain limitations, as follows :—(a) the
gears are small in relation to conventional reduction gears, viz. $3\frac{1}{4}$ inch pitch diameter; (b) the operating speed is relatively low, viz. 2000 r.p.m., (c) there is a definite limit on the maximum loading which the machine will stand; (d) the tests are normally of short duration.

The above limitations call attention to the need for developing a test machine which will take bigger gears, operate at speeds up to say, 20,000 r.p.m., and be sufficiently robust to transmit high torques for long periods.

In the meantime, results on the I.A.E. machine should be taken with a certain degree of reserve from the standpoint of direct application to engine design, although there is reason to believe that they are not misleading.



LOGIO (VISCOSITY AT 50 °C, C5.)

FIG. 22.

INFLUENCE OF E.P. ADDITIVES ON GEAR SCUFFING LEVER LOADS ON THE I.A.E. TEST MACHINE.

Oil inlet temp., 30° C. Gear steel, E.N. 39 spec. Spec. tooth loading (lb/in.) = lever load \times 61.04.

The test method used at Thornton was to run-in the gears for 5 minutes and then to increase the load on the lever arm (which is a measure of the transmitted torque) by 5 lb after every 5 minutes running. Scuffing was indicated by a sudden increase in the temperature of the lubricant leaving the gears and was verified by subsequent visual observation.

Fig 22 shows the observed effect of viscosity on the scuffing load for a number of lubricants.

It has been generally assumed that, at least as a starting point, the film strength of turbine lubricants used for reduction gears should be comparable with that of DED.2472B/O oils and in Fig 22 the range of lever loads for typical 2472B/O oils is indicated.

It is clear that undoped oils which meet the low temperature require-

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ments already discussed in this paper will be deficient in film strength at normal operating temperatures and consideration has, therefore, been given to increasing the film strength of such thin oils by the use of mild E.P. additives. In Fig 22 the effect of some typical additives on the scuffing load is shown. It will be noted that load-carrying capacities were attained exceeding that of the undoped 2472B oil.

In Fig 23 the effect of oil inlet temperature on scuffing load for a number of doped and undoped oils is shown. It will be noted that, while there is



INFLUENCE OF TEMPERATURE ON GEAR LOAD CARRYING CAPACITY OF UNDOPED AND DOPED OILS.

little loss in scuffing load with reduced temperatures using undoped oils, there may be an appreciable loss with doped oils. It will be obvious that since an additive is effective by virtue of its chemical effect on the surface of the gears, this chemical effect will tend to diminish with decreasing temperature. It is clearly necessary for the doped oil to have sufficient film strength to enable the reduction gears to transmit full engine torque at low starting temperatures.

The chemical activity of the more active additives, by virtue of which they operate, may give rise to harmful corrosion of certain metallic components if it is excessive. In general, the corrositivity of an E.P. additive will increase with its effectiveness in relation to film strength and corro-

sivity will, for the same reason, tend to increase with increasing temperature. The component which is most likely to suffer under corrosive attack is the bronze cage of the turbine bearing, the copper of which is liable to be attacked by the usual E.P. additives. Corrosion of bronze cages may result in a roughening of the cage surface and in deposits, resulting in an increase in friction and wear which may cause a complete failure of the bearing. Further evidence is required to establish the maximum permissible E.P. activity, as limited by the effects of corrosion in service.

Since it is necessary to limit the chemical activity of E.P. additives, where such are used, a corrosion test should be included in a specification. Such a test may be combined with an oxidation test and carried out at a temperature between 120° and 180° C, using a copper or bronze specimen, the gain or loss in weight of specimen, the change in oil viscosity, the amount of lacquer, and the petroleum ether insolubles being determined.

If E.P. additives are used it is obviously important that they should retain their E.P. properties over prolonged periods of use. This may be checked under laboratory conditions by subjecting the doped oil to a degree of oxidation greater than is likely to occur in service, followed by a determination of its film strength.

There is some evidence to show that E.P. additives may exercise a slightly beneficial effect on the durability of balls and cages through a polishing action, but further experimental evidence is required.

Fire Hazard.

The possibility has to be borne in mind that the lubricant might be ignited through contact with the hot turbine disc, and, as discussed in the section on fuel fire hazard, there are two possible forms of ignition, viz. first, spontaneous ignition on a sufficiently hot surface and, secondly, ignition of vapour from some extraneous igniting source. The latter is usually assessed by the flash point.

In the following table are given the minimum specification flash points, and the spontaneous ignition temperature measured on Thornton apparatus, for DED. 2472B and 44D oils :—

Lubri	icant	t.		Minimum flash point.	Spontaneous ignition temperature.
DED 2472 B DTD 44D	•	:	•	243° C 154° C	355° C 430° C

It will be observed that the more volatile oil, *i.e.*, 44D, has the higher spontaneous ignition temperature but, owing to its greater volatility, has a lower flash point.

Engine experience may indicate which of the above criteria should be used to denote inflammability.

CONCLUSION.

Sufficient has been said to indicate that the fuel and oil requirements of aero gas turbines are to a large extent determined at the present time

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f which ic comlditive corroby considerations of engine design and operating conditions. Any changes in these conditions may exert an important influence on fuel and oil requirements so that there is everything to be said in favour of close collaboration between the engine designer and the petroleum technologist.

In regard to fuels, the general trend of the argument in this paper has been to call attention to the advantages of a distillate fuel having a boiling range of $65-300^{\circ}$ C. The relatively low viscosity and high volatility of such a fuel confers considerable advantages in relation to atomization, cold starting, blow-out, and carbon deposition. A fuel of this type could be made available in large quantities.

The main requirement of a lubricant at the present time is a very low viscosity combined with the highest possible V.I. The development and application of additive-type lubricants for propeller-turbine engines is in hand, and their future will depend very largely on certain details of engine design.

ACKNOWLEDGEMENTS.

The author would like to thank the Directors of the "Shell" Refining and Marketing Co., Ltd., for permission to write this paper.

The author is also indebted to many colleagues who provided data for this paper and who assisted in the reading of proofs.

He would also like to thank Messrs. Lucas Ltd., and the de Havilland Engine Company for permission to reproduce certain data.

DISCUSSION.

THE CHAIRMAN : Dr Williams has given us a very well co-ordinated paper which gives a very good picture of the problems attending the gas turbine. In my view it is just about time that such a paper was given and I hope there will be more papers as further knowledge on the subject becomes available, for they will help both the oil man and the turbine engineer. To me, the only unfortunate thing is that no reference has been made to tetra-ethyl-lead and I am not sure that I am not going to be put out of a job !

MR E. L. BASS: A great deal has been said and written about gas turbines in varying degrees of prophecy, optimism, and accuracy. This inevitably happens with any new development and it is therefore refreshing to have a paper such as this by a recognized authority, giving a clear picture of one of the most important subjects connected with the gas turbine. The importance of the subject is emphasized when it is reflected that a typical jet engine burns its own weight of fuel in some twenty-one minutes at full throttle at sea level, and in one and a half hours under cruising conditions. I believe this is the first paper to be presented to any scientific society on the subject of fuels and oils for gas turbines, and it is so comprehensive that it will long be of value as a reference work.

One of the most important points to be underlined is the profound influence of availability on the type of fuel to be used. At first sight it appears unfortunate that, whilst at last we have in view an aircraft power plant capable of burning a less volatile fuel, and therefore one of reduced fire hazard, such a fuel is already in short supply. We must be quite

DISCUSSION.

realistic on this point, and unless the petroleum technologists can give a reasonable assurance that fuels of the kerosine type can be made available in the quantities required, it will be well immediately to direct engine development towards the use of those fuels which are most readily available. Otherwise the proper application of the gas turbine to aviation will be delayed and restricted.

The JP2, or so-called wide range distillate, referred to by Dr Williams, offers substantial advantages over kerosine in combustion performance and freezing point. Its disadvantage is some increased fire risk, the extent of which is still a matter of conjecture. The practical significance of the SIT and inflammability tests quoted by Dr Williams has still to be established. On the basis of the data given in the paper, it appears that the JP2 fuel is approximately half way between kerosine and gasoline in respect of fire risk. Whilst this is an appreciable advance in safety, it is clear that no effort should be spared to enable the still safer type of fuel to be produced in adequate quantities for the aviation gas turbine. I would like Dr Williams to enlarge upon the point that, whilst he has gone to some length to show the point at which ignition occurs, surely the rate of spread of the flame is of very vital importance in the event of a crash. In view of the fact that the JP2 fuel is unlikely to lead to any vapour-locking troubles (with a Reid vapour pressure of 1 lb, its critical altitude at a fuel temperature of 30° C, is of the order of 60,000 ft), it only remains whether any difficulties are likely to arise from the release of dissolved air. Perhaps the author could give some further information on that point.

The turbine engine promises to be quite catholic in its taste for fuel, and no doubt further development will make it more so. If and when we can think of the less volatile fuels (e.g., kerosine and gas oil) the limitation on availability of fuel imposed by the demand for a low freezing point, is one that cannot be blamed on to the turbine engine, *per se*. It is, nevertheless, likely to prove a formidable stumbling-block in the way of obtaining adequate supplies of cheap fuel. From this point of view, therefore, it will be well to study more closely the aircraft engine and fuel system installation problems associated with using fuels of higher freezing point than those at present specified. In the same way, limitation of aromatic content of the fuel is likely to prove restrictive, and combustion chambers should therefore be developed to use fuels of the maximum aromatic content likely to be encountered. By such means, the much claimed omnivorous nature of the gas turbine can be preserved.

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There has been a great deal of very elegant research work carried out under Dr Williams' direction on small flame tubes. The practical advantages of using these tubes in comparison with the full-scale burners are obvious and it is interesting to recall that, before embarking on the design and installation of these small units, there was a general consensus of opinion against their use. Dr Williams has shown how extremely valuable these laboratory test units can be, but I am sure he will agree that they must be used in conjunction with the full-scale burners for the purpose of correlation and interpretation of results.

In connexion with the use of E.P. additives for the prevention of gear scuffing, since additives worked by their chemical reaction with the surface of the gears, it seems possible that the effectiveness of the additive will vary

according to the gear material. If this is so, it clearly points to the need for the closest collaboration between the engine designer and oil technologist.

The remarks already passed in connexion with the restrictive nature of fuel specifications can, in a general way, be applied to lubricants. The low freezing point demanded, for example, might prove extremely restrictive and is a requirement which might conceivably be avoided by changes in engine design and installation.

I know from personal experience how much effort Dr Williams has put into this paper, and I am quite sure that none of it will be in vain.

MR A. R. OGSTON: I would like to compliment Dr Williams on his most interesting and comprehensive survey of the field of fuels and lubricants for gas turbines. The author has included a wealth of technical data and useful information in his paper, and it should thus serve for some time to come as a valuable source of reference for those engaged in the design manufacture, and operation of aero gas turbines. I entirely agree with Dr Williams when he draws attention to the fact that, contrary to what was at first rather too readily assumed, the aero gas turbine is not going to be capable of digesting almost any liquid fuel, and we may find that in the years to come history may repeat itself and, in order to obtain maximum efficiency from the gas turbine, a fuel will be required which may be almost as specialized as that now required for the high-octane piston engine.

It is interesting to note that there have been one or two indications that even the ugly head of detonation may rear itself sooner or later in gasturbine combustion and at this stage it seems to be a matter for conjecture as to whether the desirable property in the fuel will correspond to high octane number as in the case of aviation petrol, or high cetane number as required for diesel engines. I am inclined to think that it will more likely be a case of high cetane number, the effect of which may be to reduce flame length, although, on the other hand, recent tests with a turbine fuel which happened fortuitously to have a high octane number did, nevertheless, give a particularly clean and short flame, so this illustrates the uncertainties of the turbine fuel problem at the present time.

There is only one point on which I would beg to disagree with Dr Williams and that is his apparent advocacy of wide-cut distillate fuels which, I would point out, will have a flash point in the region of 0° F or -18° C. I feel very strongly that it will be extremely unfortunate if we do not take the opportunity, now that it is laid before us, to standardize the use of what would undoubtedly be a much safer fuel, namely, one corresponding to kerosine with a flash point of, I suggest, not below 100° F. Anyone who has studied the recent crop of accidents to air liners must have been impressed by the fact that in several instances most, if not all, the passengers would have survived if they had not been burnt to death by the inevitable petrol fire which follows the rupture of the fuel tanks and the damaged aircraft being immersed in a cloud of highly inflammable vapour. Typical examples of this were the recent Spencer Airways' crash at Croydon, the American Constellation crash near Shannon, the Belgian DC-4 crash near Gander and the French Dakota crash at Le Bourget last September. On the other hand, it is significant to note that a majority of the passengers survived in the recent Dakota crash in Kent where there was no fire because the aircraft

DISCUSSION.

had run out of petrol, and the British Dakota crash near Oslo some months ago, where by some freak of chance fire did not follow the crash. I also recall a crash at Hatfield about two years ago when a Vampire flown by one of the De Havilland test pilots skidded along the ground for two or three hundred yards and came to rest with the wrecked cockpit and the pilot completely doused in the kerosine fuel, but the fire which would have followed with petrol did not occur and the pilot was uninjured except for a few cuts and bruises.

I therefore put forward a plea that we should here and now decide to follow the straight and narrow path of insisting on the safest fuel possible for all turbine-powered passenger-carrying aircraft and resist the temptation to follow the easy downward path of adopting the volatile and more inflammable fuels just because they might be more easily available and happen to simplify one or two problems, such as cold starting and high altitude blow-out; in fact, I would go so far as to suggest to the Air Registration Board that they should refuse to grant a certificate of air-worthiness to any turbine-powered passenger-carrying aircraft unless its fuel has a minimum flash point of, say, 100° F.

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I do not agree that the problem of supplying the necessary quantities of fuel in the kerosine range will by any means prove insuperable, or even difficult. Exactly parallel forecasts were made at a Meeting of this Society in February 1937, when the gravest misgivings by certain authorities were then expressed at the proposal to design engines to require what they called "a theoretical type of fuel," namely, 100 octane petrol, which they contended would never be available in adequate quantities in time of war. If these authorities had been listened to then, and R.A.F. Fighter Command had had to fight the Battle of Britain on low octane fuel, the result of that critical battle would probably have been very different.

The growth in the demand for kerosine type turbine fuel is likely to be gradual, and it may quite possibly coincide with some reduction in the demand for this class of fuel for other purposes, such as illumination or tractors. I am therefore of the opinion that the oil industry will find ways and means of coping with any peace-time demand that is likely to arise for civil aviation, and I see no justification for any fears of a shortage and a consequent need to resort to fuel in the petrol range.

DR J. W. DRINKWATER : I agree in general with a number of the author's remarks regarding the problem of fuel and oil for the gas turbine. He is right in saying that, generally speaking, the gas turbine will operate on almost any fuel. I consider that the difficulties arise when the turbine is put into the aircraft, in so far that it is the latter which imposes certain restrictions on the fuel, and this should be borne in mind. Again, I agree with the author in saying that the supply potential of any particular type of fuel must be remembered, but, on the other hand, we must not allow ourselves to be deceived that this is the fuel we are going to get rather than the type of fuel we would really like. This, of course, brings up the question of safety, but it is very difficult to say how safe these low volatile fuels are. So far, all our experience has been with fuels of the high volatile type and, of course, we rely on experience gained from the war. Can anybody say, from the mishaps which Mr Ogston has mentioned, just what would have been the

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difference in the nature of these crashes if a lower volatile fuel had been used ? I agree that, from the physical characteristics of the fuel, a low volatile fuel should be safer in so far that there is a lower rate of diffusion of the inflammable vapour round about the aircraft, but I still feel that the answer to the problem will not be obtained until either there are some full-scale crash experiments carried out (*laughter*) to test these low volatile fuels, or—and he hated to make that suggestion—there was another war to get the same evidence with regard to low volatile fuels as we have on high volatile fuels.

In Fig 15 the ignition time lag in seconds is compared with the surface temperature, but I feel that the surface temperature is rather low, or rather, if this diagram was extended to temperatures corresponding to something of the order of the temperature of exhaust pipes or turbine discs, I am not sure whether the kerosine would show very much advantage over the gasoline. I agree that at a temperature of 70° or 80° C, or up to those temperatures, kerosine shows some advantage, but it is necessary to ascertain how the fire started. A fire is usually started by some inflammable material becoming ignited and then igniting a general envelope of fuel mixture round about the aircraft, in which case the low volatile fuels would probably give a quicker source of ignition than high volatile fuels. On the other hand, the volatile fuels will give a large envelope of ignitible vapour, and it is therefore very difficult to say how safe one fuel is compared with the other. I would like to hear more views on that particular point.

I cannot help feeling that the problem of filter clogging has been given undue prominence. Fig I gives the water solubility of various fuels against temperature, and shows that gasoline is really a little worse than kerosine, and yet, referring to experience during the last war, there are very few instances of filter clogging due to freezing. The only ones I can remember are those in which fuel coolers had been placed in the fuel system to lower the fuel temperature with a view to overcoming vapour lock. That precaution will not be necessary with a kerosine type of fuel on account of the lower vapour pressure, and therefore the problem of filter clogging is not quite so important as the author has indicated.

With regard to the author's suggestion that the possibility of ice formation could be overcome by the addition of $\frac{1}{2}$ to 1 per cent. of *iso*propyl alcohol to the fuel, here again I would draw on the last war experience. In order to overcome the problem of freezing in the carburetter, 5 or 6 per cent of ethyl alcohol was added to the fuel but, if only, say, 3 per cent was added, there was trouble due to the leeching out of the alcohol and that was a bigger source of trouble than carburetter icing.

Finally, on the question of detonation I would like to hear more.

DR K. E. W. RIDLER: The paper surveys in a very comprehensive manner the work which the author's laboratory has been carrying out on the development problems associated with the fuel and lubricating oil requirements of turbine engines for aircraft. I would like to do no more than focus attention on the background against which this work had to be viewed and to underline the remarks made by Dr Williams on safety and availability.

One rapidly acquired the point of view that, because a specification

existed, there must necessarily have been logical reasons and data to support the writing of all its clauses, but it is forgotten that even in the best cases the experimental work is concentrated on the limiting factors and the rest is filled in at convenience. Even with the specifications for fuels for reciprocating engines at this stage of their existence, one would, I think, be hard put to it to sustain by experimental evidence the necessity for some of the actual figures. The present specification for turbine fuels must be looked at in the light of the situation which existed when it was written. At that time very little development work had been carried out on any of the turbine engines now in service or under development, and the specification was an attempt to do no more than write down on paper the fact that people concerned had been using the then current supplies of burning oil available in the United Kingdom during war time. Whereas in normal times specifications are written with one eye on the supply situation, the aviation kerosine specification was, in fact, written with both eyes on the then existing available stocks, and we have therefore reached the position in which the engine development has taken place on a fuel arbitrarily chosen at a time when all the emphasis was being placed on short-term supply considerations, and without any thought about the possible implications of wide use of these engines in military or civil operation. The only limitation from the point of view of engine operation, viz. aromatic content, was included, if my memory serves me, because of test results with an engine now obsolete.

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It is unfortunately true that one cannot see the possibility of kerosine becoming available for a good many years for use on the scale of, say, 100-octane fuel in the last war, and it is as well that we should, in realizing this fact, remember that the specification was not "heaven sent." The use of kerosine for these engines has been considered desirable by many because it has been regarded as a safer fuel than petrol. When one considers the enormous effort and the long time required to make kerosine available in the necessary quantities, the probable need for building large "shadow" refineries to enable the "tap" to be turned on quickly if an emergency arose, and the difficulty of finding outlets for the enormous quantities of other products which might accompany the large production of additional kerosine, it would appear that the protagonists of the "kerosine for safety" view should be asked to evaluate the significant fuel characteristics from the point of view of fire risk in full-scale experimental work and to determine how far away from petrol one must move in these particular characteristics to achieve a degree of safety in keeping with the effort involved in obtaining a fuel in sufficient quantities. Dr Williams has mentioned the possible significance of volatility, flashpoint, and selfignition temperature, and although he quotes laboratory experimental results which are extremely interesting and provide certain pointers, we must all realize that full-scale results will have to be obtained before any opinion could be finalized.

For myself, I believe that so far the proponents of "kerosine for safety" have singularly failed to prove that one must have that fuel for the requisite degree of safety, and that, pending some substantiation of their case, it will be as well to arrange for turbine engines to use a fuel which can be obtained in sufficient-quantities to cope with any eventuality.

MR W. A. PARTRIDGE : With reference to Dr Williams' remarks on the influence of hydrocarbon composition on cloud point, it is instructive to examine the published data for the melting points of the hydrocarbons. It is evident that the majority of hydrocarbons boiling up to about 180° C, had melting points below -60° C, the few exceptions comprising benzene, cyclohexane and the normal paraffins from C₈ upwards. Above 180° C, hydrocarbons with low melting points are to be found in the following classes : isoparaffins, naphthenes with isoparaffin side-chains, and mono-alkylbenzenes. The normal paraffins soon become solid as the boiling points increase, e.g., tetradecane boiling point, circa 250° C, has a melting point of 5.5° C. Even the isoparaffins above C₁₈ appear to have melting points generally above -60° C.

The C₅ naphthenes generally have melting points below -60° C, up to normal octylcyclopentane, boiling point 235° C, and melting point -45° C. Higher normal alkylcyclopentanes are all relatively high in melting point. No data is available on the higher *iso*alkylcyclopentanes, but it may be conjectured that many of these will have low freezing points.

The C_6 naphthenes are generally low in melting point up to normal heptylcyclohexane, boiling point 240° C, melting point -41° C. Such data as are available suggest rather high melting points for the majority of the higher alkylcyclohexanes.

Data are very scanty for other naphthenes, but *cyclo*heptane and *cyclo*octane have melting points round about 0° C, whilst the higher *cyclo*paraffins without side-chains are solid at room temperature.

With regard to the aromatics, the monoalkylbenzenes generally have low melting points up to normal octylbenzene, boiling point 260° C, melting point -45° C, but the polyalkylbenzenes tend to have higher melting points, *e.g.*, hemimellitene has a boiling point of 176° C, and a freezing point of -25° C, and the 1:4-diethylbenzene a boiling point of 183° C, and a melting point of -35° C.

The dicyclic hydrocarbons generally show high melting points, whilst the olefins follow fairly closely the characteristics of the corresponding saturated compounds.

It would therefore appear that in the event of it being necessary to produce a kerosine type aero turbine fuel of low freezing point, the petroleum industry will be forced into the position of segregating or manufacturing fuels predominating in *iso*paraffins, naphthenes with *iso*paraffinic sidechains, and monoalkylbenzenes. In other words, we shall be manufacturing fuels of a higher boiling range, but close in hydrocarbon composition to the present aviation fuels for piston engines. Having regard to the past record of the petroleum industry there is some reason to suppose that, given time, the industry can produce such fuels in adequate quantity, but at a price probably around that of the present 100/130 aviation fuel. The whole question of acceptable cloud point of aero turbine fuels must therefore be closely studied in an effort to avoid following the lines of development of the piston engine which had resulted in the use of " tailor made " fuels. It will indeed be a pity if the gas turbine is not developed to use cheap and widely available fuels.

In connexion with this question of acceptable cloud point, such data as I have been able to obtain shows that the lowest possible temperatures of

the atmosphere vary from about -80° C over the equator to something of the order of -50° C towards the poles. These temperatures occur above approximately 40,000 ft, *i.e.*, in the region of the stratosphere. Therefore, there appears to be no particular virtue in either of the cloud points so far specified, viz. -60° C and -40° C.

I would like to sound a note of warning regarding the use of aromatics to depress cloud points. At Sunbury we have found that the aromatics appear to have "blending" cloud points around -70° C. For example, it is found that 30 per cent of toluene, melting point -95° C, is required to depress the cloud point of a kerosine from -56° C to -60° C, *i.e.*, the apparent blending cloud point of toluene is -75° C. Similar results have been obtained with other aromatic materials.

Finally, Dr Williams has mentioned the possible use of pour point depressants in aero turbine fuels. At Sunbury we have examined three such materials and have found, as might be expected, that these do not affect the cloud point in any appreciable manner.

MR E. A. EVANS: There is very little I can say about the oil because it seems to be controlled by the one factor which has been imposed, namely, the low temperature conditions. If it is intended to limit the pour point to -40° C or perhaps -60° C, then it appears that there is only one oil available for the job. If that be true there is nothing more to be said. I am rather curious to know whether the safe limit of the film strength is equal to that of the 2472B oil. If that is a fact, it is not very high. Consequently, it should not be very difficult to raise the film strength of 44D to that value with the aid of an additive. I am not sure that that is precisely the actual state of affairs, so perhaps Dr Williams can tell us a little more about it.

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The author passed over very quickly and, if I might say so, very modestly, his reference to the Institution of Automobile Engineers gear-testing machine. That machine was developed at the Research'Laboratory of the Institution of Automobile Engineers when it was under the jurisdiction of Dr Williams, and no doubt he had an affection for that machine; or it might be that Dr Williams used that machine because it was given to him without charge, or he felt that he must use it in deference to the susceptibilities of the Ministry of Aircraft Production. Be that as it might be, the fact remains that that machine is hardly suitable for the particular problem which is facing Dr Williams and his colleagues at the present time. I might mention, in passing, that this machine has been developed into a more robust brother in the Motor Industry Research Association Laboratory.

Reference has been made in the paper to the chemical activity of the more active additives. I am wondering whether we are not getting just a little out of phase with reality and whether we are not becoming too fussy about the staining of copper. I think we have garnered a good deal of that inclination from our American cousins who had to comply with various specifications for extreme pressure lubricants in hypoid gears. From the curves it appears to me that as the temperature is lowered the activity is very much reduced, so we are dealing with a material which does not have any, or at most very little, activity at very low temperatures as the gears spend most of their life at high temperatures, when copper staining can

occur, the objection to slight staining seems to be reduced. Those who have anything to do with E.P. additives know that the additive should stain at a temperature in the neighbourhood of 240° F. Therefore they depend on some staining or chemical activity. I have seen active E.P. additives used in conjunction with bearings having copper or cuprous cages which, of course, did stain, but no harm resulted. They have gone on perfectly merrily so perhaps we are getting a little too fussy.

I would like to ask Dr Williams how his colleagues managed to measure the viscosity index of 44D?

MR E. THORNTON : I should like to comment on the suggestion made by Mr Ogston that we should limit ourselves to safe fuels. We must surely guard against losing our sense of proportion when confronted with the question of fires in crashed aircraft. We have to remember that the whole development of motoring and of aircraft as we know them to-day would have been impossible if we had started from the viewpoint that only safe fuels must be used. There is no inherently safe fuel, except one which will not burn at all and that will be of very little use in the engine !

It is true that kerosines, by virtue of lower flash point, will have less tendency to vaporize at once but, as Dr Williams has shown, other features of fire hazard are more marked with kerosine than with petrol. We should develop our fuels and our jet engines together, without undue regard to aircraft crash fires, and simultaneously develop methods of fire prevention and fire fighting, which are the province of the fire engineers.

The incidence and spread of fire depends on other factors than the flash point of the fuel (indeed, fires have occurred with kerosine-type fuels) and methods of preventing and combatting fires, such as the use of methyl bromide, water fog, carbon dioxide, etc., will be necessary whatever fuel is used and can be made to deal with petrol if they can be made to work at all.

We must keep closely in mind that we are developing jet engines and jet fuels and concentrate on these points unhampered by considerations which, as stated, belong to the province of fire engineering.

MR H. G. SPENCE : The lubrication side seems to have been comparatively neglected in the discussion so far. The most important point in this connexion is the temperature of the oil, and the problem, as usual, has been thrown back on the petroleum technologist to develop an oil which will do absolutely everything that is asked of it. The oil technologist will be considerably helped in the present case by a simple mechanical alteration; if the oil cooler is placed between the filter and the feed to the gears it should be possible to control the temperature of the oil in the gearbox either by a by-pass valve or some sort of baffle controlling the air stream flowing past the cooler. The temperature of the feed to the turbine bearings could probably also be controlled by the same system. It is a matter of making adjustments to obtain the correct state of thermal equilibrium under flight conditions, and I think that this might be done more conveniently on the aircraft in service, than on the test-bed or in the wind tunnel. By a little experimenting the temperatures to bearings and to the gearbox might be adjusted to the optima, giving the best viscosities for each component.

MR R. B. GODFREE: With regard to lubrication the importance of complete rig testing of a lubricant can not be over-estimated. Many engines are being developed and bench-tested on lubricants which are unsuitable for high altitudes unless protected by lagging and heaters, and it is a big step for the engine builder to change from these lubricants to lighter oils of adequate low temperature properties without definite indication of the general performance of these oils in the engine.

I fully endorse Dr Williams' remarks with regard to bearings. The testing of ball bearings is a very elusive subject. In practice, a sudden increase in loading in flight manœuvres, as, for example, gyroscopic loading, might, in conjunction with the high temperatures to which the turbine bearing is subjected, make the bearings rather critical of the load carrying quality of the oil, although in normal operation anti-friction bearings do not appear to be particularly dependent on the kind of lubricating oil used.

The lubrication of reduction gears of the propeller turbine is undoubtedly of major importance. The development of lubricants to withstand the high surface pressures encountered in these reduction gears in itself presents no major problem. Additives of the sulphur chlorine type and others are already in existence which should promote the load carrying capacity of lubricants to an extremely high range—in many cases well outside the range of loads which the I.A.E. gear machine can apply. However, it is not only the E.P. properties of the lubricant which counts, as Dr Williams has pointed out. It is this property in conjunction with low pour point, high viscosity index, anti-oxidation, anti-corrosion, and stability over long periods of use, which are of importance and which collectively can be more fully developed.

My own laboratory tests have also shown that the scuffing load of straight mineral oils increases with the viscosity of the oil as the temperature is reduced and that of doped oils shows a marked tendency to fall off. The viscosity effect in the case of doped oils appears thus to be relatively minor, and the disparity between the physical viscosity effect of the base oil and the chemical effect of the additive will increase with a greater concentration of additive and with additives of greater chemical activity.

It seems, therefore, that in these circumstances the numerical loadcarrying capacity of an oil in the gear machine at low temperatures is of more value to the engine designer than the relative rating of oils at an arbitrary temperature.

Finally, whilst the I.A.E. gear machine has its limitations, nevertheless until the importance of higher sliding velocities and higher surface pressures in changing the relative order of merit of lubricating oils have been established, I would say that it is a basically sound test apparatus that has played a definite part in the development of gear lubricants in the past and will continue to do so for some time in the future.

MR T. THISTLETON : I would like to make a few remarks about the I.A.E. gear-test machine, as I have been concerned with the operation of both units at Esso European Laboratories on behalf of Intava Ltd.

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Since testing was begun with the first of these, well over two years ago, several hundred tests have been completed, in the course of which considerable experience of this kind of test has been gained. Throughout, our greatest difficulty has been test gears. Our requirements for precision are

of a high order and, for the benefit of those not directly concerned with the I.A.E. machine, I would like to mention that, at a meeting held this afternoon, we spoke of tooth profile modification in terms of tenths of a thousandth of an inch.

We find that, using gears carefully selected on the basis of profile measurements, we can obtain reproducible results, but this profile selection is a relatively laborious and costly process.

It is therefore encouraging to find that, in general, our results agree with those given by Dr Williams. It is more than a year since we established a relation between scuffing load and lubricant viscosity. We found that, for a series of undoped oils ranging in viscosity from about 2 to 26 cs at the test temperature of 90° C, there was a linear relation between the square root of the scuffing load and the viscosity. The Hertz stress between the gear teeth is also proportional to the square root of the tooth load per unit face width. So it appears that there is a relation between surface stress at failure and lubricant viscosity. I suggest that if Dr Williams plots his figures for undoped oils in a similar way, he may find a linear relation.

We have also done some tests on the effect of oil inlet temperature on load-carrying capacity. We have noted a similar effect to Dr Williams'; finding that the load-carrying capacity of undoped oils is appreciably increased by reduced temperatures, whilst there may be a serious decrease for doped oils. Covering a wider range of temperatures than Dr Williams has reported, we have noticed a tendency for the failure load to increase over a certain range of temperature reduction before falling off towards still lower temperatures. This suggests that there is an optimum temperature at which the load-carrying capacity will be greatest, presumably this will occur at a point where the effect of increased viscosity is not overshadowed by reduction of the chemical activity of the additive.

I cannot but agree with Dr Williams' remarks regarding the I.A.E. geartest machine, both in criticising it and in suggesting that the results are not misleading. We are interested in developing a test for turbine lubricants which is nearer practice. One obvious requirement is higher speed and it is doubtful whether the gear machine can be made to operate safely at sufficiently high speeds to correspond with conditions in turbine reduction gears. However, any increase of operating speed must be regarded as a step in the right direction. It will be difficult to bring any single gear test very close to practice as the reduction gears used are of at least two types, namely, simple spur and spur epicyclic, and the individual gears cover a relatively wide range of pitch, size, and speed.

Mr Evans has suggested that the I.A.E. 5-inch centres gear machine would be more suitable for testing turbine lubricants. I disagree with this, as I do not think that this machine has nearly such great possibilities for operation at high speeds as the smaller 3- and $\frac{1}{4}$ -inch centres machine, since it has large shafts with heavy universal joints.

MR E. H. WARNE (speaking also for MR LAWRENCE) : Whilst Dr Williams and other people have indicated that the gas turbine would burn almost anything—and although this is very nearly true—great difficulties are encountered when an attempt is made to burn these general types of fuel.

I am surprised that Dr Williams favours volatility as the cause of loss of

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combustion efficiency. My experience had been that the major factor appears to be viscosity. Since viscosity and volatility seemed to go hand in hand, it is difficult to distinguish their effects, but it is possible to reduce the effect of viscosity to negligible proportions by different designs of burner. There is no doubt a certain effect due to volatility, but, in general, this appears to be completely drowned by the viscosity effect. The major difficulty in overcoming viscosity with regard to atomization is the fact that with the gas turbine a very large range of flow is required and with a simple type of burner this necessitates the use of exceedingly high pressures. Unfortunately, spill burners have their shortcomings which make them difficult to use on aircraft engines, but duplex burners are in use.

There is a small point with regard to the effect of water on the fuel system. It is stated in the paper that the pump design originally included sliding parts whose movement was small and occasional and that the moisture content caused them to stick. These sliding parts were, of course, incorporated in separate components in the fuel system and are not part of the pump at all. They are the Barostat (or Altitude Control Unit), Lubbock Burners, and the Throttle Valve. All three have now been replaced by components which have no such sliding parts. The elimination of sliding parts is also beneficial from the standpoint of dirt causing sticking. It has been found that particles far too fine to be removed by any type of filter tended to collect and build up round the fine clearances and cause sticking. If there are sufficient forces available, it should not matter, but in these cases the forces are very small.

With regard to lubricants, there is the question of aeration or frothing. Has Dr Williams found any trouble due to this cause, and if so, what did he do to overcome it? I believe there has been quite a lot of trouble on ordinary aircraft engines due to frothing of lubricating oils.

DR C. G. WILLIAMS, replying to the discussion : Mr Bass has asked what is the effect of volatility on the rate of spread of flame in the event of a crash. The effect is a very close one. In general, the higher the volatility the more rapidly will the flame spread, once ignition has occurred. With regard to the possibility of air release from kerosine, as far as I can remember, the air solubility of kerosine is lower than that of gasoline. It is necessary to bear in mind that gasoline might boil at high altitude and this will result in the very rapid release of air and accentuate vapour lock. In the case of kerosine, boiling will not occur and the fuel may become super-saturated with air, which may be released at the booster pump, if one is fitted.

Some influence of gear material on the effectiveness of oil additive has been noted, but closer investigation is required to confirm the magnitude of such effects.

The remarks of Mr Ogston indicate that he is very much in favour of a safer fuel and, of course, if it is possible to have a "safe" fuel along with the other properties, all the better. Unfortunately, with some "safe" fuels there are technical difficulties. It is not easy to get a low freezing point and, in general, they have a high viscosity at low temperatures. However, with further engine development it may be possible to use fuels of the gas oil variety.

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As regards full-scale crash experiments, hinted at by Dr Drinkwater, I

understand that such tests are under consideration in the United States, so that the suggestion is not so farcical as it might at first appear. As to filter clogging, I do not wish to over-emphasize its importance. I have referred to it in the paper as a possibility—a possibility which has to be considered in view of the emphasis on the low-temperature requirements of the gas turbine, particularly when engines are shut down at altitude. In addition, the gas turbine requires a high degree of filtration of the fuel which will accentuate filter clogging. I agree with Dr Drinkwater that *iso*propyl alcohol will leach out of the fuel in the presence of water. Dr Drinkwater has also asked if there is any evidence of detonation having occurred. All I can say is that there are well-authenticated cases of very violent explosions which have been sufficient to disintegrate the very heavy valve at the outlet of a single-cylinder combustion chamber installation.

I do not think I have any comments to make on Dr Ridler's observations, but would add that from what I have heard there have been kerosine fires both in America and in Britain following the crash of gas turbine aircraft. In other words, the use of kerosine does not eliminate the fire possibility.

I thank Mr Partridge for the data he has given, which calls for no comment.

Reference has been made by Mr Evans to the effect of additives. It is possible to get film strengths with doped 44D oil which are considerably greater than those obtained with an undoped 2472B oil, the latter being assumed to be the "target." The types of additives used are, of course, relatively mild. Mr Evans has also referred to the I.A.E. gear-testing machine and queried its suitability. The answer is that this was the only machine available and it has been used by at least one prominent engine manufacturer for quite a long time. As far as I know, that particular firm thought the machine gave results of significance.

It has also been implied by Mr Evans that there is too much nervousness about the corrosivity of these additives. I do not think we are worried about the staining of copper, but we do worry when additives gave rise to bearing failure. That has happened with an oil containing an additive which attacks the cage and gives rise to pick-up between the balls and the cage. This resulted in the destruction of the bearing, an extremely serious occurrence in a turbine engine.

Reference has also been made by Mr Evans to the effect of low temperatures on E.P. additives. Tests have been carried out on the I.A.E. machine in a cold room down to -40° C. Under certain conditions there is a serious loss of E.P. strength.

I thank Mr Thornton for his comments, with which I agree.

I do not think that the system mentioned by Mr Spence, in which loadcarrying capacity of a light oil is maintained by cooling it instead of by doping it, will necessarily work since, as shown by Fig 23, a reduction in temperature does not always result in an increase in film strength.

I thank Mr Godfree for his remarks, with which I agree.

Mr Thistleton's comments on the effect of temperature on load-carrying capacity are very interesting.

Finally, Mr Warne suggests that I have implied in the paper that the gas turbine will burn almost any fuel. As a matter of fact, I have not implied that; far from it.

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The relative influences of fuel viscosity and volatility are difficult to separate, but the particular results given in the paper seem to suggest that volatility is the more important, but I quite agree that under other conditions, particularly at low temperatures, and with heavy fuels, such as gas oil, the viscosity effect takes control. I have not heard of any trouble due to aeration of lubricants on turbine engines, but presume it can be got over in exactly the same way as it has been overcome in other types of aviation engines, viz. by the use of one of the silicone dopes.

THE CHAIRMAN, referring to kerosine fires in connexion with jet machines, said: When I was at the Ministry there was a definite fire. There was no doubt about it, but the cause was not apparent from an examination of the wreckage. Afterwards, however, it was found not to be so serious as a petrol fire.

With regard to gears, when I last had anything to do with them, in connexion with turbines, everybody went about the design of them lightheartedly and chances were taken. If the frequency of meshing is lowered on a single reduction gear on a piston engine there are chances of tooth deflection, but at the high rate of meshing on the high-speed end on a turbine gear, that does not occur. Indeed, a sort of construction is arrived at that follows almost infinitely Young's modulus, which does not mean a thing, so far as I can see. It is possible to make safer gears for turbines and I think there will be either a single helical or a double helical gear with a high-speed train running on the final drive.

In conclusion, I propose a cordial vote of thanks to Dr Williams for his excellent paper, which is a classic and which will be a most valuable work of reference for others to start upon.

The vote of thanks was cordially given.

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WRITTEN DISCUSSION.

EDWARD P. HAWTHORNE : Both in the lecture and the discussion, strong emphasis was laid on the desirability of using some fuel other than kerosine, chiefly owing to its poor supply position. I noted, however, that there is some difference of opinion as to whether the alternative fuel should be a lighter or heavier fraction than kerosine; the lighter fuels being easiest to produce, but the heavier fuels having greater fire safety.

From the standpoint of engine operation, a lighter fuel requires that the fuel system must be specially lubricated, increases the fire hazard and the possibilities of vapour locking, but should improve starting characteristics. A heavier fuel would have increased coking characteristics, but no mechanical disadvantages.

However, I would point out especially the advantages, particularly on a propeller gas turbine, which would accrue from the use of a heavier fuel which could first be passed through the gearbox and bearings as a lubricant, and finally burnt in the combustion system as a fuel. Such a product would enormously simplify the engine designers' and operators' problems by eliminating quite a few of the accessories which festoon modern aircraft engines. Thus it would be unnecessary to have oil pressure and scavenge pumps with their drives, thermometers and temperature and pressure

gauges; oil coolers with their temperature controls, air ducts, flaps, and flap controls; oil filters and all the oil piping; or the oil tank with its negative "G" devices and quick-release fillers, etc., representing in all some 10 per cent of the weight of the complete engine. Against this saving would have to be set the effects of a 40° C temperature variation of the fuel passing through the metering unit, and the increased production cost, which, of course, would be reduced as the demand increased.

Fig 22 of the paper shows that with the inclusion of a suitable additive, oils of quite low viscosities can be persuaded to carry as high loads as the more conventional lubricants, so that the production of a single product, with the characteristics of good combustion as a fuel and of high loadcarrying capacity as a lubricant, does not seem to be incapable of solution.

KENNETH C. HUNT: This paper gives welcome emphasis to the fact that what may be termed the "fuel problem" associated with the gas turbine engine is, for the present, almost entirely physical in nature, and that the basic physical requirements in terms of viscosity, freezing point, volatility, etc., must be settled before the secondary work of tackling the hydrocarbon variants in the desired physical range can be started.

Dr Williams makes a case for the use of a wide range distillate, but it is possible that his championship of such a fuel is coloured by the fact that it is readily available at the present time.

It is unarguable that at any given stage of the development of an engine the technical fuel requirement must be considered in terms of immediate fuel availabilities, in the light of anticipated civil and military requirements. On this basis, grade 100/130 gasoline or a wide range distillate of the JP2 type would seem to be the only fuels available immediately in adequate quantities for large-scale operations. I do not believe, however, that this is any reason for believing that fuel of the JP2 type is fundamentally the most desirable. It is open to severe criticism in that it makes the worst of all worlds in providing an explosive mixture in the free space in the fuel tanks under almost all attainable conditions of altitude and temperature, and although inert gas dousing of the tanks will reduce explosion risks, it is only at the expense of a severe weight penalty.

The fact that a wide range distillate may be used as the immediate aviation turbine fuel on the score of availability and other virtues, does not mean that the development of what are fundamentally more suitable fuels should not be pursued. In the advent of this new aircraft prime mover we have a golden opportunity to do something to make flying safer, and I believe that everything possible must be done to develop : (a) A fuel of 150° F minimum flash point and at least a -40° F freezing point, and (b) Burner systems capable of handling such a fuel.

A minimum flash point of 150° F has been suggested, as providing an adequate margin of safety in tropical conditions under which the conventional 100° F flash point kerosine may represent a border-line case as far as crash fire risk is concerned.

It is all very well for the opponents of high flash fuels to insist that those who support them must prove their case and establish that such fuels are in fact safer : it is most comforting if sufficient data can be accumulated on any project, so that the necessity of making a decision is removed by the weight of evidence and the course to be followed becomes self-evident. However, very few worth-while advances are made in this way, and in the end it usually rests with a person, or group of people, to back common sense and instinct. On this basis, it is submitted that a heavy landing in which aircraft tanks are split and the immediate crash area saturated with fuel is very much less likely to result in a severe fire if 150° F flash fuel is used than if it is a wide-range distillate, and it is much more in the public interest and in the long-term interest of civil aviation generally that the protagonists of low flash turbine fuels should be made to prove that they are in fact as safe as the high flash, rather than place the onus of proof of greater safety on the high flash school. The question of relative safety should in any case not come into the argument. If it is reasonable to suppose that one fuel is only fractionally safer than the other, then it should be used. It cannot be argued that property and money are of more value than lives.

A. W. POTTIER : Dr Williams states that, for additive lubricating oils to work satisfactorily and prevent scuffing of the reduction gearing, there must be chemical layers upon rubbing metal surfaces, and also that the operating temperatures are between 125° and 150° C. The oil temperatures may even rise to 250° C in the back turbine bearing when the engine is shut down, and heat soaks through to this region.

Temperatures of 300° C are prophesied. I think it would be very difficult to find an additive with a chemical structure where the extreme pressure elements, such as sulphur and phosphorus, are loosely combined and will decompose to form the desirable anti-weld layers on metal surfaces and yet will be stable at the temperatures already mentioned and will not be corrosive to metals and form deposits in the gas turbine engine. Experience of additive lubricants designed for the gas turbine engine and studied in the laboratory at a maximum temperature of 120° C would indicate that these additives, which give the best results, both on the I.A.E. machine and in the gas turbine reduction gears, are not chemically stable at this temperature. Those which are thermally stable have poor load-carrying properties.

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I would like to know what experience Dr Williams has had in this respect and what he envisages for the future of an additive oil which must, to satisfy other needs, be a low viscosity oil with a low pour test and yet must carry both a high-tooth loading in the reduction gearing and be chemically stable through a temperature range of $125-300^{\circ}$ C.

Although I agree that, to evaluate gas turbine additive oils more accurately, it is advisable for the I.A.E. machine to operate at higher speeds, my experience is that the $3\frac{1}{4}$ inch I.A.E. machine gives fairly reliable data, and I would not share Mr Evans' criticism, but think that Dr Williams' statement "the results are not misleading" is a fair one.

C. D. SOLTZ: It would be an understatement to say that the gas turbine is still in a very embryonic stage of development, it therefore seems a little strange to note this stress on fuel availability. After all, no major power is in a position to wage war within the next ten years and if they did "The Lamps of China" would probably go out anyway. There would seem, therefore, very little point in sacrificing any technical advantage or delaying mechanical development at the present time on this score.

It may be that the turbine engine will be omnivorous in its fuel requirements, if so, it will be the great exception to all things that "go up in the air." It seems, however, far more likely that when the engineers have time to settle down to "gild the lily," and this will take about ten years, the type of fuel they will require and the availability thereof will be very different from the present and will sort itself out accordingly.

There is nothing sure in this world, but having been associated for three years with the Accident Investigation Branch of the Air Ministry and seen numerous burnt aircraft and occasionally had the opportunity to talk to survivors, it is my view that anyone who can believe that the high flash point characteristics of the present kerosine would not provide greater safety from ground fires in the sort of crash landing, which would not kill the occupants anyway, and should not be regarded as the minimum goal, is deluding himself and basing his delusions on back room, rather than on field experience.

With regard to the type of oil that will be necessary, it seems opportune here to suggest that the engine manufacturers should at least indicate how they intend to stop their engines in the air, as at the moment no turbojet installation could be stopped and although the feathering propeller may be satisfactory for some turbine propeller designs, the free turbine type will probably require a brake and a mechanism for preventing rotation of the turbine compressor end.

DR C. G. WILLIAMS, in reply to the written discussion, said : Mr Hawthorn calls attention to the advantages of using one hydrocarbon, such as gas oil, for both fuel and lubricant. This sounds attractive for a jet engine but Mr Hawthorn recommends it for a propeller gas turbine, in which case the gas oil will have to contain a suitable E.P. additive. While it may be economic to add an additive to two or three gallons of lubricant, it is extravagant and probably uneconomic to add such a dope to fuel consumed at the rate of, say, 400 gallons an hour.

I agree with Mr Hunt that in general a high-flash fuel will be safer than a low-flash fuel, and provided high-flash fuels of the requisite physical properties can be produced in adequate quantities and will run satisfactorily in engines, I am certainly in favour of them.

Replying to Mr Pottier's comments, I do not prophesy bearing temperatures of 300° C, in fact it is to be hoped that bearing temperatures will, in general, be kept below 150° C. E.P. oils for operation at such temperatures will be useful, at least as an interim measure, while the design of reduction gears undergoes further development.

The paper on "Fuels and Lubricants for Aero Gas Turbines" was also read by Dr C. G. Williams at a joint meeting of the South Wales branches of the Institute of Petroleum and the Institute of Fuel. This meeting was held in Swansea on March 12, 1947, when the Chair was taken by Mr E. Thornton and the following discussion ensued.

MR JEFFRIES: Is there any explanation of the very surprising facts given about the relative ease of ignition of petrol and heavy lubricants on hot surfaces?

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DR WILLIAMS : This is due to cracking, which occurs with the heavier hydrocarbons, producing reactive molecules.

MR J. G. PROBERT : Would the lecturer give his views on the question of axial flow v. radial compressors, as Commander Whittle had stressed the value of axial flow ?

DR WILLIAMS: Britain has, on the whole, adopted radial, and Germany axial, flow compressors. The attraction of axial flow compressors is their smaller diameter and greater efficiency, the objections being that the fine clearances are apt to be interfered with by dirt. My view is that the future lies with the axial flow compressor.

MR STRADLING: What is the fuel cost per H.P. of jet engines?

DR WILLIAMS: The thermal efficiency is about 18 per cent, but it runs on a cheaper fuel. A more definite answer cannot be given since it depends upon too many variables, including the price of fuel.

MR E. S. SQUIRE: In the diagram of flame blow-out conditions there is an extraordinarily high air/fuel ratio beyond anything reasonable in combustion. Why is this?

DR WILLIAMS: Because it includes the tertiary air which is a diluent after combustion. But the extinction occurs in a region where these ratios are much more normal. However, since the ratio of total air to combustion air is roughly constant, it is convenient to graph the total air/fuel ratio.

MR SQUIRE : Inflammability measurements surely depend very largely on the apparatus ?

DR WILLIAMS : Yes, of course; kerosine tanks present a greater risk than gasoline tanks.

MR SQUIRE : Pressure loss in the jets is said to depend upon the viscosity. Surely since all the flow will be turbulent, this is unexpected as it should be independent of the viscosity.

DR WILLIAMS : The swirl in the atomizer may be affected by viscosity, particularly at low flows, although the bulk of the pressure loss will be turbulent.

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MR D. W. THOMAS: It was stated that the physical characteristics of the fuel determine its efficiency. What influence will refining have, *e.g.*, what about sulphur ?

DR WILLIAMS: I had expected that question to crop up in London, but it did not. Corrosion could occur with high sulphur and also the presence of sulphur seems to affect adversely the adherence of carbon deposits. Sulphur on the whole is bad.

MR J. G. PROBERT : What is the future of the "athodyd" type of engine as used in flying bombs?

DR WILLIAMS : It has great simplicity, but is not very efficient. It will probably remain chiefly for military use.

MR JOHNSTON: What is the future of the gas turbine?

DR WILLIAMS: Very considerable, because: (1) It requires no water cooling; (2) it has great simplicity; (3) servicing will be very easy; (4) the weight/power ratio is very good, about one-third that of other types.

MR I. CAMERON: How is the air/fuel ratio maintained at high altitudes ?

DR WLILIAMS : By a barometric capsule giving compensation for lower air pressure.

MR H. W. MURPHY: How is a jet engine started ?

DR WILLIAMS: By an electrical starter and electrical ignition, the cranking speed being 1300 r.p.m., as against 30 to 40 for a piston engine.

MR MURPHY: Can icing troubles at very high altitudes be avoided by keeping the fuel warm, using the heat of the engine ?

DR WILLIAMS : Yes, but complications of this kind are frowned on by designers.

MR E. THORNTON: With regard to hot-spot troubles, is no insulating coat possible, however thin, which by preventing direct flame impingement will lessen the likelihood of hot spots?

DR WILLIAMS: No such light coat is known, but refractories may supply an answer for stationary or ground engines where weight is not important.

NAPHTHENIC ACIDS: BOILING POINTS AND DISTRIBUTION IN GAS OIL DISTILLATES.

By K. F. Coles.*

SUMMARY.

The fractionation of a Trinidad gas oil at reduced pressure has enabled the distribution of naphthenic acids to be studied. It has been found that naphthenic acids with acid values 350 to 250 boil 60° to 40° C above the boiling points of the gas oil fractions in which they are found. The vapourpressure/temperature relationship for some naphthenic acid fractions is also presented.

INTRODUCTION.

It would be expected that the naphthenic acids present in petroleum distillates would come over below their boiling-points during distillation of oil, but no quantitative information on this has been published. The fractional distillation of a Trinidad gas oil has provided information on this point.

There is also little published information on the boiling-points of naphthenic acids and no convenient nomograph for relating vapour pressure with temperature for this material. Boiling-points were therefore determined on a number of fractions of naphthenic acids at varying pressures for acids between 350 and 250 acid value (mg KOH equivalent to 1 g acids).

EXPERIMENTAL.

Gas Oil Distillation.

The gas oil was distilled through 10 ft of 6-in diameter Stedman packing with a reflux ratio of 20:1 at a pressure of 50 mm Hg. The charge was 50 gallons of a Trinidad gas oil (sp. gr. at 60° F; 0.8682; aniline pt, 58.0° C; neutralization value, 0.59) and $\frac{1}{2}$ -gallon fractions were collected at 2 hourly intervals. Neutralization values (I.P. method 1/46, A) were determined on every third fraction.

Recovery of Naphthenic Acids.

The naphthenic acids were recovered by washing selected fractions with 5 per cent sodium hydroxide solution and purifying the recovered acids by the analytical technique described by Klotz and Littman.¹ This treatment gave the acid number of the recovered acids freed from unsaponifiable material.

Boiling Points.

Fractions of naphthenic acids from gas oil of similar origin to that reported above were available, freed from unsaponifiable material. Boiling

^{*} Trinidad Leaseholds Ltd., Central Laboratory, King's Langley.

points of these fractions, and of the gas oil fractions, were determined at varying pressures with a boiling-point apparatus constructed according to the design described by Willard and Crabtree.²

Vapour-pressure / Temperature Relationship.

A useful nomograph has recently been published by Lippincott and Hyman³ relating vapour-pressure to temperature for various substances. For this purpose the compounds reported have been divided into 8 groups, in which scheme, for example, hydrocarbons are found in group 2 and most alcohols and organic acids in groups 5 to 8. Examination of the boiling



FIG. 1.

THE NEUTRALIZATION VALUES OF FRACTIONS FROM THE DISTILLATION OF A TRINIDAD GAS OIL.

point results for naphthenic acids shown in Table II indicates that this nomograph can be reliably used for converting naphthenic acids boilingpoint data, if acids of 350 to 300 acid value are placed in group 6 and acids of 300 to 250 acid value in group 5.

For convenience the boiling-points of the naphthenic acids at 10, 50, and 760 mm Hg pressure have been read from the nomograph and are shown in Fig. 2. In applying this data it should be remembered that it is derived from Trinidad acids free of unsaponifiable matter, and is therefore only strictly applicable to these materials.

Distribution of Naphthenic Acids in Gas Oil Distillations.

The neutralization values of the gas oil fractions (Table I and Fig. 1) show that the fractionation of the gas oil was sufficiently precise to achieve some separation of the naphthenic acids into groups. These appear to

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Fr. no.	B.p. ° C. (760 mm).	% Vol. distilled.	Neut. value.	Fr. no.	B.p. ° C. (760 mm).	% Vol. distilled.	Neut. value.
2	193	1.9	0.15	45	265.5	41.1	0.74
5 '	205	4.8	0.34	47	267	42.5	1.09
8	217	7.8	0.46	49	268	44.3	0.97
9	218	8.7	0.48	50	269	45.2	0.94
11	222.5	10.9	0.41	53	271	48.1	0.90
14	225.5	13.2	0.39	55	273	50.1	0.86
17	230	16.3	0.44	56	274	51.1	0.83
20	232.5	19.0	0.65	59	277	53.6	0.84
23	235	21.3	0.77	62	279	56.1	0.87
26	239	24.0	0.80	65	281	59.0	0.91
29	244	26.8	0.80	68	287	61.4	0.99
32	249	29.5	0.77	71	292	64.6	0.98
35	254	32.1	0.67	74	296	67.8	0.72
38	259	34.9	0.61	77	301	70.9	0.57
40	261	37.0	0.57	78	302.5	72.0	0.51
41	262	38.0	0.60	80	306	73.6	0.46
42	263	39.0	0.64	83	310	75.9	0.43
44	265	40.4	0.70	86	315	78.3	0.39

TABLE I.

Neutralization Values of Gas Oil Fractions.

T	ABLE	II.

Boiling Points of Naphthenic Acid Fractions.

Acid no.	Mol. wt.*	Press. mm. Hg.	В.р. ° С.	Group on nomograph.				
355 355 355 355 355	$158 \\ 158 $	23 55 100 751	146 169 186 251	6 6 7				
327 327 327 327 327	171 171 171 171 171	$12 \\ 35 \\ 100 \\ 751$	149 173 203 271	6 6 7 —				
306 306 306 306	183 183 183 183	18 55 100 751	$171 \\ 197 \\ 214 \\ 284$	6 6. 6				
290 290 290 290 290	$193 \\ 193 \\ 193 \\ 193 \\ 193$	$ \begin{array}{r} 18 \\ 51 \\ 104 \\ 751 \end{array} $	175 202 223 295	5 5 5				
271 271 271 271 271	193 193 193 193 193	$15 \\ 34 \\ 128 \\ 752$	184 204 242 309	6 5 5				
257 257 257 257 257	218 218 218 218 218	3 32 105 751	154 212 244 321	5 5 5				

* Calculated from acid number, assuming monobasic acids.

† Industr. Engng Chem., 1946, 38, 322.

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THE BOILING-POINTS OF NAPHTHENIC ACID FRACTIONS (FREE OF UNSAPONIFIABLES) AT VARYING PRESSURES. THE VALUES AT ATMOSPHERIC PRESSURE WERE DETER-MINED EXPERIMENTALLY AND THE VALUES AT OTHER PRESSURES ARE TAKEN FROM THE NOMOGRAPH.

T	A	BI	Æ	Ы	

	Ga	s oil.		Recovered acids.							
Fraction no.	% Vol. dis- tilled.	B.p. (760 mm).	B.p. ° C. 60 mm). (50 mm).		Acid no.	$n_{\mathbf{D}}^{20}$.	% w.w. in gas oil fraction.†				
6	5.7	210	119	176.5	317	1.4604	0.14				
7	6.8	214	123	180	311	1.4590	0.15				
8	7.8	217 -	126	186	306	1.4620	0.15				
24	$22 \cdot 2$	235.5	141	194	289	1.4664	0.27				
25	23-1	236.5	142	196.5	285	1.4678	0.28				
26	24.0	239	144	197	284	1.4676	0.28				
40	- 37.0	261	163	199.5	281	1.4688	0.20				
46	41.6	267	167	202	-277	1.4702	0.40				
48	43.4	268	168	205	274	1.4714	0.36				
50	45.2	269	169	209	268	1.4726	0.35				
55	50 1	273	173	214	262	1.4742	0.33				
67	60.8	285	183	224	250	1.4774	0.39				
71	64.6	292	189	234	239	1.4810	0.41				
72	65.7	293	191	237	236	1.4810	0.36				
85	77.5	313	203	252	222	1.4878	0.18				

* Calculated from acid number, assuming monobasic acids.

† Calculated from neutralization value of oil and acid number of recovered acids.

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BOILING POINTS AND DISTRIBUTION IN GAS OIL DISTILLATES. 329

have no special significance, but it is clear from consideration of the boilingpoint data (Table III and Fig. 3) that the acids were distilling 40 to 60° C below their boiling-points. This comparison is made at the pressure at which the gas oil was distilled (50 mm Hg). Comparison of the corresponding boiling-points of the acids and gas oil fractions at atmospheric



THE BOILING-POINTS OF NAPHTHENIC ACIDS AT 50 MM HG PRESSURE SHOWN IN RELATION TO THE FRACTIONS OF THE TRINIDAD GAS OIL FROM WHICH THE EQUIVALENT ACIDS WERE RECOVERED.

pressure shows a temperature gap differing by less than 5° C from that at 50 mm Hg, so that it seems highly probable that an effect of the same order occurs in distillation at atmospheric pressure.

ACKNOWLEDGMENTS.

The author wishes to thank the directors of Trinidad Leaseholds Ltd. for permission to publish this work, which was carried out in the Company's laboratories.

References.

- ¹ Industr. Engng Chem. Anal., 1940, 12, 76.
- ² Industr. Engng Chem. Anal., 1936, 8, 79.
- ³ Industr. Engng Chem., 1946, 38, 320.

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THE INSTITUTE OF PETROLEUM.

ADJOURNED THIRTY-THIRD ANNUAL GENERAL MEETING.

THE proceedings of the Thirty-Third Annual General Meeting of the Institute of Petroleum were resumed at Manson House, 26, Portland Place, London, W.1, on Wednesday, January 8, 1947, Mr G. H. Coxon (Chairman of the Council and of the Finance Committee) presiding.

THE CHAIRMAN, opening the resumed meeting, said : The purpose of this adjourned Annual General Meeting is to complete the meeting held in October 1946. The delay has been due to the inability of our auditors to get the accounts passed at an earlier date.

THE SECRETARY (Mr F. H. Coe) read the notice convening the resumed Annual General Meeting, and the Auditors' report on the Accounts and Balance Sheet for 1945.

ACCOUNTS.

THE CHAIRMAN, presenting the Accounts and Balance Sheet for the year 1945, said : The accounts, which are before you, show that the Institute did quite well financially in 1945. In that year and in previous years a revenue item of £4175 has been built up. It has been the policy of your Finance Committee during the last two or three years to bring that item as quickly as possible to a figure of £6000 or £7000, knowing that in this postwar period we should have to face quite a bit of rehabilitation and with the knowledge that in 1948 we shall want to draw on our funds fairly heavily.

There being no questions, the CHAIRMAN moved "that the Accounts and Balance Sheet, as audited by the Institute's Auditors, and showing the position of the Institute's affairs as at December 31, 1945, be approved and accepted."

MR T. DEWHURST: It is with very great pleasure that I second the motion. In doing so I would emphasize what you know already, how much we are indebted to Mr Coxon, as Chairman of the Finance Committee, for having put the position so well in presenting these Accounts.

The resolution was carried.

THIRTY-SECOND ANNUAL REPORT.

THE SECRETARY read the Council's Report for the year 1945.

On the motion of Mr Dewhurst, seconded by Mr E. A. Evans, the Report was adopted, without discussion.

AUDITORS.

On the motion of Lt.-Col. S. J. M. Auld, seconded by Mr J. S. Jackson, Messrs Price, Waterhouse & Co. (Chartered Accountants) were re-elected Auditors to the Institute for the ensuing year.

THE INSTITUTE OF PETROLEUM.

THIRTY-SECOND ANNUAL REPORT.

THE Thirty-Second Annual Report of the Council, covering the activities of the Institute during 1945, is presented for the information of members.

MEMBERSHIP.

In this report the former practice of presenting the membership in a summarized form has been resumed and the details are set out below :

		Changes during 1945.									
	Total Dec. 61, 1944.	New.	Trans- ferred.	Resigned.	Deceased.	Trans- ferred from.	+ or 	Dec. 31, 1945.			
Hon. Fellows . Hon. Members . Fellows . Members . Assoc. Members . Students .	13 435 579 592 155	$ \begin{array}{c} $	$ \begin{array}{r} 1\\ -14\\ 16\\ 6\\ \end{array} $	1 4 4 5 4	1 2 3 2		+ 1 - 2 + 24 + 69 + 42 + 6	1 11 459 648 634 161			
Totals .	1774	166	37	18	8	37	+140	1914			

The above figures include a number of members with whom contact has been lost temporarily, but whose names are retained on the roll of the Institute.

The Council has to record with deep regret the deaths during 1945 of the following members of the Institute :

			 Date	Class of
			elected.	membership.
W. Calder .			1913	Member
Alexander Duckham			1914	Fellow
J. J. Fox			1936	Hon. Member
H. A. Harris .			1936	Member
A. L. Mond .			1940	Fellow
A. H. Pott.			1923	Member
D. Redding .			1932	Assoc. Member
D. B. Richardson			1917	Assoc. Member

MEETINGS.

Eight meetings were held in London during 1945, of which one was a joint meeting with the British Rheologists' Club.

A list of papers presented is given below :

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1945.	Subject.	Authors.
Jan. 10	"Spectrographic Methods Applied to the Petroleum Industry."	G. B. B. M. Sutherland. and H. W. Thompson.
Mar. 14	"Some Aspects of Standardization in Oil Measurement."	H. Hyams.

1945.

Mar. 14

Subject.

Authors.

- "Sulphur Estimation by Lamp Method Using I.P. Test 107/45(T)." " Stability of Fuel Oil."
- "The Problem of Devising Tests for Soil Stabilization.
- "The Use of Liquid-in-Glass Thermometers.
- "The Precision and Accuracy of Visco-metry Using B.S.I. Tubes." "The Testing of Greases for Ball-Apr. 18
 - Bearings."
 - "A Rational Basis for the Viscosity Index System."
 - "The Problem of Engine Deposits."
 - " Lubricating Greases."
- May 9 "Code of Electrical Practice for the Petroleum Industry."
- "H.D. Lubricating Oils." June 13
- Oct. 10 "Some Notable Wartime Oil Fires." Nov. 14 " Investigation of Piston-Ring Sticking in High Duty Aero-Engines.

Dec. 12 . "Some Problems Encountered During Well Shooting Operations in the Nottinghamshire Oilfields.'

- A. R. Javes.
- W. E. J. Broom. L. G. Gabriel.

J. G. Durham.

Viscosity Panel.

S. R. Pethrick.

- E. W. Hardiman and Alfred H. Nissan.
- A. Lahiri, Z. Karspinski, and E. W. J. Mardles.

A. S. C. Lawrence.

Alan D. Maclean.

Special Sub-Committee of Standardization Committee.

- V. J. Wilmoth.
- A. Lahiri and F/Lt. Mickolajewski.

J. F. Waters.

PUBLICATIONS.

The publication of the Journal continued monthly throughout 1945, despite the handicaps of paper restriction and other difficulties.

STANDARDIZATION.

No less than forty-five active Committees and Panels of the Standardization Committee, with a total membership of over one hundred and sixty, met frequently during the year. The Council desire to place on record their appreciation and thanks to the members of these Committees and Panels.

AWARDS.

A Student's Scholarship of £50 was awarded to M. Gaston of the Royal School of Mines, and a Scholarship of £33 6s. 8d. was awarded to R. B. Shearn of the Birmingham University.

FINANCE.

The audited accounts for the year, with the Balance Sheet, the Receipts and Payments Account of the Benevolent Fund, and the list of contributors to this Fund, are before you and members will note that the financial position of the Institute continues to be satisfactory.

COUNCIL AND OFFICERS.

Professor F. H. Garner, O.B.E., was unanimously re-elected by Council as President for the year.

Messrs Ashley Carter, G. H. Coxon, A. C. Hartley, V. C. Illing, J. S. Jackson, and J. A. Oriel were re-elected Vice-Presidents, and Messrs

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THIRTY-SECOND ANNUAL REPORT.

M. A. L. Banks, R. Crichton, E. J. Dunstan, J. E. Haslam, R. I. Lewis, J. S. Parker, E. R. Redgrove, F. B. Thole, G. H. Thornley, E. Thornton, and W. J. Wilson were elected members of Council.

ACKNOWLEDGMENTS.

The thanks of the Council are tendered to the British Chemical Plant Manufacturers' Association for the use of their Committee Room for meetings.

The Council records its appreciation of the services to the Institute of Messrs Price, Waterhouse & Co., Auditors, Messrs. Ashurst, Morris, Crisp & Co., Solicitors, and the Westminster Bank Limited.

The Council also wishes to record its appreciation to the Institute Staff for the way in which they have carried out their duties.

By Order of the Council.

F. H. COE, Secretary.

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(A Company	limited	by	Guarantee
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BALANCE SHEET AS

						e	0	d	£		d	1944
Capital of the Institute under By-I	aws	Secti	on 6	Par	a -	£	0.	u.	*	0.	u.	L
oranhs 14 and 15 :		Been	он v,	Lai	a-							
Life Membershin Fund												
As at 31st December 1944						899	4	0				200
Entrance and Transfer Fees			£	8.	d.		-	v				033
As at 31st December, 1944			4014	16	9							3801
Received during year-					-							
Entrance Fees			256	4	0							107
Transfer Fees			16	16	0							15
						4287	16	9				10
Profit on Sale of Investments—												
As at 31st December, 1944 .						351	10	11				351
Donations—												
As at 31st December, 1944 .						326	- 5	0				326
								<u> </u>	5864	16	8	
T. C. J. Burgess Prize Fund :												
As at 31st December, 1944				•					5	0	0	5
Cadman Memorial Fund :												
Balance as per separate account	•	•		•	•				2808	10	7	2730
War Contingencies Reserve :									1005		~	
As at 31st December, 1944		• •	•	•					1985	17	8	1985
Members' Subscriptions Received	in Ad	vance		•					242	17	2	106
Journal Subscriptions Received in	Adva	ace		-					703	3	1	551
Sundry Creditors, General Account		•	•	•					809	10	8	1030
Bewenne Account	•	•	•	•	•				203	18	T	247
Revenue Account :						5010	10	0				4114
Add Balance on Research Fund per	ottac	had a	·	tra	ng.	3010	10	0				4117
forred	autac	nou a	count	ora	119-	148	4	10				128
Add Surplus for year as per separate	state	ment				1569	16	10				100
The output for your as per separate	500000			-					6728	10	10	000

(Signed) G. H. COXON, Chairman of Council. R. R. TWEED, Member of Finance Committee.

£19,462 10 9 £17,397

AUDITOR'S

We report to the Members of THE INSTITUTE OF PETROLEUM that we have examined the above we have required. We are of the opinion that such Balance Sheet is properly drawn up so as to according to the best of our information and the explanations given to us, and as shown by the

3, FREDERICK'S PLACE, OLD JEWRY, LONDON, E.C.

OF PETROLEUM.

and not having a Share Capital.)

AT 31ST DECEMBER, 1945.

	£	8.	d.	0		,	1944
Investments :				£	<i>s</i> .	d.	r
Con Account of Capital, at cost—	491	12	6				.491
525 0 0 3% Savings Bands 1955/65	525	10	ŏ				525
500 0 0 3% Defence Bonds	500	Ő	0				500
867 8 6 2 ³ / ₄ % Bristol Corporation Redeemable Stock,	0.4.5	17	-7				845
1955/65	845	14	1				020
1956/58	151	4	9				151
806 8 3 3% Manchester Corporation Redeemable Stock, 1958 .	151	0	'				101
solidated Stock, 1958	845	17	7				845
1958/63	597	7	3				597
664 6 6 3% London County Consolidated Stock, 1920	481	10	6				481
400 0 0 3% Metropolitan Water Board "A" Stock, 1963	346	10	7				346
150 0 0 5% Wandsworth and District Gas Co., Debenture Stock	154	8	6				154
125 0 0 5% Great Western Railway Co. Consolidated							105
Preference Stock	105	4	9				105
(Market Value at 31st December, 1945, £5439.)	5196	0	7				5196
Cash awaiting Investment on Deposit with Post Office Savings	660	16	1				395
Bank	008	10	1	5864	16	8	5591
On Account of Revenue, at cost—				0001		Ŭ	0001
£790 8 3 3% Conversion Stock, 1948/53	842	8	0				842
500 0 0 3% Defence Bonds	500	0	0				500
475 0 0 3% Savings Bonds, 1955/65	475	0	0				475
2000 0 0 3% Savings Bonds, 1960/70	2000	0	0				2000
336 5 10 3% Conversion Stock, 1948/53	357	14	8	4175	0	0	357
(Market Value at 31st December, 1945, £4171.)		1		4170	4	0	
On Account of Cadman Memorial Fund, at cost-							
£2730 0 0 3% Savings Bonds, 1965/75	2730	0	0				
(Market Value at 31st December, 1945, £2777.)							
Cash at Bank awaiting investment	40	17	10				
Income Tax recoverable on interest received net	37	12	9	2808	10	7	2730
Office and Library Furniture (excluding Presentations) :				2000			2.50
As at 31st December, 1944	170	19	0				31
Additions during year	10	4	9				158
	181	3	9				
Less Depreciation	18	2	4	1.00		~	18
Library Pooles (avaluding Presentations) :				163	1	5	
As at 31st December 1944				-	_		
Subscriptions in Arrear :							
Not Valued				070	1."	10	ENT
Cash at Bank on Current Account and in Hand				979	10	10	071 1169
Cash on Deposit with Post Office Savings Bank :				2003	10		1104
General Account	2553	6	11				2747
World Petroleum Congress Account	253	18	1		-		247
				2807	5	0	5-4-
			£	9,462	10	9	£17,397
a contraction of the second			=		-	-	

REPORT.

Balance Sheet with the books of the Institute and have obtained all the information and explanations exhibit a true and correct view of the state of the Institute's affairs as at 31st December, 1945, books of the Institute.

PRICE, WATERHOUSE & Co., Chartered Accountants. Auditors.) THIRTY-SECOND ANNUAL REPORT.

THE INSTITUTE

REVENUE ACCOUNT FOR THE

								1944
		£	\$ 0	7	£		d	ę
То	Administration Expanses	~	0. U	-	~	0.		~
10	Administration Expenses :	1201	10	0				2000
	Stan Salaries	1191	19	9				2009.
	Printing and Stationery	206	0	8				196
	General Postages	198	12	8				213
	Telephone, Cables, Telegrams, and Travel-							
	ling Expenses	45	18 1	1				47
				_	2242	11	0	
	Establishment Chardes						Ŭ	
3.5	Bart les energies	974	10	4				199
	Rent, less amounts recovered .	914	19	*				662
	Cleaning, Lighting, and Lift Expenses	208	3	0				200
	Depreciation of Office and Library Furniture	18	2	4				18
				-	601	5	2	
	Publications :							
	Journal Publication Expenses	2356	2	7			-	2103
	Abstractors' Food	186	81	i i				263
	Doctors on Journals	105	1					170
	I Ustage on Journals	100	1	3				023
	Standard Methods Publication Expenses	038	9	+				025
	Cost of other Publications	24	1	0				
	Tables for Measurement of Oil .	890	7	6				
					4280	10	9	
	Meetings :			-				
"	Hire of Hall Pre-prints Reporting				168	7	10	232
	Professional Fees				200			Non
23	Leel Emerses	2	2	0				0
	Legal Expenses	0	9	V				9
	Auditor's Fee.	41	0	U				43
				_	47	5	0	
	Students' Scholarships and Prizes .				83	6	8	100
	Library Expenditure				74	4	1	6
	Branches and Sections :							
,,,	Students Section (Birmingham)	10	0	0				10
	Stanlow Branch	69	10	6				10
	Northam Branch	45	19	0				10
		40	0	U				10
	South Wales Branch	38	10	0			-	
					162	9	6	
27	Sundry Expenses				177	12	0	126
	Balance, being Surplus for Year, carried							*
	to Balance Sheet				1569	16	0	893
					£0107	0	0	\$7803
					79401	0	0	r1039

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YEAR ENDED 31ST DECEMBER, 1945.

		£	8.	d.	1944 £
By Subscriptions for 1945 received		3889	4	0	3498
Special Subscription		20	0	0	- 20
", Special Subscription	ar	238	11	6	506
" Subscriptions in Arrear, received during ye	ai	4002	15	5	3547
" Sale of Publications		 4904	17	1	20
" Interest and Dividends (Gross)	• •	350	11	1	20

£9407 8 0

£7893

CADMAN MEMORIAL FUND.

INCOME AND EVERNMENTE ACCOUNT FOR THE PERIOD ENDED 31ST DECEMBER 1945

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THOUSE THE TAX PARTICULAR TROUGHT FOR THE LENGT DIST DESCRIPTION TO THE
To Balance as at 31st December, 1945 . 2808 10 7 By Balance as at 31st December, 1944 . 2730 0 0 0 0, with the Anglo-Iranian Oil Company, Ltd. 3 5 0 1, Interest received during the year and tax 75 5 7
<u>£2808 10 7</u>
KENEARCH FUND. Income and Expenditure Account for the Year ended 31st December, 1945.
To Balance transferred to Institute of Petroleum£ s. d.By Balance as at 31st December, 1944£ s. d.£ s. d.Revenue Account148410148410
<u>£148 4 10</u>
HYDROCARBON RESEARCH GROUP. Income and Expenditure Account for the period ended 31st December, 1945.
To Grants :
" Balance as at 31st December, 1945/ 5263 7 7
£8999 15 9 £
We have examined the above Income and Expenditure Account with the books and vouchers of the Group, and find it to be in accordance therewith. We have verified the cash with Bankers to be in accordance with the balance on 31st December, 1945.
3, FREDERICK'S PLACE, OLD JEWRY, LONDON, E.C. 2. 22nd August, 1946. Auditors.

THIRTY-SECOND ANNUAL REPORT.
BENEVOLENT FUND.	YEAR ENDED 31ST DECEMBER, 1945.	PAYMENTS. \pounds $a.$ $d.$ \pounds Benevolent Fund : Grants in Aid \vdots $s.$ $d.$ \pounds Grants in Aid \vdots \vdots 1504 $8.$ $i321$ Balance on 31st December, 1945 * $:1504$ $8.$ $i321$ \vdots $:1504$ $8.$ $:i321$ * The Balance on 31st December, 1945, was held as follows :- $:1321$ * The Balance on 31st December, 1945, was held as follows :- $:1331$ * The Balance on 31st December, 1945, was held as follows :- $:1331$ * The Balance on 31st December, 1945, was the fild as follows :- $:1331$ * The Balance on 31st December, 1945, was the fild as follows :- $:1331$ * The Balance on 31st December, 1945, was the fild as follows :- $:1331$ * The Balance on 33st December, 1945, was the fild as follows :- $:1331$ * The Balance on 3% December, 1945, was the fild as follows :- $:1330$ $:16600$ * The Balance on 3% December, 1945, was the fild as follows :- $:16316$ $:16600$ $:16316$ $:16600$ $:166000$ $:166000$		
	RECEIPTS AND PAYMENTS ACCOUNT FOR Y.	Recentrs. \pounds a. d. \pounds a. d. \pounds 1944 Balance on 1st Januáry, \pounds a. d. \pounds a. d. \pounds 1945 1945 1321 5 6 1106 Recepts during 1945 :- 131 0 10 1221 5 6 1906 Subscripts during 1945 :- 133 0 10 24 24 Interest and Tax recoverable 52 2 183 3 0 24 Interest and Tax recoverable 52 2 183 3 0 24	 (Signed) (Signed) A. E. DUNSTAN, Chairman, Benevolent Fund Committee. We have examined the above Receipts and Payments Account with 1 herewith. We have verified the Investments and the Balances with 1 list December, 1945. 3, FREDERICK'S PLACE, LONDON, E.C. 2. For list of Donors and Subscribers to 	WA AN ANALYMANIA NIV STAUAT TO ASI TO T

THIRTY-SECOND ANNUAL REPORT.

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LIST OF DONORS AND SUBSCRIBERS TO THE BENEVOLENT FUND DURING 1945.

Adams, A. C. Anonymous, Auld, S. J. M. Baylis, A. N. Bell, O. A. Blakiston, J. H. Blakiston, J. H. Bolton, R. P. Brailey, B. S. Braun, C. F. Brown, C. F. Brown, C. F. Brown, C. B. Brown, C. B. Brown, C. B. Brown, C. B. Brown, R. G. Cameron, I. Catchpole, W. Charlton, H. E. Chrisman, A. E. Clifford, Guy Connor, W. W. Cooke, A. K. Ocoke, A. W. Crichton, B. Dolton, R. H. Downs, W. W. Dansten, A. E. Dunck, A. E. Wansten, A. E. Dyson, G. M. Filis, J. Evans, A. Evans, K. B. Evans, K. B. Hers, K. M. Farthing, V. L. Parthing, V. L. Goidrey, R. Goidstein, R. F. Grant, J. Gray, W. Griffiths, P. M. Hawris, B. Hawroth, A. J. Heaton, W. B. Henson, F. R. S. Hersch, L. H. J. Hirst, W. P. Howard, G. P. E. Hunter, F. E. Hunting, E. A. Jameson, J. A. Kenyon, H. Kidd, T. G. McCreath, T. T. McCreath, T. T. Maclean, T. T. Marsden, A. Masters, J. S. S. Mesurier, L. J. le Mitchell, R. G. Moon, C. A. Nixon, I. G. Odams, R. C. Owen, R. M. S. Perks, A. J. Pink, E. P. Porter, P. N. D. Purves, A. R. Redgrove, E. R. Richards, G. A. Robathan, T. Roger, A. Sams, C. E. R. Scott, L. D. Scott, T. R. Smallwood, W. Suthwell, C. A. P. Spielmann, P. Tait, G. S. Taylor, J. F. M. Teidow, N. Thomas, H. C. H. Thomson, G. Tweed, R. R. Walsh, D. M. Walter, G. Watson, A. Webb, J. F. N. Wigney, W. J. Young, R. H. Trinidad Branch (I.P.) Bushe, L. A. Darley, H. O. H. Fletcher, H. D. Goodwin, J. A. Harris, H. A. Knights, J. W. Kugler, H. G. Lavington, H. V. Middleton, F. Murray, A. J. Ruthven-Richards, A. H. Scott, G. H. White, L. K.

Staff of Shell Central Laboratories. Barrett, Tagant & Gotts, Ltd.

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OBITUARY.

PROFESSOR FREDERICK BYRON PLUMMER.

FREDERICK BYRON PLUMMER, research geologist and professor of petroleum engineering at the University of Texas, died of a heart attack on February 17, 1947, in his sixty-second year.

Born on August 31, 1885, at Hanover, New Hampshire, and educated at Dartmouth College and at Chicago University, he was instructor in chemistry and geology in Vassar College, Poughkeepsie, 1911–13, and in 1914 was chief of geological field parties for the Wisconsin Geological Survey.

In 1915 he joined the Roxana Petroleum Corporation as geologist in the Mid-Continent and Texas oilfields, and in 1920 was transferred to the Bataafsche Petroleum Maatschappij headquarters at The Hague. During the years 1923 to 1928 he was geologist successively to the Rycade Petroleum Co., the Amerada Petroleum Corpn., and the Vacuum Oil Co.

In 1928 Prof. Plummer joined the University of Texas as geologist for the Bureau of Economic Geology. In 1933 he founded the Department of Petroleum Engineering and remained its chairman until the work became too onerous to enable him to meet the requirements of the Bureau. However, he continued his association with the Department on a part-time basis.

Author of many papers dealing with geological research, he was particularly interested in the recovery of salt water in oil wells. At one time he was director of the A.P.I. Research Project No. 25 on the investigation of underground waters and temperatures of oil sands. During 1946 he was president of the Texas Academy of Science.

Shortly before his death he had spent some months in Brazil on behalf of the Government, and had worked out the stratigraphy and structure of some Permian basins in the northeast part of that country.

Elected a member of the Institute in 1922, he was also a member of the American Association of Petroleum Geologists, of the Society of Economic Geologists, and of the American Institute of Mining Engineers.

His widow survives him and to her we express our sincere condolences.

FRANCIS ARTHUR FLINN.

FRANCIS ARTHUR FLINN who died on February 6 after an illness lasting several months, had been an Associate Member of the Institute since 1927.

Born on December 30, 1901, he was educated in Manchester and in 1922 obtained his degree of Bachelor of Technical Science in the University of Manchester in general chemical technology.

From 1922 to 1925 he was employed as a petroleum research chemist at Aberdeen by the Anglo-Persian Oil Co. In 1926 he joined the Phœnix Oil & Transport Co. as chemist in Ploesti, Roumania, and in 1930 became associated with the Shell group and remained with that organization until at the time of his death he was chief field chemist and gas engineer in Mararaibo with the Caribbean Petroleum Co.

