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THE INSTITUTE OF PETROLEUM.

A meeting of the Institute of Petroleum was held at Manson House, Portland Place, London, W.1, on Wednesday, October 16, 1946. Mr E. A. Evans, Vice-President, was in the Chair.

THE CHAIRMAN : This evening we are to have the pleasure of a paper by Mr A. T. Wilford, the Chief Chemist, Road Services, London Passenger Transport Board.

Mr Wilford is no stranger to many of us. He is a Fellow of the Institute, and has served for many years upon a number of our Panels. I feel that we are particularly fortunate in having the services of such a man, who has so many opportunities for carrying out tests, which opportunities are not available to most of us.

The London Passenger Transport Board and its officers are able to gain a good deal of practical experience from a vast number of vehicles operating under various conditions. They are able to observe very accurately the behaviour of oils. Mr Wilford's paper deals with one aspect of the Board's experiences of some of the oils which have been provided by the petroleum industry. It is indeed of great interest.

The following paper was then read :

THE LUBRICATION OF PRE-SELECTIVE GEAR-BOXES.

By A. T. WILFORD, B.Sc., A.R.C.S., A.R.I.C. (Fellow)

SUMMARY.

The paper deals with the lubrication problem which presented itself following upon the introduction of pre-selective gear-boxes on buses operated in the London Passenger Transport Board's area. Considerable difficulties were encountered attributable to severe oxidation of the oil, leading to drivers' complaints, service delays, and abnormal gear-box maintenance. The trouble, after much investigation, was kept within bounds by the use of a straight mineral oil of Pennsylvanian origin changed every 6000 miles; it was in course of time completely solved by the adoption of an inhibited turbine oil which remains in use throughout the 80,000 miles elapsing between consecutive gear-box overhauls. The results of service tests carried out both prior and subsequent to this satisfactory outcome and involving a variety of lubricants, eight of which contained oxidation inhibitors, are briefly reviewed. The necessity for conducting such tests on an adequate scale and for a sufficient length of time is emphasized, while the need for developing an oxidation test which might serve to reduce the duration of service tests is remarked upon. With the object of widening sources of supply, tests with a further number of inhibited oils have quite recently been commenced, and it is pointed out that those eventually approved as suitable for use as pre-selective gear-box lubricants must be compatible with one another.

INTRODUCTORY.

AMONG the lubrication problems encountered in connection with London's buses during the past sixteen years, two have been outstanding. One arose in the course of the development of the compression ignition engine and its adaptation to public service vehicles; an account of the comprehensive service tests carried out, eventually leading to the adoption of a solvent refined oil, was given in a paper presented at the Summer Meeting of the Institute of Petroleum held in Birmingham in May 1939.[1] At no time, however, was there any serious difficulty in lubricating these engines, and the only aim was to discover the most suitable oil for the purpose, with particular regard to extending engine life.

The second problem was of a very different nature, and concerned the lubrication of pre-selective gear-boxes. The oil originally employed for this purpose was of S.A.E. 40 viscosity, and contained about 2½ per cent of a fixed oil. Some degree of trouble was encountered due to formation of gummy deposits, and in 1932 use of the compounded oil was discontinued, a Pennsylvanian grade of 104–110 sec Redwood at 140° F being adopted in its place.

The gear-boxes fitted to the great majority of the fleet at that time were of the clash type, and were being successfully lubricated with a comparatively cheap oil of about 900 sec Redwood at 140° F; the oil was not changed throughout the life of the boxes, though make-up was required at intervals. It was natural, therefore, that at the onset no oil-change period was laid down for the pre-selective gear-boxes. It soon became evident, however, that there was no analogy between the two types in respect of the behaviour of the lubricant, and as the number of p.s. gear-boxes in service increased, there was an increasing amount of trouble arising from severe oxidation of the oil, evidenced by the presence of a gummy deposit on the working parts of the box. Accumulation of this deposit rendered it difficult or impossible for drivers to change speed, with consequent service delays and inconvenience to the travelling public. When in this condition—often after only a few thousand miles in service—the boxes had to be removed, completely dismantled, and the individual parts cleaned. The facilities available at garages for exceptional maintenance of this character were limited, and it became necessary to devise means for effectively cleaning the boxes. A 7 per cent aqueous solution of sodium metasilicate, maintained at a temperature of about 200° F, was eventually found to be very satisfactory for the purpose, and suitable equipment was installed at a number of garages.

An increase in maintenance troubles coincident with an increase in the number of vehicles fitted with a new feature was contrary to general experience. The anomaly would seem to have been due to the fact that the pre-selective gear-box was very sensitive to traffic conditions. The oil is subjected to more strenuous usage when the box is in low or intermediate gears than when in top gear, and as more and more vehicles became allocated to heavy traffic routes, the intensity of the gumming troubles became greater. That this explanation is in the main a correct one is confirmed by the fact that no particular difficulties were being encountered with p.s. gear-boxes on buses operating on country routes within the Board's area, while it is probably true to say that trouble comparable with that experienced within the London area has only been met with elsewhere in cities such as Manchester, Leeds, and Sheffield.

Service tests were instituted with alternative lubricants, but, with one possible exception, none of a total of at least fifteen was significantly better than the Pennsylvanian grade adopted as standard. The trouble which at one stage—when castor oil was temporarily adopted—had assumed very serious proportions, was eventally kept within bounds by modifications to the design of the gear-box, a reversion to the Pennsylvanian grade of lubricant and the strict enforcement of an oil change after each 6000 miles. For a time the used oil if not severely oxidized was clarified by Streamline filtration and was reused for one further period of 6000 miles. The recovery procedure, which necessitated a considerable amount of laboratory work, was never a very satisfactory undertaking and was eventually allowed to lapse.

Although the peak of the trouble had passed it remained apparent that the lubrication problem had not yet been solved. An oil change at 6000 miles might have been tolerated indefinitely had it completely avoided drivers' complaints of " speeds sticking," service delays and premature failures, but this it did not do. Alternative lubricants were still being investigated, and amongst those submitted was an inhibited oil which, for reasons which will be stated later, was allowed to remain in use beyond the normal oil change period, its behaviour, however, being closely watched. Samples of used oil removed from the twenty-five boxes involved in the test were examined at intervals of a few thousand miles, and it was observed that the viscosity of the oil remained practically unchanged and that acidity did not exceed 0·2 mg KOH/grm. The gear-boxes allocated to the test were neither new nor freshly overhauled, though prior to filling with the inhibited oil they were dismantled, cleaned, and re-assembled. Despite the fact that they were in various stages of life, no less than fourteen were still in service after having performed 40,000–50,000 miles without an oil change. The test was then extended to comprise all vehicles fitted with p.s. gear-boxes (about 150) at one garage, and the performance of the oil, which again was not changed, was observed over a further period of up to 60,000 miles. Once more it was found that viscosity at 140° F increased by no more than a few seconds, while acidity did not exceed 0·2 mg KOH/grm; more importantly the boxes remained in exceptionally clean condition and were performing much greater mileages than had hitherto been the case. The lubricant, which was an inhibited turbine oil (Oil N, Table I), was thereupon adopted for the whole of the fleet of vehicles equipped with pre-selective gear-boxes.

The change over to the inhibited oil was effected by employing it for first-filling of new boxes, by refilling with it after overhaul, or by dismantling and cleaning boxes which were still serviceable with the previous standard oil in use, followed by refilling with the newly adopted oil. From that date (May 1939) the lubricant has continued to give an entirely satisfactory performance, and " sticking " or other service troubles attributable to the oil are unknown. The oil remains in use for the life of the gear-boxes, about 80,000 miles, and upon removal is clarified by Streamline filtration, adjusted by the addition of a standard amount of inhibitor, and is then passed to the garages for re-use. The mileage mentioned does not represent the maximum life of the oil, since there have been examples of isolated boxes remaining in service for as long as 120,000 miles without an oil change, the lubricant being still in a satisfactory condition apart from contamination with adventitious matter. It should perhaps be added that the lubricant becomes gradually changed—about twice per year—by additions of fresh oil; this is not, however, equivalent to a conventional oil change, since the fresh oil is introduced into a large excess of used oil.

It is thought that it may be of interest briefly to survey the performance under service conditions of some of the oils which were investigated during the period covered by the foregoing account of the problem and its ultimate solution. Mention will also be made of isolated tests which were carried out soon after the adoption of Oil N, and of the more extensive ones which it has been necessary to conduct during the past two years with the object of finding one or more alternatives to the lubricant at present adopted as standard. It will be useful to precede these remarks with a short description of the pre-selective gear-box and its lubrication system.

Description of the Wilson Pre-selective Gear-box.

The gear-box, a general arrangement of which is shown in Fig. 1, consists essentially of four sets of epicyclic gear-trains, interconnected one with the other and able to rotate on an input and an output shaft, which are co-axial with each other. The function of the gear-trains is to transfer the driving torque from the input to the output shaft, and at the same time to vary the speed of the output shaft in accordance with the range of gear ratios provided by each particular train, or to change the direction of rotation to give reverse gear.

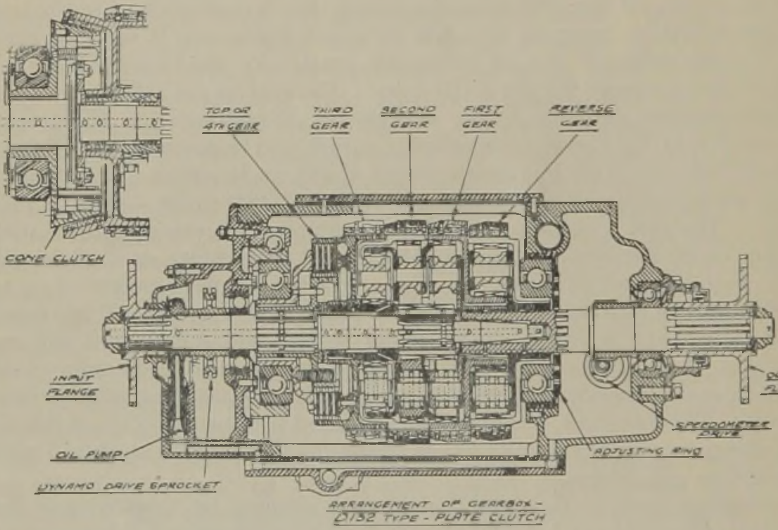


Fig. 1.

The gear ratios desired from the first, second, third, or reverse trains are obtained by holding the annulus drum of each particular train stationary. This is achieved by means of brake bands, applied to the drums under a heavy spring-loaded toggle leverage. The system of leverage employed applies an increasing load on the bands during the actual braking application, this being necessary because the various gears offer different torque reactions. Wear taking place on the brake-band linings (and also on the clutch lining) is compensated for by means of an automatic adjustment.

Direct or top gear is obtained by means of a cone or multiple type of clutch. The gear-trains are free from the brake-bands when in top gear, and, being interconnected, revolve at the same speed as the engaged clutch, giving in effect a solid drive. The size of the clutch is comparable with that of the gear-drums, this small size being possible owing to the fact that the engine torque is taken through the gear-trains, and consequently only about one third of the torque is borne by the clutch.

Each brake-band with its toggle mechanism and strut is a self-contained unit. The strut forms the medium whereby, firstly, the brake-band (and thus the desired gear) can be selected as and when required, and secondly, the load supplied by the main spring can be transferred to the brake-band when its engagement follows selection. When gears are disengaged the strut on each gear is in contact with the selector mechanism situated on the cover side of the gear-box. The gear selection places the strut in a position where it can be picked up by the bus-bar. The latter, which extends throughout the length of the gear-box, rises and falls in an arc radiused from a fulcrum groove insertion piece fixed to a cast ridge on the bottom cover. This movement of the bus-bar is brought about under the pressure exerted by the heavy main spring by means of two swinging buckets, and is controlled by the operating foot pedal in the driving-cab. Depression of the foot pedal depresses the bus-bar, thereupon releasing the main spring pressure from the toe of the engaged strut and allowing the strut to swing back under its own spring action (each strut being spring loaded), so that it makes contact with the selector mechanism on the side cover. When the foot pedal is allowed to return, the main spring swings the bus-bar buckets over and causes the bus-bar to rise. The selected strut is picked up, transfers the bus-bar loading to the brake-band mechanism, and thus contracts the brake-band on the gear-drum.

A neutral strut is provided, positioned on the side cover, and is selected in the same way as the speed-gears, but when engaged it takes the load of the bus-bar, leaving all the other gears entirely free. Originally there was no individual neutral gear, the neutral state being obtained by the simultaneous engagement of first and reverse gears. This was followed in later boxes by the engagement of second and third gear, a method which has been discontinued with the introduction of the neutral strut.

The Wilson gear-box is employed in conjunction with a fluid flywheel, and references to this type of transmission, contrasted with alternative types, will be found in a paper by E. C. Ottaway [2]; the mechanism of the gear-box has been very fully described by W. G. Wilson.[3]

Lubrication System.

The lubricant is circulated by means of an oil-pump driven by an eccentric mounted on the input shaft. Oil is forced into the interior bore of this shaft and flows through its entire length. It passes from the shaft to the bushes and the first and second gear sun wheel teeth through oil drillings; other drillings convey it to and through the hubs of the drums. Oil from the input shaft is also fed through connecting holes in the output shaft to the interior of the reverse brake-drum. Oil is liberally supplied to the gear-trains, brake-gear, and adjuster gear by centrifugal action. The contacting edges of the annulii drums are grooved in order to admit oil to the faces, and several holes are provided in the drum walls to assist oil movement between the drums. In order that the amount of oil present shall not adversely effect the braking application, the liners are cut diagonally at intervals so that the oil film may be quickly broken down.

There is approximately an oil depth of 1½ inch in the base of the box when the running gear has been stationary for some time. When the running gear is revolving the oil depth is decreased both by the action of the pump and through oil being picked up by the rotating drums. The oil drillings in the base of the box form a sump from which the oil is drawn by the pump. The capacity of the box is 2 gallons, this being increased to 3 gallons for mechanical reasons in the most recent design, of which only 150 are yet in service.

Gear-Box Oil Temperatures.

In the introductory section reference was made to the fact that in the case of oils which suffered a significant degree of deterioration during use, trouble was more marked in gear-boxes fitted to vehicles operating in heavy traffic areas than in those running on lighter traffic routes. This difference in behaviour is obviously related to oil temperature. For double-decked buses operating at peak load in heavy traffic, the maximum temperature attained by the gear-box oil varies between 65° and 70° C, the vehicles concerned being fitted with gear-boxes provided with a neutral strut. For the same type of gear-box fitted to a single-decked vehicle, loaded, but running in comparatively light traffic, the maximum oil temperature is approximately 55° C. The higher oil temperature reached with vehicles operating in heavy traffic is mainly attributable to the greater proportion of running in low gears. Appreciably higher oil temperatures up to 90° C, and perhaps more, were encountered in gear-boxes of earlier design, but even after the latter had been modified, with consequent reduction in temperature, the conditions imposed on the lubricant were still such that all except one of the oils tested prior to 1939, and several of those tested since that date, failed to possess the requisite degree of resistance to oxidation.

Service Tests.

In deciding on the manner in which the results should be presented, it is considered that it will be preferable to classify the lubricants into four groups—namely, straight mineral, compounded, vegetable (represented by one member only) and inhibited oils—rather than to deal with the tests in a strictly historical order. The procedure involves a certain amount of cross-reference, but this would not be avoided by an alternative presentation.

Straight Mineral Oils.

As will be seen from the data given in Table I, the straight mineral oils covered a viscosity range of 92·5 to 218 sec Redwood (21·8 to 53·3 cs)

TABLE I.

Particulars of Oils Employed in Pre-selective Gear-box Lubrication Tests.

Oil reference.	Specific gravity at 60° F.	Viscosity at 140° F. secs. Redwood.	Viscosity index.	Asphalt after oxidation (A.M. method), %.	Remarks.
A	0·872–0·875	104–110	Above 100	0·5–0·7	Pennsylvanian origin.
B	0·879	218	,,	Under 0·05	? ,, ,,
C	0·875	140	,,	,,	Solvent refined.
D	0·880	123·5	,,	1·2	S.A.E. 20 grade.
E	0·912	112	About 20	1·9	Edeleanu refined.
F	0·883	173	About 90	Under 0·05	S.A.E. 30 grade; solvent refined.
G	0·870	110	Above 100	,,	Arctic grade.
H	0·897	80	—	—	Contained approx. 6% animal fat.
J	0·868	65	—	—	Contained approx. 4% animal fat.
K	0·911	130	About 80	—	Contained aluminium oleate.
L	0·961	335	—	—	Castor oil.
M	0·884	110	Approx. 105	—	Inhibited (hydroxylated aromatic).
N	* 0·890 0·882	99 105	Approx. 60 80 (average)	— —	Inhibited turbine oil (β-naphthol + corrosion inhibitor).
O	0·882	109	Above 100	—	Inhibited.
P	0·875	113	,,	—	,,
Q	0·881	157	105	Under 0·05	Pool grade.
R	0·880	112	100	,,	,,
S	0·874	134	100	—	Inhibited turbine oil (2190T).
T	0·890	92·5	95	2·1	Uninhibited turbine oil.

Notes.—Oil A was employed as the base oil for three other lubricants tested. Tests were also conducted with Oil R plus an amine type oxidation inhibitor and Oil T plus β-naphthol.

* The first set of figures relate to the oil supplied for the original tests, while the second set are typical of the present supply.

at 140° F, and with one exception were of high Viscosity Index. It will be observed that in several instances V.I. is given as " above 100 "; in that the viscosities of these oils, determined some years ago, are available only for temperatures of 140° F and 200° F, it is not possible to quote a precise figure; there is indication, however, that the V.I.s were well above 100. The lubricants included Pennsylvanian grades, Edeleanu and solvent refined oils, a conventionally refined motor oil, and a turbine oil.

Oil A, of viscosity 104 to 110 sec Redwood (24·8 to 26·4 cs) at 140° F and of Pennsylvanian origin, was, with two brief interludes, employed as " standard " lubricant for the pre-selective gear-box over a period of about seven years. Fig. 2 shows the viscosity at 140° F of a large number of samples of this oil taken from gear-boxes after periods of use ranging from 750 to 16,000 miles. The chart does not include all the data available, and under-emphasizes the degree to which the oil thickened during use; records show isolated viscosities well in excess of 436 sec Redwood (the maximum value plotted), and in one instance a figure of " over 1000 seconds " is mentioned; moreover, in some cases the oil became so viscous as a result of use that it was impracticable to drain boxes at normal temperature. It is possible that Oil A was not, in fact, the worst of those tested so far as viscosity increase is concerned. Thus five samples were taken after not more than 8000 miles from two gear-boxes filled with Oil G; one yielded a viscosity of nearly 3000 sec Redwood at 140° F and two others were recorded as "too viscous" for test at that temperature; other examples will be seen in Fig. 3.

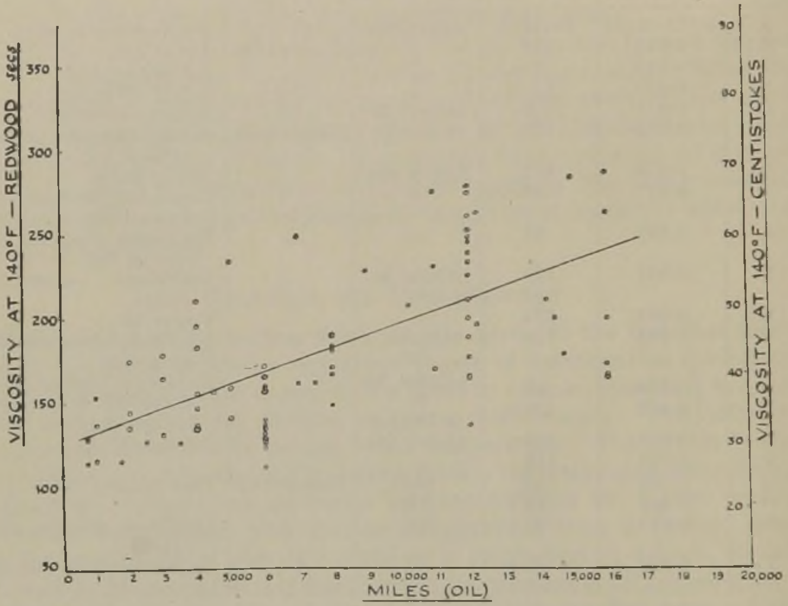


FIG. 2.

VISCOSITY OF SAMPLES OF USED OIL "A" TAKEN FROM A LARGE NUMBER OF P.S. GEAR-BOXES AFTER OIL MILEAGES RANGING FROM 750 TO 16,000.

Returning to Oil A, it is unfortunate that, despite the very large number of used samples examined, there are very little data available in respect of acidity; it will be seen from Table II, however, that a value as high as 45 mg KOH/gm is on record. At the time these samples were being examined it was the more normal practice to determine hard asphalt [4]—again by analogy with used oils from clash gear-boxes and rear axles—and very high values, up to a maximum of 16·3 per cent, were found; amongst examples of sludge from boxes, one yielded a figure of 32·7 per cent. It was observed that the "asphaltenes" were quite different from those derived from used rear axle oils, for example, being flocculent and of much lighter colour. It was inferred that the material contained a high proportion of acidic compounds, and determinations of ash content would have thrown light upon this point. Whereas this was not done, several determinations were made of the ash content of used oils, recovered after extraction with pure benzene for the purpose of removing suspended matter.

The ash figures, which were regarded as indicative of the presence of metallic soaps soluble in benzene, varied between 0·07 and 1·19 per cent, and it seems not unlikely that some or all of these soaps may have been insoluble in petroleum ether and would have been precipitated with the asphaltenes in a conventional determination. On the other hand, the ash contents of the filtered oils showed no proportionality with the "asphaltenes" and corresponding to values of 2·6, 11·7, and 16·3 per cent for the latter, ash figures of 0·98, 0·24, and 0·29 per cent were found. The acidities of these three used oils in the "as received" condition were 3·7, 45, and 32 mg KOH/gm, respectively, from which it might perhaps be concluded that the "asphaltenes" contained both free and combined acids.

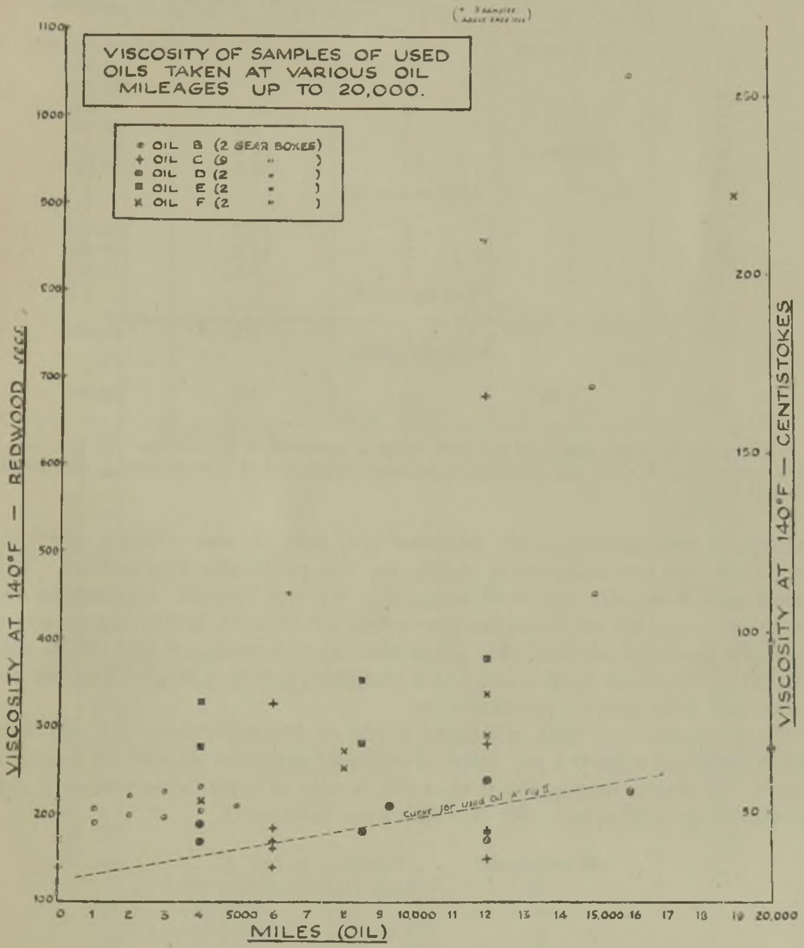


FIG. 3.

The general condition of the oil was indicative of severe oxidation at

TABLE II.

Maximum Acidities of Certain Uninhibited and Inhibited Oils after Use in P.S. Gear-boxes in Course of Service Tests.

Oil reference.	Uninhibited or inhibited.	No. of boxes sampled.	Maximum acidity found, mg KOH/gm.	Maximum mileage represented by samples.*
A	Uninhibited	10	45	About 20,000
C	,,	10	37	13,000
Q	,,	6	32	12,000
R	,,	6	30	9,250
T	,,	1	4·3	12,000
M	Inhibited	14	20·4	12,000
N	,,	37 (113 samples)	0·2	58,500
O	,,	5	12·7	12,000
P	,,	2	16·3	48,000
R	,,	6 (41 samples)	0·2	74,000
S	,,	6 (33 samples)	0·3	62,000
T	,,	6	5·2	9,500

* Maximum acidity amongst samples from a number of gear-boxes did not necessarily correspond with the maximum mileage represented (for example, see Tables VI and VII).

moderate rather than high temperature, and it was evident that the lubricant was not sufficiently stable for the particular application. This conclusion was only too well supported by the drivers' complaints and excessive gear-box maintenance previously mentioned, and it cannot be too strongly emphasized that this particular oil and many of the others submitted to test have been classed as unsuitable, not as a result of laboratory tests, but from service performance.

Tests carried out with a higher grade of Pennsylvanian oil and with Oil A admixed with 0·2 per cent of colloidal graphite showed no improvement. It might be suggested that Oil A was of unsuitable viscosity, but service tests conducted with the following lubricants

Oil reference.	Viscosity at 140° F.	
B	218 sec Redwood	(53·3 cs)
C	140 ,,	(33·9 cs)
D	123·5 ,,	(29·8 cs)
F	173 ,,	(42·2 cs)

did not indicate that a more viscous oil was of any particular benefit. The viscosities of a number of samples of used oils taken from gear-boxes involved in these tests are shown in Fig. 3. (It will be observed that six of the samples of Oil B obtained up to 5000 miles were actually of lower viscosity than the fresh oil; this was, of course, due to the fact that the boxes were drained but not flushed out prior to refilling with the experimental lubricant.) On the other hand, the results of tests with Oil T of 92·5 sec Redwood (21·8 cs) at 140° F and Oil H (Compounded) of 80 sec

Redwood (18·4 cs) could be regarded as establishing that these viscosities were not inherently too low, though the poor performance of Oil J in comparison with H might be taken as proof that a viscosity of 65 sec Redwood (14·15 cs) at 140° F was below the safe minimum. In passing, it may be said that a broad survey of all the tests carried out shows that the pre-selective gear-box is not particularly sensitive to viscosity as such. Furthermore, almost any of the lubricants investigated might have been tolerated had we been willing to change the oil at, say, 1000 miles intervals—an

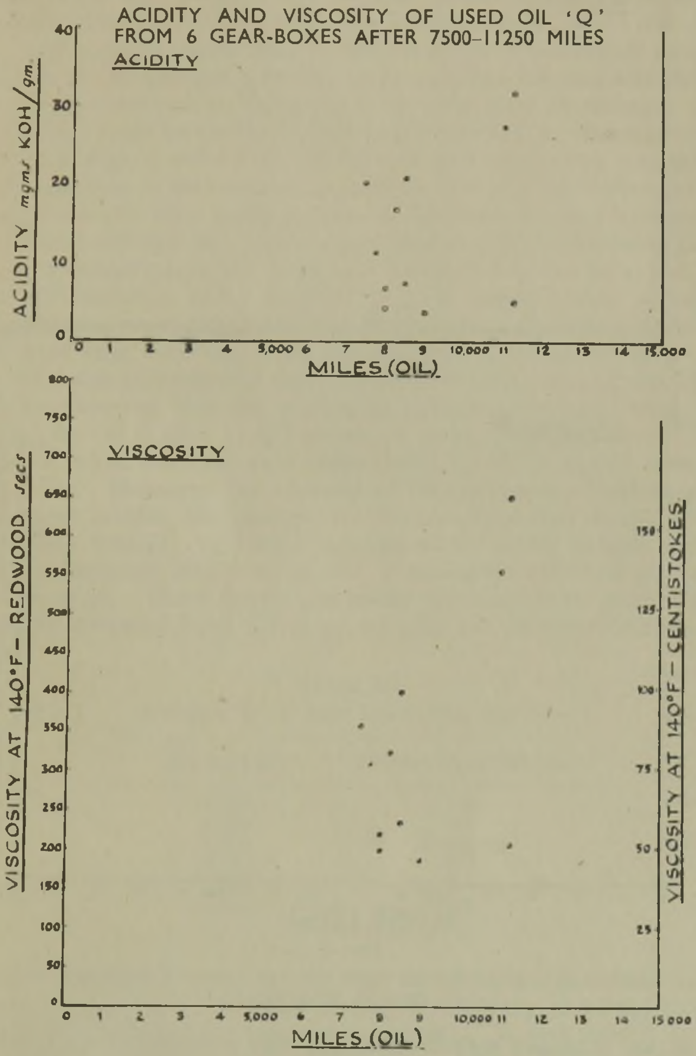


FIG. 4.

expedient which was, of course, never even contemplated. This observation may serve to explain the fact that no troubles were experienced with p.s. gear-boxes fitted to armoured vehicles in W.D. service whether the lubricant was M.220, M.160, or H.D. 30.

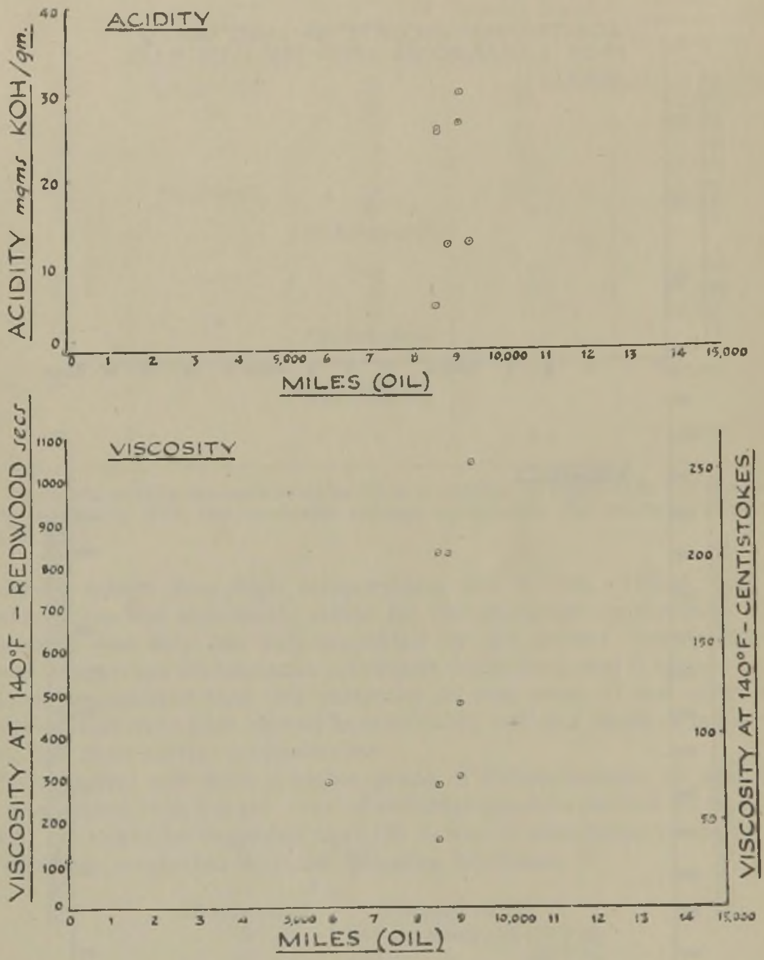


Fig. 5.

ACIDITY AND VISCOSITY OF USED OIL "R" FROM 6 GEAR-BOXES AFTER 6000 TO 9250 MILES.

Oil E, an Edeleanu refined distillate, was comparable with Oil A in respect of viscosity at 140° F, but was of much lower V.I. It was tested in two gear-boxes, but, as will be seen from Fig. 3, it was distinctly inferior to Oil A in respect of resistance to oxidation under service conditions. It was also the less stable as judged by a determination of hard asphalt after oxidation employing the Air Ministry method, though it should be remarked that this particular test was of no value whatever in predicting the behaviour of an oil when used in a p.s. gear-box; this is quite evident from the data given in the fifth column of Table I.

Oils Q and R were Pool grades of high Viscosity Index, Q having a viscosity significantly higher than that of either Oils A or N. At request, service tests were put in hand with these lubricants some two years ago, and the results were of particular interest, since they fully confirmed the conclusions derived from the extensive investigations carried out prior to 1939. The respective oils were employed in six pre-selective gear-boxes on vehicles at two garages operating comparable routes, and samples of the used oil were examined for acidity and viscosity after oil mileages varying from 7500 to 11,250 for Oil Q and 6000 to 9250 for Oil R; the data obtained are shown in Figs. 4 and 5. It will be seen that while there was the usual marked variation in performance in individual boxes, both oils exhibited a tendency towards very rapid increase in both acidity and viscosity, and curves faired through the points would bear a close resemblance to those given in a recent paper by Auld and Lawrie [5] relative to the A.S.T.M. turbine-oil oxidation test. Judged by these limited tests, which were sufficiently convincing and were abandoned before any damage was done, it would seem that both oils were less resistant to oxidation in p.s. gear-boxes than was normally the case with Oil A when in use. From Table II it will be observed that the maximum acidities developed were 32 mg KOH/gm for Oil Q after 11,250 miles and 30 mg KOH/gm for Oil R after 9000 miles, while the maximum value found for Oil A was 45 after about 20,000 miles. Moreover, the viscosity of Oil Q showed a fourfold increase in the worst sample, the increase for the corresponding sample of Oil R being nearly tenfold; two other samples of the latter yielded viscosities of 824 sec Redwood (202·0 cs) at 140° F compared with 112 sec (26·8 cs) for the fresh oil. These figures are really amazing when compared with the results obtained from the same oil plus an oxidation inhibitor (see further).

TABLE III.

Acidity of Oil T after Use in One Gear-box.

Oil mileage.	Acidity, mg KOH/gm.
1,000	Nil
1,750	0·1
3,000	Negligible
4,750	0·3
9,500	3·6
12,000	4·3

Oil T, a high-quality turbine oil, was tested in one gear-box only; as will be seen from Table III it had developed an acidity of 4·3 mg KOH/gm after 12,000 miles when the test was completed. At first sight it might be concluded that the performance of this oil was better than that of many of the other uninhibited lubricants investigated, but, as may already have been appreciated, and will be clearly demonstrated as the paper proceeds, small-scale tests can be very misleading. The most that can be said is that had the result been obtained prior to instead of after the adoption of the inhibited Oil N, experiments with Oil T would have been extended.

The isolated test with this oil was only of significance by reason of its having been carried out in conjunction with other work.

The tests briefly described in this section do not exhaust those conducted with straight mineral oils, but the information is probably sufficient to support a conclusion that there was little likelihood of a really satisfactory lubricant for pre-selective gear-boxes being found within this class.

Compounded Oils.

It has already been mentioned that the lubricant employed when pre-selective gear-boxes were first introduced into service on London buses was of the compounded type, and that it was replaced by Oil A in an effort to eliminate gumming troubles. In retrospect it is very doubtful whether the latter effected any improvement, and one of the earliest alternatives tested consisted of Oil A containing a small proportion of free fatty acid; no benefit appeared to be derived from this. Another test on similar lines comprised Oil A compounded with 6 per cent of lard oil. This was tested in four gear-boxes, one of which had to be removed after only eighteen days' life, and it was soon evident that, despite complications arising from certain mechanical defects, this particular lubricant was no more promising than any of the others so far tested.

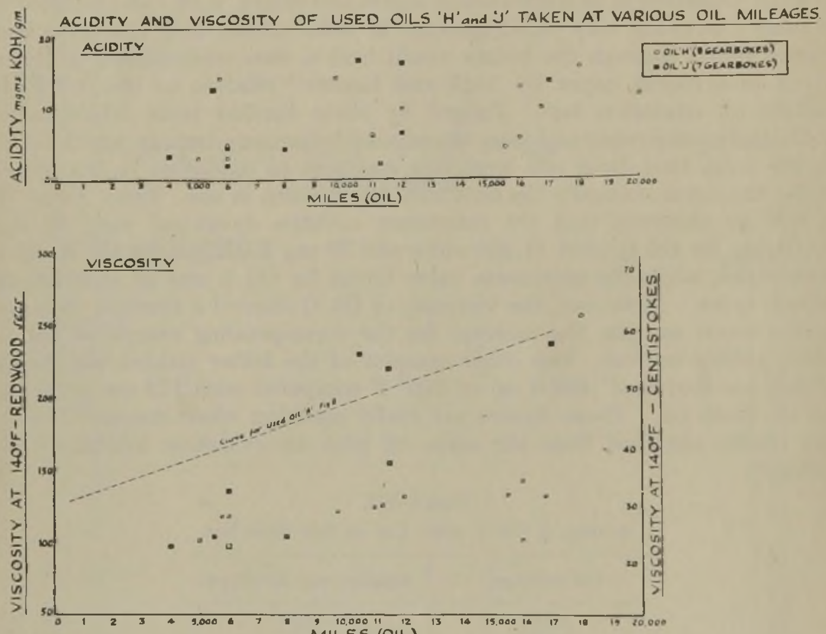


Fig. 6.

Two other compounded oils (H and J—Table I) were also investigated in service; both were of distinctly lower viscosity than Oil A and contained some 6 and 4 per cent respectively of animal [illegible] A total of twenty-four gear-boxes was involved, twelve on each oil, and the data obtained from the examination in respect of acidity and viscosity of a number of samples of the lubricants after use are shown in Fig. 6. Except for one sample, the viscosity of Oil H increased less rapidly than was normally the case with Oil A; Oil J, however, compared unfavourably with both A and H in this regard, and it would not perhaps be unreasonable to infer that its inherently low viscosity prior to use was a contributory factor. Both oils exhibited a marked increase in acidity during use, the maximum values being approximately 16 mg KOH/gm for each. It will be observed from the upper chart of Fig. 6 that the acid values showed a disturbing degree of spread, with no detectable trend in relation to mileage performed. There were no reasons for supposing that individual determinations were either more or less reliable than those carried out on other used oils from p.s. gear-boxes, and it is suspected that the samples of used Oils H and J may not have been giving a true indication of development of acidity, in that variable amounts of volatile acids may also have been produced; this would be all the more likely on account of the low viscosity of the base oils and the presence of animal fat. An assessment of the performance of the gear-boxes run with the two lubricants confirmed the conclusions reached from examination of the used oils, these being that, so far as could be judged from limited tests, Oil J was definitely inferior to Oil H, while the latter was slightly superior to Oil A. Tests with Oil H were not, however, extended, since at the time the results were available it was thought that a lubricant more suitable than either it or Oil A had been found.

Oil K, a mixed base oil of about 130 sec Redwood (31·4 cs) at 140° F and containing a small proportion of aluminium oleate, is appropriately included in this Section. Preliminary tests indicated it to be of some promise, and for a period of about six months it was adopted as standard lubricant for all p.s. gear-boxes in place of Oil A. A careful survey of its performance at the end of that time indicated that it was closely equivalent to Oil A from a practical aspect, a similar conclusion being reached from examination of a number of samples of the used oil (for which reason tables or charts relating to it are omitted from the paper). In that the cost of Oil K was about 25 per cent greater than that of Oil A, it was decided to revert to the latter.

Castor Oil.

Castor oil was the only representative of its class among the many lubricants which have been tested in p.s. gear-boxes; it was submitted to trial in the belief that the oils hitherto investigated were perhaps deficient in load-carrying capacity. Castor oil was, of course, appreciably more viscous than any of the others tested, but this did not in itself appear to be a fundamental objection. First pressings quality was employed with a maximum acidity of 4 mg KOH/gm (Oil L—Table I).

Experience with this lubricant will be described in rather more detail than has been the procedure so far, since it emphasizes to a marked degree the pitfalls which may be encountered by drawing conclusions from tests carried out for too short a period and involving a number of vehicles too small to constitute a representative sample of the fleet.

The test was originally commenced with two p.s. gear-boxes, and despite initial contamination with mineral oil, both performed at least 35,000 miles without an oil change, before being withdrawn. In the meanwhile another twelve boxes, filled with castor oil, were placed in service, and after about 20,000 miles only one of these had given trouble attributable to the oil itself; even this adverse result was open to doubt, since the lubricant was found to be contaminated with mineral oil, which might, therefore, have been the cause of the gumming. Before this, however, the test had already been extended to comprise another fifty boxes, and a little later, with only the failure already mentioned on record, it was decided to standardize the lubricant in place of Oil A. Within two months, serious troubles identifiable with the use of castor oil became apparent, and it was only another two months before Oil A was introduced once more.

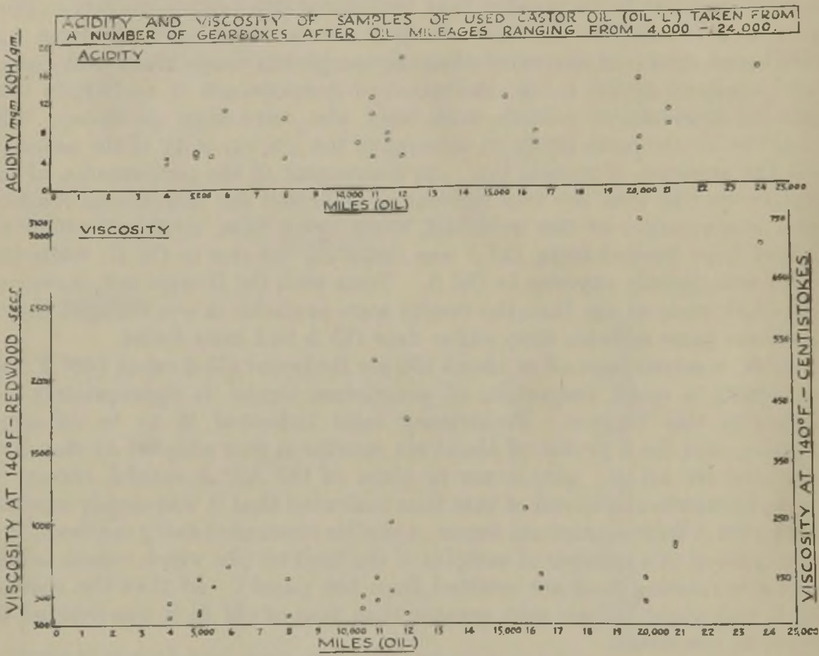


FIG. 7.

The trouble took the form of a solidification of the oil to a gelatinous, rubber-like mass, which in some instances completely prevented operation of the gears. That the boxes had in many cases not been completely drained and cleaned before refilling with castor oil was probably a contributory factor, since in such circumstances it was likely that the internal parts would be coated, to a greater or lesser degree, with gummy deposits; the resulting increase in friction during operation, combined with the relatively high viscosity of the lubricant, inevitably led to an excessive temperature rise, thus providing one of the factors necessary to cause polymerization of the vegetable oil.

The data given on the charts in Fig. 7, which show the acidity and viscosity of used oil samples taken from a number of boxes at various mileages up to 24,000, are not a full measure of the degree to which the lubricant had deteriorated. There were many instances in which a liquid sample could not be provided, and in several other cases the sample received was too viscous for a viscosity determination at 140° F; one of these latter represented oil which had performed only 6000 miles. The charts well illustrate two points, one being that in certain gear-boxes the oil remained in a tolerably good condition for as long a period as 20,000 miles, the other that its performance in different boxes varied to an enormous extent.

A laboratory investigation was carried out primarily with the object of ascertaining whether the gelatinization was promoted by the presence of mineral oil as a contaminant. Lewkowitch states that castor oil is converted to a spongy, rubber-like mass by heating, out of contact with air. It is further stated that the oil is polymerized by heating for 10 hours at 260 to 300° C at a pressure of 4 to 6 atmospheres; moreover, the change from fluid to rubber-like consistency appeared to occur quite suddenly. While the description of the polymerized oil and the sudden change corresponded with what was being found in service, conditions in the box were not such as to exclude air, nor to produce a general temperature of anything like 260° C, while the polymerization, affecting as it did the whole of the oil in the box, was obviously occurring at atmospheric pressure.

Experiments proved that it was not possible to polymerize either castor oil alone or contaminated with 15 per cent of mineral oil (A) by air blowing for over 18 hours at 200° C. Evidence that a catalyst might be involved was obtained from the analysis of the ash of both gelatinized and very viscous samples from gear-boxes; in both cases large proportions of copper and iron were found. Tests were therefore carried out in which castor oil and castor oil plus 15 per cent of Oil A, respectively, were subjected to air blowing for 16 hours at 200° C in the presence of brass and iron filings; at the end of the period the castor oil was very viscous, but the castor oil-mineral oil mixture had become solidified. There were, therefore, grounds for concluding that mineral oil tended to accelerate the change, though it was also clear that it was mainly due to the metals, acting as catalysts. It was subsequently found possible to cause gelatinization of uncontaminated castor oil by air blowing for 18 hours at 200° C in the presence of reduced iron; it was also proved that iron filings were much more potent than brass in promoting the thickening.

One further point arising from the use of castor oil as a p.s. gear-box lubricant is worthy of mention. In the case of boxes which were giving no apparent trouble, reversion to Oil A was effected by draining out the castor oil and re-filling with mineral oil, no special cleaning being undertaken. Draining was not complete (it being necessary to remove the box to effect this), and as a result the lubricant in use contained from 10 to 15 per cent of castor oil, this being reduced to 1 or 2 per cent after the next oil change. Samples of used oil were taken at weekly (approximately 1000 miles) intervals from five boxes over a period of about ten months immediately following the reversion from castor to mineral oil. In each box it was observed that during the 6000 miles period in which from 10 to 15 per cent of castor oil remained in the box, and in three instances when it had become reduced to 1 or 2 per cent, the viscosity of the mineral oil increased at a noticeably lower rate than was the case when no contamination was present. It will be appreciated that previous experience with castor oil offered no encouragement for further tests to determine the significance of the observations.

Inhibited Oils.

The first tests with an inhibited oil were made in rather an amateurish manner following upon the perusal of a paper appearing in the September 1934 issue of *Industrial and Chemical Engineering*.[6] The only compound of a nature similar to those mentioned in this paper and which was immediately available was methyl *cyclo*hexanol. A batch of Oil A containing 0·05 per cent of the latter was prepared, and was initially tested in one gear-box, which was merely drained prior to filling with the experimental lubricant. Samples of used oil taken from this box up to 19,000 miles, when trouble was reported due to " pedal continually sticking," indicated the lubricant to be much less prone to oxidation than the average untreated Oil A; it seemed possible that the failure might have been due to pre-existing deposits which had become increasingly more gummy as the test proceeded. The test was repeated in another box which, unfortunately, had to be removed for mechanical reasons after 6000 miles, though the oil was in relatively good condition. Three more boxes which had performed only very short mileage on Oil A were then drained and refilled with the " inhibited " oil. Although it was the intention that the lubricant should not be changed, a gear-box oil-change period at 6000 miles was introduced when the experiment had been in progress for about 12,000 miles, and judged more than anything by the comparatively satisfactory condition of used oil samples from the three boxes, it was suspected that the lubricant might have been changed on one or more occasions during the 54,000 miles they were kept under observation. Fig. 8 shows the viscosity of twelve samples of used " inhibited " Oil A (six from the first box, two from the second and four from the other three boxes) for which reliable oil mileage figures were available; a line corresponding to the average rate of increase in viscosity of uninhibited Oil A (derived from Fig. 2) is traced on the chart, from which

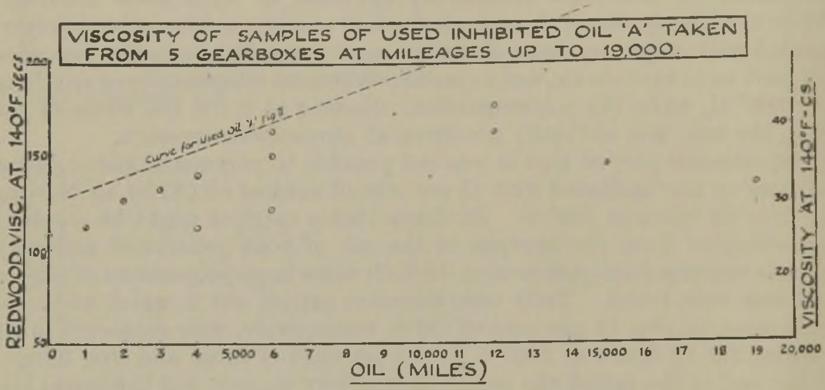


FIG. 8.

it is apparent that the " inhibited " oil was the more resistant to oxidation. Data in respect of viscosity and " hard asphalt," obtained from the remaining thirteen samples of used oils taken from the three boxes, are given in Table IV.

While these results were by no means conclusive, and, if reliable, indicated that methyl *cyclo*hexanol had but a slight inhibiting effect in a Pennsylvanian type oil, the performance obtained encouraged us to carry out service tests on a rather larger scale than usual when two inhibited lubricants were brought to notice towards the completion of tests with " inhibited " Oil A. Both oils were appreciably more expensive than A, and since the latter was by that time giving no very serious amount of trouble if discarded after 6000 miles use, it was considered that the inhibited oils would have to remain in satisfactory condition for a longer period than this if they were to be of interest.

The two oils are shown in Table I under the designations M and N; both were of a viscosity comparable with that of the majority of the oils tested. Oil M was of high viscosity index, while Oil N was of moderate V.I.; both contained oxidation inhibitors of the hydroxylated aromatic type, and it has since been ascertained that that present in Oil N was β-naphthol. The latter was in fact an inhibited turbine oil of the highly refined white-oil type, and also contained a corrosion inhibitor.

TABLE IV.

*Viscosity * and " Hard Asphalt" Content of Used " Inhibited " Oil A.*

Gear-box mileage.	Oil mileage.	Viscosity at 140° F sec Redwood.	" Hard asphalt," %.
18,000	Not less than 6,000 and possibly much more.	139, —, —	0·34, —, —
24,000		146, 122, 150	0·45, 0·03, 0·67
30,000		—, 125, 140	—, 0·21, 0·83
36,000		—, 127, —	—, 0·19, —
42,000		129, 134, 132	0·07, 0·15, 0·06
54,000		277, 144, 123	4·06, 0·26, 0·08

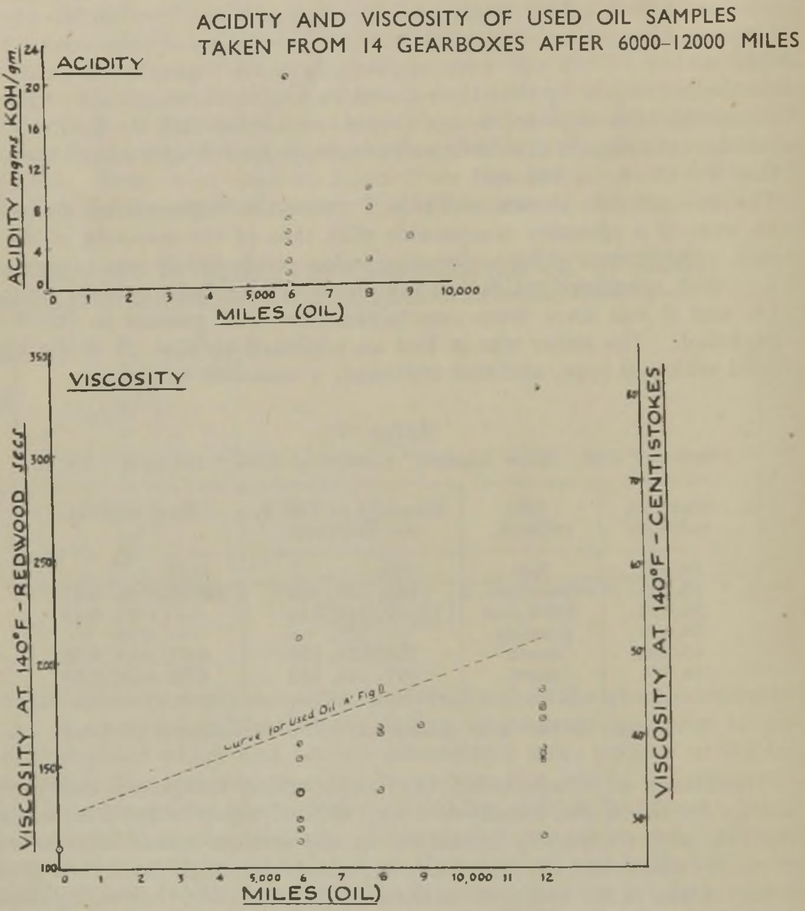
* Viscosity at 140° F of unused oil—111·5 sec Redwood (26·7 cs).

Preparatory to commencing the tests, which comprised thirty-seven vehicles for Oil M and twenty-five for Oil N, the gear-boxes were drained, removed, and completely immersed in the sodium metasilicate solution previously mentioned to remove any deposits which might have been present on the interior of the casing or on the moving parts; the thoroughly cleaned boxes were then refitted and filled up with the respective lubricants.

Of the gear-boxes operated with Oil M as lubricant, two were removed due to formation of gummy deposits, and two more on account of serious thickening of the oil after from 6000 to 14,000 miles in service, while there is record of at least five others in which deterioration of the oil was apparent at inspections made before 12,000 miles had been completed. Samples of used oils obtained from a total of fourteen boxes were examined for acidity and viscosity, the data obtained being shown in Fig. 9. The degree of deterioration of the oil in individual boxes was as usual erratic, but it is evident that the inhibited oil showed no worth-while improvement over

Oil A. The performance of Oil N was just as spectacular as that of Oil M was disappointing, and has already been described in sufficient detail in the early portion of the paper; it need only be reiterated that two prolonged service tests, one on a medium scale, and the other involving about 150 vehicles, were carried out before it was decided to adopt this lubricant.

It was always appreciated that there might be other inhibited oils which would prove equally satisfactory, but we were by this time only too well aware that while unsuitable lubricants could be eliminated by tests involving no more than one or two boxes, experiments on a very much larger scale and extending over a period of up to two years would be necessary to establish an oil as equivalent to Oil N.



ACIDITY AND VISCOSITY OF USED OIL SAMPLES TAKEN FROM 14 GEARBOXES AFTER 6000–12000 MILES

FIG. 9.

The benefits derived from a lubricant which was entirely free from any tendency towards gumming, and which outlasted the life of the gear-box, were of particular value upon outbreak of war, when both labour and spare parts became scarce and periods of air attacks put a great strain on depleted maintenance staffs. Two other inhibited oils (O and P—Table I) were submitted to small-scale service tests during 1940–1, though, as will be seen from Tables V and VI, neither approached the performance given by Oil N.

Table V.

Acidity and Viscosity of Oil O (Inhibited) after Use.

Oil mileage (Gear-box Serial No.).	Acidity, mg KOH/gm.					Viscosity at 140° F sec Redwood				
	1.	2.	3.	4.	5.	1.	2.	3.	4.	5.
3,000	0·3	—	—	—	—	111	—	—	—	—
6,000	7·9	0·3	1·8	0·3	0·3	160	105	130	111	109
9,000	—	—	12·7	—	—	—	—	222	—	—
12,000	—	8·4	27·3	0·6	—	*	154	226	117	—

* Sample too viscous for determination at 140° F; yielded 18·8% "hard asphalt."

Table VI.

Acidity and Viscosity of Oil P (Inhibited) after Use.

Oil mileage (Gear-box Serial No.).	Acidity, mg KOH/gm.		Viscosity at 140° F sec Redwood.	
	1.	2.	1.	2.
6,000	—	0·1	—	114
9,000	16·3	—	368	—
12,000	—	0·2	*	114
24,000	—	1·5	—	127
36,000	—	4·7	—	312
48,000	—	3·2 †	—	301 †

* Sample too viscous for determination at 140° F; yielded 9·9 per cent "hard asphalt." Test recommenced in Gear-box No. 2.

† Presumably topped up with fresh oil prior to sampling.

Table VII.

Acidity of Oil T (Inhibited with β-Naphthol) after Use.

Oil mileage (Gear-box Serial No.).	Acidity, mg KOH/gm.					
	1.	2.	3.	4.	5.	6.
4,500–5,000	4·4	—	—	—	0·2	3·0
5,250–6,250	5·2	0·1	0·9	0·2	—	4·9
9,000–9,250	—	Under 0·1	—	1·4	—	—

More recently, service tests were carried out employing a straight mineral type of turbine oil (Oil T), inhibited by the addition of 0·05 per cent of β-naphthol. Six gear-boxes were involved, and prior to being filled with the experimental oil they were drained and flushed out. Samples of used oils were taken at various mileages up to 9250, when, having obtained the desired information, the boxes were again drained, flushed out, and refilled with the standard lubricant. The results of acidity determinations on the used oils are shown in Table VII and may be compared with those relating to the uninhibited oil given in Table III. The last-mentioned data were sufficient to show that Oil T possessed no unexpected properties when used as a pre-selective gear-box lubricant, while those of Table VII demonstrate that β-naphthol was not an effective oxidation inhibitor for Oil T, a conclusion which again was not entirely unexpected. It is quite unlikely that the inhibitor had any adverse effect, though this inference might have been drawn by comparing the acidities of the inhibited oil from boxes Nos. 1 and 6 with those of the uninhibited used oil; conversely, the reverse conclusion could also be arrived at by selecting other data from Table VII for the comparison. The results as a whole once more serve to emphasize the variable conditions to which an oil is subjected during use and the false conclusions which might be derived from isolated tests.

In 1944, at the urgent request of the Lubricating Oil Pool, service tests were again instituted with the object of finding one or more alternatives to Oil N, though a more inappropriate time for commencing so important an investigation could hardly have been chosen. In actual practice the difficulties were even greater than had been anticipated, since three of the four oils submitted arrived and were put into service at a period when attack by flying bombs was at a peak. It was necessary to select for the tests garages from which comparable routes were operated, and to obviate delays in commencing it was decided to employ gear-boxes which were already in service, rather than newly overhauled ones; so far as was possible, the boxes selected were those likely to remain in use for eighteen months or more, before becoming due for repair, though this objective could not always be achieved. The results obtained with two of the oils—Q and R—both of the straight mineral type, have already been described, and are shown graphically in Figs. 4 and 5; it may be recalled that both showed rapid deterioration, R being the worse.

The third lubricant involved consisted of Oil R to which an oxidation inhibitor of the amine type had been added. Like the first two, it was introduced into six gear-boxes previously drained and flushed out with the experimental oil, and to ensure that the correct lubricant was employed for topping up, each box had a metal label affixed in the vicinity of the oil-filler cap, which itself was painted a distinctive colour. All the boxes were still in service after 49,000 miles, and while two were subsequently removed for mechanical reasons, four were still running after a minimum of 77,000 miles without an oil change. Samples of used oils were taken at intervals, a total of over forty having been examined; in no case did acidity exceed 0·2 mg KOH/gm, while the highest viscosity recorded was 120 sec Redwood (28·9 cs) at 140° F.

The fourth oil submitted for test in 1944 was one complying with U.S. Navy Specification 219OT for Inhibited Turbine Oil, and is included in Table I under the reference letter S. The specification does not require the use of a particular inhibitor, and clearly contemplates that oils containing different inhibitors may be offered in compliance with its provisions. The nature of the inhibitor(s) present in the oil supplied to us is not known. The lubricant was employed in six gear-boxes, the precautions observed being precisely similar to those followed with the first three. One of the boxes was lost sight of after 18,000 miles, while another two were removed for mechanical reasons after 36,000 to 39,000 miles; the remaining three were still in service after a minimum of 66,000 miles without an oil change. A total of thirty-three samples of used oil has been examined; one representing 57,000 miles use yielded an acidity 0·3 mg KOH/gm, which figure is not, however, significantly different from that of 0·2 found for several of the remaining samples; viscosity showed an insignificant amount of change.

The performance of these two inhibited oils so far is such as to indicate that they may be able to satisfy the high standard now demanded for a pre-selective gear-box lubricant. In that the number of gear-boxes employed in the respective tests constituted less than 0·2 per cent of those in service, it would have been too great a risk to adopt one or both of the oils on a really large scale; further tests which will involve their use in a total of at least 200 boxes are, however, in progress. With the view of thoroughly exploring the field of inhibited oils, small-scale service tests with another eight lubricants of this type have been commenced quite recently, the undertaking being one which could not have been attempted during the war years.

OXIDATION TESTS.

Before bringing this paper to a conclusion, brief reference must be made to two matters which are causing some anxiety at the present time.

It will have been appreciated from the foregoing that service testing of modern types of inhibited oils is inevitably a lengthy business. In addition, it causes some dislocation of normal maintenance procedure at the garages involved, and necessitates the examination of a number of used oil samples which must be handled with the minimum of delay, so that the experiment may be terminated at the first indication of unsuitability of the lubricant; should this occur, extra work is again thrust on garage staff, since the boxes must be drained and flushed out, or perhaps be removed for cleaning, prior to reverting to the standard oil.

There is, therefore, an urgent need for a laboratory oxidation test which would produce results, acceptable to both supplier and user, of sufficient reliability to enable the rejection of oils not likely to give a satisfactory performance in p.s. gear-boxes. Such a test would not dispense with the necessity for conducting service tests with an oil which reached the required standard, but might permit its initial use in, say, fifty gear-boxes instead of only six, and so reduce the time which must elapse before it could be finally approved.

Neither the Air Ministry Oxidation Test nor the Michie Test is applicable to inhibited oils, and while the lubricant at present standardized for our p.s. gear-boxes is an inhibited turbine oil, as are several of those recently submitted for test, it is by no means self-evident that the proposed A.S.T.M. turbine-oil oxidation test would correctly rate a p.s. gear-box lubricant, though more by coincidence than design it might do so. In the A.S.T.M. test, the oil, besides being in contact with metallic catalysts, which are quite admissible, is admixed with 20 per cent of its volume of water. Apart from moisture introduced as a result of breathing, there is no water in a p.s. gear-box, and the used oil after settlement of adventitious matter, such as metallic particles and brake-lining debris, is invariably clear and bright. As a corollary to this it is evident that it is not essential that the inhibitor in a p.s. gear-box oil should possess an exceptional degree of water-insolubility; furthermore, in view of the fact that the box is virtually a closed system and air changes are infrequent, the inhibitor need not be exceptionally non-volatile. In these respects the requirements are not necessarily parallel with those demanded of a modern type of inhibited turbine oil, though this is not to say that the latter may not prove quite suitable for use in p.s. gear-boxes; nevertheless, it would be desirable for an oxidation test to be applicable to any type of inhibited oil which would be passed by our very stringent service tests. A further possible objection to the A.S.T.M. test is the time required to obtain a positive result, this being comparable with that occupied by a small-scale test in p.s. gear-boxes under service conditions. This might be tolerated in the preliminary examination of unknown oils, but is the reverse of ideal if the test is to be employed, even if only occasionally, for checking supplies. Analytical methods for detecting and perhaps estimating the inhibitor in an inhibited oil have their use, but they will not prove that the lubricant possesses the necessary degree of resistance to oxidation. An oxidation test which would give a reliable result within a week or two at most would, therefore, be of real value.

COMPATIBILITY.

The other problem which requires solution is that of determining whether two or more inhibited oils are compatible with one another, again under conditions of usage in p.s. gear-boxes. It is the normal practice of large users such as the London Passenger Transport Board to purchase lubricants for a particular application from more than one source of supply, and while this has not hitherto been convenient in the case of pre-selective gear-box oil, it is an eventual aim. It has therefore to be contemplated that, having approved a number of inhibited lubricants by means of service tests, half-a-dozen or more, similar only in being within the same viscosity range, may be in use at the same time. While no more than one of these oils would be employed in a garage group—the latter consisting of from one to four garages—the possibility of transfers of vehicles from one group to another according to service requirements, and the practice, not uncommon in the country area, whereby a vehicle may sometimes be parked in a garage other than its normal one, must always be borne in mind. It is quite possible, therefore, that a p.s. gear-box might be topped up with all of the grades in use during its two years or more in service between overhauls, and it is for this reason essential that any inhibited oil adopted shall be compatible with all others in use. It is obvious that this requirement would also apply to inhibited or additive type oils which might at some future date be employed for rear axles, engines, etc.

Laboratory tests consisting of mixing the oils in various proportions, and observing whether cloudiness or sediment develops during a period of time and over a range of temperatures, would perhaps serve to reject certain lubricants, but it could not be assumed that mixtures which remained clear under all conditions of mixing and heating or cooling would give a performance equivalent to that of the individual oils when used in p.s. gear-boxes. Mixing tests followed by an oxidation test on mixtures which were not previously rejected might be more convincing, but it is evident that an investigation of this kind would be very time-absorbing, even were a suitable oxidation test available.

The alternative—namely, the carrying out of compatibility tests under service conditions—is being undertaken at the present time. It is necessary however, to proceed cautiously, and samples of used oils must be examined regularly and with promptitude, to avoid the possibility of service complaints or premature failures; furthermore, it is difficult to determine when it can be assumed that a final answer has been obtained. For example, if two, or perhaps three, oils are found to be quite compatible over a period of, say, 12,000 miles, will they remain so for the remainder of the life of the gear-box ?

Compatibility tests of the types mentioned, whether carried out under laboratory or service conditions, are at the best only empirical, and it seems possible that a more satisfactory approach would be to come to a decision following upon consideration of the chemical characteristics of the various inhibitors present in the group of oils concerned. This would call for detailed information respecting the make-up of the lubricants such as is not generally available to users.

CONCLUSION.

In conclusion, the author would say that he is only too keenly aware of the limitations of his own knowledge of lubricants, inhibited or otherwise, and he has often been indebted to the oil industries' laboratories for help and advice. In one respect, however, it is possible that the suppliers stand at a disadvantage, in that their recommendations have to be made either by analogy or as a result of tests carried out on the bench or on a limited number of vehicles run under a particular set of conditions. Difficulties may arise when applying this knowledge to a large fleet of vehicles where so many more variables, not excluding the human element, may be involved. It is for this reason that a user can seldom be convinced without carrying out service tests which must inevitably be of a protracted nature. If the contribution has succeeded in demonstrating this point, it has perhaps served some useful purposes.

Finally, the author would express his thanks to the London Passenger Transport Board for permission to present the paper and for allowing full use to be made of the relevant experimental reports compiled in the Department of the Chief Mechanical Engineer (Road Services).

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DISCUSSION

THE CHAIRMAN (Mr E. A. Evans) : I am sure we are very much indebted to Mr Wilford for this long and extraordinarily interesting paper. He deals, of course, with a series of observed facts, and it must be very difficult for any of us to challenge any of his statements. But I do not think that should exclude us from considering in detail some of the underlying reasons for the observations which have been made. Some of us are familiar with the additives which are used in lubricating oils for diesel and petrol engines, or, alternatively, at the other end of the motor vehicle—*i.e.*, the back axle, particularly the hypoid-type back axle. But I think this is the first occasion on which we have had a very detailed description of the behaviour of the transmission gear-box. Admittedly, the transmission gear-box is of rather special design in this case, and it may introduce factors which are different from the ordinary gear-box. Indeed, I think it is true to say that the observations made by the London Passenger Transport Board have indicated that there are in the pre-selective gear-box very strong oxidation conditions which do not occur in either the back axle or the orthodox transmission gear-box.

Many of you, I feel sure, will be very eager to question Mr Wilford on some of the statements he has made. The paper is one which requires a good deal of study, and there are points in it which can only be properly understood when one has had time to examine them at leisure.

In connexion with the table showing the oils which have been used, there must be some matters which will need explanation. There will be people who will want to know a little more about the inhibitors, about the types that are being used, and why some behave in one way and some in another way. The reference to castor oil will take our minds back a good many years and lead us to ask questions or to express views upon polymerization and the effect of the metals. Mr Wilford has almost put forward a challenge when he says there is not an oxidation test in existence which will give him the satisfaction he requires. I hope that I understood him correctly.

PROFESSOR J. S. S. BRAME (Past-President) : One can hardly appreciate what an immense labour lies behind this paper—labour which we may perhaps divide into two parts. First there is the statistical side. One thinks of the number of vehicles involved and the number of tests which have been carried out, of the difficulty of keeping in touch with the gear-boxes, especially when vehicles may be shifted from one garage to another; it is remarkable that the data have been kept so well.

In addition to what might be called the purely clerical side there is an immense amount of work involved in all the laboratory tests, and I am sure the Institute is extremely fortunate in having Mr Wilford's account of this work.

From my own point of view the most interesting part of the work is probably that in connexion with finding some test which will give in a reasonable time a result which can be depended on as indicative—I will not say as a positive indication—of the likely behaviour of the oil in the gear-box. We are up against many difficulties with these oxidation tests, and members of the Standardization Committee in years past will know how often this subject has been discussed. We want a test which, in a fortnight or so, will give us an indication of the probable behaviour or, shall I say, the possible misbehaviour of a lubricant.

In the pre-selective gear-box the temperatures are low—round about 60° to 70° C. Any of the ordinary oxidation types of test would probably never be completed in one's lifetime if one used temperatures such as that. On the other hand, if we try to accelerate reactions by increase of temperature, then, as was shown in the papers presented to the Transformer Oils Symposium, erratic results appear when the temperatures approach something between 120° and 150° C. So that there does not appear to be very much hope of getting reliable results by increasing temperature; indeed, the indications are rather the other way.

Then there is the question of possible change in the oil itself, apart from oxidation. There may be certain changes which have not been fully investigated. What would happen to certain types of oil on prolonged heating at a moderately high temperature? It is perhaps unfair to refer to castor oil in this connexion. Mr Wilford has told us of the remarkable behaviour of castor oil, and it is quite correct that it polymerizes in a very remarkable manner at certain temperatures. It has been stated that castor oil at 260° changed to a rubbery, gelatinous mass. In the 1914–18 war, when many machines in the Royal Naval Air Service were lubricated with castor oil, I had some very choice specimens of material from the engines, material which resembled Sorbo sponge, except that it was darker in colour. This gave no end of trouble.

The question is, then, in what direction can we look for some acceleration of the test which can be carried out at a more moderate temperature than is usually involved? It is very difficult to decide in what direction to look. One direction is towards the use of some pro-oxidant; there are certain substances which stimulate the oxidation of the oil, just as there are some inhibitors.

Oils are very fickle substances. In some cases an oil will flirt with an inhibitor and will make a very happy and firm union with another. The same thing, I think, applies to the pro-oxidants. One which will suit Mr Wilford's oil A might not suit oil B, and so on, so that work in that direction will not be very helpful.

Another direction is to find out whether the action can be accelerated by ozonized oxygen or ozonized air. The difficulty may be the control of the concentration with ozone. I do not know of any experimental work in which ozonized air or ozonized oxygen has been used to see whether they will stimulate the action.

I should like to ask Mr Wilford for further information on one or two matters. He refers to sludge. In his introductory remarks he speaks of a gummy deposit in the working parts; and in the section of the paper dealing with service tests on straight mineral oils he refers to "asphaltenes" which are flocculent and of much lighter colour than those from used rear-axle oils. Are those two distinct types—the gummy type and the flocculent type—or does the flocculent type become a gummy mass under the action of the gears?

Again, the average temperature in the gear-boxes is 60° to 70° C. Is it possible that there are hot spots anywhere, as the result of brake-bands acting, and so on, raising the temperature locally in the gear-boxes far above the 60° to 70° C which apparently has very little effect on the oil?

I should like to express the thanks of the Institute to Mr Wilford for having given us this very valuable paper, which certainly we shall have to read and digest before we are in a position to criticize.

The Chairman : It is clear that we have two phases covered by the paper, one being engineering and the other chemical. I hope the engineers will not feel that this is just a field day for the chemists; it is not. The chemist wants to know something of the working of the gear-box, not necessarily the pre-selective type of gear-box, because there may be analogies in other types which will throw light on the problem. There is obviously an analogy here, and we want discussion of this matter so that we may come to some sort of conclusion.

Mr P. W. L. Gossling : Mr Wilford is to be congratulated upon a very valuable record showing the development and ultimate solution of a very difficult problem indeed. I think there are two very important object lessons to be learned from the study of this work.

The first is with regard to collaboration between the chemical control and the engineering and maintenance side within the transport organization. It is quite obvious that this successful solution could not have been attained without a very high degree of collaboration between the two sides, such as possibly does not always exist so happily.

The second lesson to be learned concerns the statistics in this job, the avoidance of the drawing of probably erroneous conclusions from single tests. Very different conclusions might quite easily have been drawn if the matter had not been dealt with in a large way. Not always does the opportunity exist to carry out the right tests and to employ the right people to do it. I often think that the chemical departments of the oil companies spend a lot of time explaining to their salesmen and their representatives in the field that they do not have to come weeping on the chemists' shoulders on the occasion of a first unsuccessful trial. It would be a good thing to issue reprints of Mr Wilford's paper to a large number of the representatives with whom we have to deal, because it would be of great encouragement to them in carrying out tests in the development of special products.

I would like to be able to see further into the real cause of this very extraordinary failure of a number of oils which would be regarded as high-class materials. After all, the temperature attained, which I think is 70° C (about 160° F), is not very high; one would meet temperatures of that order in turbine lubrication without finding gummy deposits and, in fact, quite good service is obtained. I am inclined to think that in the gear-boxes there may be hot spots, as Professor Brame has suggested, particularly with reference to the brake-bands, and I am wondering if there is any information available on the temperatures attained in any particular parts of the gear-boxes. That is probably rather difficult to obtain. But the idea has occurred to me that it might be possible to make use of some of the paints which change colour at various temperatures; we might daub them on strategic points in the gear-box and examine them afterwards with a view to gaining some idea of the temperatures at those points.

I think that a knowledge of the temperatures attained is very important from more than one aspect. First, there is the question of the evident robustness of an inhibited turbine oil of highly refined white-oil type, although the particular oil under consideration is obsolete in turbine-oil practice. Secondly, there is the question of a suitable test; my ideas tend to run in the direction of a bomb oxidation test, using oxygen, and operated at a temperature similar to those revealed in the experimental determination of hot spot temperatures.

Mr H. D. Mansion (in charge of Gear Research at the Motor Industry Research Association): In the section of the paper headed "Oxidation Tests" Mr Wilford refers to brake-lining debris in a pre-selective gear-box. I am interested in that, and would like to know to what extent the oil becomes contaminated with brake-lining debris, and whether or not that is liable to cause abrasive wear of the gears. Unfortunately, I do not know what kind of brake-linings are used in these gear-boxes; obviously the material must be an oil-immersion type. A good many clutch linings and ordinary motor-car brake linings are not suitable for use in oil.

I am impressed by the fact that some of these gear-boxes have given very long lives—up to 140,000 miles. Does one set of brake-linings last as long as that? If so, is all the worn matter collected in the oil which is put into the gear-box to lubricate the gears? I wonder whether or not any filter is incorporated in the oil circulating system. From the drawings I rather gather that there is not. However, if there is, I should like to know whether the debris is filterable from the oil.

With regard to the presence of metallic particles in the oil, is there a magnetic plug fitted in order to remove those particles?

Coming back to the brake-lining debris, is it possible that it could act as a catalyst, in the same way that the iron powder was found to act in the case of the castor oil?

I note that oils covering quite a range of viscosities have been used in these gear-boxes. Oil J, although a compounded oil, has a low viscosity, of only 65 sec Redwood; oil B, the highest mineral oil, has a viscosity of 218 sec Redwood; and the castor oil (L) has a viscosity of 335 sec Redwood. From the construction of the box and its method of operation I should imagine that these rather wide variations in viscosity might result in quite wide variations in the performance of the box mechanically. I have driven several cars fitted with that type of gear-box, and on one of them I noticed that, when cold, there was almost a tendency for the car to creep along when in neutral, simply because of oil-drag on the brake-lining band. Is that liable to be affected by viscosity?

Recently I have been carrying out some research on the effect of oil viscosity on gear-scuffing, and should like to know whether the highly loaded gears in the box became scuffed when lubricated with the lighter oils.

I am not very familiar with the type of load applied to these epicyclic gears, but imagine that the gears are made no larger than necessary, and that there may be some high tooth loading on some of the wheels.

To what extent is noise in the gear-box affected by the viscosity of the oil used? It seems to me, in view of the oil-churning, that the lighter and the heavier oils might have different effects with regard to noise. I believe one of the troubles that has occurred with the Wilson gear-box is that it gives a whining noise when the vehicle is stationary, with the engine running and the gear in neutral. I wonder whether the viscosity of the oil or any other particular property has affected that.

Has Mr Wilford any information as to whether the pre-selective gear-boxes on private cars are liable to give these gumming troubles such as occur in buses, or should we assume that the duty performed by the oil in the private car is infinitesimal as compared with that in the bus, the driver of which is changing gear every few seconds ?

Dr D. Clayton : I should like to ask why Oil J was regarded as too low in viscosity. Was there some direct effect or was it due to the amount of debris formed ?

Apart from the presence of any debris, I wonder how the gears themselves behaved, whether they showed any signs of polishing. Also whether the inhibitors had any effect in preventing corrosion, thus reducing the amount of debris and the degradation of the oil from that cause. Probably one is being wise after the event in suggesting that figures of the amount of debris in the oil would have been significant.

I would support Mr Wilford's comments on the problems mentioned at the end of the paper—namely, compatibility and the derivation of a satisfactory oxidation test ; from a service point of view we are very much concerned with these problems. As regards the oxidation test it is apparent that, owing to the infrequent change of air mentioned, a conventional oxidation test in which there is much bubbling with air is unlikely to imitate the behaviour of the oil in this gear-box. At the same time, I would agree with the second sentence of Mr Wilford's conclusions, regarding the disadvantage at which suppliers stand, and wonder whether the users could not help the suppliers more by an extension of work of this kind.

In view of the immense amount of work involved I should have thought it would have been worth while to have carried out bench tests, not to attempt to imitate closely the behaviour in practice, but to allow an examination of the box to see in more detail what was happening to the oil. Professor Brame has referred to the possibility of hot spots ; measurements of temperature could have been made to see which parts contributed most to the temperature rise so that an appropriate laboratory test might have been devised.

I congratulate the author on the large amount of work extremely well presented.

Mr E. Thornton : If I dare, I would like to bring the engineer into the laboratory to assist with this problem of devising a test for oxidation.

After reading the paper carefully and listening to its presentation, I am impressed by the apparently anomalous fact that oxidation occurs in these gear-boxes, which is out of line with expectations based on observed temperatures and pressures, and what would be expected in laboratory work under such conditions of temperature, pressure, oxygen concentration, etc. The polymerization has been referred to as an effect of temperature and pressure, but I am left wondering whether under conditions occurring in the gear-boxes one other factor might contribute.

In my early days as a chemist I learned that certain exciting reactions could be brought about by rubbing powders in pestle and mortar.

Has any work been done to find out the effects on oxidation of a continuous film of oil of mechanical liquid pressure, and " rub " such as must occur in these boxes? Localized hot spots have been referred to, but that may not be the whole story. Certainly the average temperature and pressures would not be expected to produce such a degree of polymerization. Localized liquid pressure and " rub " might conceivably affect the degree of oxidation by promoting very intimate mixing of oil, oxygen, and debris, and I suggest we might profitably explore this effect rather than a straight bomb test, and seeing whether we can incorporate controlled conditions in the test which would more closely simulate the gear-box conditions of mechanical liquid stress to which the oil may be subjected.

Dr R. F. Goldstein: One of the striking things about the author's tests is the low temperature to which the oil is subjected, although there is a certain amount of doubt as to whether the actual oxidation occurs at hot spots; the oil temperature is about 70° C. The first identifiable products of the oxidation of hydrocarbons under these conditions are peroxides. Has he made any measurements of the course of peroxide growth and decay during service?

We have every sympathy with his desire for an accelerated laboratory test, when he is compelled to carry out tests on some 200 gear-boxes over a period of eighteen months or two years before he knows where he stands. However, the first criterion of any accelerated laboratory test is to know that what goes on in the course of that test is the same as what happens under service conditions. Using this criterion, we can say that attempts to accelerate oxidation by working at high temperatures will fail, because the course of the oxidation of hydrocarbons undergoes a change between the low temperatures in service operation, when peroxides can build up, and temperatures of 150° to 200° C, when peroxides, if formed at all, have only a momentary life.

Other suggestions put forward can be examined in this light. Professor Brame mentioned adding oxidation accelerators with some misgiving, and I think he was right, because unless we have one which is identical with one generated in service, the results will not correlate with service results. The same objections apply to the use of ozonized gases, my experience in related cases being that oxidation with ozone is completely different from oxidation with oxygen.

The last suggestion, put forward by Mr. Gossling, is the use of pressure, and I think this is on the right lines. The rubber industry has used with great success the oxygen bomb operating at 20 atmospheres and at a temperature of 70° C. A pressure of 20 atmospheres of oxygen gives a partial pressure 100 times that obtained in ordinary atmospheric air tests, and by that means a useful acceleration of the rate deterioration may be obtained.

Mr J. S. Elliott: With regard to the oxidation test problem, a test has been developed recently, as many will know, for evaluating the oxidation characteristics of turbine oil, the temperature being 110° C, the standard Michie sludge test apparatus being employed in the presence of a copper catalyst. In view of what has been said already, it may seem that these conditions are rather far removed from those desired for evaluating this type of oil; but it does seem that the test would be more applicable than any of those mentioned by Mr Wilford in his paper. The temperature, although higher, is not far removed from the temperature of operation, and probably the type of oxidation that would take place is somewhat similar. Furthermore, a copper catalyst is employed. I think a good deal of work has been published recently to indicate that copper and iron, and possibly lead, are to some extent interchangeable as catalysts of oxidation, not necessarily producing the same amount of effect, but promoting the same type of oxidation reactions. The test has other advantages in that volatile oxidation products are condensed back into the reaction vessel, simulating to some extent the closed conditions in the boxes, the time (90 hours) is conveniently short and water is not present. In view of all this, I wonder whether it would be worth while paying some attention to this test, for example, subjecting to it the oils to which Mr Wilford has referred, in order to see what correlation is obtained.

Mr J. Romney : There are two rather important points which are well brought out by the paper. In the first place, Mr Wilford has obtained spectacularly good results with oil N, an inhibited white turbine oil. I have heard murmurs on this particular subject. It is suggested that it is very risky to use a white oil ; that it is all very well when the inhibitor is present, but supposing the inhibitor disappears ? A white oil, it is said, will oxidize rapidly. It would be argued that Mr Wilford was lucky to get good results, that he was lucky that the inhibitor remained. But this retention of the inhibitor was not a matter of chance. There were two good reasons for it. One was that the new oil used for replenishment contained inhibitor, and the other that the amount of inhibitor originally present was considerably more than was actually necessary, so that there was ample margin for loss. However, if it is argued that the inhibitor might disappear, and that it would be much safer to use a good-class conventional oil (not a white oil) which would not deteriorate in the same way, Mr Wilford's results have shown that that is not the case, because he used all sorts of reputable high-class oils without inhibitor, and he suffered considerable trouble. If he had used them with an inhibitor, and the inhibitor had disappeared, he would still have had trouble. Furthermore, he would have had much worse trouble than he could have had with the white oil, because in the oxidation of these conventional oils there is a terrific increase of viscosity and the formation of gummy deposits, which would prevent the proper functioning of the gears. With the white oil, if the inhibitor had disappeared, there would have been fairly rapid oxidation, but it would have been along one particular channel, the development of acidity. Corrosion possibilities leap to the mind, but as a matter of fact there is not a considerable amount of corrosion from the acids from white oils in the absence of water vapour, though it is true that a certain amount of moisture is formed in the oxidation of white oil. On the whole, assuming inhibitor loss from each, there would be much less trouble when using a white oil, of which people seem to be so much afraid, than when using a conventional oil, which would have given trouble with deposits. To the final possible argument, that the white oil would oxidize so rapidly that if the oil in the gear-box was not tested every few days it would not be noticed in time, the reply is that as a matter of fact it would be noticed, because one of the manifestations of acidity is smell, and there would soon be complaints from drivers about smell from gear-boxes.

The second important point is that Mr Wilford's results have shown a fairly well-known phenomenon—*i.e.*, the specificity of inhibitors. He said the inhibitor which gave such good results in oil N was β-naphthol; but when he introduced this inhibitor into a first-class conventional oil he got very poor results.

It boils down to this, that there is no such thing as a first-class inhibitor as such. You can get a combination of a good inhibitor and a particular oil, however. This argues that it is very undesirable for users to buy inhibitors to put into their oils, because they can have very little evidence that the inhibitors will necessarily work with all deliveries of oils they are using, and they will have no real control over the oils, whereas the oil supplier can ensure that he uses in a particular oil the inhibitor which has been found to be suitable for that oil, and will stick to that particular inhibitor in respect of all future supplies of that particular oil for that particular purpose.

Mr R. Stansfield: It seems that there is not much hope of developing a satisfactory oxidation test which is merely a modified current type of test carried out at slightly elevated temperature. At the places where the brake bands rub the drums these must be at very high local temperatures, which are quickly reduced again when these parts are subsequently immersed or swamped in oil. In the course of, say, 1000 hours of operation there may be 1 per cent or possibly 10 per cent of slipping time leading to local high temperatures. If it is 10 per cent, that means only 100 hours of slipping time, which is not a long period for a laboratory test. Would it be possible, therefore, to arrange a gear-box so that the gears could be changed in quick succession, with one or other of the bands always slipping? It would not be possible, of course, to use a form of test where one band was slipping continuously; there would have to be changes from gear to gear, upwards and downwards. Then, during the periods between running on one gear and returning to that gear, the bulk of the oil would re-cool the heated surfaces. In such a test it would be necessary at the same time to cool the whole of the box in order to maintain the temperature of the oil in the system at the normal 60° to 70° C.

That is an engineer's and not a laboratory method, but it might be possible, at the expense of one gear-box, or one gear-box overhaul, and 10 hours or maybe 100 hours of running, to reach an answer which otherwise may require a year or two, and it might enable data to be obtained leading to an intelligently developed laboratory oxidation test.

Mr C. I. Kelly: I should like to give a pointer to a comparatively simple mechanical test-method that would probably be useful in a laboratory for the comparison and selection of inhibited oils intended for pre-selective gear-boxes. The suggestion is based on a not-too-well-known paper on oil-deterioration by a research worker named Gilson, published in the *General Electric Review* in 1923 or 1924, I think. In that work Gilson submitted a large range of oils to mechanical treatment between concentric metal cylinders; the outer was a cup linked to a torque-recording instrument and the inner was motor-driven, the oil being in the annulus. There was no metal-to-metal contact.

Gilson recorded markedly different " torque " behaviours against time, speed, temperature, and oil-composition. Castor and like natural fatty oils rapidly polymerized, sperm being an exception; mineral oils were less prone to this and, among themselves, responded differently. In these tests, there was a *limited* access of air (oxygen) to the oil. The remarkable fact is that in Gilson's results there is much that resembles those got by Stanton at the National Physical Laboratory with oils, like Gilson's, lubricating a journal under varied speeds, temperature, and pressure. In Stanton's work there was more oil-circulation and greater access of air (oxygen) to the deteriorating oil.

This raises the whole question of mechanical agitation of oil. There is an abundance of information in the scientific literature on the effects of mechanical agitation on the rate of deterioration (change) undergone by an oil subjected to " mechanical treatment " with but little opportunity for access of air (oxygen) to the oil. All this supports the remarks of Dr. Wolff, and adds emphasis to the need for more attention to this aspect of " oil-stability."

On the point of compatibility of inhibited oils I think Mr Wilford has set the biggest problem he could have set. Actually, it is a " problem " because there is a buying policy which strives after the purchasing of a commodity, from at least two competitive suppliers. Indirectly it is a difficulty because there is such a subject as " inhibitor-selectivity." As a difficulty it is increased by the fact that a crude can go into different refineries, be subjected to refining processes similar in type but different in effect so that quite different oils come out—each very often needing a different inhibitor. Hitherto it has been up to the refiner to make an oil and select an inhibitor to render it fit for a particular application. Because of all this I suggest London Transport's " problem " is rather difficult.

The only solution I see is that London Transport buys the straight basic oil or oils direct from different makers and that London Transport, after a study and selection of inhibitors, adds an inhibitor or inhibitors compatible with two oils from different sources, and with each other.

Dr Alan Wolf : I should like to associate myself with the congratulations expressed by previous speakers to Mr Wilford on a most excellent paper. It contains so much interesting new information that one could discuss it for hours.

I can entirely sympathize with him in his desire to find a test which will, in a sufficiently short time to be applicable for purposes of control, enable the behaviour of an inhibited oil in actual service to be foretold, and I agree that the A.S.T.M. turbine oil test is inadequate for this purpose. Is it not, however, true that this test might be useful as at least a temporary stop-gap ? In the examination of inhibited oils for the lubrication of steam turbines, it is sometimes assumed that if the oil does not develop an acidity in excess of 1·0 mg. KOH/gm in less than about 200–300 hours, it will prove satisfactory even in " difficult " turbines. Might not a similar criterion be temporarily applied to oils for pre-selective gear-boxes ?

Another point is that the manufacturers of pre-selective gear-boxes should surely feel profoundly grateful to the oil industry as a whole, inasmuch as it has been able to develop at least one type of oil which enables these gear-boxes to be used under the severe conditions which obtain in Mr Wilford's organization, without the serious drawback of having to change the oil and remove, completely dismantle, and thoroughly clean the gear-box after the absurdly small mileage of 6000.

I think an oxidation test of the bomb type might prove useful. The great drawback of oxygen bomb tests as at present carried out are that under static conditions the oxygen is used up quickly. But I venture to prophsey that quite likely in the future the oxygen bomb test as far as oils are concerned will be made dynamic in the sense that, although conducted under pressure, there will be an inlet and outlet from the bomb, so that the oxygen is renewed at a specified rate, enabling sufficiently large samples to be used to allow of their subsequent examination.

Finally, speakers have suggested that metal catalysts should be added to the oil as a means of speeding up the tests. It may perhaps be worth while pointing out that this has already been done to a certain extent, particularly in the examination of motor oils. Thus, in America particularly, it is customary to perform simultaneously a number of oxidation tests such as the Indiana on a single sample of oil, a range of very small proportions of some very potent oil-soluble metallic catalyst—*e.g.*, lead or iron naphthenate, being added to the charges of oil for these tests. The maximum concentration of metal which the oil can tolerate without developing undue acidity, sludge, etc., in a given time is thus determined, and referred to as the " lead " or " iron tolerance " of the oil towards oxidation.

Written Contribution.

As is already well known in the oil industry, the mere addition of oxidation inhibitors much more potent even than β-naphthol to " any old oil " affords no guarantee that the oil will pass the A.S.T.M. turbine oil test; the lubricating oil base must be carefully selected to provide the necessary " inhibitor response," and failure to do this may have been the main cause of the disappointing results given by inhibited oils M, O, P, and T, as shown in Table II. Mr Wilford does not mention in his paper the most important point as to whether the above inhibited oils gave good results in the A.S.T.M. turbine-oil tests. This is a matter of vital importance, for if they did, we are faced with the highly disconcerting fact that neither the A.S.T.M. turbine oil test nor, for that matter, any other so far put forward as a standard, is of the slightest value for predicting the service stability of the oil in pre-selective gear-boxes under heavy duty conditions, except in so far as oils failing the A.S.T.M. turbine oil test (as do *all* uninhibited oils) might perhaps be expected to fail in service.

Previous speakers have referred to the possibility of the high pressure of the brake bands when contracted on to the epicyclic gear train annulus drums of the box in some way greatly accelerating oxidation of the oil. This may well be the case, not so much as the result of the high pressure *per se*, but because such high pressure results in the oil-film on the opposing surfaces becoming rapidly and completely broken down, followed by actual brake band to metal contact. Such a complete rupture of the oil-film is, of course, essential to enable the contracting brake-bands to grip the drums firmly. Now, immediately after metallic surfaces have been drastically rubbed in this manner, their surface molecules are stimulated into a momentary condition of great chemical activity, being supremely sensitive, for example, to oxidation (*cf* the well-known phenomenon of the rusting or "fret-corrosion" of not quite tight steel surfaces in roller chains, inner races of ball bearings on line shafting, etc). It seems logical to assume that when in this condition of abnormal chemical activity (comparable with that of, for example, an element in the "nascent" condition), the steel of the epicyclic gear train drums also has abnormally high *catalytic* activity, and that the more frequently the brake-bands are contracted in the gear-box, *i.e.*, the greater the number of gear changes per hour the longer will be the total period in which the surfaces of the drums are in this active condition.

None of the standard oxidation tests reproduce such conditions, and even the more elaborate, such as, for example, the American Underwood, are pitifully crude and inadequate in their attempts to simulate the complex conditions obtaining in even the simplest oil-bath lubricated engine, gear, or other mechanism. Small wonder that they fail to forecast the behaviour of oils under severe operating conditions!

Mr Stansfield, as an engineer of wide experience, has in this discussion very rightly advocated the testing of oils in an actual pre-selective gear-box under load in the laboratory, fitted with automatic means of frequently changing the gears in turn, cooling of the box to prevent excessive temperature rise of the oil, and in fact, so arranged as to simulate as closely as possible, without undue complication, the conditions under which the box is operated on routes in densely populated urban areas. There would appear to be little doubt that much could be learnt in this manner, and that by increasing the number of gear changes per hour and the oil temperature to the maximum possible degree, unsuitable oils could be made to show marked deterioration in a comparatively short time.

The weakness of such testing technique, invaluable though it may be for lubrication research and for the preliminary examination of new types of oil is, apart from the costliness and complex nature of the equipment, the difficulty of making the conditions sufficiently reproducible for quantitative routine testing purposes. For example, the rate of deterioration of the oil may be very greatly influenced by such uncontrollable factors as the area of oil film breakdown and true frictional brake-band to gear-drum contact area of each epicyclic unit in the box, and so forth.

These difficulties might perhaps, at least in part, be overcome by using in place of a full-size gear-box with its four sets of epicyclic gear-trains, a greatly shortened box with only one such train, retaining, however, the necessary means for circulating the oil with a pump. In fact, since the essential feature of the pre-selective box tending to oxidize the oil would appear to be the alternate gripping and releasing of the annulus drum with a brake-band, even a much simpler box, containing only an annulus drum, an oil-circulating pump and a contracting brake-band, might be all that would be required. In such an ultra-simple box all epicyclic gear trains would be completely omitted, and therefore no actual gear-changing would occur. Nevertheless, the essential feature of having a steel surface alternately flooded with hot, highly aerated, oil and gripped by a brake-band sufficiently tightly to cause complete rupture of the oil film (and hence "activation" of the steel surface) would be retained, and the simplification of the test-box would not only greatly reduce the cost, complication, and space required, but would offer a greater opportunity for rendering the conditions reproducible.

The brake-band could be automatically contracted at frequent and regular intervals by a simple mechanically-operated cam mechanism, a high-speed splash-wheel could be mounted on the shaft to intensify aeration of the oil, and the severity of the test could be further increased by passing a slow current of pure oxygen through the box.

Some of the previous speakers have raised the question of the possible acceleration of the oxidation of the oil in service by the catalytic activity of the metallic wear debris formed after a few thousand miles of operation. It would seem unlikely, in view of the very small amount of such debris compared with the total area of the ferrous metal surfaces in the box, that the debris is a factor of any importance. On the other hand, if the brake bands are made of compressed asbestos fibre bonded with copper wire, the latter reinforcement where freshly rubbed by the annulus drums may have an appreciable effect, in view of the well-known oil oxidation-promoting action of copper.

In conclusion, it may be worth while pointing out that the rubbing of steel surfaces by brake drums, etc, not only greatly increases their oil oxidation catalytic power as the result of disturbance and consequent activation of the surface molecular layers, but also by the less scientifically subtle method of rubbing off protective fibres. In the operation of gasoline and high speed diesel engines under heavy duty conditions, it is well known that the lubricating oil oxidizes and deteriorates much more rapidly in new or very drastically cleaned engines than in engines which have been used for some time. This is because in the former case the oil comes into contact with newly machined or cleaned ferrous metal surfaces and, in the latter, protective varnish, oxide or sulphide film has formed on these surfaces and keeps the oil out of direct contact with the metal itself.

The protective action of such films is so great that in tests to determine the tendencies of oils to become corrosive (as the result of the development of organic acids by oxidation) to certain metals and alloys, it is now becoming to an increasing extent the practice to rub the metallic test pieces mechanically, in order to remove any protective films as rapidly as they are formed.

The Chairman: I am sorry that time does not permit us to continue this extremely interesting discussion.

All that I can say at this stage is that we have learned one or two extraordinarily vital lessons from the paper. The first is that the conventional oils, which we had thought were so tremendously stable for gear lubrication, are quite unsuitable for what appears to be a very simple type of gear-box. The ordinary pinion-type gear-box will tolerate oils of this kind for years. Now we have a case where Mr Wilford's organization has been compelled to go to a white oil. I think many of us would have felt that that was a rather crazy thing to do.

The next point is that we are being compelled to use additives and de-oxidants for this type of gear-box, and we are faced now with the difficulty of explaining why it is so necessary. A vast amount of work and observation lies ahead. I think we have opened up a new phase in gear lubrication, and I am sure the discussion will be a source of stimulus to those of us who are really interested in the production of additives.

Mr H. C. Ives (*written contribution*): During my eighteen years' experience as a chemist in connexion with lubricants I have come up against this oxidation of oils at moderate temperatures of 60–70° C in various types of gear-boxes, not only those used in the transmission of motor vehicles, but also those doing less arduous work, such as lift-gears, etc, and I have noticed that this oxidation generally occurs where " foaming " or " mistifying " of the lubricant takes place. The same condition of oxidation and sludging appear in turbine oils should there be an air leak anywhere in the system, causing aeration of the oil, especially in the presence of moisture. It would therefore appear that the trouble is mostly due to intimate contact of very fine particles of the oil with the surrounding air. The particles are so small that they sometimes have the appearance of a vapour over the actual surface of the oil.

I once inspected lift gear-boxes at a large stores. There were about six boxes, all using castor oil as a lubricant, and one of these boxes was giving trouble. The oil was polymerizing to a dark, " gummy " consistency. The gears were of phosphor-bronze, and the engineer said the oil in this box always foamed. This foaming was apparently due to a worn gear, and after refitting, the foaming stopped. The oxidation in this instance was apparently due to the foaming in conjunction with the metallic particles which were also present.

Another instance of oxidation of a light mineral oil at low temperature (the viscosity of the oil being in the region of 55 sec Redwood at 140° F) was experienced in connexion with a " demonstration piece " which we were exhibiting at one of the pre-war motor shows. This apparatus consisted of a centre pipe of about 8 in diameter fitted with a " mushroom-shaped " head of about 18 in diameter. The oil was pumped up this centre pipe and, coming out over the head, did not cascade down as was anticipated, but curved itself inwards to the outside wall of the centre pipe by molecular attraction, forming a continuous film, so that the whole thing looked like an elongated bubble. However, the temperature of the oil was never more than 100–110° F, but after about ten days this very pale oil became quite dark in colour due to oxidation. In this instance the same conditions were present, a lot of aeration where the oil returned to the reservoir, and also the very thin film in contact with the air. I therefore wonder if conditions of aeration or mistifying might be responsible for some of the oxidation experienced in the pre-selective gear-boxes; both conditions would probably be more prevalent with a lighter oil than a heavier one. Possibly larger oilways from the pump and a reduction of pump pressure might prove advantageous.

Regarding an accelerated oxidation test, I am wondering if an apparatus designed to comprise a mistifier spray nozzle similar to a paint spray gun, only on a smaller scale might produce any useful information or data. This could be mounted in a fairly large glass container, which could be immersed in a water bath kept at the constant temperature at which the oil has to function under working conditions. A continuous stream of oil could be blown through the nozzle, the mist mixing with the surrounding air in the vessel, then coagulating into droplets and draining back for recirculation; the air used for blowing could be taken from the surrounding atmosphere in the room, which could be arranged to have a similar humidity to that out of doors (see Fig. 1).

I do not know if any experiments have been made on these lines, but thought perhaps it might be of interest.

Mr **Wilford**, replying to the discussion, said: Mr Evans remarked that the strongly oxidizing conditions which exist in the pre-selective gear-box are not encountered in either the back axle or the orthodox transmission gear-box. Within my experience this is true of the latter, but so far as rear axles on buses are concerned, it is unfortunately not so. In this instance severe trouble due to oxidation of the oil has been met with from time to time and is only kept within bounds by careful maintenance of the correct level in the axle-pot and by changing the oil at 12,000-mile intervals. With the particular axle in use, which is of the worm-driven type and is admittedly overloaded, the degree of deterioration appears to be almost, though perhaps not quite, independent of the type of oil employed. On the other hand, oxidation-inhibited oils have not yet been tried in this application.

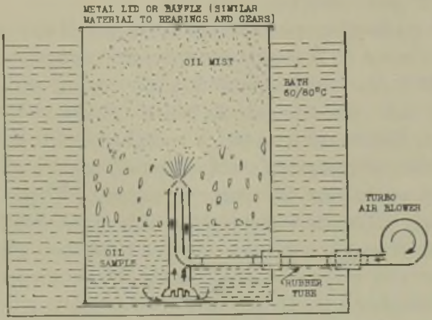


FIG. 1.

Professor Brame inquired as to whether two sorts of sludge had been encountered in the boxes, one a gummy type and the other flocculent. This is not so; the term "gummy" was employed to describe the material found to be adhering to the casing and working parts of the box, while "flocculent" was intended to indicate the appearance of the asphaltenes derived from the used oil. Professor Brame and other speakers also referred to the relatively low temperature of the oil when in use, suggesting that there might be hot spots. There is little doubt that this is the case, though we have no data with regard to the peak temperatures which may be encountered. Such information would, in fact, be very difficult to obtain, since the heat is generated momentarily at surfaces in contact with one another, and it would, for example, be impossible to employ temperature-indicating paints, as suggested by Mr Gossling. The assumption that these high temperatures exist, probably in conjunction with high pressures, favours proposals that oxidation tests on thin films of oil under pressure might be of some help.

Both Mr Mansion and Dr Clayton referred to the possible influence of debris derived from the brake-lining material; this is of the resin-bonded asbestos type, and we have always regarded it as substantially inert. The material is the chief source of suspended matter in the oil, metallic particles being relatively insignificant, as witnessed by the fact that the gears show no appreciable signs of wear or scuffing when the boxes become due for overhaul, the necessity for which is primarily governed by wear of the linings and need for their renewal. The gear-box is equipped with a coarse strainer, but a magnetic plug is not fitted. It is not, of course, impossible that metal particles, a proportion of which would seem unavoidable, act as catalysts, but conditions in this respect are probably no worse than in the crash-type box, the lubricant in which has never given trouble of the type encountered in the pre-selective gear-box.

With reference to further points raised by Mr Mansion, the pre-selective gear-box does not seem to be very sensitive in regard to the viscosity of its lubricant, though it can be conceded that castor oil was very probably too viscous. On the other hand, it is not unusual to find oils of either 160 sec or 220 sec Redwood at 140° F recommended for this type of gear-box, though London Transport's selection of an oil of about 105 sec has proved to be an optimum for our purposes. There was, however, no evidence of scuffing of gears when lighter oils were tested. With regard to noise from pre-selective gear-boxes, this is a matter which has never been brought to our notice, either by the public, from whom few complaints of any sort are received, or from the uniformed staff, who, in spending one-third of their lives on the vehicles, can with reason call attention to any objectionable feature. It is, I think, true to say that gumming troubles of the type encountered by London Transport have not occurred in pre-selective gear-boxes as fitted to private cars, nor, with few exceptions, in those fitted to buses operating in the provinces. There are various reasons for this, the major one being that traffic conditions in London are far more strenuous than those encountered elsewhere; furthermore, the 6000 miles which was at one time our oil-change period represents a year's running on many a private car.

Dr Clayton asked why oil J was regarded as too low in viscosity. This suggestion was advanced in an attempt to explain the fact that judged by increase in viscosity during use, it deteriorated appreciably more rapidly than oil H. These two lubricants were analogous in containing animal fat—admittedly J had only 4 per cent, as against 6 per cent in H—but H was the more viscous of the two. It is also a fact, however, that on the average samples of used oil J contained more suspended matter, both organic and inorganic, and in addition a higher proportion of metallic soaps (indicated by the ash contents of the filtered oils), than did oil H. Dr Clayton suggested that significant information might have been derived from determination of the amount of debris in the used oils. We have a considerable amount of data in this connexion segregated to show organic and inorganic suspended matter, total ash, and ash of the used oils after removal of suspended matter. No mention of these figures was made in the paper, however, for the reason that they did not as a whole exhibit any particular degree of correlation with performance, though it is true that in the case of oils which became severely oxidised during use the proportion of the ash attributable to formation of metallic soaps was high. With regard to suspended matter, this varied widely even among samples from the same box, figures obtained being between 0·1 and 1 per cent or more. This may be due to the fact that the samples examined are intended to represent the oil in circulation, and the amount of suspended matter taken up at any given moment is probably fortuitous.

Concerning Dr Clayton's inquiry as to the possible effect of the inhibitors in preventing corrosion, this may have had some influence in the case of oil N, which contained a corrosion inhibitor. Oil R, however, which failed very quickly in the uninhibited condition, has given mileages up to 70,000 or more when treated with an oxidation inhibitor. I do not think that the oil contained a corrosion inhibitor as well, but perhaps Mr Romney can confirm.

MR J. ROMNEY : The additive in that case can be regarded as a corrosion inhibitor, but there was not a separate one in it.

MR WILFORD : Finally, in regard to Dr Clayton's remarks concerning bench tests, it must be agreed that, looking backwards, such an approach would probably have assisted us to an earlier solution of our problem. On the other hand, when the matter is one affecting the performance of vehicles serving the public there is a great urge to do something quickly, and, since any proposed solution must eventually be tested under service conditions, to do this something on the vehicles themselves in the hope that the troubles may be mitigated thereby.

In reply to Mr Thornton, I can only say that I have no knowledge of any work which has been carried out on the lines he suggests; it is an aspect which might perhaps be tackled by a research laboratory.

In reply to Dr Goldstein, I think it possible that useful information might be obtained from a study of the course of peroxide growth and decay in the oil during service, but it is very difficult to find time for work of this nature in a laboratory which is concerned with a variety of problems connected with transport and amongst which lubrication, though of great importance, is only one. His remarks and those of other speakers regarding a pressure oxidation test are of interest, but I am afraid that for the reason just mentioned there would be great difficulty in developing such a test in a user's laboratory. One of my objects in writing the paper and presenting it was to obtain useful suggestions such as these, in the hope that they might stimulate someone to work out a test which we would then be only too willing to apply. Mr Elliott referred to the recently developed oxidation test employing the standard Michie sludge-test apparatus. It would seem worth while ascertaining whether it would give results in reasonable correlation with our service tests; it appears to possess one advantage, in that it would not automatically reject an oil which contained a volatile inhibitor.

I am afraid that I cannot agree with Mr Romney's remarks, which were to the effect that if the inhibitor employed were of a type which disappeared, it would be preferable for the base oil to be a white oil rather than a good-class conventional oil. I am inclined to think that the very rapid development of acidity in the white oil would be more objectionable than the slower increase in viscosity of the conventional oil. Neither should I like to depend on Mr Romney's criterion of breakdown of the white oil. If the odour of the acids is as marked as he suggests, it would be inviting complaints from the public, which would be an unjustifiable risk. The characteristic smell of an oxidized gear-box oil was well known to us during the time we were in trouble and was, in fact, an indication to experimental inspectors following the tests at garages that yet another lubricant had failed; the smell was not, however, noticeable until the oil-filler cap was removed.

Mr Stansfield's suggestion is a very valuable one, and is in line with my own ideas on developing an accelerated test. In that we have been free from gear-box lubrication troubles for the past eight years, I have not so far been able to persuade my engineering colleagues to collaborate in the necessary work. In view of the volume of service testing now in progress, it is possible that my approaches may be more favourably received.

Mr Kelly's remarks in connexion with Gilson's work are very interesting, and it is possible that tests on these lines might yield valuable information; it is certainly a fact that the oil in a pre-selective gear-box is subjected to considerable "mechanical treatment." With regard to his comments on the problem of compatibility between inhibited oils from different sources of supply, I am very much hoping that London Transport will not be forced to the solution he suggests, and I look to the oil industry for assistance in avoiding this.

In comment on Dr Wolf's suggestion that temporary use might be made of the A.S.T.M. oxidation test for turbine oils, I can only say that to be acceptable—and this, of course, applies to any other test—it would have to pass all (of the very few) oils which our service tests have shown to be satisfactory lubricants, and at the same time reject with certainty all that have failed to meet our requirements. It might be possible by such cross-checking to establish that the test was significant, but I am doubtful as to whether it would not reject an oil such as we are at the moment using, the inhibitor in which is to some extent both water-soluble and volatile. The test is, however, one which is in actual use—as contrasted with certain others suggested in the discussion—and I am hoping to be able to carry out a programme of work on it when time permits.

Replying to the written contribution from Mr Ives, I am not sure that "foaming" or "mistifying" of the lubricant occurs in a pre-selective gear-box, though we do know that it is thrown about in very thin sheets, and it can be agreed that, in view of this and of the relatively small volume in rapid circulation, it is exposed to conditions which favour oxidation; moisture, however, is for all practical purposes absent. The very latest design of box has a larger oil capacity, but was introduced subsequent to our having solved the lubrication problem; it has not been involved in any of the recent tests, and it is not possible to say whether this change has reduced the strenuous conditions to which the oil is subjected. The oxidation test proposed by Mr Ives is yet another which might be worthy of trial.

Dr Wolf in his written communication suggests that the disappointing performance of inhibited oils M, O, P, and T may have been due to the use of inhibitors which were not matched to the respective base oils. So far as M, O, and P are concerned, I can only say that these inhibited oils were supplied by the oil industry, doubtless in the anticipation that they would do the job. With regard to oil T (inhibited), I will agree that its failure was almost certainly due to the use of an inhibitor which was not suitable for this type of base oil.

As indicated in replies to speakers in the discussion on the paper, opportunity has not yet been found for carrying out investigations employing the A.S.T.M. turbine-oil test. Dr Wolf's association of the rapid deterioration of unsuitable oils with the highly catalytic action of the activated surface of the annulus drum following upon rupture of the oil-film is a logical one. It is not likely that this effect would be caused by the brake-lining material, which, as previously mentioned, is of the resin-bonded and not of the copper-woven type. It is interesting to find that he supports my view that debris in the oil, whether arising from the asbestos liners or metal parts of the box, is not in itself a significant factor in the deterioration of the lubricant.

Dr Wolf makes some cogent criticisms on the proposed accelerated test employing a full-scale gear-box. It could, of course, be replied that the authorities responsible for drawing up the specification for H.D. oil were content to make use of full-scale engine tests as a means for approving suitable lubricants. It must be agreed, however, that such tests are very expensive to carry out, and that they tend to be qualitative rather than quantitative. In a bench test employing a pre-selective gear-box it would certainly be the object to evaluate changes in the oil, rather than to assess the performance of the lubricant by reference to the degree of wear or the appearance of critical parts of the gear-box. The suggestion of a very much simplified gear-box, or in effect a rig which would reproduce an essential feature of the gear-box, seems therefore to be a valuable one, and opportunity will be taken to bring it to the notice of those more qualified than is the author to express an opinion on its practicability and usefulness. I can, however, foresee at least one adverse comment, this being that the ultra-simplified rig would not simulate conditions in the type of gear-box fitted with a phosphor-bronze plate clutch; although, as mentioned in the paper, gear-boxes with either cone or multiple-plate-type clutches are in use, the latter represents the more modern design of the two.

Vote of Thanks

THE CHAIRMAN: It is now my pleasure to propose a very cordial vote of thanks to Mr Wilford for his extremely interesting contribution to the proceedings of the Institute of Petroleum. I am sure the discussion this evening has proved conclusively the interest which the paper has aroused, and we wish now formally to convey to you, Mr Wilford, the thanks of the Institute for having presented it.

(The vote of thanks was carried with acclamation, and the meeting closed.)

THE VAPORIZATION OF FUELS FOR GAS TURBINES. PART II. HEAT QUANTITIES REQUIRED TO VAPORIZE GAS TURBINE FUELS.

By B. P. Mullins.

Summary.

The true specific heats in the liquid and vapour states and the latent heats of vaporization of 100-octane fuel and kerosine have been evaluated at various temperatures from empirical relationships and experimental data taken from the scientific literature.

The heat contents (above 15° C) of the heated liquid fuels were evaluated, and a method was devised to enable the heat contents of the two standard fuels to be calculated under different total pressure and mixture ratio dew-point conditions. The method was carried out using the dew-point values calculated in Part I of this report, and the results are presented in the form of curves and two nomograms (Figs 9 and 10).

These results have been converted into forms which may be applied directly to gas-turbine practice. The air temperature necessary to vaporize each of the standard fuels at a given total pressure and given final mixture ratio have been calculated. Further, the fuel temperatures necessary to produce vaporization under similar conditions have been calculated, and the results are presented in the form of six nomograms with auxiliary duplex scales (Figs 14 to 19).

Finally VOFAM charts (Vaporization of Fuel-Air Mixtures) were devised, one for each fuel, from which bubble-points, dew-points, heat contents, and air and fuel temperatures for vaporization at given pressures and mixture ratios may be read off with the aid of a straight edge—Figs 20 and 21.

List of Symbols.

Notation.

C = true specific heat at const. pressure (liquid state).
C' = true specific heat at const. pressure (vapour state).
$d(\ )$ = differential increment.
h = heat content (C.H.U./lb)—always refers to preheated liquid fuel.
H = heat content (C.H.U./lb).
k = characterization factor.
L = latent heat of vaporization.
M = molecular weight.
$\bar{M}$ = mean molecular weight.
P = vapour pressure.
π = total pressure.
s = specific gravity $\frac{60° \text{ F}}{60° \text{ F}}$.
s' = ° A.P.I. gravity.
S = slope of the A.S.T.M. distillation curve.
t = temperature.
t_0^p = fuel temp. required for vaporization with air preheated to T_p ° C.
T_0^p = air temperature required for vaporization with fuel preheated to t_p ° C.
T_p = air preheat temperature.
V = volume of gas or vapour.
V' = volume of liquid.
x = variable quantity.

Suffices.

a = air.
B = bubble-point.
c = critical.
D = dewpoint.
EAD^x = equilibrium air distillation (temp.), x per cent fuel evaporated.
$MABP$ = molal average boiling point.
NB = normal bubble-point.
ND = normal dew-point.
p = preheat.
q = A.S.T.M. distillation q per cent point.
t = temperature, ° C unless otherwise stated.
$VABP$ = volumetric average boiling point.

x = variable quantity.
1, 2, 3 = "distinguishing labels."

Double Suffices.

t_{ND} = normal dew-point temperature.
t_θ = temperature at equilibrium condition.
t_{MABP} = temperature of the *MABP*.
t_p = preheated fuel temperature.
T_p = preheated air temperature.

Treble Suffix.

t_{DR} = dew-point temperature under R to 1 air-fuel ratio conditions.

Superscripts.

$^{a}(\overline{X})^{b}$ = the mean value of property X between temperatures a and b.
15 = 15° C.

1. Introduction.

The work started in Part I of this report[1] has been completed by calculating the heat quantities required to vaporize a fuel to produce a definite final air/fuel mixture at a given total pressure.

Bubble-points which are essentially extrapolated or limiting equilibrium–air–distillation conditions have proved to be of fundamental importance in this work, and Table I, Part I, deals with the various types of equilibrium that may occur between fuel and air mixtures showing clearly the relationship between bubble-points and dew-points. The relevant bubble-points and dew-points may be obtained from the nomograms in Part I.

The first step was to calculate the necessary thermal data—*i.e.*, specific heats in the liquid and vapour phases, and latent heats of vaporization—for each of the fuels in question at various temperatures. This was carried out by many different methods, to ensure that the resultant values would be reliable to within, say, 5 per cent. During the course of this work it was evident that an extensive study of these properties would be necessary owing to the divergence of the values obtained, particularly in the case of the latent heats. This necessitated a small amount of indirect calculation—characterization factors, critical data, distillation data—in order that full use could be made of the empirical equations found among the literature.[2, 3, 4, 5]

The work has been limited to two standard fuels,[6]—namely, 100 octane fuel, batch 2, and reference kerosine SR. 312—although the methods used are sufficiently general to be applicable to other fuels.

All calculations have been based upon air/fuel ratios in the range 0 : 1 to 20 : 1, and total pressures from 0·1 to 10 atmospheres.

The ultimate objective has been to express the requirements for vaporization of air/fuel mixtures in the simplest and most direct practical terms.

Throughout the whole of the work equilibrium conditions only have been considered, and it has been assumed that perfect mixing, complete heat transfer, and perfect heat-insulating conditions have obtained.

2. Calculation of Average Boiling Points, Characterization Factors, Critical Data.

The volumetric average boiling points were calculated from the true boiling-point distillation curves in Part I of the report by the use of the following equation :—

$$t_{VABP} = \frac{1}{x} \sum_{x=1}^{9} t_{10x} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

The 100-cc Engler distillation curve is used instead of the T.B.P. curve to obtain a fair approximation to the $VABP$, although there is a tendency for this to give higher values.

The molal average boiling points were calculated from the equation :

$$t_{MABP} = t_{VABP} - Z \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where Z is a function of S and is obtained from Ref. 2, p. 881, Fig 1.

The characterization factors were calculated from the defining equation :

$$k = (t_{MABP})^{1/3}/s \quad . \quad . \quad . \quad t \text{ in } {}^{\circ}\text{R} \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

The critical temperatures and pressures were estimated from the C.F./A.P.I. Gravity/t_c/p_c curves given in references 4 and 5.

The mean molecular weights, A.S.T.M. distillation curves, and specific gravities were taken from reference 6.

The A.P.I. Gravity, s', was calculated from the defining equation :

$$s' = \frac{141{\cdot}5}{s} - 131{\cdot}5 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The results for the two standard fuels are recorded, together with the appropriate literature references in Table I.

In estimating the $VABP$ it should be noted that values taken from the true boiling-point distillation curves in Part 1 of this report were used rather than the less reliable A.S.T.M. temperatures.

The methods employed in these calculations are quite general for fuel having a specific gravity between 0·5 and 0·9, and are reliable to within 10 per cent for most fuels.

3. Calculation of Specific Heats.

Between 1925 and 1935 a number of empirical equations were developed expressing the true specific heat of fuels and hydrocarbon fractions as a function of temperature and one physical property of the liquid. The greater majority of these relations originated in the U.S.A., where physical data for hundreds of oils derived from a wide variety of crudes has been analysed. The more reliable of these equations will now be given and applied to 100-octane fuel and reference kerosine.

Specific heat values are plotted as "true specific heats," and, owing to linearity of the curves, mean values may readily be read from the appropriate curve between any two temperatures. The values are recorded in C.H.U./lb/° C unless otherwise stated, and, as elsewhere, the 15° calorie is the chosen unit of heat.

3.1. *Specific Heats of Fuels in the Liquid Phase.*

Cragoes' equations [7, 8, 9, 10] :—

$$C = s^{-\frac{1}{2}} (0{\cdot}403 + 0{\cdot}00081t) \text{ at } t^{\circ} \text{ C} \quad . \quad . \quad . \quad . \quad (5)$$

and

$$C = s^{-\frac{1}{2}} (0{\cdot}388 + 0{\cdot}00045t) \text{ at } t^{\circ} \text{ F} \quad . \quad . \quad . \quad . \quad (6)$$

TABLE I.

Average Boiling Points, Characterization Factors, Critical Data, etc.
For 100 Octane Fuel Batch 2 and Reference Kerosine, S.R. 312.

Property.	Symbol.	100 Octane.				Ref. Kerosine.				References.
		° F.	° C.	° R.	° K.	° F.	° C.	° R.	° K.	
Normal bubble-point	t_{NB}	154½	68	614½	341	367	186	827	459	(1) Fig. 11.
Normal dew-point	t_{ND}	225	107½	685	380½	462	239	922	512	(1) Fig. 12.
Critical temperature	t_c	510	265	970	538	770	410	1230	683	(4) p. 1276, Figs. 7 & 8. (5) pp. 1313–1315.
Critical pressure	P_c	Atm. 34		P.S.I. abs. 500		Atm. 25½		P.S.I. abs. 375		(5) p. 1317, Fig. 334.
Volumetric average boiling point	t_{VABP}	197	92	657	365	428	220	888	493	(2) p. 880.
Molal average boiling point	t_{MABP}	189	87	649	360	418	214	878	487	(2) p. 880, (5) p. 1315, Fig. 332.
Mean of normal bubble and dew-points	$\frac{1}{2}(t_{NB} + t_{ND})$	190½	88	650½	361	415	212½	875	485½	
Specific gravity 60°/60° F.	s	0·726				0·805				
A.P.I. gravity	s^1	63·4°				44·3°				This report Defn. 4.
Characterization factor	K	11·95				11·90				This report Defn. 3.
Mean molecular weight	M	98				170				(6)

For oils from paraffin base crudes add 2 per cent.
For oils from naphthene base crudes subtract 2 per cent.
Another relation in terms of the specific gravity is

$$C = 0{\cdot}0009t - 0{\cdot}499s + 0{\cdot}856 \text{ at } t^\circ \text{ C} \quad . \quad . \quad . \quad . \quad (7)$$

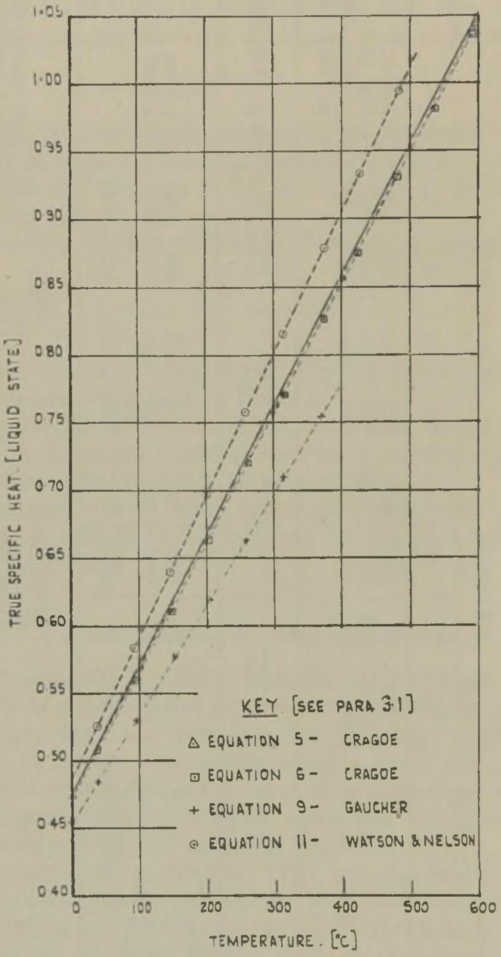


FIG. 1.

TRUE SPECIFIC HEATS (LIQUID) OF 100-OCTANE FUEL/TEMPERATURE.

Fortsch and Whitman's equation,[11] which holds fairly well for the heavier fuels ($s > 0{\cdot}75$), is as follows :—

$$C = \left(\frac{t + 670}{2030}\right)(2{\cdot}10 - s) \text{ at } t^\circ \text{ F} \quad . \quad . \quad . \quad . \quad (8)$$

L. P. Gaucher[12] developed two equations, one in terms of specific gr and one in terms of the C.F.

$$C = 0{\cdot}623 - 0{\cdot}0187\,(t_{MABP} + 460)^{\frac{1}{2}}/s^{3/2} + 0{\cdot}000355\,(t_{MABP} + 460)s/^{3} + 0{\cdot}00045\,(t - 32) \quad \text{at } t^\circ\text{ F} \qquad (9)$$

and

$$C = 1{\cdot}323 - 0{\cdot}2005\,k + 0{\cdot}0107\,k^2 + 0{\cdot}00045\,(t - 32) \text{ at } t^\circ\text{ F} \qquad (10)$$

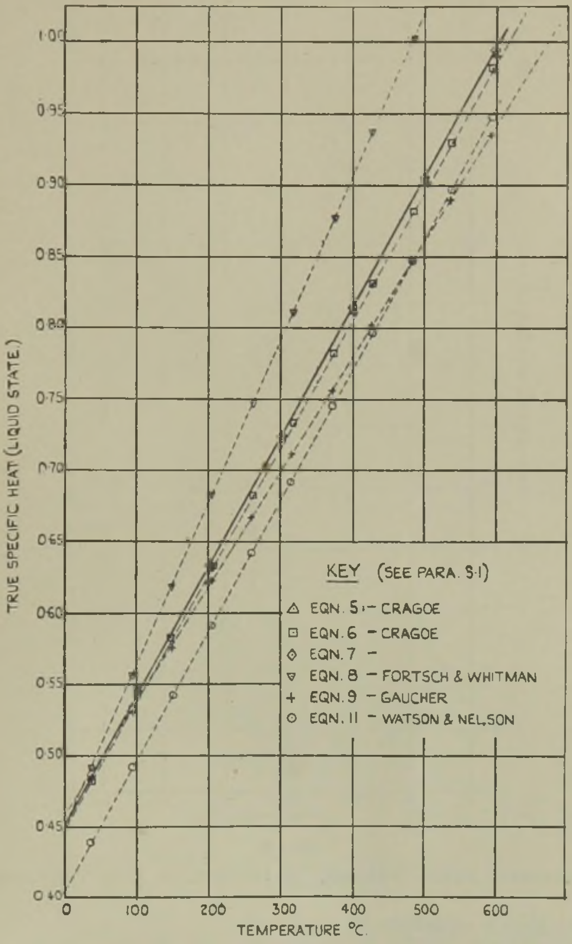


FIG. 2.

TRUE SPECIFIC HEATS (LIQUID) OF REFERENCE KEROSINE/TEMPERATURE.

Watson and Nelson[2] expressed the specific heats in terms of both the specific gravity and the C.F. in the following equation :—

$$C = 0{\cdot}6811 - 0{\cdot}308s + t\,(0{\cdot}000815 - 0{\cdot}000306s) \times (0{\cdot}055k + 0{\cdot}35) \text{ at } t^\circ\text{ F} \qquad (11)$$

the second product factor vanished for U.S. Mid-Continental oils where $k = 11{\cdot}80$.

3.2. *Specific Heats of Fuels in the Gaseous Phase.*

There are two important equations for the vapour state true specific heats, and these are in good agreement for 100-octane fuel and reference kerosine.

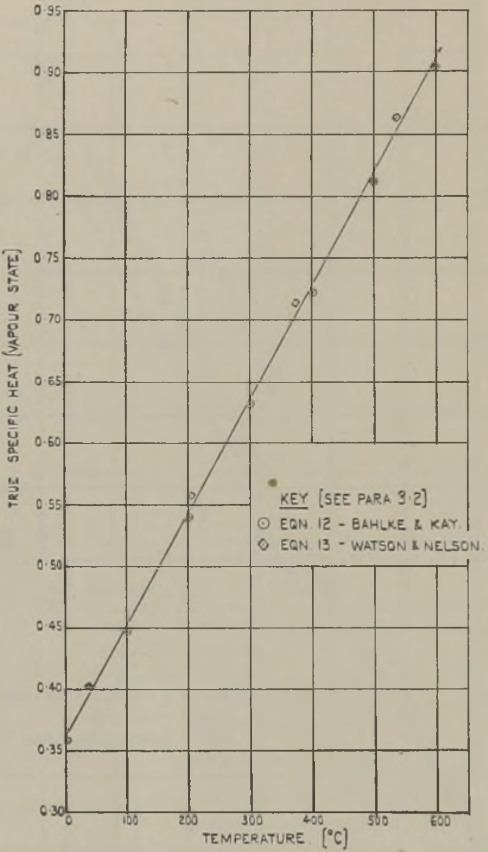


FIG. 3.

TRUE SPECIFIC HEATS (VAPOUR) OF 100-OCTANE FUEL/TEMPERATURE.

Bahlke and Kay's equation [13, 14] :—

$$C' = (0{\cdot}109 + 0{\cdot}00014)\,(4 - s_1) \quad . \quad . \quad . \quad . \quad (12)$$

where $s_1 = \text{sp. gravity } \substack{15{\cdot}5^\circ\text{ C.}\\ 15{\cdot}5^\circ\text{ C}}$

Watson and Nelson's equation (see ref. 2, p. 884) :—

$$C' = \left(\frac{4 - s}{6450}\right)(t + 670)\,(0{\cdot}12k - 0{\cdot}41) \text{ at } t^\circ\text{ F} \quad . \quad . \quad (13)$$

3.3. *Results for* 100-*Octane Fuel and Reference Kerosine.*

Plots of true specific heats for the two standard fuels are shown in Figures 1–4 :—

Fig. 1. True specific heats (liquid) of 100-octane fuel.
Fig. 2. ,, ,, ,, ref. kerosine.
Fig. 3. ,, ,, (vapour) of 100-octane fuel.
Fig. 4. ,, ,, ,, ref. kerosine.

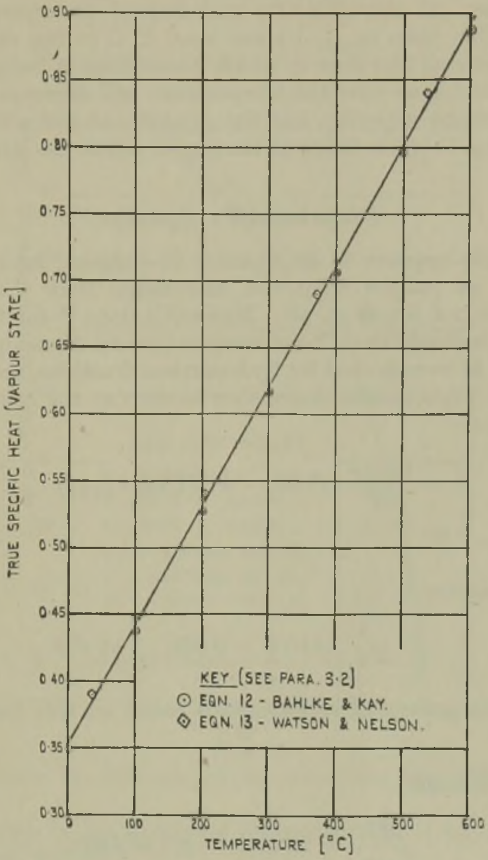


Fig. 4.

TRUE SPECIFIC HEATS (VAPOUR) OF REFERENCE KEROSINE/TEMPERATURE.

These values, which have been obtained by solving equations (5)–(13), have been represented by the dotted lines. The full lines have been drawn through the best mean positions, and have been used in the subsequent calculations.

It was found that for 100-octane fuel Cragoes' equations gave values less than those computed through the use of the characterization factor, whilst for kerosine the reverse was the case.

4. Calculation of Latent Heats of Vaporization.

4.1. *Latent Heats at the* MABP *Temperature* (1 atmosphere pressure).

All latent heat values were calculated at temperatures corresponding to the molal average boiling points; at pressures other than atmospheric this temperature had to be estimated indirectly, as the relevant distillation data were not available. The average of the bubble-point and dew-point of the fuel under the appropriate conditions was chosen as being the best estimation of the *MABP*, and indeed at atmospheric pressure $\frac{1}{2}(t_B + t_D)$ differs from t_{MABP} by less than 2° C in the case of both fuels. The pressure during the time in which latent heat is being absorbed whilst a fuel is vaporizing at constant temperature will decrease steadily as more and more fractions vaporize, but the pressure at the actual *MABP* temperature (or $\frac{1}{2}t_B + \frac{1}{2}t_D$) is taken as the one to define the latent heat pressure condition.

Kistyakowskii's Equation.[15]

This equation appears to be superior to Cragoes' latent heat equation given below, as judged from the knowledge that the variation with temperature is not linear at all; Maxwell's data [16] for the pure paraffin hydrocarbons indicate that linear temperature relationships for latent heat values are not to be expected for hydrocarbon fractions, and in any case the latent heat of vaporization diminishes to zero at the critical temperature very suddenly :—

$$L = \frac{t_{MABP}}{\overline{M}} \cdot (7{\cdot}58 + 4{\cdot}571 \log t_{MABP}) \cdot \frac{5}{9} \quad . \quad . \quad . \quad (14)$$

where $t_{MABP} = {}^\circ$ R.

Cragoes' Equation.[7]

$$L = \frac{1}{s} \cdot (110{\cdot}9 - 0{\cdot}09t) \cdot \frac{5}{9} \text{ at } t^\circ \text{ F} \quad . \quad . \quad . \quad (15)$$

Goodliffe [17] has presented a nomogram based on this equation; see also ref. 8, p. 265.

Trouton's Formula.

$$\frac{\overline{M}L}{t_{MABP}} = 20{\cdot}5 \text{ at } t^\circ K \; (MABP) \quad . \quad . \quad . \quad . \quad (16)$$

Clausius–Clapeyron Equation.

$$\frac{dp}{dt} = \frac{L}{(v - v')t} = \frac{LP}{Rt^2} \quad . \quad . \quad . \quad . \quad . \quad (17)$$

4.2. *Latent Heat at Higher Pressures* (i.e. *Higher* MABP *Temperatures*).

Cragoe's equation and Maxwell's data for pure paraffins are relevant in evaluating the latent heat/temperature curve of a hydrocarbon fraction.

The values for those paraffins of similar molecular weight to the mean molecular weight of the fuels may be compared with any values obtained for the fuel at super-atmospheric pressures. This has been done in Figs 5 and 6.

Having calculated the value of L at normal atmospheric pressure use may be made of the empirical equation of Watson[18] :—

$$L_t = e \, . \, L_{MABP} \cdot \frac{t}{t_{MABP}} \quad . \quad . \quad . \quad . \quad . \qquad (18)$$

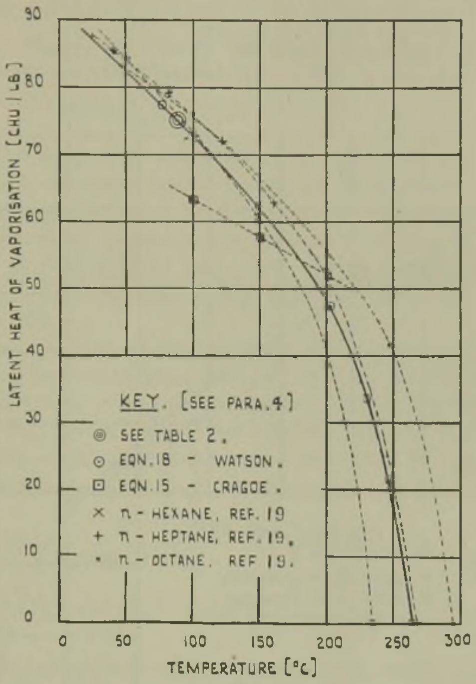


FIG. 5.

LATENT HEATS OF VAPORIZATION OF 100-OCTANE FUEL/TEMPERATURE.

Values of e may be found from a knowledge of t/t_C and t_{MABP}/t_C for the fuels—ref. 2, pp. 885–6.

This method is unreliable in the region of the critical temperature, and so the values of L_t near the critical region were checked by comparison with the curves for the pure paraffins of similar molecular weight.[16, 19]

4.3. *Results for* 100-*Octane Fuel and Reference Kerosine.*

Results for atmospheric latent heats of vaporization as calculated from the empirical equations of para. 4.1 are shown in Table II, whilst the latent heat/temperature curves are plotted in Figs. 5 and 6; values corresponding to the full lines were used in the subsequent calculations.

TABLE II.

Latent Heats of Vaporization of 100 *Octane Fuel Batch* 2 *and Reference Kerosine at Atmospheric Pressure.*

(I.e., pressure at t_{MABP} = 760 mm. Hg—see Para. 2.)

Latent heat of vaporization. Method of calculation.	100 octane fuel.	Reference kerosine.
	(C.H.U./lb.)	(C.H.U./lb.)
Kistyakowskii's equation (para. 4·1, eq. 14) . .	75·2	60·5
Cragoe's equation (para. 4·1, eq. 15) . . .	64·5	56·0
Trouton's formula (para. 4·1, eq. 16) . . .	75·3	58·8
Clausius–Clapeyron equation (para. 4·1, eq. 17) .	71	58
Maxwell's data for normal paraffins (ref. 16) . .	77·3	61·8
Value accepted for the basis of further calculations	75	60½

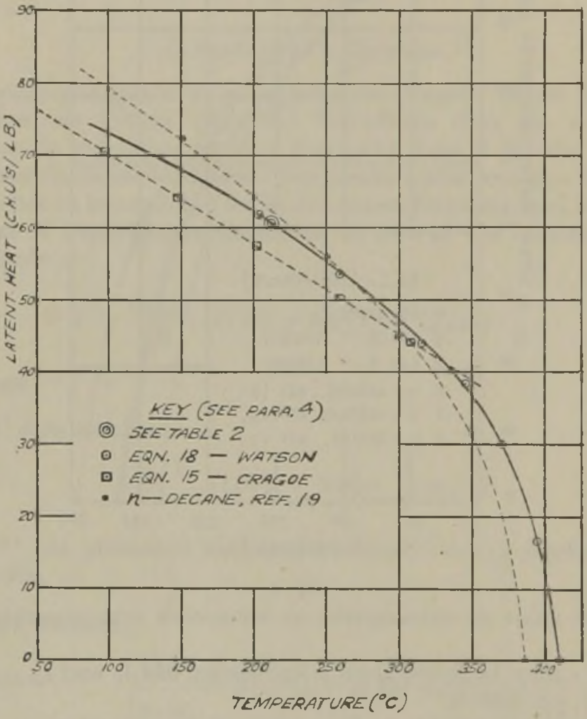


FIG. 6.

LATENT HEATS OF VAPORIZATION OF REFERENCE KEROSINE/TEMPERATURE.

5. CALCULATION OF HEAT CONTENTS.

5.1. *Heat Contents of Liquid Fuels at Various Temperatures.*

Since fuel preheating is of considerable interest in the following paragraph it was necessary to calculate the heat content, above 15° C, of the fuels at various preheat temperatures :—

Now

$$h_t = \overset{15-t}{C} \, . \, (t - 15) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (19)$$

or

$$h_t = C_{\frac{1}{2}(15+t)} \cdot (t - 15) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \qquad (20)$$

since C varies linearly with temperature.

In using the values of h_t it should be borne in mind that if t exceeds the appropriate bubble-point, then the relation no longer holds since a finite percentage of vapour will be present.

5.2. *Heat Content of Vaporized Fuels at the Dew-point.*

For unit mass of a pure liquid the heat content H at its dew-point (= the boiling point) is simply :—

$$H = C_{\frac{1}{2}(15+t_D)} \cdot (t_D - 15) + L_{t_D} \quad . \quad . \quad . \quad . \quad . \qquad (21)$$

However, in the case of a complex liquid mixture possessing a boiling range, such as fuel, once the bubble-point is reached liquid and vaporized fuel are present together and latent heat of vaporization is absorbed continuously at constant pressure from temperature t_B to t_D; at any given time x per cent of fuel vapour and $(100 - x)$ per cent of liquid fuel are simultaneously present and the composition of each changes steadily as x goes from 0 to 100.

If L_x be the latent heat of vaporization at constant pressure of the dx per cent liquid fuel boiling at temperature t_x when x per cent has evaporated, C_x the true specific heat of the dx per cent of liquid fuel with boiling range from t_x to $(t_x - dt_x)$, and C'_x the true specific heat of the dx per cent of vaporized fuel with boiling range t_x to $(t_x + dt_x)$, then at any temperature t_x lying in the interval $t_B < t_x < t_D$, H the heat content may be written as :—

$$H = \overset{15-t_{15}}{C} (t_B - 15) + \frac{1}{100 - x}\left(\int_0^{100-x} C_x \, . \, dx\right)(t - t_B)$$
$$+ \frac{1}{x}\left(\int_0^{x} C'_x \, . \, dx\right)(t_D - t_x) + \frac{1}{100 - x}\left(\int_0^{100-x} L_x \, . \, dx\right) \quad . \qquad (22)$$

To solve this equation it would be necessary to know the ultimate composition of the fuel and the specific heats and latent heats of vaporization of every constituent. Since most natural fuels contain very large numbers of isomeric hydrocarbons and even a relatively simple paraffin such as $C_{16}H_{34}$ may exist theoretically in 10,359 structurally isomeric forms,[20] it is not possible to solve the equation compound by compound.

It is therefore necessary to select some representative temperaǝɹnʇ t_θ at which :—

$$C_{t_\theta} \doteqdot \frac{1}{100} \cdot \int_0^{100} C_x \, . \, dx \quad . \quad . \quad . \quad . \quad . \quad . \qquad (23)$$

$$C_{t_\theta}' \doteqdot \frac{1}{100} \cdot \int_0^{100} C_x' \, . \, dx \quad . \quad . \quad . \quad . \quad . \quad . \qquad (24)$$

$$L_{t_\theta} \doteqdot \frac{1}{100} \cdot \int_0^{100} L_x \, . \, dx \quad . \quad . \quad . \quad . \quad . \quad . \qquad (25)$$

The choice depends on the way in which the values of C_x, C_x', and L_x vary with x as it varies from 0 to 100, and in general cannot satisfy all three of equations 23 to 25, and so will be at best an approximation.

It is known that for hydrocarbons, C_x, C_x', and L_x all decrease at x increases; [7, 8, 9, 16] in other words, the values of these thermal propersies becomes smaller as the molal average boiling point of the hydrocarbon fraction and the specific gravity of the hydrocarbon fraction increase. Further, to a first approximation for fuels with a boiling range of roughly 100 to 200° C the values of C, C', and L at the *MABP* are equal, respectively, to the mean values of C, C', and L for all of the fractions present. This follows from an examination of the specific heat and latent heat/boiling-point curves which prove to be very nearly linear over the range of temperature 50 to 500° C.

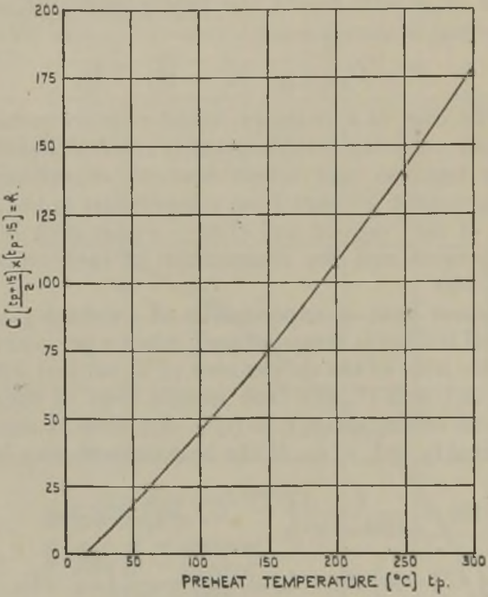


FIG. 7.

HEAT CONTENT OF LIQUID 100-OCTANE FUEL/TEMPERATURE.

Thus $t_\theta = t_{MABP}$ is an approximate solution to equations 23–25.

At pressures other than atmospheric however, t_{MABP} can only be calculated if the corresponding boiling-point curves are available. This is not the case for the two standard fuels under consideration although t_B and t_D are known. Since the mean of the bubble-point and dew-point temperatures is not likely to differ from the *MABP* by more than a few C °,* this temperature

$$t_\theta \doteqdot \tfrac{1}{2}\,(t_B + t_D) \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (26)$$

will be used in the calculations in place of t_{MABP}.

---

* At 1 atm pressure $t_\theta \doteqdot t_{MABP} \pm 2$ C° for 100-octane fuel and reference kerosine.

Finally, substituting equations 23–26 in equation 22 we obtain as our working equations :—

$$H_{t_D} = \overset{15-t_\theta}{C} \, . \, (t_\theta - 15) + L_{t_B} + \overset{t_\theta - t_D}{C'} \, (t_D - t_\theta) \quad . \quad . \qquad (27)$$

or

$$H_{t_D} = C_{\frac{1}{2}(15+t_\theta)} \cdot (t_\theta - 15) + L_{t_\theta} + C'_{\frac{1}{2}(t_\theta + t_D)} \cdot (t_D - t_\theta) \quad . \quad . \qquad (28)$$

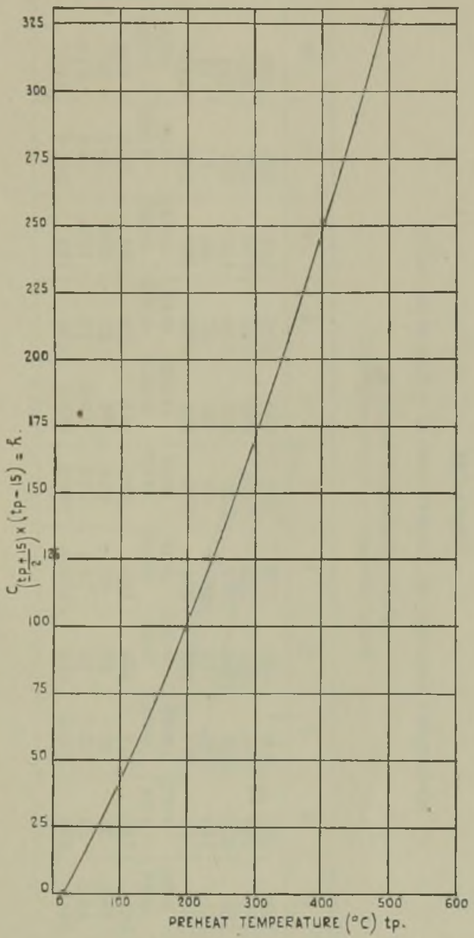


FIG. 8.

HEAT CONTENT OF LIQUID REFERENCE KEROSINE/TEMPERATURE.

5.3. *Results for* 100-*Octane Fuel and Reference Kerosine.*

Figs 7 and 8 show the variation of heat content of the heated liquid fuels with temperature.

An example of the tabulation method for computing the dew-point heat contents at two given pressures for various air/fuel ratios is shown in

TABLE III.

Method for Computing the Heat Content of a Fuel at the D.Pt.

Fuel : Reference kerosine.
Total pressure = 5 atmospheres.

A./F. ratio.	0	$\frac{1}{4}$	$\frac{1}{2}$	$\frac{3}{4}$	1	2	3	4	6	8	10	15	20
t_B	264	220	200	182	175	152	138	128	114	106	100	88	82
t_D	311	268	249	236	229	210	198	188	176	167	161	150	142
$\theta = \frac{1}{2}(t_B + t_D)$ . .	288	244	225	209	202	181	168	158	145	137	131	119	112
$\frac{1}{2}(15 + \theta)$ . . .	151	130	120	112	109	98	92	87	80	76	73	67	64
$\frac{1}{2}(\theta + t_D)$ . . .	300	256	237	223	216	196	183	173	161	152	146	135	127
$C_{\frac{1}{2}(15 + \theta)}$ . . .	0·59	0·575	0·56	0·555	0·55	0·54	0·535	0·53	0·525	0·52	0·52	0·515	0·51
$C_{1\frac{1}{2}(\theta + t_D)}$ . . .	0·62	0·58	0·565	0·55	0·545	0·53	0·515	0·505	0·495	0·485	0·485	0·475	0·465
$C_{\frac{1}{2}(15 + \theta)} \cdot (\theta - 15)$.	161	132	118	108	103	89·5	82	76	68	63·5	60·5	53·5	51
L	48·5	56	59	61	62	64·5	66	67	68·5	69·5	70	71	72
$C_{\frac{1}{2}(\theta + t_D)} \cdot (t_D - \theta)$.	14·5	14	13·5	15	14·5	15·5	15·5	15	15·5	14·5	14·5	14·5	14
H (C.H.U./lb.) . .	224	202	190·5	184	179·5	169·5	163·5	158	152	147·5	145	139	137

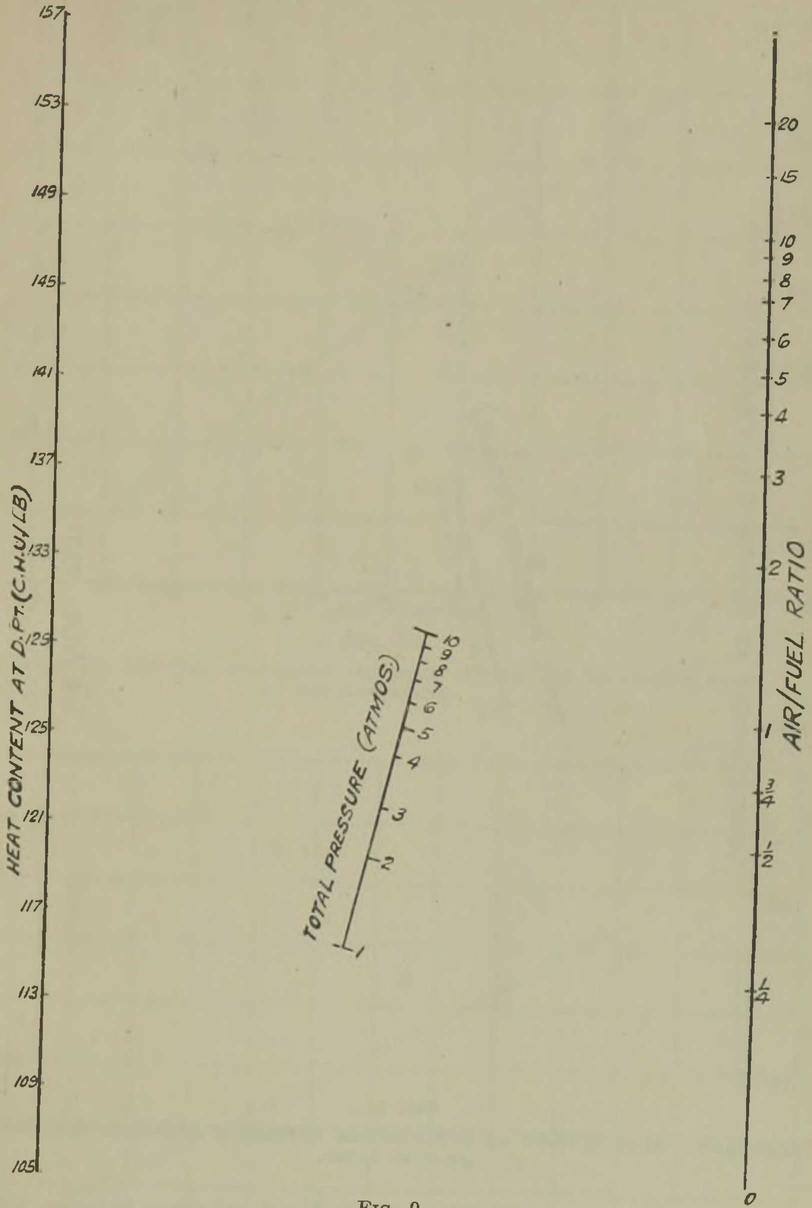


FIG. 9.

NOMOGRAM. HEAT CONTENT AT DEW-POINT OF 100-OCTANE FUEL/PRESSURE/AIR-FUEL RATIO.

Table III, which is for reference kerosine at 5 and 6 atmospheres total pressure.

Nomograms have been constructed to represent the variation of the

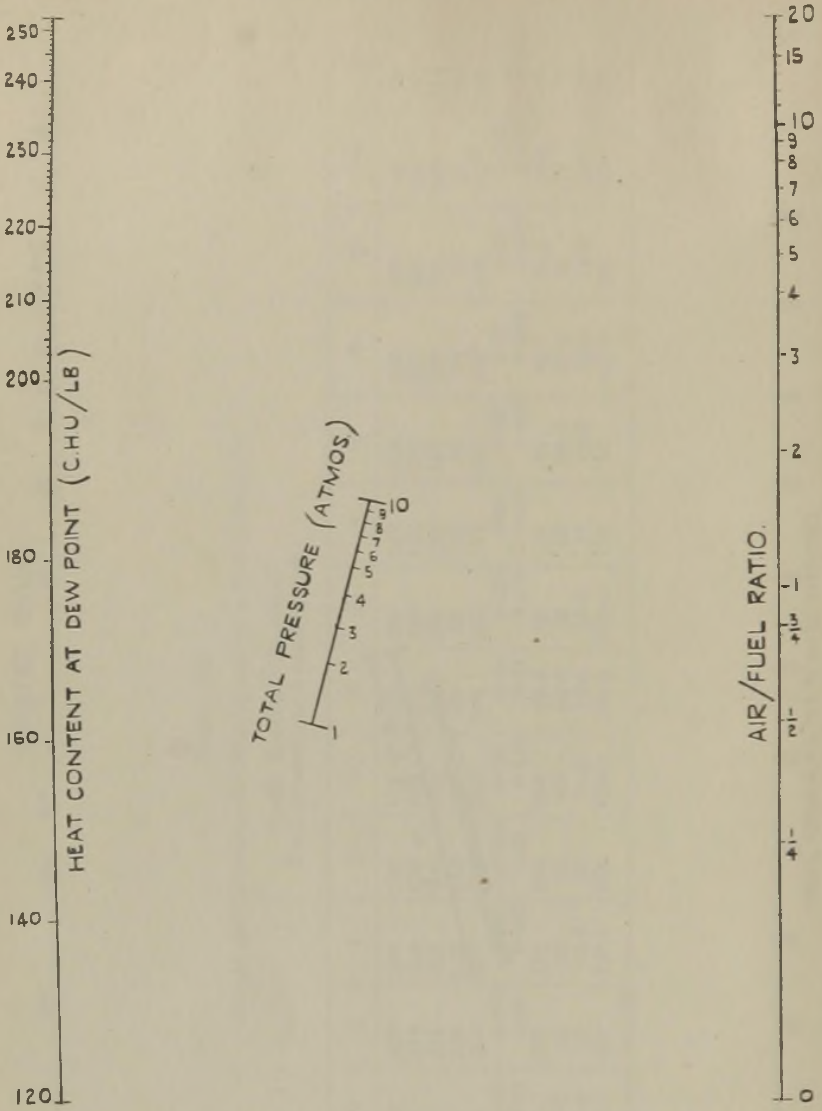


FIG. 10.

NOMOGRAM: HEAT CONTENT AT DEW-POINT OF REFERENCE KEROSINE/PRESSURE/AIR-FUEL RATIO.

dew-point heat contents of 100-octane fuel and reference kerosine with total pressure and air/fuel ratio. Figs 9 and 10.

Figs 11 and 12 depict the interesting relations between dew-point heat content and dew-point temperature; it was found, rather unexpectedly, that these relations were linear except for the kerosine at the higher dew-point temperatures.

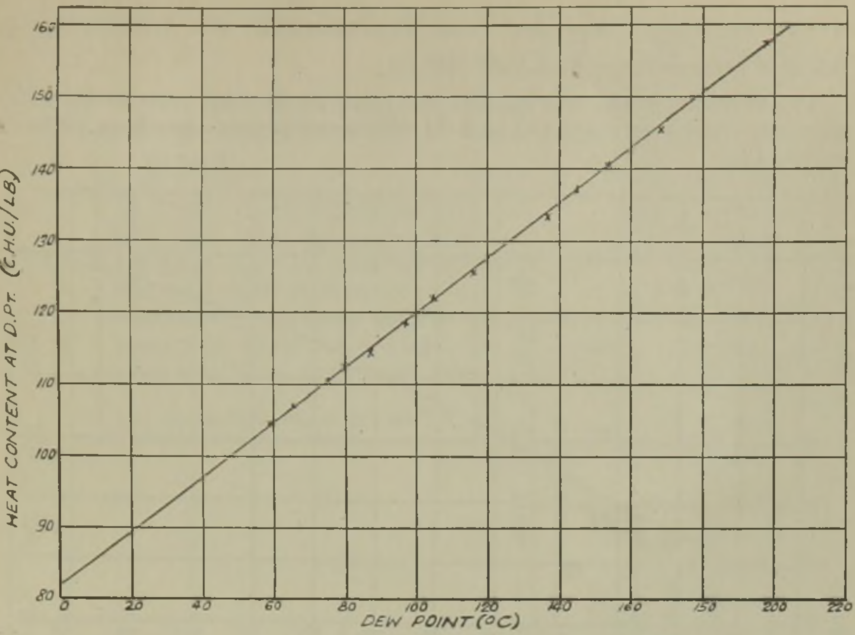


FIG. 11.

RELATION BETWEEN DEW-POINT AND HEAT CONTENT OF 100-OCTANE FUEL AT THE DEW-POINT.

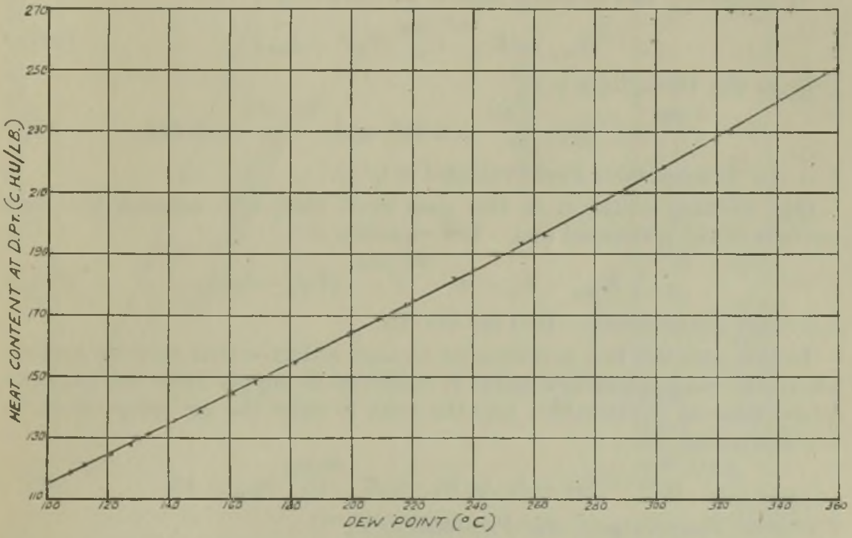


FIG. 12.

RELATION BETWEEN DEW-POINT AND HEAT CONTENT OF REFERENCE KEROSINE AT THE DEW-POINT.

6. Calculation of Air and Fuel Temperatures for Vaporization.

6.1 *Air Temperatures, Fuel Cold* (15° C).

The variation of the true specific heat of air at constant pressure (*a*) with pressure—has been neglected and (*b*) with temperature—has been plotted in Fig 13.

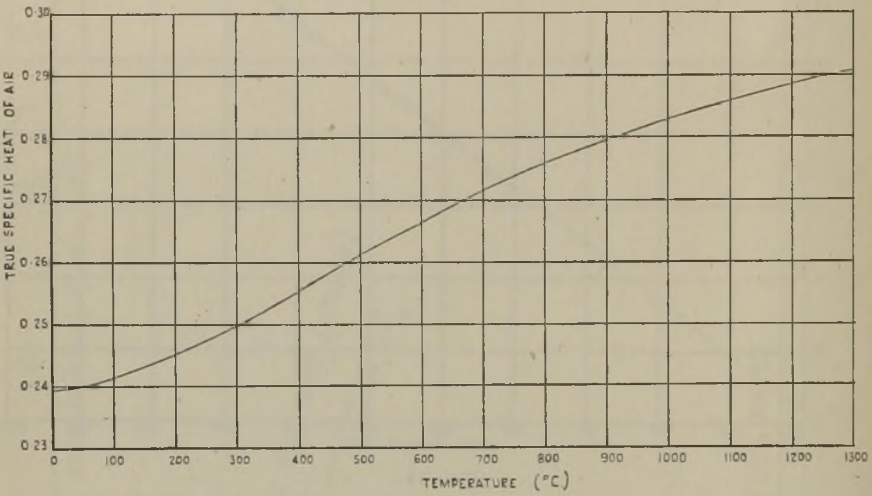


Fig. 13.

TRUE SPECIFIC HEAT OF AIR FROM 0° TO 1300° C.

At pressure π and mixture ratio R we have :—

$$H_{t_{D_R}} = R \,.\, \overset{T_0^{15}-t_{D_R}}{C_a} (T_0^{15} - t_{D_R}) \quad . \quad . \quad . \quad . \quad (29)$$

From Fig 13 we have :—

$$\overset{0-300}{C_a} = 0{\cdot}240, \quad \overset{0-200}{C_a} = 0{\cdot}243 \text{ and } \overset{300-1300}{C_a} = 0{\cdot}274.$$

6.2. *Air Temperature, Fuel Preheated to t_p° C.*

Our working equation in this case must take into account the heat content of the preheated fuel. Our equation is :—

$$H_{t_{D_R}} - h_{t_p} = R \,.\, \overset{T_0^p-t_{D_R}}{C_a} \,.\, (T_0^p - t_{D_R}) \quad . \quad . \quad . \quad (30)$$

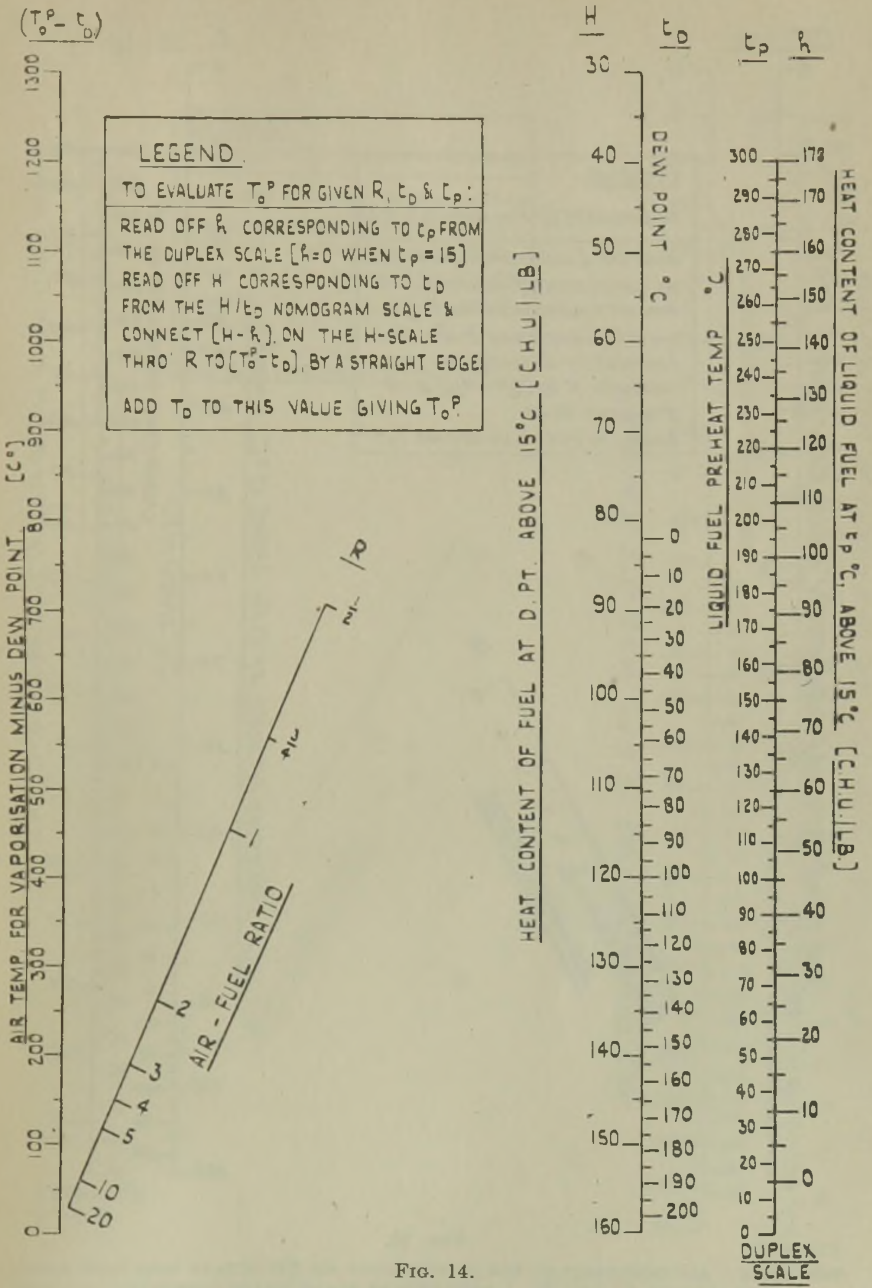
6.3. *Fuel Temperatures, Air Cold* (15° C).

In this case the fuel is preheated to such a degree that its heat content above the subsequent dew-point is sufficient to supply both the requisite latent heat of vaporization and the heat to raise the air temperature to the dew-point, *i.e.* :—

$$\overset{15-t_p}{C} (t_0^{15} - 15) = h_{t_p} = H_{t_D} + R \,.\, \overset{15-t_{D_R}}{C_a} (t_{D_R} - 15) \quad . \quad . \quad (31)$$

6.4. *Fuel Temperatures, Air Preheated to T_p °C.*

In this case, if $T_p < t_D$ some heat from the fuel is still required to raise the air to the final dew-point. If $T_p > t_D$, however, some of the heat content of the air will contribute toward the latent heat required to change



LEGEND.

TO EVALUATE T_0^P FOR GIVEN R, t_D & t_p:

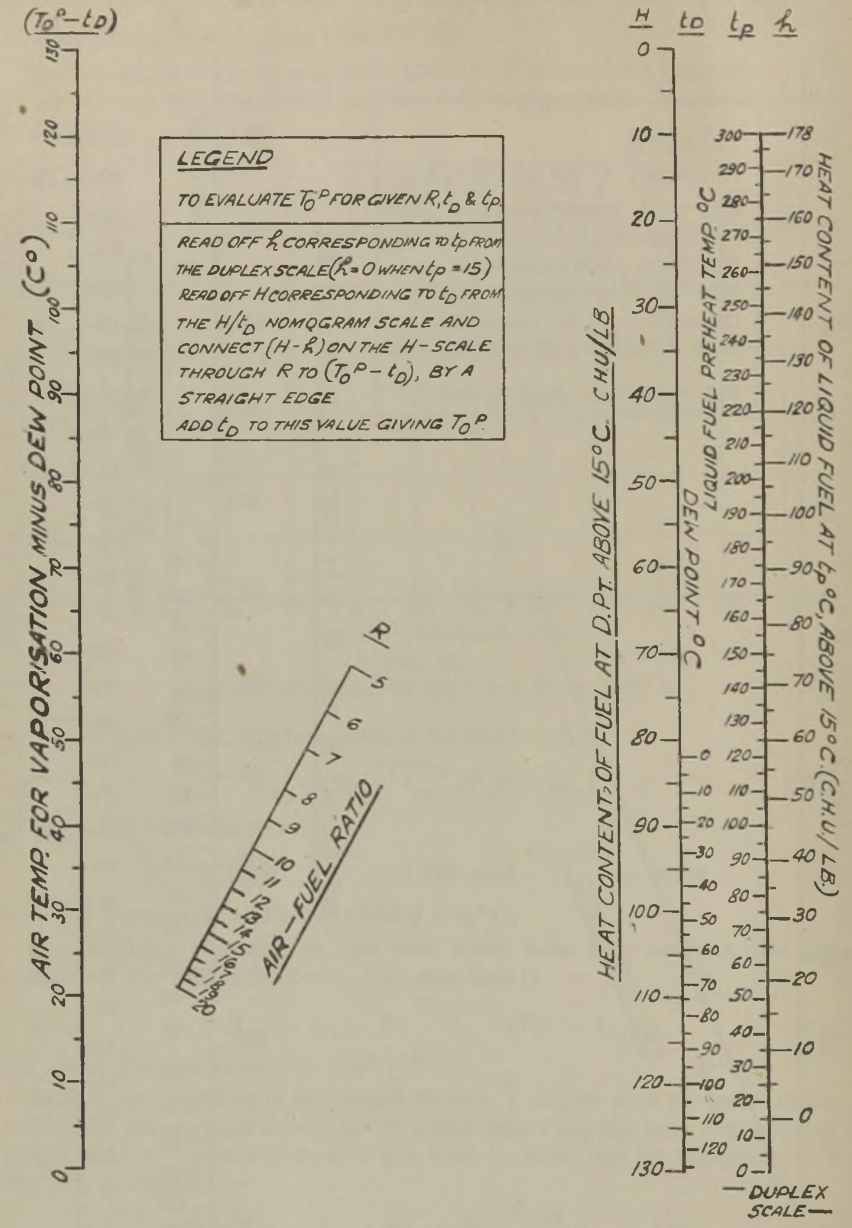
READ OFF h CORRESPONDING TO t_p FROM THE DUPLEX SCALE [$h=0$ WHEN $t_p = 15$] READ OFF H CORRESPONDING TO t_D FROM THE H/t_D NOMOGRAM SCALE & CONNECT [H - h]. ON THE H-SCALE THRO' R TO [$T_0^P - t_D$], BY A STRAIGHT EDGE.

ADD T_D TO THIS VALUE GIVING T_0^P.

Fig. 14.

NOMOGRAM: AIR TEMPERATURE FOR VAPORIZATION OF 100-OCTANE FUEL/DEW-POINT/AIR–FUEL RATIO $\frac{1}{2}$: 1 TO 20 : 1 WITH DUPLEX SCALE GIVING CORRECTION FOR FUEL PREHEATING.

(*N.B.*—For more accurate values of T_0^p when $R \geqslant 5$, *see* Fig. 15.)



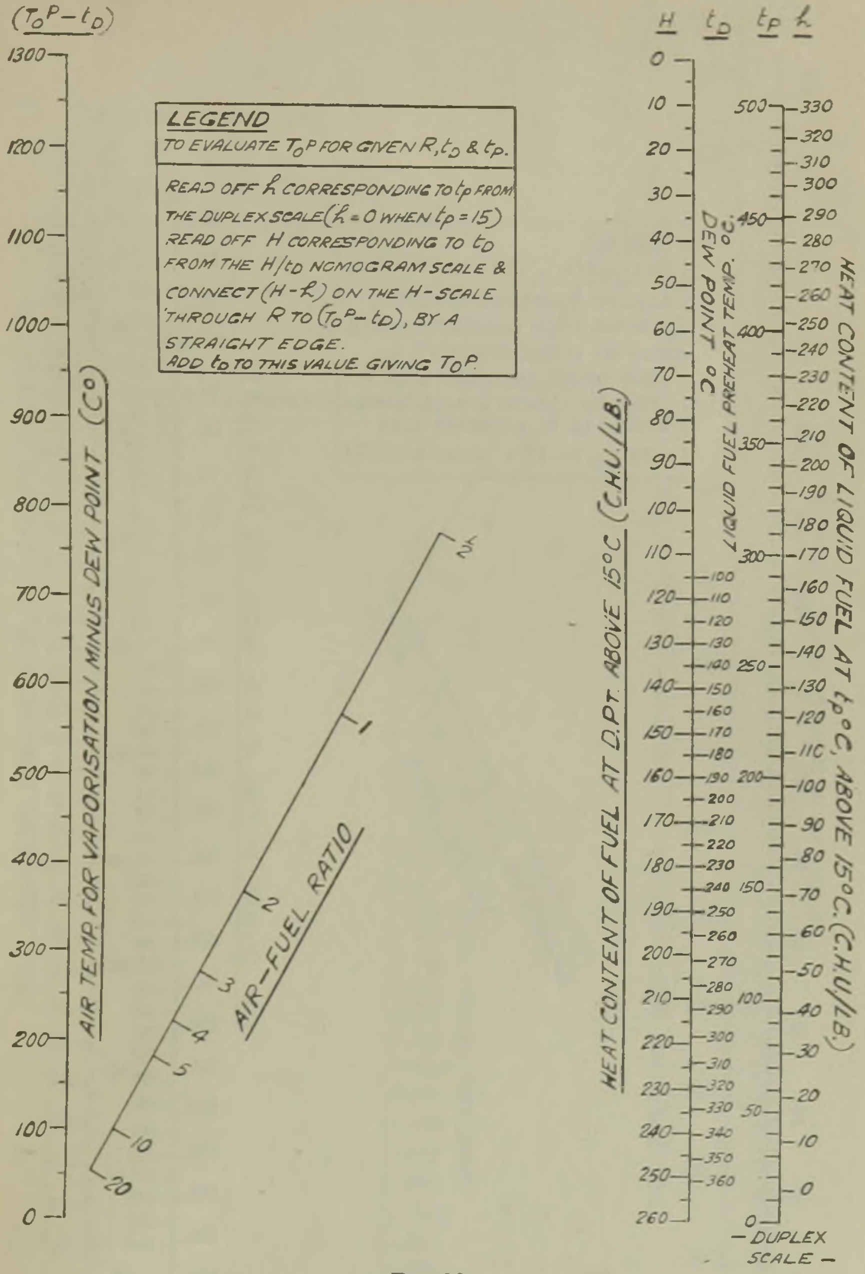
LEGEND

TO EVALUATE T_0^P FOR GIVEN R, t_D & t_P.

READ OFF h CORRESPONDING TO t_P FROM THE DUPLEX SCALE (h = 0 WHEN t_P = 15) READ OFF H CORRESPONDING TO t_D FROM THE H/t_D NOMOGRAM SCALE AND CONNECT (H − h) ON THE H-SCALE THROUGH R TO $(T_0^P - t_D)$, BY A STRAIGHT EDGE ADD t_D TO THIS VALUE GIVING T_0^P.

FIG. 15.

NOMOGRAM : AIR TEMPERATURE FOR VAPORIZATION OF 100-OCTANE FUEL/DEW-POINT/AIR–FUEL RATIO 5 : 1 TO 20 : 1 WITH DUPLEX SCALE GIVING CORRECTION FOR FUEL PREHEATING.



LEGEND

TO EVALUATE T_0^P FOR GIVEN R, t_D & t_P.

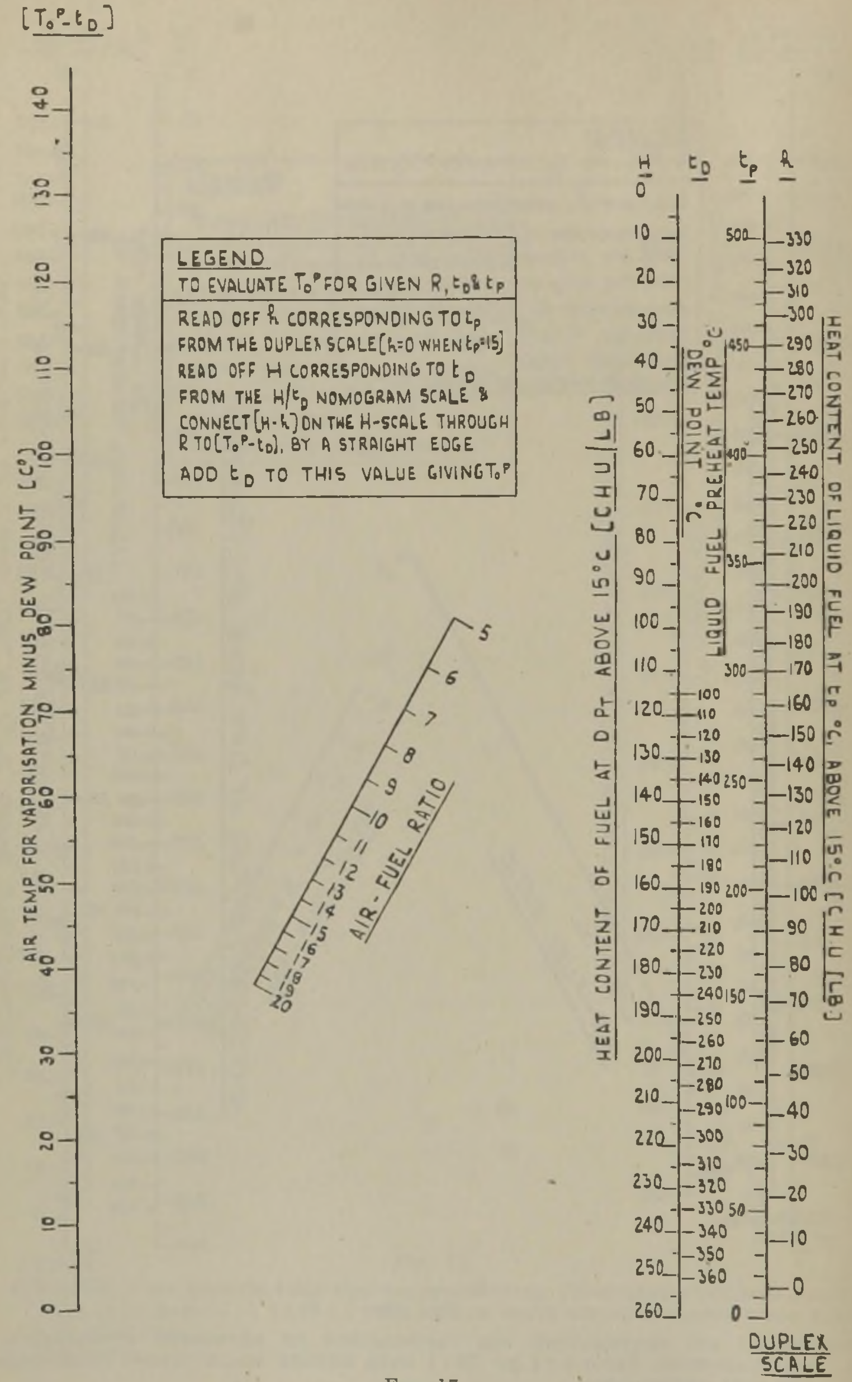
READ OFF ℎ CORRESPONDING TO t_P FROM THE DUPLEX SCALE (ℎ = 0 WHEN $t_P = 15$) READ OFF H CORRESPONDING TO t_D FROM THE H/t_D NOMOGRAM SCALE & CONNECT (H − ℎ) ON THE H-SCALE THROUGH R TO $(T_0^P - t_D)$, BY A STRAIGHT EDGE.

ADD t_D TO THIS VALUE GIVING T_0^P.

Fig. 16.

NOMOGRAM: AIR TEMPERATURE FOR VAPORIZATION OF REFERENCE KEROSINE/DEW-POINT/AIR–FUEL RATIO ½ : 1 TO 20 : 1 WITH DUPLEX SCALE GIVING CORRECTIONS FOR FUEL PREHEATING.

(*N.B.*—For more accurate values of T_0^p when $R \geqslant 5$, *see* Fig. 17.)



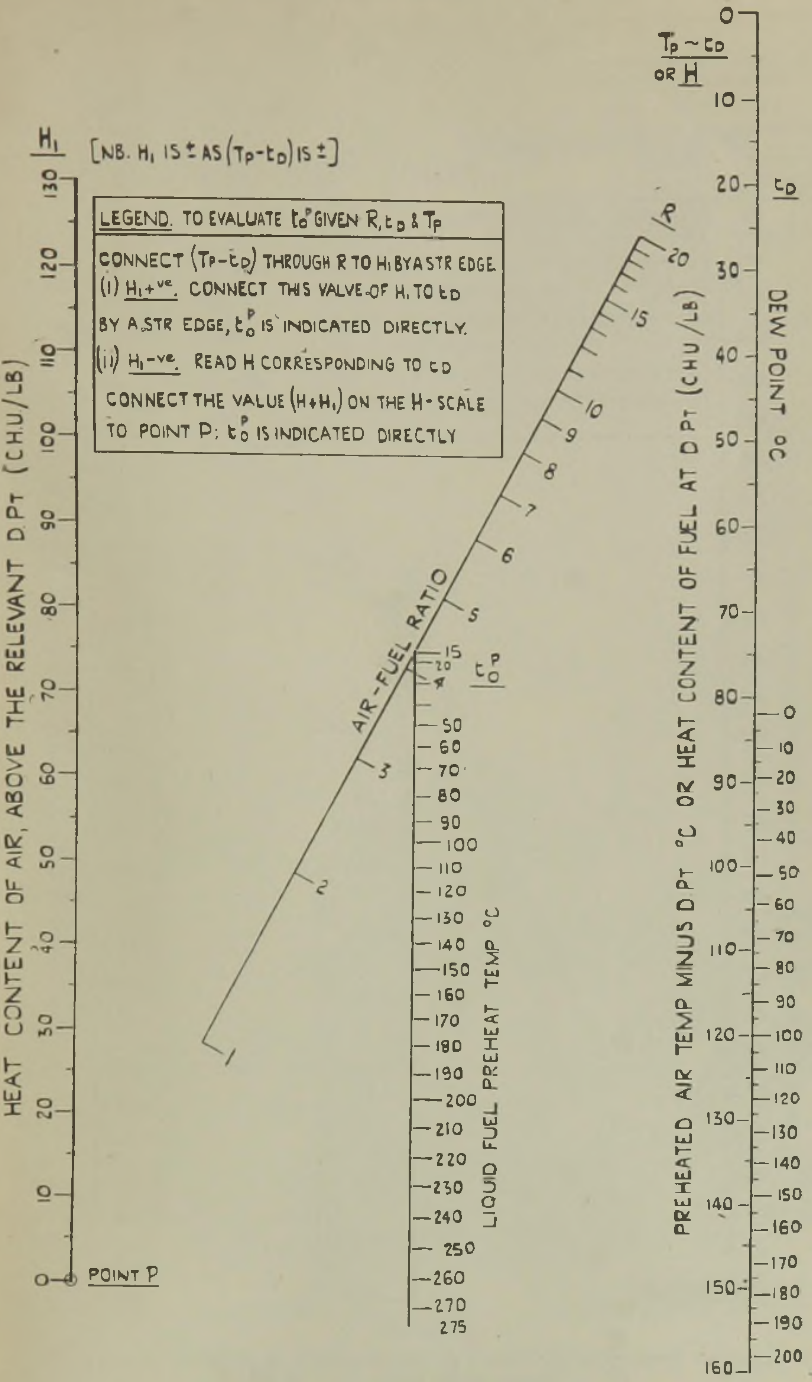
LEGEND

TO EVALUATE T_o^P FOR GIVEN R, t_D & t_P

READ OFF h CORRESPONDING TO t_p FROM THE DUPLEX SCALE (h=0 WHEN t_p=15) READ OFF H CORRESPONDING TO t_D FROM THE H/t_D NOMOGRAM SCALE & CONNECT (H-h) ON THE H-SCALE THROUGH R TO [$T_o^P - t_D$], BY A STRAIGHT EDGE ADD t_D TO THIS VALUE GIVING T_o^P

Fig. 17.

NOMOGRAM: AIR TEMPERATURE FOR VAPORIZATION OF REFERENCE KEROSINE/DEW-POINT/AIR–FUEL RATIO 5 : 1 to 20 : 1 WITH DUPLEX SCALE GIVING CORRECTION FOR FUEL PREHEATING.



[NB. H_1 IS ± AS $(T_P - t_D)$ IS ±]

LEGEND. TO EVALUATE t_0^P GIVEN R, t_D & T_P

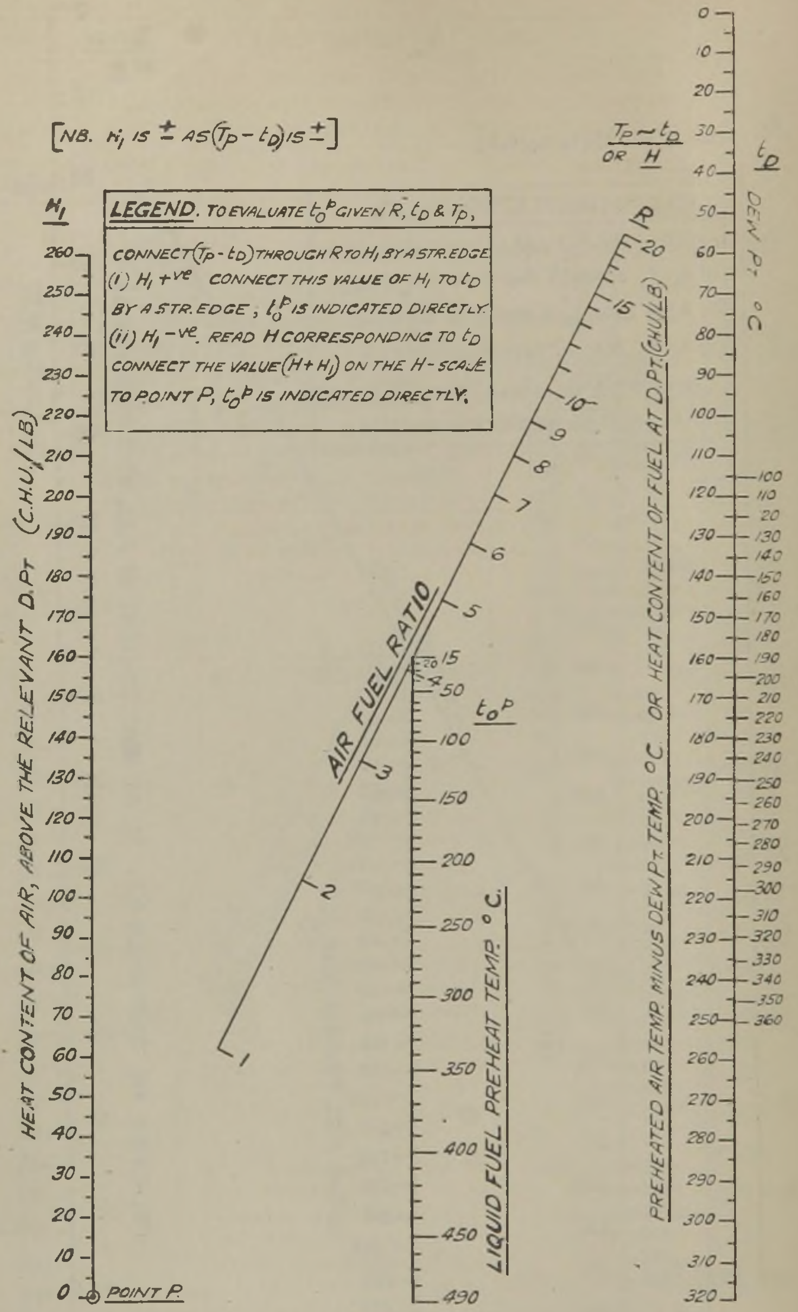
CONNECT $(T_P - t_D)$ THROUGH R TO H_1 BY A STR EDGE.

(I) H_1 +ve. CONNECT THIS VALVE OF H_1 TO t_D BY A STR EDGE, t_0^P IS INDICATED DIRECTLY.

(II) H_1 -ve. READ H CORRESPONDING TO t_D CONNECT THE VALUE $(H+H_1)$ ON THE H-SCALE TO POINT P; t_0^P IS INDICATED DIRECTLY

FIG. 18.

NOMOGRAM: FUEL TEMPERATURE FOR VAPORIZATION OF 100-OCTANE FUEL/$(T_p - t_D)$/AIR-FUEL RATIO 1 : 1 TO 20 : 1.



[NB. H_1 IS ± AS $(T_P - t_D)$ IS ±]

LEGEND. TO EVALUATE t_0^p GIVEN R, t_D & T_P,

CONNECT $(T_P - t_D)$ THROUGH R TO H_1 BY A STR. EDGE

(i) H_1 +ve CONNECT THIS VALUE OF H_1 TO t_D BY A STR. EDGE; t_0^p IS INDICATED DIRECTLY.

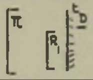
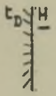
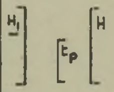
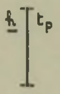
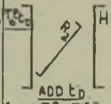
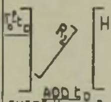
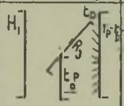
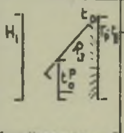
(ii) H_1 −ve. READ H CORRESPONDING TO t_D CONNECT THE VALUE $(H + H_1)$ ON THE H-SCALE TO POINT P, t_0^p IS INDICATED DIRECTLY.

Fig. 19.

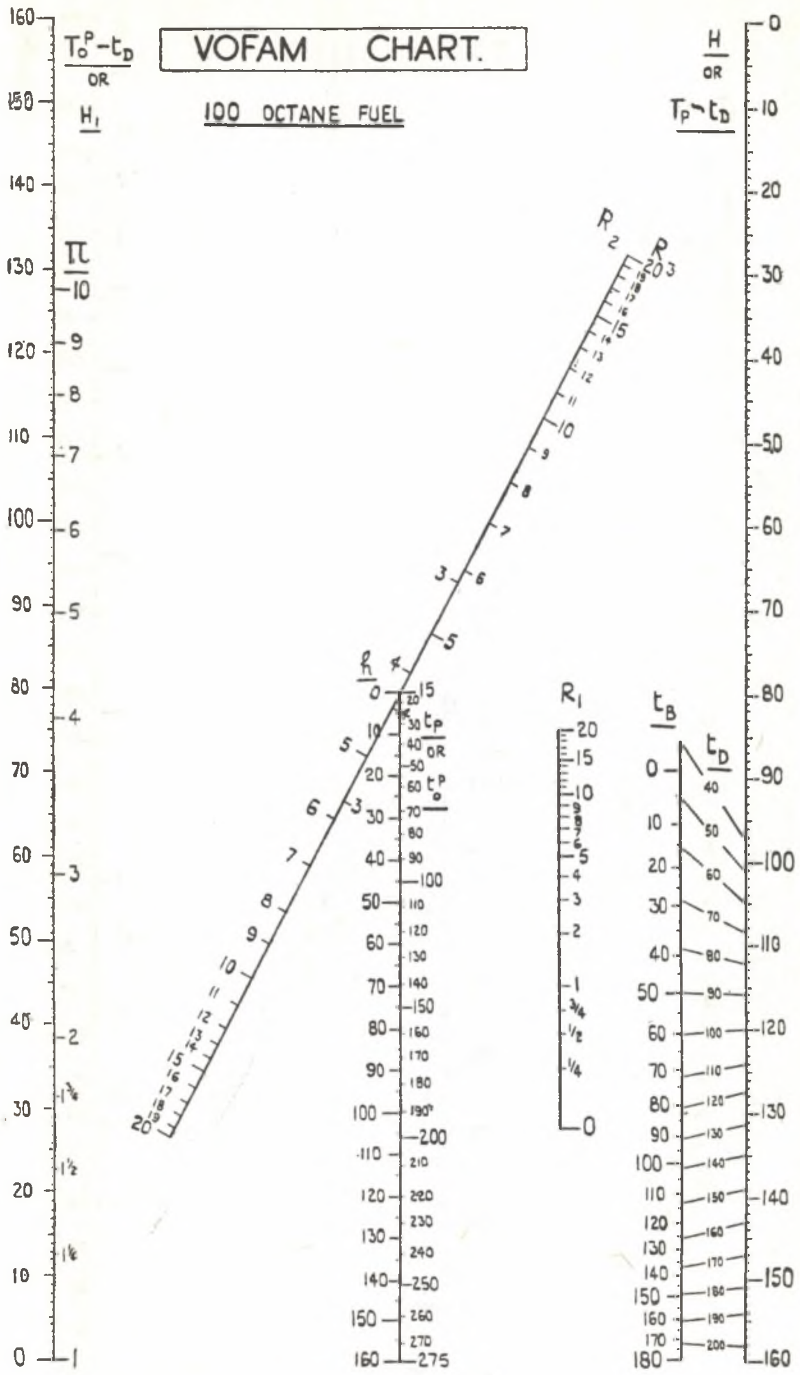
NOMOGRAM: FUEL TEMPERATURE FOR VAPORIZATION OF REFERENCE KEROSINE/$(T_p - t_D)$/AIR–FUEL RATIO 1 : 1 TO 20 : 1.

KEY TO VOFAM CHART.

FOR A GIVEN AIR-FUEL RATIO, R, AND TOTAL PRESSURE, π, EQUILIBRIUM VAPORISATION CHARACTERISTICS ARE OBTAINED FROM THE VOFAM CHART, WITHIN THE AIR-FUEL RANGE 5:1 TO 20:1 AND TOTAL PRESSURE RANGE 1-10 ATMOS. AS FOLLOWS

CHARACTERISTIC	SYMBOL	OPERATIONS.	RELEVANT SCALES.	EXAMPLE. $R=10. \pi=4.$
BUBBLE POINTS [=NORMAL BUBBLE POINTS WHEN R=0]	t_B	CONNECT π BY STR. EDGE THRO' R ON THE R_1-SCALE TO t_B AND READ.		$t_B = 8°C$
DEW POINTS. [=NORMAL DEW POINTS WHEN R=0.]	t_D	CONNECT π BY STR. EDGE THRO' R ON THE R_1-SCALE TO t_B AND READ THE CORRESPONDIND t_D FROM THE T_B/T_D DUPLEX SCALE.		$t_D = 53°C$
HEAT CONTENT OF THE VAPORISED FUEL AT THE DEW POINT TEMP. REFERRED TO A LIQUID-PHASE TEMP. 15°C.	H	FIRST DETERMINE t_D AS ABOVE, THEN READ H CORRESPONDING TO THIS VALUE OF t_D FROM THE $t_{D/H}$ DUPLEX SCALE		H = 102 C.H.U/LB.
HEAT CONTENT OF THE VAPORISED FUEL AT THE DEW POINT TEMP. REFERRED TO A LIQUID PHASE PREHEAT TEMP. t_p°C	H_p	FIRST DETERMINE H AS ABOVE THEN CONNECT H BY STR. EDGE THRO' t_p TO H_1 AND READ.	 [HERE H_1 IS H_p]	SAY t_p=100°C $H_p = 57$ C.H.U/LB.
HEAT CONTENT OF THE PREHEATED LIQUID FUEL AT t_p°C REFERRED TO 15°C [INDEPENDENT OF R & π]	$\hbar$	READ $\hbar$ DIRECTLY FROM THE $\hbar/t_p$ DUPLEX SCALE.		SAY t_p=100°C $\hbar = 45$ C.H.U/LB
MINIMUM AIR TEMP FOR VAPORISATION STARTING WITH LIQUID FUEL AT 15°C.	T_o^{15}	FIRST DETERMINE H AS ABOVE, THEN CONNECT H BY STR. EDGE THRO' R ON THE R_2-SCALE TO $[T_o^P - t_D]$ AND READ ADD t_D TO THIS VALUE GIVING T_o^{15}.	 [HERE T_o^P IS T_o^{15}]	$T_o^{15} = 41+53 = 94°C$
MINIMUM AIR TEMP. FOR VAPORISATION STARTING WITH LIQUID FUEL PREHEATED TO t_p °C	T_o^P	FIRST DETERMINE H_p AS ABOVE THEN CONNECT H_p ON H-SCALE BY STR. EDGE THRO' R ON THE R_2-SCALE TO $[T_o^P - t_D]$ AND READ. ADD t_D TO THIS VALUE GIVING T_o^P	 [HERE H IS H_p]	SAY t_p=100°C $T_o^P = 23+53 = 78°C$
MINIMUM FUEL TEMP. FOR VAPORISATION STARTING WITH AIR AT T_p °C. $[T_p > t_D]$.	t_o^P $[T_p > t_D]$	SUBTRACT t_D FROM T_p CONNECT $[T_p - t_D]$ BY STR. EDGE THRO' R ON THE R_3-SCALE TO H_1 NOW CONNECT THIS VALUE OF H_1 BY STR. EDGE TO t_D THROUGH t_o^P WHICH IS READ DIRECTLY.	 [HERE H_1 IS A PARAMETER]	SAY T_p=80°C $t_o^P = 87°C$
MINIMUM FUEL TEMP. FOR VAPORISATION STARTING WITH AIR AT T_p °C $[T_p < t_D]$	t_o^P $[T_p < t_D]$	SUBTRACT T_p FROM t_D CONNECT $[t_D - T_p]$ BY STR. EDGE THRO' R ON THE R_3-SCALE TO H_1 CONNECT THE VALUE $[H + H_1]$ ON THE H-SCALE TO 0 ON H_1-SCALE THRO' t_o^P WHICH IS READ DIRECTLY.	 [HERE H_1 IS A PARAMETER]	SAY T_p=30°C $t_o^P = 273°C$.

0-OCTANE FUEL.



KEY TO VOFAM CHART.

FOR A GIVEN AIR-FUEL RATIO, R, AND TOTAL PRESSURE, π, EQUILIBRIUM VAPORISATION CHARACTERISTICS ARE OBTAINED FROM THE VOFAM CHART, WITHIN THE AIR-FUEL RANGE 5:1 TO 20:1 AND TOTAL PRESSURE RANGE 1-10 ATMOS. AS FOLLOWS

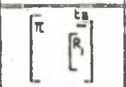
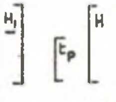
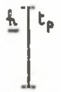
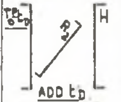
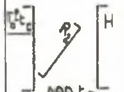
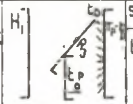
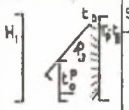
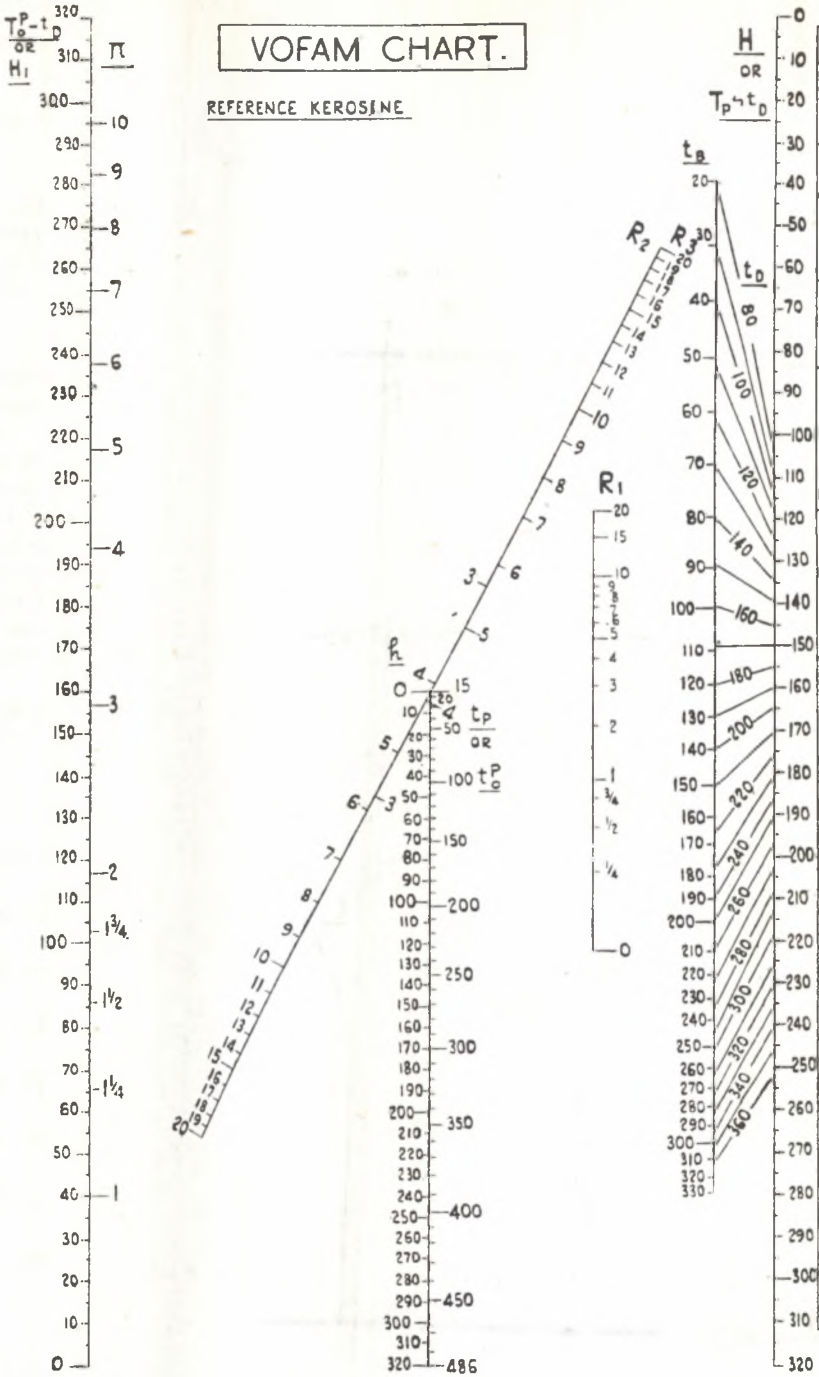
CHARACTERISTIC	SYMBOL	OPERATIONS.	RELEVANT SCALES.	EXAMPLE. R=10. π=4.
BUBBLE POINTS [=NORMAL BUBBLE POINTS WHEN R=0]	t_B	CONNECT π BY STR. EDGE THRO' R ON THE R_1-SCALE TO t_B AND READ.		t_B = 8°C
DEW POINTS. [=NORMAL DEW POINTS WHEN R=0.]	t_D	CONNECT π BY STR. EDGE THRO' R ON THE R_1-SCALE TO t_B AND READ THE CORRESPONDIND t_D FROM THE T_B/T_D DUPLEX SCALE.		t_D = 53°C
HEAT CONTENT OF THE VAPORISED FUEL AT THE DEW POINT TEMP. REFERRED TO A LIQUID-PHASE TEMP. 15°C.	H	FIRST DETERMINE t_D AS ABOVE, THEN READ H CORRESPONDING TO THIS VALUE OF t_D FROM THE t_D/H DUPLEX SCALE		H = 102 C.H.U/LB.
HEAT CONTENT OF THE VAPORISED FUEL AT THE DEW POINT TEMP. REFERRED TO A LIQUID PHASE PREHEAT TEMP. t_p °C	H_p	FIRST DETERMINE H AS ABOVE THEN CONNECT H BY STR. EDGE THRO' t_p TO H_1 AND READ.	 [HERE H_1 IS H_p]	SAY t_p=100°C H_p=57 C.H.U/LB.
HEAT CONTENT OF THE PREHEATED LIQUID FUEL AT t_p°C REFERRED TO 15°C [INDEPENDENT OF R & π]	h	READ h DIRECTLY FROM THE h/t_p DUPLEX SCALE.		SAY t_p=100°C h= 45 C.H.U/LB
MINIMUM AIR TEMP FOR VAPORISATION STARTING WITH LIQUID FUEL AT 15°C.	T_o^{15}	FIRST DETERMINE H AS ABOVE, THEN CONNECT H BY STR. EDGE THRO' R ON THE R_2-SCALE TO $[T_o^P - t_D]$ AND READ ADD t_D TO THIS VALUE GIVING T_o^{15}.	 ADD t_D [HERE T_o^P IS T_o^{15}]	T_o^{15}=41+53 =94°C
MINIMUM AIR TEMP. FOR VAPORISATION STARTING WITH LIQUID FUEL PREHEATED TO t_p °C	T_o^P	FIRST DETERMINE H_p AS ABOVE THEN CONNECT H_p ON H-SCALE BY STR. EDGE THRO' R ON THE R_2-SCALE TO $[T_o^P - t_D]$ AND READ. ADD t_D TO THIS VALUE GIVING T_o^P	 ADD t_D [HERE H IS H_p]	SAY t_p=100°C T_o^P=23+53 =78°C
MINIMUM FUEL TEMP. FOR VAPORISATION STARTING WITH AIR AT T_p °C. [$T_p > t_D$]	t_o^P [$T_p > t_D$]	SUBTRACT t_D FROM T_p CONNECT $[T_p - t_D]$ BY STR. EDGE THRO' R ON THE R_3-SCALE TO H_1 NOW CONNECT THIS VALUE OF H_1 BY STR. EDGE TO t_D THROUGH t_o^P WHICH IS READ DIRECTLY.	 [HERE H_1 IS A PARAMETER]	SAY T_p=80°C t_o^P = 87°C
MINIMUM FUEL TEMP. FOR VAPORISATION STARTING WITH AIR AT T_p °C [$T_p < t_D$]	t_o^P [$T_p < t_D$]	SUBTRACT T_p FROM t_D CONNECT $[t_D - T_p]$ BY STR. EDGE THRO' R ON THE R_3-SCALE TO H_1 CONNECT THE VALUE [H + H_1] ON THE H-SCALE TO 0 ON H_1-SCALE THRO' t_o^P WHICH IS READ DIRECTLY.	 [HERE H_1 IS A PARAMETER]	SAY T_p=30°C t_o^P=273°C

Fig. 20.

VOFAM CHART FOR 100-OCTANE FUEL.

[*To face p.* 68.



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CHARACTERISTIC	SYMBOL	OPERATIONS	RELEVANT SCALES.	EXAMPLE R=10 π=4
BUBBLE POINTS. (=NORMAL BUBBLE POINTS WHEN R=0)	t_B	CONNECT π BY STR EDGE THRO' R ON THE R_1-SCALE TO t_B & READ.	π R_1 t_B	t_B=93°C.
DEW POINTS (=NORMAL DEW POINTS WHEN R=0)	t_D	CONNECT π BY STR EDGE THRO' R ON THE R_1-SCALE TO t_B AND READ THE CORRESPONDING t_D FROM THE t_B/t_D DUPLEX SCALE.	π R_1 t_D	t_D=154°C
HEAT CONTENT OF THE VAPORISED FUEL AT THE DEW-POINT TEMP REFERRED TO A LIQUID-PHASE TEMP. 15°C	H	FIRST DETERMINE t_D AS ABOVE THEN READ H CORRESPONDING TO THIS VALUE OF t_D FROM THE t_D/H DUPLEX SCALE	t_D H	H=141½ C.H.U/LB
HEAT CONTENT OF THE VAPORISED FUEL AT THE DEW-POINT TEMP REFERRED TO A LIQUID-PHASE PREHEAT TEMP t_p°C:	H_p	FIRST DETERMINE H AS ABOVE THEN CONNECT H BY STR EDGE THRO' t_p TO H_1 AND READ.	H_1 t_p H (HERE H_1 IS H_p)	SAY t_p=100°C H_p=98½ C.H.U/LB
HEAT CONTENT OF THE PREHEATED LIQUID FUEL AT t_p°C REFERRED TO 15°C (INDEPENDENT OF R & π)	h	READ h DIRECTLY FROM THE h/t_p DUPLEX SCALE	h t_p	SAY t_p=100°C h=43 C.H.U/LB
MINIMUM AIR TEMP FOR VAPORISATION STARTING WITH LIQUID FUEL AT 15°C	T_o^{15}	FIRST DETERMINE H AS ABOVE THEN CONNECT H BY STR. EDGE THRO' R ON THE R_2-SCALE TO $(T_o^P - t_D)$ AND READ ADD t_D TO THIS VALUE GIVING T_o^{15}.	$T_o^P - t_D$ R_2 H ADD t_D (HERE T_o^P IS T_o^{15})	T_o^{15} = 59+154 = 213°C
MINIMUM AIR TEMP FOR VAPORISATION STARTING WITH LIQUID FUEL PREHEATED TO t_p°C.	T_o^P	FIRST DETERMINE H_p AS ABOVE THEN CONNECT H_p ON H-SCALE BY STR EDGE THRO' R ON R_2-SCALE TO $(T_o^P - t_D)$ AND READ. ADD t_D TO THIS VALUE GIVING T_o^P	$T_o^P - t_D$ R_2 H ADD t_D (HERE H IS H_p)	SAY t_p=100°C T_o^P = 41+154 = 195°C
MINIMUM FUEL TEMP FOR VAPORISATION STARTING WITH AIR AT T_p°C $(T_p > t_D)$	t_o^P $(T_p > t_D)$	SUBTRACT t_D FROM T_p CONNECT $(T_p - t_d)$ BY STR. EDGE THRO' R ON R_3-SCALE TO H_1. NOW CONNECT THIS VALUE OF H_1 BY STR. EDGE TO t_D THRO' t_o^P WHICH IS READ DIRECTLY	H_1 t_D R_3 t_o^P $T_p - t_D$ (HERE H_1 IS A PARAMETER)	SAY T_p=180°C t_o^P=162°C.
MINIMUM FUEL TEMP FOR VAPORISATION STARTING WITH AIR AT T_p°C $(T_p < t_D)$	t_o^P $(T_p < t_D)$	SUBTRACT T_p FROM t_D. CONNECT $(t_D - T_p)$ BY STR EDGE THRO R ON R_3-SCALE TO H_1 CONNECT THE VALUE $(H + H_1)$ ON THE H-SCALE TO 0 ON H_1-SCALE THRO' t_o^P WHICH IS READ DIRECTLY	H_1 t_D R_3 t_o^P $T_p - t_D$ (HERE H_1 IS A PARAMETER)	SAY T_p=100°C t_o^P=429°C

FIG. 21.
VOFAM CHART FOR REFERENCE KEROSINE.

[To face p. 68.

the state of the fuel from liquid to vapour. The following equation covers both eventualities :—

$$\overset{15-t_p}{C} (t_0{}^p - 15)\, h_{t_p} = H_{t_D} + R \,.\, \overset{T_p-t_D}{C_a} (t_{D_R} - T_p) \quad . \quad . \quad (32)$$

6.5. *Results for* 100-*Octane Fuel and Reference Kerosine.*

Equations 29 to 32 have been evaluated for the two standard fuels, and the results have been presented as a set of six nomograms with auxiliary duplex scales, to make full use of the simplicity and elegance which this method of presentation can offer for such equations—see Figs 14 to 19.

7. *VOFAM Charts for* 100-*Octane Fuel and Reference Kerosine.*

Two multiple nomograms, Figs 20 and 21, termed VOFAM charts have been devised, one for each fuel, from which nine vaporization functions may be quickly obtained by the use of a straight edge.

The charts consist of five parallel scales and one slanting scale, and were chosen, after more than a dozen alternative designs had been considered, for possessing the greatest simplicity and being the most direct to read.

The VOFAM chart is necessarily somewhat complicated, but when it is realized that it summarizes the substance of at least a dozen equations, or as many sets of curves, the saving of labour made possible by this method of presenting the data will be apparent. A comprehensive key has been designed to overcome any difficulties, and has been placed in juxtaposition with the chart.

From these charts it is possible to read off the following equilibrium vaporization characteristics for any air–fuel ratio in the range 5 : 1 to 20 : 1 and total pressure in the range 1 to 10 atmospheres :—

(1) Bubble-point.
(2) Dew-point.
(3) Heat content of the vaporized fuel at the dew-point referred to a liquid-phase temperature, 15° C.
(4) Heat content of the vaporized fuel at the dew-point referred to a liquid-phase preheat temperature, t_p ° C.
(5) Heat content of the preheated liquid fuel at t_p ° C referred to 15° C (independent of R and π).
(6) Minimum air temperature for vaporization starting with liquid fuel at 15° C.
(7) Minimum air temperature for vaporization starting with liquid fuel at t_p ° C.
(8) Minimum fuel temperature for vaporization starting with air at T_p ° C. ($T_p > t_D$).
(9) Minimum fuel temperature for vaporization starting with air at T_p ° C ($T_p < t_D$).

It is considered that all of these functions have been estimated to within ± 10 per cent, and in many cases to within ± 5 per cent.

8. CONCLUSIONS.

This report concludes the theoretical study of the vaporization of air–fuel mixtures.

In order to approach the problem it has been necessary to consider idealized conditions, and this means that in practice where equilibrium conditions are only approximately reached and heat transfer and thermal insulation are imperfect, deviations from the calculated results will occur.

Such results do, however, offer the best general means for the comparison of the suitabilities of different fuels for a combustion system, as judged purely from the vaporization standpoint.

Many futile attempts have been made to express the general volatility of a fuel by a single number : here, however, an attempt has been made to express the general volatility by a single chart.

The minimum heat quantities for vaporization at the dew-point have been considered throughout, and it is believed that the term " minimum " assumes a double meaning when the results are applied to practice. In other words, the deviations due to imperfect mixing and heat transfer will usually outweigh those due to the failure to reach true equilibrium—conditions, with the consequence that an extra heat quantity will be required to achieve vaporization.

In the case of a conventional combustion chamber, once ignition has taken place, the question of whether the fuel will vaporize is transformed into—how long does the fuel take to vaporize? The latter question automatically involves such factors as the nature of the atomization, the rates of evaporation of the fuel droplets, the heat transfer to the droplets and the relative velocity between the air and the droplets. The information given by the VOFAM Charts contributes to this more general problem by quantitatively differentiating between the various fuels and defining the heat requirements for vaporization over a wide range of conditions, thus rendering the " fuel " variable completely determinate.

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