

INTRODUCTION: Despite years of research on engines, it appears that only recently has it become possible to solve the riddle of knocking in the gasoline engine, physically at least, and to answer the question whether knocking is a real detonation with super-sonic speed and corresponding super-pressures¹⁾. Although knocking is crudely designated as detonation, especially abroad, the latest work, especially that by Weinhard²⁾, has shown that knocking has nothing to do with detonation, but is to be explained by spontaneous ignition. Therefore, we have to think of the process of knocking as the advance of the flame front in the combustion chamber compressing the remainder of the mixture more and more, heating it until the pressures and temperatures necessary for self-ignition are reached. At this instant the remainder of the mixture burns more or less instantaneously, with the result that there is a sudden (generally small) rise in pressure, which sets the whole body of gas vibrating in sympathy. As the speed of sound at the combustion temperatures is in the region of 1000 m/s, and the combustion chambers generally have a diameter of about 10 cm., the natural frequency amounts to several 1000 Hertz, and the vibration is perceptible outside as a hard impact.

Whereas scientists are more interested in the theory of knocking in all its details, in practice it is more a question of finding a satisfactory and sufficiently accurate knock-measuring device, which could replace the aural method, still in wide use, by an objective deflection of an instrument. Above all, it is the limit of the beginning of knocking, that is, of the super-charging, compression, etc., up to which the engine can be loaded without danger, that is important. The classical method of measuring knocking is that of determining the octane number with the aid of a bouncing pin, but in view of the justifiable general criticism (see A. von Philippovich³⁾, G. Schütz⁴⁾), it cannot continue in use much longer. Persistent attempts were made in many test installations to use the above-mentioned gas oscillations for measuring knocking. As regards this, it may be said that, while the oscillations in general are the result of knocking, they cannot be used to define spontaneous ignition, i.e., knocking. It can be imagined that knocking could occur without vibrations, and it has already been proved (Boerlage, Broeze, van Driel, Pelotier⁵⁾) that even with very violent knocking vibrations there exist certain nodal points in the combustion chamber having zero amplitude. Apart from this, the measurement of vibrations is difficult because of the necessity for filtering out certain frequencies: as Stanton and MacGoul⁶⁾ have established, the intensity of knocking, if measured with a microphone or similar device, varies with the frequency range selected. In the same way one can detect the onset of knocking at various compressions or degrees of supercharge, and therefore not at any absolute fixed point, according to the sensitivity of the amplifier. Schütz⁴⁾ came to a similar conclusion, and indicated the possibility of interference from the other engine noises. Still, this method is the only means of determining the intensity of knocking even roughly, if provision is not made for fitting an additional indicator (see A. W. Schmidt⁷⁾). There have also been various attempts made to determine knocking from alterations in the pressure diagram. It is already a well-known fact that the changes brought about by a slight degree of knocking are very small in the pressure-time diagram, and can only be observed by a practised eye. Therefore, Dodds⁸⁾, Illgen and Hintz⁹⁾ carried out the electrical differentiation of the pressure diagram, thus detecting a certain difference in amplitude between knocking and the absence of knocking. Attempts by the author, and also by Schütz, have not succeeded in making these differences sufficiently large to justify the replacement of the aural method. Therefore, in an earlier work

the authors proposed 20) to draw d^2p/dt^2 diagrams, that is, to perform a second electrical differentiation, which should magnify the difference between knock and no knock to a substantial order of magnitude, and further to make it possible to determine incipient knocking objectively, thus, if the d^2p/dt^2 is plotted against boost pressure, the resulting curve has a definite kink at incipient knocking. The processes discussed so far only show a rise in the amplitude of the knock intensity, whose initial value (corresponding to the onset of knocking) has to be fixed arbitrarily each time. On the other hand, the kink in the d^2p/dt^2 curve represents a clear pressure limit; as soon as the boost pressure oversteps the line of demarcation, the engine will knock, while at lower pressures combustion is knock-free.

Before proceeding to the main section of this work, namely, the description and method of using this process, mention should be made of a very interesting proposal by Schütz 4), which has so simplified the measurement of the speed of combustion by the Schnauffer 1) method, by means of a practical circuit, that it can be used for measuring knocking directly. Schütz also established the presence of a kink in the compression or super-charge curve, which might prove to be the same as that which was observed in the d^2p/dt^2 method, as further described below.

Description of the D.V.L. Pressure Acceleration Method

Any electrical indicator will serve as a transmitter for a recording instrument, provided it is robust enough to withstand shock and strains due to knocking 22). The quartz indicator is especially suitable for this purpose, and is the only one in use at D.V.L. With any other system the input of the amplifier would have to be suitably modified.

It is also possible in principle to differentiate the pressure diagram graphically, and this method is at present preferable, particularly for determining the absolute magnitude in atm./sec. or atm./sec². The graphical method is, however, too elaborate for practical use, and should therefore be replaced by an automatic, that is, an electrical differentiation. This can be done as in Figure 1. The value to be measured, e.g. dp/dt , is fed into the grid of an amplifier tube, so that its anode current i is exactly proportional to dp/dt . If a choke coil is now connected to the anode circuit, then the voltage at its ends is $L di/dt$, or proportional to d^2p/dt^2 . This differentiation is accurate if the resistance of the choke is negligible and it has a small capacity, and provided the anode current is not affected. The initial voltage, which corresponds to d^2p/dt^2 , is now indicated on the oscillograph (Cathode ray tube), and is there observed or photographed. It appeared that the deflections of the individual combustion diagrams fluctuate a great deal, being actually more than double with knocking. To begin with, about 30 combustion diagrams were photographed at once, and the graphic mean was calculated. Later, this was done electrically by means of a condenser, which is gradually charged by the knocking impulses, and the voltage of which is recorded via an amplifier tube by a measuring apparatus. When the resistances and condensers have been equalised, this process works so well that the current, which corresponds to the degree of knocking, can be recorded by a recording instrument throughout the series of measurements. Figure 2 shows such a curve,

which not only has the advantage of being an objective record, but also demonstrates the frequent fluctuations in the behaviour of the engine during measurements. The variation of the individual points makes it clear that the behaviour of the engine altered whilst the fuel was running out of the gauge-glass, a fact easily overlooked without the recorder and leading to inaccuracies in the curves. The extraordinary sensitivity of the d^2p/dt^2 measurement led to finer adjustment of the engine, and showed that in measuring knocking exactly, not only must the excess air ratio be maintained at about 2%, but also that the temperature of the mixture, the temperature of the cylinder wall, etc., must be kept constant.

To establish the point at which knocking begins a whole series of settings with rising boost pressure is photographed, and the mean values for d^2p/dt^2 are then superimposed on the boost-pressure. Apart from boost pressure, any other engine factor can be used which, if increased, will definitely stimulate knocking, e.g., compression or mean effective pressure. Although it can be established theoretically that the use of Super-charge as an abscissa will provide a clearer picture, in many cases it is useful to plot against p.m.e. to have some idea of the M.E.P. attained in the tests. In the curve constructed in this way there is a kink or irregularity at the beginning of knocking, as can be seen from the illustrations at the end of the report. In the experience of D.V.L., the accuracy of the photograph considerably influences the accurate observation of the kink, as do also the intervals between the points measured and the scale of the abscissa and ordinate. In case of doubt, a repetition of the series of measurements would clarify the picture, and it must be emphasised here that the good reproducibility of the process could be proved from the agreement in the measurements after a lapse of months 10; tests repeated in doubtful cases showed either an improvement in the measurement of a doubtful point, or a change in the knock behaviour of the engine, due to the fact that one of the engine factors had been disregarded. The beginning of knocking was determined with an accuracy of ± 20 mm. Hg. even in the most unfavourable cases, while in most of the measurements it was ± 5 mm. Hg., which is a great improvement on the degree of error when the aural method is used in heavy engines, such as the C.F.R. engine. It is an essential requirement that the supercharge be altered in small stages (30 to 50 mm. Hg.), which is of course bound up with an increase in the time required to complete the test.

III - Physical Conditions.

1. Amplitudes of the pressure functions.

In order to appreciate the method, it is necessary to understand the physical processes going on. To this end, individual pictures were made with great care of the p-t, dp/dt and d^2p/dt^2 diagrams at various supercharges in the C.F.R. engine with a commercial fuel OZ 87. These clearly showed that the individual functions vary with the intensity of knocking. The amplitudes of these three functions are shown in Figure 3 (see F. Seeber 13). As the boost pressure increases, the values for $p = f(t)$ and dp/dt show a linear or curviform rise. There is no unsteadiness in the course of these characteristic curves. On the other hand, the measurement of d^2p/dt^2 has a pronounced kink. In Figure 3, the values are taken from the p-t or dp/dt diagram, and agree well with the electrically differentiated dp/dt or d^2p/dt^2 measurement. Whereas the pressure diagram has gentle curves everywhere when there is no knocking (Figure 4), as the knocking increases in intensity there are increasingly steep curves. The reversion of the curve at the pressure-peak

after top dead centre becomes increasingly sharp. The derivatives behave in the same way; from no knocking to intense knocking, dp/dt increases from $1 \cdot 10^4$ atm./sec. to two or three times this value ($3 \cdot 10^4$ atm./sec.). The point of the greatest rate of alteration in pressure moves from the steep climb to the peak (Figure 4). As already mentioned, this increase in amplitude is insufficient to measure the knocking exactly, since when the differences in knocking are small they are submerged in the general fluctuations of each gasoline engine. The second derivative shows much greater differences. According to Figure 4, this increases from $6.5 \cdot 10^6$ to $55 \cdot 10^6$ atm./sec.² (these figures are for the negative deflection, the positive one actually increases in the ratio 1:20). According to Figure 4, the greatest deflection of d^2p/dt^2 is at the pressure peak when there is no knocking and not in the rising curve as Schütz 4) supposes. The effectiveness of measuring d^2p/dt^2 is due to the fact that the peak of the pressure curve after top dead centre can be quantitatively established by the second derivative, which is closely linked mathematically with the radius of the bend.

The series of tests referred to above was later repeated with a knock-free fuel at a high engine speed, and in particular with a more sensitive amplifier. In Figure 5 are the instantaneous values for the respective diagrams at the various super-charge pressures. The single picture $p = 100$ mm. Hg. was unfortunately taken on a larger scale. In the original diagram, $p = 300$ mm. Hg. knock vibrations can be seen on the expansion curve of frequency 5000 herz. There are clearer copies of this diagram available. The waves at the zero line of the pictures dp/db and $d^2p/dt^2 + 300$ are not to be confused with the actual knock vibrations, since the former are caused by the mechanical grid oscillations of the amplifier tubes. These diagrams show differences in amplitude of 1:10 for dp/dt and of over 1:100 for d^2p/dt^2 . The abscissa magnitudes atm./sec. and atm./sec.² are entered on the right edge, the values for simple pressure (atm.) are entered in the diagrams.

2. Theoretical basis of the kink which accompanies the onset of knock.

W. Jost, Freiherr von Müffling, W. Rohrmann¹⁴⁾, and W. Jost¹⁵⁾ with F. A. F. Schmidt¹⁶⁾ established mathematical relationships for the consumption of gas mixtures, of which only the basic formulae are important for present purposes.

From a few calculations it is possible to obtain an expression for the rise of pressure brought about by the progress of combustion. There is no need to go into the details of the calculation here, especially as the necessary simplification precludes close agreement with practical conditions. It is enough for present purposes to establish the relationship $p = f(t, p_0, T_0)$, p being the cylinder pressure at time t , p_0 the initial pressure (intake pressure) and T_0 the initial temperature. The function f , which includes the increase in compression caused by the movement of the piston, and many variable engine factors, and which is therefore only valid for a certain condition of the engine, obeys laws of combustion which are established mathematically on the basis of the formulas mentioned above. As soon as the conditions of combustion are fundamentally changed, with the occurrence of knocking at a point dictated by spontaneous ignition, the function f is replaced by another :-

$p = F(t, p_0, T_0)$, where the values of p for the instant of spontaneous ignition must be the same for both functions. As was already mentioned in the practical exposition, the differences in amplitude of the p - functions are very slight, which is illuminating, since even with violent knocking, spontaneous ignition does not occur till the final stage of the combustion of the mixture, and can only alter the speed of combustion. The available combustion energy (calorific value in calories) is the same with or without knocking, therefore as compared to the condition of no knocking there can only be a certain increase in pressure, caused by the conversion of the last combustion calories closer to dead centre, that is, at a higher rate of compression. Local rises in pressure are left out of the calculation here, for owing to the equalisation of pressure, which occurs at the speed of sound, these only come into the picture if we are considering processes which last for a time shorter than 10^{-4} sec., and consequently cannot be recorded by the majority of indicators.

The slight alteration in the shape of the p - t function is transformed into an alteration in amplitude by a differentiation. The result of the sudden combustion of the residue, and the instantaneous rise in pressure, should in theory result in an infinitely great first differential. Actually, spontaneous ignition also occupies a certain time, so that however intense the knocking, the first differential remains finite.

The second differential reacts much more strongly to this unsteadiness, and higher differentials would give even greater deflections. But in view of the excessive distortions, it is better to remain at the second differential, which can still be presented with sufficient accuracy, and, as the tests show, is adequate for measuring knock. If we superimpose the d^2p/dt^2 maximum amplitudes on the values of initial pressure p_0 , the result is a steady curve, corresponding to the function d^2f/dt^2 . As soon as combustion conforms to the function d^2f/dt^2 , that is to say, there is knocking, the curve changes its character, and an irregularity appears, characterised by the above-mentioned kink.

The identification of the onset of knock by the kink really consists only in rendering visible the irregularity which takes place in the combustion as it changes over to knocking. It is interesting that in addition to the pressure function, it is possible to enter another function, viz., that of the speed or time of combustion; this was investigated by Schütz, who found the same, or a similar kink. In practice the Schütz process would have the disadvantage of requiring 2 cylinder bores.

IV - ENGINE TESTS.

The D.V.L. method of using the second derivative to determine the knocking tendency was used in practice on two different single-cylinder test engines for fuels of octane number 87 and above. Both of them, a C.F.R. engine and a B.M.W.132 single-cylinder aero-engine, were equipped with a super-charger.

1. Physico-chemical properties of the fuels investigated, and their octane numbers.

3 fuel mixtures, all of different chemical structure, with an octane number of 87, and a fuel with an octane number of 100 were selected to test the DVL process of pressure acceleration. Their properties are set out in the following table:-

Fuel	Technical Iso-octane	75% technical iso- octane + 25% avia- tion gasoline	75% benzole + 25% avia- tion gasoline	47% ethyl- alcohol + 53% aviation gasoline
Record No. (B.M.W. knock- limit curves)	216	218	221	222
Density at 20°C.	0.700	0.704	0.828	0.747
Ref. Index at 20°C.	1.3980	1.3990	1.4732	1.3810
C/H Ratio	5.4	5.6	8.9	5.1
Theoretical air requirements Kg/Kg.	1.502	14.95	13.66	12.44

Distillation by the A.S.T.M. method.

I.B.P.°C.	96	70	67	51
at 60°C. % v.	-	-	-	4.0
70°C. %	-	-	-	36.0
80°C. %	-	2.0	13	96.0
90°C. %	-	13.0	55	-
100°C. %	5.0	41.0	76	-
110°C. %	90.0	81.0	85.0	-
120°C. %	-	94.5	90.5	-
121°C. %	98.0	-	-	-
130°C. %	-	97.5	94.5	-
135°C. %	-	98.3	-	-
140°C. %	-	-	-	98
141°C. %	-	-	98.2	-
Residue	1.3	1.0	1.0	1.2
Loss	0.7	0.5	0.8	0.8

The octane numbers and the compression at the onset of knock of the four different fuels which were investigated in the C.F.R. engine were as follows :-

Fuel	motor method		Research method	
	octane no.	Onset of knock	octane no.	Onset of knock
Technical iso-octane	97.5	6.96:1	95.9	6.27:1
75% Technical iso-octane 25% aviation gasoline	88.7	5.81:1	89.1	5.70:1
75% Benzene 25% aviation gasoline	88.9	5.88:1	98.6	6.61:1
47% Ethyl alcohol 53% aviation gasoline	89.7	5.82:1	99.8	6.81:1

2. Test engines and conditions.

The particulars of the two test engines used are given below :-

	C.F.R. Engine	B.M.W.152 single cylinder aero-engine
Swept volume cm ³	611	3076
Compression ratio	6.5:1	6.5:1
Shape of combustion chamber	Disc-shaped	skull-cap shaped
Material	Cast-iron piston	Right metal piston
Sparking plugs	1	2
Ignition	battery	magneto
Coolant	distilled water	air
Intake valve	screened	normal
Valve overlap	21° Crank angle	41° crank angle
pre-heating introduction of fuel	mixture heating carburettor	air heating injection

The table which follows shows the test conditions observed when testing the fuels.

	Test conditions for	
	C.F.R. engine.	B.M.W.132 single cylinder aero-engine
Throttle setting	Full throttle	Full throttle
Engine speed	600	1600
Ignition crank angle	constant 12.5	variable optimum. ignition for $\phi = 0.7$; 0.9; 1.1. 1.3 with knock-free combustion.
Cooling air pressure mm. water column	-	200
Coolant temperature °C.	100	25-30
Boost air temperature °C.	-	80
Temperature of mixture °C.	80	-
Mixture strength ϕ	0.7 - 1.3	0.7 - 1.3
Measurement of knocking	1. Determining the 2nd derivative. 2. Onset of knock determined aurally. First regular knocking. Constant number of impacts per minute.	

3. Test results.

(a) Influence of various test conditions on the moment when a fuel begins to knock.

In order to ascertain the reproducibility of the test results with the D.V.L. Pressure Acceleration Method, it was first necessary to determine how far alterations in the test conditions of the engine affected the d^2p/dt^2 measurement.

All the results of the tests, and thus the knock limit curves described later, were determined in the following manner.

As already stated, it is not possible to measure the beginning of knocking directly by means of the d^2p/dt^2 measurement; the d^2p/dt^2 curve must first be plotted under increasing super-charge for each knock onset at a certain mixture strength. At least 5 or 6 measuring points at various super-charges are necessary in order to plot this auxiliary curve; two or three of them must be in the knock-free region. When the individual d^2p/dt^2 points are joined, the onset of knock is found at the kink in the characteristic curve, being expressed as mm.Hg. of boost pressure, or in Kg./cm² mean effective pressure.

These characteristic curves are shown in Figure 6. The kinks in the characteristic curves can be read off directly as boost pressures or mean effective pressures.

Figure 6 further shows that the mixture strength only deviates from the value of $\lambda = 0.9$, which must be maintained in this case, within narrow limits. This presentation also shows that the kink in the characteristic curve always occurs roughly at that point where the incidence of knocking as determined aurally was 8 to 10 sharp knocks per minute. This was confirmed by all the other characteristic curves for the B.M.W. aero-engine single cylinder. Figure 7 shows the d^2p/dt^2 characteristics for technical iso-octane at various test conditions in the B.M.W. 132 single-cylinder aero-engine. The effect of the

mixture strength,	} measured at a
boost air temperature	
ignition	
compression and engine speed	
	constant mixture
	strength of 0.9

was investigated.

The increase in permissible boost pressure with falling boost air temperature, the reduction in boost pressure as ignition advance is increased, as well as the sharp fall in boost pressure as compression rises are clearly expressed by the shifting of the kinks in the auxiliary characteristic curves. The increase in engine speed from 1200 to 1600 r.p.m. also causes a rise, however slight, in boost pressure. This agrees with what was generally expected. If the engine speed is further increased, technical iso-octane, which was used in these tests, causes a fall in boost pressure at the knock limit in the B.M.W. 132 single-cylinder air engine. How far this phenomenon is due to the fuel and how far to the test engine is a question which will be the subject of future investigations, which are outside the scope of the present work. Investigations are being made in this direction. The supercharge value at the onset of knock (pm_0) for the excess air ratios $\lambda = 0.7; 0.9; 1.1$ and 1.3 can be taken from the four auxiliary characteristic curves for technical iso-octane. The result is the knock limit curve as a function of the excess air ratio and the mean effective pressure, which appears in the same illustration. The test conditions for this knock limit curve are the same as for the B.M.W. 132 single-cylinder aero-engine.

Figure 8 shows the characteristic curves for d^2p/dt^2 , again for technical iso-octane, under various test conditions, such as occur in the C.F.R. engine. In the C.F.R. engine tests the absolute boost pressure in mm.Hg. was used instead of M.E.P., as the brake horse-power was not measured on the C.F.R.

From the four kinks in the mixture strength characteristic, the knock limit curve can be established in terms of the mixture strength. This characteristic is included in Figure 8.

The B.M.W. 132 tests were repeated on the C.F.R. by varying the compression ratio. A rise in compression ratio corresponds to a fall in boost pressure. From the test results with various mixture temperatures and ignition timings, the boost pressure (abs.) at the knock limit reached a minimum at a mixture temperature of 800°C. and an ignition advance of 12.5° crank angle B.T.D.C. The minimum value of mixture temperature is probably determined by the mixture distribution in the C.F.R. engine. The tests were repeated, and the sequence found to be the same. Within the range of engine speeds selected for these tests (600 to 1200 r.p.m.) with technical iso-octane the limiting boost pressure could be raised with increasing

engine speed. Finally, increasing the coolant temperature produced a fall in boost pressure.

All these results obtained by the D.V.L. pressure acceleration method show that very variable running conditions considerably affect the knock behaviour. The d^2p/dt^2 results reveal any alteration in the test conditions, and may therefore be considered a reliable indication of the knock properties of fuels, as compared with the results obtained by the aural method.

(b) Knock limit curves of different fuels by the pressure acceleration method and the aural method.

Knock limit curves at various mixture strengths were plotted for the four fuels named above in the B.M.W. 132 single cylinder and the C.F.R. engine by the pressure acceleration method and the aural method (see Figure 9). The test conditions were those laid down in Section IVb.

These results showed, in the first place that there was good agreement between the measurements by the pressure acceleration method and those by the aural method, especially in the B.M.W. single-cylinder aero-engine. The onset of knocking was generally very hard to determine aurally in the C.F.R. engine, or was very indistinct, especially with fuels which are predominantly aromatic (curve 3). It must also be emphasised that in the region of 20% to 30% excess air in the B.M.W. 132 single-cylinder aero-engine the beginning of knocking always appears to occur earlier with the pressure acceleration method than with the aural method.

Secondly, with both test engines, the fuels under test are rated in a different order than their C.F.R. octane numbers would lead one to expect. Technical iso-octane (octane number 100) is less knock-free in both test-engines (curve 1), judged by the D.V.L. test (super-chargeability at incipient knock¹²) than the blends with motor benzole or ethyl alcohol (curve 3 and 4), although the latter have an octane number of 87. The mixture which is predominantly iso-paraffinic, and which also has an octane number of 87 (curve 2), has the lowest super-chargeability.

Thirdly, it must be emphasised that the 4 fuels are rated in the same order in both the B.M.W. 132 and the C.F.R. engine. Admittedly the range of super-charging of the fuels was about 1/3 greater, at 225 mm., in the B.M.W. 132 than in the C.F.R. engine. This might be due to the structural difference between the two test engines and the difference in mixture distribution or ignition.

It is specially interesting that curves 3 and 4 intersect at practically the same mixture strength. the D.V.L. pressure acceleration method makes it possible to establish quickly the onset of knock, whether this was established distinctly, or very indistinctly, aurally.

Figure 10 shows the results in both test engines with the four test fuels, by both methods, with percent super-charge as a function of the mixture strength. The reference point selected (100%), was in both engines the super-charge pressure at the onset of knock, when using technical iso-octane at $\lambda = 1.1$. The absolute super-charge for technical iso-octane (reference) point is 960 mm. Hg. in the B.M.W. 132, and 795 mm. Hg. in the C.F.R. engine.

This method of presentation has the advantage that the test results in both engines are assessed on the basis of the same fuel, and can therefore be directly compared. The order in which the fuels are rated is the same as in Figure 9. This presentation also shows the effect of the different designs of the engines. It is possible to compare the individual characteristic curves directly, since the individual test points obtained aurally are confirmed by the objective D.V.L. method.

V - CRITICISM AND CONCLUSIONS.

In contrast to other methods of measuring knocking, the pressure acceleration method is not only more sensitive, but is also an objective indication of the onset of knock. Over and above this, it is possible to measure knocking on an absolute scale (atm./sec.^2) - as mentioned in the author's earlier works, and demonstrated in Figures 3 and 5. This makes it possible to compare measurements made at different places, without using one and the same instrument. For instance, if the knocking has been measured each time in atm./sec.^2 , it is possible to compare an American measurement by means of an electro-magnetic pick-up with a quartz indicator diagram which was made here. The author has already mentioned in an earlier work⁽⁶⁾ that the method gives good reproducibility after a lapse of months, and it has been possible to confirm this.

When the onset of knock in a B.M.W. 132 single-cylinder aero-engine was measured, first aurally, and then by the D.V.L. Pressure Acceleration Method, and the two compared, there was found to be an agreement within the range of accuracy of the aural method, i.e., $\pm 15 \text{ mm. Hg.}$, up to a mixture strength of $\lambda = 1.15$. Variations only occurred at high excess air ratios (from 20 to 30% excess air). In view of the difficulty of the aural method in the region of high air excess, the objective pressure acceleration method must be considered more reliable. If the aural method and the pressure acceleration method are used in the C.F.R. engine, it is possible to obtain an agreement between different fuels, although if the fuel is predominantly aromatic (in which case knocking is known to be difficult to determine), the variation is greater.

It is noteworthy that where there was a clear agreement between the results obtained by the two methods, at the onset of knock according to the pressure acceleration method there were between 5 and 10 knocks per minute. In the B.M.W. 132 there are 800 explosions at an engine speed of 1600 r.p.m., so that 8 explosions, i.e., 1%, will introduce knocking.

The pressure acceleration method fulfils the frequently met need for expressing the knock rating of a fuel as a curve rather than as a point (octane number). The time lag due to the actual measurement of d^2p/dt^2 is practically non-existent if a recording device is used, since the recording is done automatically during the setting of the engine. The time required for measuring the onset of knock is rather due to adjusting the mixture strength, since the engine must be allowed to attain the thermal equilibrium between one determination and the next, especially in air-cooled engines.

Efforts are at present being made to fit the necessary amplifier with a small cathode ray tube for observation, a deflection instrument for reading off, and a recording instrument for making a completely objective recording, in such a way that when the installation is set up on an engine, it will be possible even for non-experts to measure knock ratings.

BIBLIOGRAPHY

- 1) J. J. Broeze; H.v.Driell, L.A.Peletier; Betrachtungen über den Klopfvorgang im Otto-Motor. Deutsche Akademie der Luftfahrtforschung, Report before open meeting on 10th and 11th May, 1939.
- 2) H. Weinhart; Das Klopfen im Otto-Motor. Luftfahrtforschung Vol. 16 (1939), 2nd Inst., P.74.
- 3) A.v.Philippovich; Der Verbrennungsvorgang im Explosions-motor. Luftfahrtforschung Vol. 13 (1936), VDI Publ.
- 4) R. Schütz; Messung der Klopfestigkeit an Otto-Motoren. Dtsch. Kraftfahrtforschung Vol. 31 (1939), VDI Publ.
- 5) G. D. Boerlage, J. J. Broeze, Dr.H.v.Driel, L.A.Peletier; Detonation and stationary gas waves in petrol engines; Engineering Vol.143 (1937), P.254.
- 6) N. MacCull and G.T.Stanton; The measurement of engine knock by electro-acoustic instruments; SAE-Journal Vol.38 (1936), P.70.
- 7) A. W. Schmidt and K.Generlich; Untersuchung der Klopfgeräusche mit electro-akustischen Messgeräten; Dt. Kraftfahrtforschung Vol. 33 (1939), VDI Publ.
- 8) E.M.Dodds; Some results obtained on the cathode ray engine indicator; J.Roy.Aeronaut.Soc.Vol.41, (February 1937) Nr. 314, P. 132.
- 9) H. Illgen and H. Hintze; Beitrag zur Prüfung von Brennstoffen mittels des piezoelektrischen Indikators; Dt. Motor-Zeitschr. Vol. 14 (1937), Coll.10, P.234.
- 10) F. Lichtenberger and F. Seeber; Beitrag zur Frage des Klopfmessverfahrens; ATZ Vol. 41 (1938), Coll. 14, P.372.
- 11) K. Schnauffer; Das Klopfen von Zündermotoren; Z.VDI Vol.75 (1931) P.455.
- 12) F. Lichtenberger; Bewertung und prüfung von elektrischen Motorindikatoren; ATZ 42 (1939), P.451.
- 13) F. Seeber; Neuere Verfahren der Kraftstoffprüfung, Luftfahrtforschung Vol. 16 (1939), 8th Inst. P.434.
- 14) W. Jost, L. Feih.v.Müffling, W. Rohrmann; Beitrag zum Oxydationsmechanismus von Kohlenwasserstoffen; Zeitschrift f.Elektrochemie Vol.42 (1939) P.488.

- 15) W. Jost; *Verbrennungsvorgänge in Gasen, Angew. Chemie Jahrg.*
51 (1938) No.40, P.687.
- 16) F. A. P. Schmidt; *Beitrag zur theoretischen und experimentellen
Untersuchung von Verbrennungsvorgängen in Zünd-
und Dieselmotor. Luftfahrtforschung Vol.14 (1937)
12th Inst., P.641.*
- 17) F. Seeber; *Prüfung hochklopfester Kraftstoffe im Flug-motoren-
Einzyylinder, Luftfahrtforschung Vol.16, (1939),
1st Inst., P.18.*

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The D.V.L. blow-by method for testing lubricants

Survey: A report follows of the tests made on a small liquid-cooled two-stroke engine, which led to the development of the D.V.L. blow-by method. This process makes it possible to observe the rate of formation of deposits in the piston ring groove of a running engine. Various lubricants, tested by this process, gave results which accorded with previous experience. (Tests in the B.M.W. 132 and Siemens oil-test engine).

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I. Introduction

The endurance behaviour of oils in aero-engines, especially their tendency to piston ring sticking, was investigated in tests on aero-engine single cylinders. The standard of evaluation was in each case the running time up to the sticking of the piston rings, under conditions which were kept constant throughout the test. The recently observed fact that a single test run is not sufficient to evaluate a lubricant, but that several runs must be made to determine the effect on the running time of temperature (1,2) has increased even more the duration of the comparatively expensive and time-consuming tests.

It is therefore advisable to replace these investigations by corresponding tests in smaller engines, and thus to save the expense and time involved. But experience has shown that not every engine can be used for such endurance tests. The development of a suitable method was generally made harder or impossible by the fact that one or several of the requirements here set out could not be satisfactorily fulfilled :-

1. Adequate reliability at high thermal loads
2. Satisfactory observation and control of operating conditions
3. Possibility of determining the time of ring sticking
 - a) by observing the power drop
 - b) by observing the gas blow-by
4. Good reproducibility of the individual tests

As these requirements cannot be fulfilled in their entirety with each engine, and as the adaptation of the usual endurance test method to small engines necessitates extensive alterations and preliminary tests, it was interesting to see how far a two-stroke engine was suitable for such investigations.

Apart from the working process, an engine of this type appeared to be

specially advantageous because of its reliability and simplicity of handling. The fact that in a two-stroke engine with mixture lubrication the fuel and lubricant get in close contact with each other in the piston-ring groove, led to the expectation that it would be possible to test the mutual effects of the two substances with particular success.

II. Engine and Test Bed

The engine used for the tests was a liquid-cooled BMW engine of 500 cc. capacity. The characteristics of this engine are set out in Table 1. It works on the familiar two-stroke system with crank-case compression and reverse scavenging.

The whole set-up of the test bed can be seen from Fig. 1. The power is absorbed by a Junkers hydro-dynamic brake. The torque is recorded by a quick-action scale (this comparatively expensive scale is admittedly not absolutely necessary for the method, and simpler means can be employed, since constant power is maintained). It should be mentioned that in all the tests the power was very accurately measured (± 0.01 H.P.), which was of course only possible when the brake and the scale were in perfect order.

The cooling system was constructed as a thermo-syphon. The coolant (ethylene glycol) passed through a water-cooled radiator. The volume in circulation was controlled by a valve before the inlet to the cylinder. With this installation it was possible at the beginning of the test runs to interrupt the circulation of the coolant completely until the required temperature was reached, and then by a gradual opening of the valve to set the coolant circulating. This means that the engine warms up quickly (two to three minutes) and that the coolant temperature is very accurately regulated, which is advantageous for the success and reproducibility of the tests.

The fuel consumption could be varied by means of a regulating needle installed in the main jet. For setting and observing ignition a neon tube timing indicator of the usual type was used (cf. Fig. 2). Since it was necessary to alter the ignition timing in many cases (for example the engine often starts badly in the blow-by method (deficient compression), unless a considerable degree of ignition advance is used), during running, the ignition was made adjustable by making the whole magneto system, including the contact breaker, rotatable about its axis, as shown in Fig. 3.

DVL thermo-couples were used to observe the operating temperatures. The temperature of the combustion chamber was measured by an element built into the cylinder head (in place of the priming cock), while the exhaust gas thermo-couple was in the exhaust gas elbow, about 30 to 40 mm. after the exhaust ports.

To eliminate the influence of fluctuations in intake air temperature, an electrical air-heater was built into the intake silencer.

As cylinder heads and pistons differed somewhat, the compression ratio ($\epsilon = 5.0$) was kept constant by changing the gaskets between the cylinder and crank case.

Just as in the tests on the BMW 132 single cylinder engine, new piston rings were used for each run. The test bed is so constructed that the engine can be fully loaded directly after starting, without causing any damage (such as piston scoring). Of course, this is only possible with an engine which has been run in.

III. Preliminary tests for observing piston ring sticking

The purpose of the test, as in the method worked out on a single cylinder aero-engine, was in the first place to note the moment of piston ring sticking from the drop in power. But it appeared that the temporary fluctuations in

power, of very varied character, could not be brought into line with piston-ring sticking. The piston rings always stuck comparatively early, accompanied by a sudden or gradual fall in power. Even when the run was continued with a stuck ring, there was no fall in power after more than 10 hours.

Simultaneously with these investigations the charge pressure was observed, and at times continuously recorded. But even so it was impossible to determine the moment at which the piston rings stuck. In certain cases the charge pressure underwent sudden changes or fluctuations, which were not sufficiently reproducible, and could not be attributed to ring sticking.

An attempt was also made, by carefully observing the different temperatures (crank case, boost air, cylinder wall, combustion chamber, exhaust gas and coolant) to indicate the condition of the piston rings. But this attempt was unsuccessful.

It was assumed that when the first ring seized the remaining two still sealed efficiently, so that power and boost pressure were not affected: therefore the investigations were repeated with a special piston which had only one ring. It appeared that even in this case the improvement as regards ring-sticking was insignificant. It was interesting to observe that while the piston became hotter, the continuous power output of the engine was the same as before, and was only slightly less favourable at peak load.

IV. Development of the Blow-by method

All the investigations just described showed that ring-sticking occurs in the two-stroke engine without any clear external indications. The same opinion was formed in various other quarters, so that the attempt to use the two-stroke engine in its usual form for testing the tendency to ring-sticking had to be given up.

But if it was required, in spite of this, to use this excellent and simple engine for endurance tests on fuels and lubricants, it would be necessary to depart from the customary method of evaluation on the basis of the running time up to the occurrence of ring-sticking, and to continue the development on a different basis:-

In the process of piston-ring sticking, deposits are formed in the ring groove, to the extent that the ring can no longer move freely, and thus no longer seals adequately. The result is that the combustion gases blow through into the crank-case. But if it is arranged that a small portion of the combustion gases can blow past the piston ring, through the groove and into the crank case, and that this flow is interrupted by the gradual formation of deposit, then the time in which this deposit reaches a certain amount could be used as a measure of the type and rate of deposit formation. The engine will have a very poor power output at the beginning, due to the inadequate compression, rising gradually as the deposits interrupt the flow of gas, and finally reaching a limiting value, corresponding to the condition in which the ring has stuck without leakage taking place into the crank case. These ideas led to the development of the DVL blow-by method.

a) Tests at constant throttle opening

In the special piston already mentioned, the ring groove was drilled through to the inside of the piston. In the first test the groove had 7 holes of 1 mm diameter distributed evenly around the circumference. In spite of the resulting low compression, the engine started up, and produced a power of about 3.0 brake horse-power, with the throttle fully open. The power then rose gradually, and more slowly as the time increased, and remained more or less constant at 5.2 brake horse-power. It appeared that no coke was deposited in the holes near the exhaust port. The temperatures were so high here that no deposits could form. For this reason the engine only attained a maximum power of 5.2 b.h.p.

Several further tests at lower temperatures and with various arrangements of the holes showed that the power rose most uniformly, and reached the highest final value when the drillings were only made at the points where the coke formation was most pronounced. Therefore, in the tests now about to be described

the piston groove had only three holes (1 mm diameter) at 275°, 290°, and 320° (the ring gap is always at 306°). (The position of the holes is given in degrees - circumference of piston = 360°, 0° being above the centre of the exhaust port: 0°-180° is the direction of the axis of the piston pin).

In Fig. 4, the course of these investigations is recorded as a function of time. From this it can be seen that the rise in power varies considerably, especially at the beginning of the tests, but that there is nevertheless a certain agreement between the curves.

In order to determine whether it is possible by this method to evaluate oils with regard to their tendency to form deposits, runs were made with different oils under the same conditions. Fig. 5 shows that the individual oils behave in a manner strikingly different from each other. That their final power values are so different is due to the fact that with some oils only some of the drillings were closed up: because of the high load there were no deposits at all the remaining holes.

These test results though excellent in themselves show that accurate and satisfactory evaluation is impossible when the reproducibility is as bad as shown in Fig. 4. Thus the two oils Grünring and Rotring would still be more or less within the range of deviation, or at least permit only a very ill-defined evaluation, whereas their behavior was very different in the single cylinder zero-engine test. But the curves in Fig. 5 show that it should be possible to form a judgement by this method, so that the method may be considered right in principle. Therefore, in furthering the development of the process, it was important on the one hand to improve the reproducibility of the individual tests, and on the other hand to find a method of evaluating the tests such that they can be brought into relationship with practical conditions. For this reason, a large number of tests was necessary, for the purpose of investigating the effect of the most varied operating conditions on the above requirements. It would take too long to describe the runs in detail: therefore, only those will be referred to which contributed to the result.

b) Tests at variable throttle

In the tests mentioned above, the engine speed was variable (cf Fig. 4): at the beginning of each investigation it was set to 2500 r.p.m. During the tests it rose in accordance with the increase in power. But since the individual oils gave different final values (cf Fig. 5), the average engine speeds were very different from each other. Similarly, it was observed that the temperature of the combustion chamber and the boost pressure had very different final and average values. Also, the power and the engine speed were naturally affected by the fluctuations in the condition of the air. Therefore, if the different oils were compared the resulting picture would be a false one, even if the reproducibility was good; as they have been subjected to different thermal and mechanical loads according to their inclination to form deposits.

Therefore it was necessary to provide in all the tests constant thermal and mechanical loads. This was best achieved by keeping the power and engine speed constant throughout the test by gradually closing the throttle. It appeared that the temperatures then fluctuated within narrow limits only. The change in throttle as a function of time is a good guide to the gradual rise in power, and has the advantage that all the conditions can be kept constant throughout the test. Figs. 6 and 7 give an indication of two investigations carried out in this way. At first the throttle curve is very steep, but then gradually becomes flatter, and finally becomes practically a straight line. It is understandable that it is not always possible to obtain an absolutely straight line curve (cf. Fig. 7). But by proper interpretation of the results of these tests (cf. section V, 1, C), these irregularities can be cancelled out. This change in the position of the throttle, corresponding to the increase in power, may be considered as an indication of the nature and course of formation of deposit in the ring-groove: the curve will therefore be steeper, the greater the tendency to deposit formation. Lubricants which gave long running times in the Siemens oil test engine or the BMW 132 single cylinder should give flat curves,

and those with short running times, steep curves. In the same way, the temperature should affect the steepness of the throttle curve as it does the running times up to piston ring sticking.

7. Application of the blow-by method

1. Initial conditions

Previous tests having shown that the method chosen was the right one, the task was now to lay down the conditions which would give maximum reproducibility with the simplest test procedure.

a. Preparation for the test: first of all the best number and type of groove drillings was ascertained. The result of a large number of tests was as follows:

i) Size of the drillings: drillings which are too small clog too quickly, so that the power rises or the throttle closes too rapidly, and the result achieved is only superficial. On the other hand, drillings which are too large cause too much blow-by and overheating to such an extent that the deposits either do not form at all, or else are swept along by the gases. The best results were obtained with drillings of 1.0 mm. diameter, which was therefore used in the further investigations.

ii) Number of drillings: the number of drillings must be kept small, since the gases should take the simplest possible route through the groove to the crank-case.

iii) Position of the drillings: as already mentioned in section IV a, it was an advantage to have the drillings at the points in the groove where most deposit forms. But since these points will be different with different temperatures, loads and oils, it was necessary to ascertain the best position by a series of tests. In all subsequent tests, therefore, two holes (1 mm. diameter, see above) were used, one at 262° and one at 298° (cf. a table 2).

It should be mentioned here that the piston used for the tests has only one ring groove with one ring.

The piston ring side clearance has an effect similar to that of the size of the drilling. The most regular and uniform curves were those obtained with a side clearance of 0.15 mm. So as to start each time with the same conditions, a new ring with this clearance was used for each run.

b. Operating conditions and test method: the conditions which are the basis of the blow-by method are compiled in Table 2.

At the beginning of each test the coolant circulation was completely stopped, and the engine started with the throttle wide open. The required power and engine speed were set as quickly as possible by closing the throttle and regulating the load. When the coolant had reached the required temperatures, it was allowed to circulate by slowly opening the shut-off valve. At the beginning slight fluctuations in coolant temperature occur - varying according to the skill of the operator - but these cease after a short time. In this way the engine may be brought to the desired operating conditions in a very short time. These conditions are then kept constant throughout.

Since slight fluctuations in power and engine speed are inevitable even if the tests are carried out with the greatest care, it is misleading to compensate immediately for an alteration in power by readjusting the throttle. It therefore proved advantageous not to readjust the throttle until the power has reached a certain limiting value. The limits fixed were 3.90 and 3.95 brake horse power: that is to say, when a power of 3.95 brake horse power was reached it was adjusted back to the initial figure of 3.90.

c. Evaluation of the test results, and their reproducibility: in order to determine the limits of reproducibility, several runs, made under the same conditions and with the same fuels, were compared with each other. Fig. 8 shows

the throttle setting in terms of running time in 4 similar tests: those points at which the power was regulated back to 3.90 brake horse power are joined together. It can be seen from this that the individual points differed comparatively little.

Also the slopes of the linear sections of the curves differ very little. As the tests were made on different days and the power recorded on any day was affected by the atmospheric conditions on that day, the curves are somewhat displaced relative to each other. This fact shows that in the evaluation it is not the general position of the curve which must be evaluated, but its gradient from a certain running time onwards.

In order that the evaluation shall be as accurate as possible, and because the assessment of the slope by the experimenter is too arbitrary, a suggestion is made here for a quantitative evaluation which would remove this difficulty:

Experience has shown that about an hour after beginning the test the formation of deposit becomes nearly uniform, that is, the throttling curve becomes linear. Therefore, in the quantitative evaluation the first 60 minutes are not taken into account. From then onwards the angles between the lines connecting the individual points and the horizontal are measured, and the average of these angles is a measure of the slope of the curve, and also of the quality of the oil under test.

The angle between the line joining two neighbouring points and the horizontal is calculated as follows:-

$$\tan \phi = \frac{(d_1 - d_2) \cdot a}{t_2 - t_1}$$

where d_1 is the position of the throttle at point 1 in scale divisions.
 t_1 is the running time in minutes
 d_2 is the position of the throttle at point 2 in scale divisions
 t_2 is the running time in minutes
 a is the measuring unit (in Fig. 8 and Table 3 $a = 20$ (20 minutes corresponding to first division of the scale)).

The average angle (evaluation angle) is then:

$$\alpha = \frac{\phi_1(t_2 - t_1) + \phi_2(t_3 - t_2) + \phi_3(t_4 - t_3) + \dots + \phi_n(t_n - t_{n-1})}{t_n - t_1}$$

where $t_1 = 60$.

For greater clarity, the figures from which the throttle curves in Fig. 8 were calculated are shown in table 3. According to this, the average angles are as follows: $\alpha = 35.5^\circ$, $\alpha = 35^\circ$, $\alpha = 34.9^\circ$, and $\alpha = 35.5^\circ$. These results show that the tests have a high degree of reproducibility. But these slight differences must not be taken as typical of all the investigations. The test results in section V, 2 show that in some cases variations occur which go beyond the above limits (cf. Fig. 12). The reason for this might be that it is not yet clear how far the result, or the angle α , is influenced by variations in the test conditions (ignition !). It is intended that this question shall be elucidated by a series of investigations, to be carried out later, so that the reproducibility can be considerably improved. For the present, variations of $\pm 1.5\%$ in the tests will be tolerated.

All the tests which are about to be discussed have been worked out according to the process described above.

2. Tests on various lubricants

In order to determine how far the evaluations made with the help of the blow-by method agree with the experiences gained up to the present, tests were made on some oils whose behaviour in the BMW 132 single cylinder engine was known. As was done recently in the single cylinder aero engine, each lubricant

was tested at various temperatures: Fig.9 shows the throttle curves at various thermal loads for the lubricant Stenevo 100, Fig.10 the same for Rotring D, and Fig.11 that for Aero Shell Medium. Table 4 sums up the evaluations of the individual tests.

As was mentioned at the end of Section IV b, steep throttle curves go with short running times in the BMW 132 oil test engine, and vice versa. Therefore a very small angle corresponds to a very long running time, and the angle $\alpha = 0$ would therefore signify an infinite running time. For this reason it might be considered correct to take as a standard of evaluation, not the angle α , but its co-tangent. If the "gradient" (co-tangent α) is plotted as a function of the cooling temperature, the result is the curve in Fig.12. The lubricant Stenevo 100 only shows slight differences in gradient at the various cooling temperatures: the curve falls at first, reaches a minimum at a coolant temperature of about 130°C, and then rises again. The test at 1500 C gave a result which deviated from the general tendency of the curve. The accuracy of this value is doubtful, especially as at every other point the course of the curve was uniform. This could be cleared up if the test were repeated.

The lubricant Rotring D proved to be considerably more sensitive to temperature. At low temperatures the throttle curves were flat, afterwards becoming steep: at about 127°C the minimum is reached, and beyond this temperature the values rise again.

With Aero Shell Medium the tests showed a similar result, but with the difference that the curve (Fig.12) lies in a lower range of temperatures. The behaviour at high temperatures is interesting: it appeared that after reaching its minimum this curve also rises again, and then from a certain value onwards (about 110°C) falls extremely rapidly as the temperature is raised. The course of this curve might be related to the nature of the deposit formation as a function of the thermal load: as the temperature rises the volume of asphaltic deposits which are formed increases. From a certain load onwards these soft deposits no longer stand up to the thermal attack, and either burn away or never form (5) (6), with the result that the running time is prolonged, or the throttle curve in the blow-by method becomes flatter. At the same time, however, the formation of hard deposits accompanies the rise in temperature, so that the volume of deposits again increases. From this point onwards, therefore, there is again a fall in the curve of running time or gradient as a function of temperature. This confirms the observations made in earlier reports (cf. FB 1177 - Behaviour of CV4b, and UM 574, Test No.70). Another report will deal with the character of the deposits, and with the tests made in the laboratory for the purpose of elucidating this process. The above remarks will therefore suffice for the present to describe the results of the engine tests.

3. Comparison with test results on the BMW 132 single cylinder engine

For the purpose of comparison, Fig.13 shows the running times as functions of the plug gasket temperature in the test on the BMW 132 single cylinder engine, for the corresponding oils. Of course these tests were made with a different fuel (Shell Ethyl 87) (cf. a Table 2). Also, Rotring, not Rotring D, was used, with different piston rings, resulting in a running time which was longer by 1 hour at a plug gasket temperature of 265°C. In spite of this, it was established that the curves were similar both in regard to their tendency and their critical temperatures. Comparing their "gradients" at a coolant temperature of 90°C shows good agreement with the previous running times in the BMW 132 and Siemens oil test engines at a plug gasket temperature of 265°C.

Lubricant	Gradient @ 90°C.	Ratio of gradients**	Running times in BMW 132 and Siemens oil test engine
Stenevo 100	2.05	6.0	6½ to 6½ hours
Rotring D	2.93*	8.6	8½ to 9 hours
Aero Shell medium	1.06	3.1	3 to 3½ hours
NP 2	1.47	4.3	4½ to 4½ hours

* mean value

** e.g. $\frac{2.05}{2.93} = \frac{6.0}{8.6}$

VI. Criticism and Prospects

It would be particularly interesting to repeat the tests by the blow-by method with the fuel used for the tests in the BMW 132 oil test engine. But the samples supplied varied in their composition (fluctuating aromatic and lead content), and such comparisons could only be made satisfactorily with completely identical products. Investigations with fuel supplied subsequently would therefore introduce an element of uncertainty, which would have to be cleared up by other comparative tests with fuels from the same source. Naturally, the question whether the blow-by method can entirely replace the test in the BMW 132 single cylinder engine can only be settled by further researches. But the object of this report is in the first place to report on the progress of the tests and to show that endurance tests are possible with the blow-by method, to give the same evaluation as previously.

The type of evaluation of tests here described and the evidence of the reproducibility of similar tests obviously admit of many alterations and improvements. Further developments to the method will probably result in even more uniform throttle curves, which will simplify evaluation to a considerable extent. More especially, this would decide from which running time onwards an evaluation is possible in all cases, and which condition is decisive for the conclusion of a run.

The value of the method lies in the fact that it can be used in a small, reliable engine, and is very economical of time and material. The advantages of the method are demonstrated in the table below.

Advantages of the DVL blow-by method

	<u>Blow-by</u>	<u>BMW 132 single cylinder engine</u>
1. Shorter running time	4-5 hours instead of	4-50 hours
2. Shorter test preparation per run	3 hours	" " 15 hours
3. Lower fuel consumption per run	15 litres	" " 80-800 litres
4. Lower oil volume per run	$\frac{3}{4}$ litre	" " 25 litres
5. Lower working costs per run	50 RM.	" " 500 RM.
6. Cost of preparing test bed	1500 RM.	" " 30,000 RM.

The possibility of testing even good oils, which give long running times under the previous test method, in a short time (4 to 5 hours), makes the method a practical proposition in all cases where only small quantities are available, or where a test is urgently required. Also the test bed only occupies a small space.

Even though future tests do not reveal a definite connection with the results on the BMW single cylinder engine, the method could be used for preliminary tests in large numbers, so that only the most interesting results would need to be checked on the single cylinder aero engine.

The fact that the operating conditions in the blow-by method, especially the coolant temperatures, can be kept within much narrower limits, makes it possible to plot the course of the curves in a large number of tests at smaller temperature intervals much more clearly than before, and at the same time to observe more closely the inter-action between the fuel and the oil.

VII. Summary

The above is a report on tests made on a small liquid-cooled two-stroke engine, with the object of using this engine for oil tests. As the process of piston ring sticking could not be satisfactorily observed by the method hitherto

in use (observation of power drop and gas flow), a new process was developed which made it possible to observe the rate of deposit formation in the piston ring groove of a running engine.

The investigation of various lubricants by this process gave results which were in accordance with previous experience with these oils (tests on BMW 132 and Siemens oil test engines). The advantages offered by this new process compared to previous methods (economy in time and material) suggest that in future it will replace the test on the single cylinder aero engine, or will at least simplify and shorten it.

Table 1

Engine Data

Engine	DKW
Manufacturer	Auto Union
Model	EW 301
Bore	74 mm. dia.
Stroke	68 mm.
Capacity	292 ccm.
Power (maximum)	6.5 to 7 b.h.p.
Engine speed	3000 r.p.m.
Maximum engine speed	3400 r.p.m.
Compression ratio	1:5.0 (see page 2)
Ignition	adjustable
Carburettor	single lever carburettor Fremo VG-V with adjustable main jet.
Cooling	Thermo-syphon
Coolant	Ethylene glycol
Brake	Junkers Hydro-dynamic brake B2K.

Table 2

Operating conditions in the DVL blow-by method

Piston	Special piston with only one ring groove
Position of drillings	at 262° and 298°
Engine speed	3000 ± 10 r.p.m.
Ignition	30° before top dead centre.
Compression ratio	$\epsilon = 5.0$
Side clearance of the piston ring	0.15 mm.
Fuel	VL 702 + 0.12 vol.% lead
Ratio of lubricant to fuel	1:20
Fuel consumption	500 ± 20g/b.h.p. per hour
Coolant	Ethylene glycol
Temperature of coolant:	
Inlet	12 to 30°C *
Outlet	various
Intake air temperature	23 to 25°C

The temperatures which occurred were as follows:-

Temperature of combustion chamber	550-620°C *
Exhaust gas temperature	470-480°C.

* According to the exhaust temperature of the coolant.

Table 3

Example for Test Evaluation (cf. Fig. 8)

$$\psi = \frac{\psi_1(t_2 - t_1) + \psi_2(t_3 - t_2) + \psi_3(t_4 - t_3) + \dots + \psi_n(t_n - t_{n-1})}{t_n - t_1}$$

$$\text{tg } \psi = \frac{(d_1 - d_2) \cdot 20}{t_2 - t_1}$$

$$t_1 = 60$$

Run 144

t	d	tg ψ	ψ	ψ(t _{x+1} - t _x)
60	34.14	0.9091	42° 16'	1050° 400'
85	33.0	1.000	45° 0'	1350° 0'
115	31.5	1.000	45° 0'	1350° 0'
145	30.0	0.5085	28° 57'	1534° 3363'
204	28.5	0.5556	29° 3'	1044° 108'
240	27.5			
$\sum \psi(t_{x+1} - t_x) = 6328° 3971'$				

$$\alpha = \frac{6328° 3971'}{180} = 35° 31'$$

Run 145

60	34.95	0.7273	36° 2'	933° 52'
85	34.0	0.8205	39° 22'	1521° 858'
125	32.4	0.7273	36° 2'	1189° 86'
158	31.2	1.000	45° 0'	630° 0'
172	30.5	0.8824	41° 26'	1394° 884'
206	29.0	0.4167	22° 22'	1056 1776'
254	28.0			
$\sum \psi(t - t) = 6725° 3636'$				

$$\alpha = \frac{6725° 3636'}{194} = 34° 59'$$

(continued overleaf)

Table 3 (continued)

Run 161

t	d	tg ψ	ψ	$\psi(t_{x+1} - t_x)$
60	34.25	0.5922	21° 25'	273° 325'
73	34.0	0.6667	33° 41'	990° 1230'
103	33.0	1.053	46° 29'	874° 531'
122	32.0	1.053	46° 29'	874° 551'
141	31.0	0.8333	39° 46'	938° 1152'
165	30.0	0.7143	35° 32'	980° 896'
193	29.0	0.4878	28° 0'	1068° 0'
234	28.0			

$$\sum \psi(t_{x+1} - t_x) = 5923^\circ 4705'$$

$$\alpha = \frac{5923^\circ 4705'}{174} = 34^\circ 54'$$

Run 169

50	34.75	0.6897	34° 36'	544° 576'
76	34.2	1.200	50° 12'	1000° 240'
96	33.0	0.9524	45° 38'	903° 756'
127	32.0	0.6452	32° 50'	992° 1553'
148	31.0	0.5263	27° 45'	1026° 1710'
186	30.0	0.6667	33° 41'	690° 1230'
216	29.0			

$$\sum \psi(t_{x+1} - t_x) = 5455^\circ 6062'$$

$$\alpha = \frac{5455^\circ 6062'}{156} = 35^\circ 27'$$

Table.

Results of investigations of various lubricants by the
blow-by method
(see table 3 for headings)

Run No.	Lubricant	Cooling Temp. °C (outlet)	Standard	
			°C	205. °C
183	Stanavo 100	90	26° 0'	2,050
184	"	110	27° 14'	1,943
185	"	130	27° 51'	1,893
186	"	150	30° 32'	1,695 ?
188	"	165	27° 7'	1,953
149	Rotring D	90	19° 13'	2,869
191	"	90	18° 29'	2,992
150	"	110	32° 1'	1,599
203	"	110	33° 30'	1,511
151	"	130	37° 33'	1,301
152	"	150	31° 11'	1,652
154	"	165	26° 36'	1,997
160	Aero Shell Medium	65	31° 34'	1,664
159	"	70	32° 34'	1,507
155	"	90	43° 18'	1,381
156	"	110	28° 0'	2,050
157	"	130	36° 35'	1,253
158	"	150	50° 3'	0.8376
144	NP 2	90	35° 51'	1,401
146	"	90	34° 52'	1,429
161	"	90	34° 54'	1,433
169	"	90	35° 27'	1,405

VIII Bibliography

- 1) A.v.Philippovich, Engine tests of lubricants and proposals for its further improvement, Oil and Coal, 15. Jahrg. (1939) Heft 28, (1939) S.551/556.
- 2) W. Glaser, The influence of the operating conditions on piston ring sticking in the lubricant endurance tests, Luftfahrtforschung, Bd.16 (1939) Lfg.8, S.438/446, cf. a. DVL-Report FB 1022, 7.2.39.
- 3) H.H.Berg, DVL Thermo-couple, ATZ 1939, Heft 7.
- 4) H. Schökel, Lubricating oil tests in the BMW 132 F single cylinder engine, DVL-report UM 574, 18.4.39.
- 5) A.v.Philippovich, New investigation method for estimating the deposit formation of engine oils, DVL-Yearbook 1933, S.VI, 36/42
- 6) M.Richter, Laboratory tests of lubricating oils for their tendency to piston ring sticking, Luftwissen Bd.5, (1938) Nr.6, S.213/18.
- 7) W.Glaser, Investigation of the behaviour of different high performance fuels in endurance tests, DVL-report FB 1177 21.2.40.

Illustrations

- Fig.1 - DKW Test bed for the DVL blow-by method.
 Fig.2 - View of crank case with ignition timing indicator and ignition adjustment device.
 Fig.3 - Ignition timing indicator and ignition adjustment device.
 Fig.4 - 3 tests performed under identical conditions with throttle fully open.
 Fig.5 - Investigation of various lubricants with throttle fully open. Cooling temperature 120°C; fuel, gasoline-benzene mixture.
 Fig.6 - Test with lubricant Rotring D at 165°C coolant temperature.
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- Fig.8 - Throttle curves of 4 tests carried out under identical conditions:
 Fuel, VT 702 + lead; lubricant, NP 2; Coolant temperature 90°C.
- Fig.9 - Throttle curves with Stenevo 100 at various coolant temperatures.
- Fig.10 - Throttle curves with Rotring D at various coolant temperatures.
- Fig.11 - Throttle curves with Aero-Shell-medium at various coolant temperatures.
- Fig.12 - Gradient ($\cot \alpha$) as a function of the coolant temperature with various lubricants.
- Fig.13 - Running times as a function of the plug-socket temperature for various lubricants in the BMW 132 oil test engine.

DVL Report FB 1292

An exact and rapid method for
the determination of lead in fuels

I. Morghen

Summary:

An accurate method of determining the lead content of aero-engine fuels in approximately 30 minutes is described: 2 cc. of fuel are required for the test.

Contents:

- I. Introduction
- II. Principles of the reactions involved
- III. The carrying out of the analysis
 - 1. The making up of the standard solution
 - 2. The analysis
 - 3. Numerical data
- IV. Summary
- V. Bibliography

I. Introduction:

Of the many methods suggested for determining lead in fuels, only the chromate (1) and the sulphate (2) methods became generally popular. These methods are very time consuming. Since the lead content is very frequently determined for control purposes it was necessary to develop a method which gives results in a considerably shorter time and which is not inferior to the above-mentioned methods in accuracy and reliability. In the following paper a method is described which meets these requirements. This was proved by tests with leaded fuels.

II. Theory of the reactions used in this estimation.

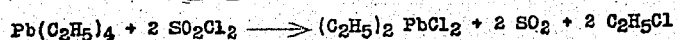
The method consists of two parts - conversion of the homopolar (tetraivalent) lead tetraethyl into a sufficiently ionisable water soluble lead compound, and estimation of this by means of a complex compound.

Preparation of the aqueous lead solution.

The usual method of converting the lead in the fuel into an aqueous solution of a divalent lead salt is too time-consuming. As it is known that the mono- & dichlor-alkyl lead compounds are water soluble, attempts were made to convert the lead tetraethyl into dichlorethyl lead by means of a mild chlorinating agent, e.g. sulphuryl chloride which would not react strongly with the fuel to give resinous substances insoluble in gasoline.

An addition of sulphuryl chloride to a leaded gasoline and heating a flaky white precipitate is obtained which is practically insoluble in petroleum ether and in gasoline (normal gasoline), but is easily soluble in water and alcohol. In order to gain cursory information the precipitate was recrystallized once from alcohol-petroleum ether, and the halogen determined on the silky needles by Carius' method. The lead was determined by the dithizone method described later. The values obtained agreed very well with those calculated for $(C_2H_5)_2 PbCl_2$.

The reaction takes place in exactly the following form :-



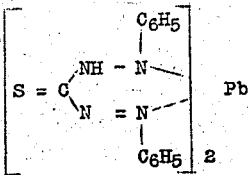
Reaction of SO_2 with the T.E.L. (giving lead ethyl sulphinate and diethylsulphone) could practically not be observed. When reacted with sulphuryl chloride for some time with heating, a little lead chloride was formed**. The small quantity of $\text{Pb}_2(\text{C}_2\text{H}_5)_6$ present is probably also converted into dichlorodiethyl lead. The course of the reaction was not investigated further. In the determination itself, it is only important practically for the tetraethyl lead in the leaded fuel to be converted quantitatively into a form which gives divalent lead ions. It is also essential for the accuracy of the determination to be unaffected by the type of fuel and its lead content. It may be said that errors may principally here occur, e.g. by the solubility of the lead precipitate in the fuel and by the retardation or by the modification of its precipitation by the fuel, or again by higher molecular unsaturated substances formed to some extent also by the action of sulphuryl chloride on certain hydrocarbon compounds. (Formation of super-saturated or colloidal solutions or finely crystalline precipitates which are liable to be pulled through the pores of the filter). In the analysis described later, the conditions of precipitation were selected so that the two essential requirements just mentioned were practically met, and so that only one mode of precipitation could be used for all fuels which may possibly be tested (natural gasolines, isoparaffins, hydrogenated gasolines, etc.). Only fuels with a benzene addition of over 40% need a further addition of paraffinic natural gasoline in order to reduce this benzene additive***).

The fuels must not contain any alcohol or undissolved water. The latter is of course a primary condition for every fuel.

Determination of the lead content of the aqueous solution

H. Fischer's process (4) was selected from a number of available methods. He developed the dithizone[†] method for the determination of lead and of a number of other metals. It was modified, since it proved to be too complicated for our purposes, and was not very accurate (according to H. Fischer - error margin 1-5%).

H. Fischer states that diphenyl thiocarbazonate with weak alkaline lead solutions gives an inner complex of lead dithizonate derived from the "Keto-form" of the dithizone. That means that 2 mols. of diphenylthiocarbazonate with one divalent Pb ion thus :-



The enol-form of the dithizone would require 1 mol. dithizone for 1 mol. of divalent lead salt.

The lead dithizonate of a purely inorganic divalent lead salt is soluble in carbon tetrachloride with a brick-red (strawberry red) colour. The (two co-ordinate) lead ion, obtained by the reaction of tetraethyl lead with sulphuryl chloride, combines with dithizone, yielding an orange-red compound which is much more easily soluble in carbon tetrachloride than the brick-red dithizone compound of the simple lead ion. It requires for its formation the same equivalent of dithizone as the brick-red lead compound.

It is not intended to enter into a detailed discussion of the various dithizone methods of lead determination suggested by H. Fischer and others. (They are usually "extraction methods"). These methods

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allow the determination of lead quantities of 6 to 120 \times lead. Instead of going into this matter, it is intended to describe at once the method which appears to be more suitable for the purposes here under consideration⁺⁺⁺).

A standard solution of dithizone in carbon tetrachloride is added to an aqueous weak alkaline lead solution, the whole being shaken at intervals, and this process is continued until the solution, which is completely colourless, clear and aqueous in the beginning, takes a yellowish colour of excess alkali-dithizonate.

The accuracy of the determination must necessarily be greater, the smaller the required quantity of dithizone excess in any particular case, (- the quantity of the aqueous lead solution must therefore be as small as possible, -), the greater the lead quantity to be determined, and the more concentrated the dithizone solution. The accuracy increases further, the less the solubility of the dithizone and the greater that of the Pb-dithizonate in the suitable solvent, (e.g., carbon tetrachloride). (When the determination is carried out as accurately as possible, the distribution equilibrium between the alkaline alkali-dithizonate solution and the carbon tetrachloride-lead dithizonate will have to be taken into consideration. This, however, is unnecessary in this particular case).

The practical titration selected was carried out with an accuracy of $\pm 0.25\%$. The standard solution used is $\approx 5 \times 10^{-4}$ molar. The quantity of the lead solution was 2.75 ml. with a content of $\approx 2.5 \times 10^{-6}$ mole (0.84 mg.) lead (calculated as dichloroethyl lead).

Sodium thiosulphate is added as an antioxidant^{##} and also to avoid emulsification when shaking and to destroy traces of residual chlorine. Rochelle salt is also added to assist the solution of any lead chloride or lead sulphate formed. (The complex lead salt thus obtained is sufficiently ionized to give practically a quantitative reaction with dithizone). Potassium cyanide^{##} is added to form stable complexes, preventing disturbing reactions of other metals (except Sn, Bi and Tl).

III. The carrying out of the analysis

(1) Making up the standard solution

600 cc. carbon tetra chloride^{###} warmed to about 40°C are shaken vigorously in a 750 cc. separating funnel with a large excess of powdered dithizone (about 0.5 gm.) for about 15 minutes, and then filtered quickly[†] into a 1000 cc. separating funnel. The dark green carbon tetrachloride solution is then covered with a layer of about 300 cc. of 0.25% ammonia and shaken for a short time (about 3 to 5 minutes). The greater part of the dithizone passes then into the aqueous layer. After allowing to settle for a short time, the dirty brown-green carbon tetrachloride solution containing the impurities (oxidation products) present in the commercial dithizone, is run off. The aqueous solution is quickly washed once with about 30 cc. carbon tetrachloride and a layer of 750 cc. pure carbon tetrachloride is poured underneath. The dithizone is then liberated from the ammoniacal solution by adding 100 cc. of 10% sulphuric acid and made to pass into the carbon tetrachloride solution by shaking vigorously. The aqueous colourless layer is now removed as far as possible with the aid of the filter pump or a second separating funnel. The carbon tetrachloride solution is then shaken again after adding 200 to 300 cc. of 2% sulphuric acid. The aqueous solution is again removed. The dithizone solution is finally shaken 3 times, each time with 200 to 300 cc. of distilled water. After the carbon tetrachloride solution has been shaken with water for the last time, it is allowed to settle awhile and then run

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off into a dry separating funnel, vigorously shaken with a little freshly heated (dehydrated) sodium sulphate for 10 minutes and filtered quickly. The dithiazene solution so obtained is then standardized by the method described later using a lead solution of known lead content. It is best to make this lead solution up from a saturated paraffinic leaded fuel free from benzene and its homologues. The lead content of this fuel should also be determined with the greatest possible accuracy by one of the usual methods. The dithiazene solution is now diluted with sufficient carbon tetrachloride to give a 9-10 cc. titration on 0.5 cc. of a leaded gasoline of 0.10% by volume lead content. The solution is now poured into a dark brown 1.5 litre flask (sufficient for about 100 determinations), a syphon fitted, a layer of 1% sulphuric acid very carefully poured onto the carbon tetrachloride solution, the bottle made air-tight, and waxed (see also illustration). The syphon is filled by suction and the burette connected with the aid of a cork, and also waxed. The air is displaced from the apparatus through the burette with nitrogen, and a low pressure wash-bottle containing pyrogallol solution or with any other oxygen absorbent connected and the tap of the burette closed. The syphon is varnished black or protected from light in some other way, the brown bottle covered with a black cloth for safety's sake. It is never advisable to let the standard solution stand for 8 to 10 days since the strength sometimes changes a little during this time. (Should this not be possible the titre should first be checked). The solution should then be accurately standardized against a freshly prepared lead solution. The titration equipment (stock-solution with burette) should be placed in a cool place without too much light. (The strength of the solution in the burette which is not protected from light then hardly alters in the course of one day).

(2) Analysis

2.00 cc. of the leaded fuel are transferred to a dry boiling flask (see illustration) using an accurate pipette, and then diluted with 3.0 cc. of a mixture of 1 part of chloroform (commercial chloroform must be freed from alcohol by shaking with CaCl_2) and two parts of a paraffinic natural gasoline. After addition of 1 cc. sulphuryl chloride a vertical tube is put on the flask and the latter then heated for 2.5 minutes on a small flame until the mixture comes to a boil. It is then cooled down for 1 minute in running water, heated again for 1 minute and cooled. Then the liquid is filtered off from the precipitate. (Do not use a full water-jet vacuum). The little flask and filter-tube are now washed well three times, each time with 2 to 3 cc. petroleum ether (the washing liquid must be filtered each time through sintered glass). The little flask is now sucked dry (also through the glass filter) and the precipitate dissolved in 3 cc. of an aqueous solution containing 0.1% ammonia, 0.5% Rochelle salt and 0.5% sodium thio-sulphate, and the solution finally sucked carefully into a 10 cc graduated flask. (see illustration). The little flask is again washed 3 times with approximately 2 cc. of the solution, the solution filtered each time, and the filtrate in the graduated flask eventually filled up to the mark and thoroughly mixed. 2.50 cc. of this solution are poured into a shaking vessel (see illustration), 0.25 cc. of a 2.5-5% aqueous potassium cyanide solution added, and then titrated.

The titration is carried out as follows :-

The quantity of standard solution to be added to the lead solution should be equivalent to the lower limit of the expected lead content. The whole is shaken for one minute (the residual aqueous layer must become completely clear as water). The solution is now titrated adding 0.2 or 1 cc. of the standard solution, shaking each time for 15 seconds, and this titration is continued until the layer, which was colourless before, becomes yellow or brown. For accurate

estimations, as much standard solution is added to the new 2 cc. of the sample as was added during the preliminary test before the colouration was noticeable, and the titrations then continued by steps of 0.05 cc. until a change ^{or} of colour takes place. The approximate total quantity can be estimated with some experience from the preliminary test and the actual determination carried out very quickly. No preliminary test is necessary when the approximate lead content is known.

Calculation:-

In the standardization, 0.50 cc. leaded gasoline ($\frac{1}{2}$ of 2.00 cc. fuel) containing a known proportion Q % by vol. TEL needed x cc. dithiazone solution.

If in the analysis the consumption of dithiazone solution is y cc., the lead content in % vol. is given by :-

$$TEL = y \cdot \frac{Q}{x} \text{ cc./100 cc.}$$

(3) Numerical data:

Table 1 gives analytical data for 18 different fuels to which was added a certain quantity of "I.T. fluid". Such a great number of fuels was selected to show to what extent the presence of various hydrocarbons affected the accuracy of the analysis when lead is precipitated with sulphuryl chloride (effects on the course of the reaction, on the solubility of the precipitate, etc.).

Only one determination was carried out with each of the listed fuels, so that the analytical data are not average values. The normal standard pipettes with 2 marks were used for the samples. The fuel-fluid mixtures were made up by adding each time 20 cc. of a normal gasoline containing 1.2 % vol. TEL to 180 cc. fuel.

Roumanian distillation gasoline (No.1) was selected for the standardisation or in the present case as a reference fuel. But U.S.A. distillation gasoline (No.2) could have been used. 12.10 cc. dithiazone solution was used for 0.5 cc. of the leaded reference fuel. The titration was carried out in 0.05 cc. steps.

Table 2 also shows the cracked gasolines (Nos. 3 and 4). The lead contents were determined as described in footnote*. Instead of 3 cc. of the gasoline-chloroform mixture, 2 cc. pure chloroform were added.

The names given to the fuels by the supplying firms were retained. The characteristics which are of interest here were also mentioned whenever available.

IV. Summary

A method is suggested which gives reliable and accurate values for leaded aero-engine fuels in a relatively short time. These values are principally not affected by the olufine-, peroxide-, etc., content of the fuel.

The process has not been fully tested yet for automotive fuels (see, however, the control analyses Nos. 3 and 4). The slight modification which might here be necessary in the case of second grade automotive fuels is indicated.

FOOTNOTES:

1) G. Grüttner and E. Krause (3) obtained monochloro-triethyl lead and dichloro-diethyl lead, by passing chlorine at -70°C and -10°C into tetraethyl lead diluted with ethyl acetate. They describe them as water and alcohol soluble substances of an acid character, insoluble in petroleum ether and in carbon tetrachloride.

* Chlorine: found 21.19%; calc. for $(\text{C}_2\text{H}_5)_2\text{PbCl}_2$ 21.1% Cl.

Lead: Titration 6.80, 6.85 mls. Calc. 6.80 mls. The dithiazone solution was standardized against lead acetate solution of known strength.

** The formation of lead chloride depends also upon the type of fuel and the diluent used.

*** Very strongly unsaturated cracked gasolines, or cracked gasolines which gum up easily (inferior automotive gasolines) could react with sulphuryl chloride causing precipitation of insoluble resinous substances (dehydrogenation by chlorine) which might partly prevent later the solution of the lead compound formed. This disadvantage can be largely avoided by adding a generous quantity of pure chloroform to the cracked gasoline. In order to obtain accurate analyses, the values have to be considered in relation to a test carried out similarly with chloroform as depending on the quantity of chloroform added the lead compound formed may be found in practice to have a somewhat increased solubility in the chloroform-fuel mixture. Considerable dilution with chloroform necessitates also an increase of the quantity of the sulphuryl chloride added, and it must of course be borne in mind that the solubility of the lead compound has a greater percentage effect with a small lead content. From the numerical data given later it can be seen that two cracked gasolines were treated first according to the normal method and then, as an example, according to the modified method described above.

* Dithiazone is the abbreviation for diphenylthiocarbazone which was synthesized for the first time by E. Fischer (5). E. Fischer also mentioned already the fact that some dithiazones are coloured.

*** Generally speaking it should be noted that this method is of course equally suitable for all colourless lead solutions provided that they have not too small a lead content. The dithiazone can then also be dissolved in a carbon tetrachloride-chloroform mixture in which the lead dithiazonate is more easily soluble (as also is the dithiazone).

H. Fischer loc. cit. recommends sodium thiosulphate as a reducing agent.

See also H. Fischer loc. cit.

A solvent which dissolves the dithiazone more easily can also be used (e.g. chloroform). Of course less is needed in this case. The solvents used should be absolutely pure (A.R.).

† Dithiazone and its salts (especially the latter) are sensitive to light and oxygen.

†† The burette tap and the syphon tap have to be coated with a carbon tetrachloride-proof lubricant made up as, e.g. suggested by Kepsenberg: "25-30 g. pure dextrin is ground with 35 cc. pure glycerine in a porcelain dish, adding the glycerine slowly. Whilst stirring the mixture with a glass rod, it is heated strongly over a flame. A transparent honey-like liquid is formed which is brought to a quick boil twice until vigorous frothing starts. The lubricant when made is bottled in a glass stopped bottle in absence of air while still hot as it is hygroscopic".

Sulphuryl chloride eagerly absorbs water from the air and is eventually hydrolysed to sulphuric acid and hydrochloric acid. The sulphuric acid may affect the fuel and the lead compound. It is therefore necessary to keep the sulphuryl chloride over slightly heated barium chloride in a tightly closed container, and it must be shaken frequently. The stopper must be kept dry and the bottle must be closed immediately after use. The measurement of the 1 cc. must be done with a pipette using a filter pump and without disturbing the BaCl_2 .

* The little flask is put for this purpose on an asbestos plate with an opening of 20 to 25 mm. and with a slightly sagging wire gauze. The liquid should just boil, but only very little. Boiling must not be confused with the simultaneous formation of gas (SO_2).

** The rubber stopper of the little filter tube is put only loosely on the (inclined) suction bottle which has a rubber stopper with a wide bore. If the filter chokes in the course of time either by the suspended particles in the fuel or for any other reason, it must be cleaned with warm chromosulphuric acid and then washed very carefully with water. The little boiling flask must be replaced by a new one after approximately 100 determinations.

*** The test point of change is the point when yellow coloration is just noticeable. 0.1 cc. excess dithiazene solution should be added in order to check. The solution should become unmistakably brown.

Bibliography

- (1) G. Edger and G. Calingaert, Ind. Eng. Chem. Anal. Ed. 1. 221/222 (1929).
- (2) W. Ulrich, Öl und Kohle, 14, 131 (1938).
- (3) G. Grüttner and E. Krause, Ber. dtsh. chem. Ges. 49, 1426 (1916).
- (4) H. Fischer, Angew. Chemie 50, 919 (1937) ibid.
- (5) E. Fischer, Liebigs Ann.Chem. 190, 118 (1878), Ann.212, 316 (1882).

Table 2

No.	Type of Fuel	T.E.L. cont. % vol.	T.E.L. found % vol.	D ₂₀	n _D ²⁰	Iodine No.	Arom. + Unsat. %	Naphthene %
1	Roumanian straight run gasoline		0.1200	0.7266	1.4074	2.3	10.1	37.1
2	Russian cracked gasoline	0.120	0.1205	0.7292	1.4100	82.2	26.3	14.6
3	Motor-car gasoline DVL		0.1200	0.7640	1.4290	31.9	-	-

Table 1

Nb.	Type of fuel	T.E.L. cont. % vol.	T.E.L. found % vol.	D ₂₀	n _D 20	Iodine No.	Arom. + Unsat. %	Naphthene %
1	Roumanian straight-run gasoline		0.1200	0.7266	1.4074	2.3	10.1	37.1
2	U.S.A. straight-run gasoline		0.1205	0.7269	1.4066	0.6	7.0	51.8
3	Russian cracked gasoline		0.1205	0.7292	1.4100	82.2	26.3	25.6
4	Motor-car gasoline DVL		0.1205	0.7640	1.4290	31.9	-	5.
5	Brown-coal LT carbonisation gasoline		0.1190	0.7153	1.4033	1.5	10.4	29.8
6	Brown-coal hydro gasoline		0.1200	0.7156	1.4020	1.0	6.8	-
7	Bituminous coal gasoline (middle oil) (Trans. note: prob- ably vapour phase)		0.1195	0.7334	1.4096	4.9	12	49.3
8	Bituminous coal hydro- gasoline (Trans. note: prob- ably liquid phase)		0.1200	0.8107	1.4582	5.2	64.0	-
9	Fischer gasoline	0.120	0.1200	0.6786	1.3830	0.5	-	-
10	Alkylate gasoline		0.1195	0.6997	1.3960	1.4	7.3	0
11	Iso-octane (tech.)		0.1200	-	-	-	-	-
12	70% Iso-octane 30% Iso-2-octane		0.1200	-	-	-	-	-
13	Synthetic aromatics		0.1195	0.8624	1.4908	-	96.1	-
14	High perform- ance fuel		0.1200	0.7900	1.4475	-	-	-
15	"		0.1195	0.7614	1.4294	-	-	-
16	"		0.1200	0.7639	1.4312	-	-	-
17	Roumanian straight-run gasoline (No.1) + 20% benzene		0.1200	-	-	-	-	-
18	Roumanian straight-run gasoline (No.1) + 40% benzene		0.1190	-	-	-	-	-
19	Roumanian straight run gasoline (No.1) diluted 1:1	0.060	0.0605	-	-	-	-	-
20	Brown coal hydro-gasoline (No.6 diluted 1:1)		0.0600	-	-	-	-	-
21	Iso-octane (tech.) (No.11) diluted 1:1		0.0595	-	-	-	-	-

On the behaviour of Greases, Diesel fuels, Instrument oils, and Brake fluids at low temperatures.Part I: On the behaviour of greases at low temperatures.

Synopsis: Various methods, in technical and scientific use for rating semi-solid lubricants when they are subjected to low temperatures, are discussed.

It is demonstrated that it is difficult, if not impossible to assess them by the methods which have been in use up to the present. A test method was evolved, which makes use of a test apparatus developed by DVL. at the suggestion of Dr. A.v. Philippovich. With this it is possible to determine the static and dynamic consistency (starting- and friction-resistances).

Contents:

- A. Introduction.
- B. General Remarks on the behaviour of greases at low temperatures.
 - I. Uses.
 - II. Chemical Structure of greases.
- C. Test Method
 - I. Test materials.
 - II. Apparatus.
 - III. Method.
- D. Test Results
 - I. Results of penetration tests.
 - II. Results of starting resistance tests.
 - III. Results of friction resistance tests.
- E. Evaluation of test results.
- F. Summary.

A. Introduction

Apart from a few industrial investigations very little has been done about the question of the low temperature behaviour of greases and similar substances. The commercial greases in use are, it is true, tested by some works laboratories as to their suitability for the purpose for which they are intended, the apparatus used being of the most varied patterns; they are found to possess adequate low temperature properties, and are brought into commercial use. The range of application of this type of lubricant is, however, so vast that it appeared desirable to characterize them on the basis of an exact test method. Also, the endeavour to produce a few types of grease which can be used for all purposes has become an important concern of those who are interested in this question.

It is naturally a necessary property that the aircraft parts which are specially important in the operation of the plane be

absolutely frost-proof. The same is also true of vehicles, which are subjected to low temperatures in severe winters. A condition for the perfect working of these machines is the use of a lubricant which can be subjected to low temperatures without noticeable change. In the winter of 1939/40 the prevailing temperature at 6000 m. above sea level was -70°C ., which made itself unpleasantly felt in the jamming of the tail unit and ailerons. This condition can be attributed to the failure of the lubricant at low temperatures.

The Institute for Fuel Research of DVL. was early concerned with the carrying out of tests with the object of classifying the ordinary commercial roller bearing greases. Above all, tests were made to discover how far the greases which are known-to-day have the required degree of resistance to low temperature. Initially well-known forms of apparatus were used, among them being the penetrometer of Richardson which was standardised by A.S.T.M. In the course of the investigations, use was also made of the apparatus developed by I.G. Farbenindustrie. The result was negative, as it was impossible with any of these apparatus to obtain a characteristic, which was not open to objection, for greases which had been cooled down. Twenty commercial roller bearing greases were investigated. The object of these experiments was to develop a test method of our own which would make it possible to classify lubricating greases and determine their value for aeronautical purposes.

Neither oils, when exposed to low temperatures, or greases, obey Newton's law, their flow behaviour being influenced in varying degrees by the friction pressure. Therefore, a practical process should either alter the frictional pressures and measure the resulting speeds of flow or at a given frictional pressure (constant r.p.m.) observe the torque as a function of temperature.

With this in view an apparatus was developed which works accurately and gives reproducible values. The results are shown in this work.

B. General Remarks on the Behaviour of Greases at Low Temperature.

I. Uses.

As has already been mentioned, lubricating greases are used for lubricating vital parts of aircraft, that is to say, all the working parts of all types of machines. They are always used at points where there is a risk that other lubricants, for instance oils, owing to their low consistency, will be thrown out of the most inaccessible engine parts. In the view of Holde (1), oils should be used where possible, for as greases increase in consistency there is an increased consumption of power. Thus, because of insufficient driving force, greases have sometimes failed. But, as stated, there is the danger that oils will be thrown out of the working parts, and it is thus impossible to dispense with lubricating greases.

Semi-solid lubricants are also used for:

Water pumps on water-cooled aero-engines,
Axle bearings of chassis,
Instruments, and slow-running ball bearings,
Adjusting gear of air-screws, and all points which are
lubricated with grease, such as ailerons, rudders etc.

According to the purpose for which they are intended, the various types of greases produced are non-saponified or saponified, but generally the latter, and are semi-solid. The latter include calcium greases, sodium greases, potassium and aluminium greases, lead greases and zinc greases. Thick greases and emulsion greases generally contain unsaponified products.

II. Chemical structure of greases.

At ordinary temperatures, lubricating greases are generally more or less solid or thin, paste-like substances, becoming fluid at higher temperatures. The Stauffer or Tovote machine greases which concern us here are normal, semi-solid lubricants. They consist of colloidal solutions of soaps, mainly gels of sodium, calcium, potassium, barium, magnesium and aluminium soaps. The loading agents in them (mainly in the light types of grease) are talcum, earths, asbestos, or graphite.

The saponified semi-solid lubricants which have been introduced into commerce under the names: axle bearing grease, Stauffer or Tovote greases, high pressure lubricating greases, ball-bearing, roller-bearing and crank-bearing greases, are calcium greases. Their drop point is below 100°C. Their water content is from 0.4 to 4%. Separation into soap and mineral oil, with loss of water, occurs at 100°C.

The high temperature bearing greases and roller bearing greases, mostly sodium or potassium greases, have a drop point between 120°C. and 230°C. Their water content is practically zero. — While the above-mentioned calcium greases are practically insoluble in water, and have a rigid structure, the sodium greases are soluble in water. They nearly always have an elastic long-fibred structure.

The aluminium greases are used instead of highly viscous lubricating oils. Their drop point is below 100°C; they do not break down at higher temperatures, as do calcium greases. In consequence of the absence of abrasive constituents, they are used for lubricating ball bearings.

For lubricating enclosed gears, lead greases with a drop point below 100°C and a high specific gravity are used.

For lubricating cables and chains, gears, stuffing-box packings, etc., zinc and similar greases are used (that is, greases with high specific gravities and low drop points) as well as mixtures of resins or wax with mineral oils, so-called thick greases.

The diminishing amount of water, which is present in the grease in the form of small drops, influences the consistency and the drop point, in consequence of the surface tension on the individual drops. If the grease is heated till the drop point is reached, then, owing to the tearing of the membranes which surround the drops of water, the grease goes over from the solid, paste-like state to the fluid.

If greases are left standing for a long time, oil sometimes separates out, the reason being the evaporation of the water on the surface of the greases. Owing to the separating out of the oily particles, water-free solutions of the calcium soaps in mineral oils become non-homogeneous after a short time. Only with greases produced in the autoclave and with high-melting, high temperature bearing greases is there no inhomogeneity. They do not separate out calcium salts, even if they are continually heated or cooled.⁽²⁾

C. Test Method.

I. Test Materials

The test materials selected were ²⁰sodium, potassium, calcium, and aluminium soap greases, all of which are commercial high-temperature or roller-bearing greases. They are designated below as Nos. 1 to 20.

Their properties are summarised in Table I.

The difference in the composition of the greases also affects their consistency, and since greases are classified according to their state, which ranges over numerous intermediate stages from semi-fluid and paste-like to semi-rigid, the test methods used had also to be varied. In the course of time, however, people came to rely on so-called consistometers. Some firms (mainly ball-bearing firms, as already mentioned) rated their products by their own test methods, examining them in test apparatus specially constructed for the purpose. The test apparatus now to be described were used in investigations carried out by the Institute for Fuel Research.

II. Test Apparatus

1. Richardson's Penetrometer: For determining the consistency of greases, the Penetrometer of Richardson was used (3). The apparatus consists of a pedestal, which is secured to a base-plate and has a movable arm of iron. The iron arm has a plate divided into degrees, whose pointer turns when a rack connected with it moves up and down. The lower end of the rack touches the head of the penetrometer in its downward motion. The penetrometer is held in the lower part of the pedestal by a sprung push-button. The push button releases the top part, which then penetrates into a container filled with the substance being investigated, which is underneath. The total weight of the cone-shaped top piece is 150 grammes. Fig. 1 shows a section of the Richardson penetrometer.

2. I.G. apparatus for measuring break-off resistance: The break-away resistances were measured in a test apparatus constructed by I.G. Farbenindustrie, and shown in Fig. 2. The installation in the test space of a cold chamber consists of a shaft and a bearing ring. The shaft is mounted on two ball-bearings, and driven by an intermediate shaft. The drive is provided by an electric motor, whose rate of revolution of 2800 r.p.m. is reduced by a worm gear to 56 r.p.m. The test shaft is connected up by engaging a claw clutch. The torque exerted on the bearing is transmitted by a light thrust rod to an indicator above the cold chamber. The other installations in the test chamber, such as: slotted intermediate wall, heating arrangements, temperature regulator, and ventilator, make it possible to maintain a constant working temperature.

In the Richardson penetrometer, which was originally constructed for asphalt investigations, as also in the I.G. Test apparatus, consistency tests and "breaking-away" tests were made after the grease had been thoroughly worked. Two distinct processes were required for this.

The DVL. test apparatus now to be described is an attempt to create a test apparatus which introduces a simplification by combining the two processes, namely working and the measurement of consistency.

3. DVL Test Apparatus for measuring the starting and friction resistances:

The test installation consists of a low temperature unit, the I.G. cold chamber, with the accessories which are necessary for the measurements, and the test apparatus built into the chamber.

The test apparatus which is actually shown in Fig. 3 consists of a worm-screw of 26 mm. diameter. Its length is 75 mm. The device is in a housing with an inner diameter of 30 mm., which is provided with a projection (threaded pipe with screw-cap) for pressing in the grease. This projection also serves to hold an inserted thermometer with a stem 35 mm. long. The worm is also bored to a depth of 30 mm. A right angle thermometer is built into the boring. Both thermometers measure from + 10°C. to - 80°C. The test apparatus has also an adjustable screw, with an indicator attached. It is surrounded by a cooling jacket, which holds the cold bath. The test apparatus is driven by a motor with a transmission and a connecting coupling.

III. Method.

1. Measuring hardness or consistency by the Richardson method.

To measure the consistency of greases in the Richardson penetrometer, the material to be investigated is melted at low temperature, with constant stirring, and is poured or worked into a 500 gramme container. The surface of the grease is evenly cut. It is important in this investigation that the grease shall be as free as possible of bubbles when it is introduced into the container. Then the point of the penetrometer is put on the surface of the grease, and the sprung push button is released, at the same time as a stop watch is started. The point of the cone is left to exercise its effect on the grease for 5 seconds, and after the rack has been depressed as far as the head of the cone, the depth of penetration is read off in units of the scale. The test is repeated several times, and the average of the readings is taken. The low temperature investigations are made by putting the grease container - in these cases, instead of boxes, WEX glasses, which are hermetically sealed by means of an adhesive - in a cold bath, and cooling down to the working temperature. The temperature was maintained for an hour, and the container was opened directly it had been taken out of the liquid in the bath. The consistency was measured at various points, and after each measurement the temperature in the funnel-shaped depression was measured. An extremely awkward feature of the investigation was the fact that after the test had been concluded at one temperature it was necessary to heat the grease up again to room temperature, and work it again, before going over to a new working temperature. Only then was it possible to cool down again to a new test temperature.

2. Measuring the "break-away" resistances

When measuring the "break-away" resistances in the I.G. test apparatus, the grease under test is well spread over the bearing and on the journal. Then the shaft and the bearing ring are assembled. To obtain an even film, the shaft is allowed to rotate a few times in the bearing ring. Excess grease is removed by shifting the ring backwards and forwards during the run. The bearing ring is prevented from becoming axially displaced during the run by a spring. The indicator and thrust rod are now put on, and the required temperature is reached by opening the ports in the slide valve, and so cooling. The temperature is kept constant by adjusting the slide valve and heating. After a period of 30 minutes, in which a condition of

equilibrium should be reached, the motor is set working, and the claw clutch is made to engage by the pressure of the indicator spring on the indicator drum. After the test has been completed, that is, after five measurements (maxima), the ports are closed. The test chamber is brought to room temperature again by switching on the heating. The bearing is then re-greased. The test is then done again at a different working temperature in the way described.

When various greases were investigated, however, it was found that the indicator deflection was too small. Also, at low temperatures it was impossible to make proper measurements. The experiments were then discontinued.

The greases could be much more simply tested by the method described below, since it was not necessary to supply the test apparatus with fresh grease. Also, the time required for cooling could be reduced to a minimum.

3. Measuring the static and dynamic consistency.

The worm gear, coated with the grease for testing, is fitted into the housing, which is also coated with the same grease. The housing is closed from the side with a screw-on cover, and a threaded screw-cap filled with grease is screwed on. This nut serves as a stuffing box, so that it is possible at any time to fill the apparatus with the grease under test. This is then fitted into the complete apparatus, and secured to a claw clutch. The worm gear is then allowed to run for 5 minutes at 56 r.p.m., and thoroughly kneads the grease. With cooling now commencing, the required test temperature is reached with all possible speed. The fluids in the bath are solid carbon dioxide and alcohol. The bath is kept at the required temperature for 15 minutes. Then the claw clutch is pushed home and the "break-away" (static consistency) is recorded. 5 "break-away" values are recorded at each particular temperature, being measured at intervals of 5 minutes.

After the "break-away" tests have been completed, the coupling remains engaged for the purpose of recording the kneading values (dynamic consistency). To measure 5 break-away values at 5 different temperatures, $3\frac{1}{2}$ hours are required. If a curve based on 3 measurements is considered adequate, for instance, the initial value, middle value, and the final value, then there is the possibility of testing 4 to 5 greases in one day. About 100 grammes of grease are required for the test. As already stated, this test method has the advantage that a grease can be tested in one process without renewing the grease, or heating after the "break-away" test and then re-cooling to the test temperature; for example, if the grease "breaks away" at -20°C ., heating to room temperature, cooling again to -20°C ., and again "breaking away". Also, it is possible to transfer to lower test temperatures without first heating to a higher temperature (room temperature). All that is necessary when going to another temperature is a pause of 15 minutes after reaching this temperature.

D. Test Results.

I. Results of penetration tests.

The results of penetration tests on 11 different greases are shown in Curve 1.

Of the greases investigated, 8 show definite points of inflection, mostly at about -20°C . The greases in question are

Nos. 1, 3, 9, 13, 16 and 21. The curve for Grease No. 7 has an inflection point at -5°C ., while that of Grease 12 has an inflection at -14.5°C . After the inflection, the curves become more or less steep. Grease 4 has a flat, linear curve, while greases 8 and 10 have linear curves, which are, however, steeper than the others. All the curves intersect more or less, so that it appears to be very difficult to obtain a good characteristic curve for the greases. It is clear that greases 1 and 3 had the best rating. These are absolutely soft greases, which, even when subjected to extreme cold, still have a fairly thin paste-like consistency, and may therefore be considered as cold resisting. Grease 1 has a depth of penetration of 140 (arbitrarily fixed) units, and its characteristic curve is easily the best. Greases 4, 7, 8, 9, 13 and 21 can perhaps be considered medium-hard, and greases 10, 12 and 16 medium-hard to hard.

Since, as already stated, it is very difficult to arrive at a good assessment of the greases by the test method suggested by Richardson, it is obviously even more difficult to bring the consistency values into line with practical conditions.

The measurements of the starting and friction resistances in the DVL test apparatus appear to be more suitable for such a comparison.

II. Results of starting resistance tests (static consistency)

The test results obtained with the test apparatus described above are related to the temperature and plotted in diagram 2.

The nature of the curves shows the different starting behaviour of the individual greases. The measurements were spread over a temperature range from -10°C to -70°C . The starting resistances were measured on a bearing which ran with interruptions. The measurements show good reproducibility. Diagram 4 shows "break-away" values which were directly recorded on the recording strip of the indicator. Conclusions can be drawn from the agreement between the maxima about the accuracy of the measuring process. The position of curves 1 to 7 indicates that they are soft greases with a fair resistance to low temperature, while greases 8-14 are fairly hard, 15-18 are of hard, and 19 and 20 of very hard consistency. While the "break-away" values of 1-7 are relatively close to each other at -50°C ., some of them tend towards the danger area at -65°C . Greases 1-5 give readings at -70°C ., from which it can be concluded that grease 4 is close to the limit, and that grease 5 is well beyond the permissible degree of cold resistance. Of the other greases investigated, Nos. 6 and 7 at -65°C . have a sufficient resistance to cold. Greases 8, 9 and 10 can still be used at -65°C . Greases 11-14 are adequate at -55°C . Only greases 15-20 were completely inadequate at low temperatures, i.e., at temperatures below -45°C . such as are encountered in high altitude flights.

The experience of DVL. was that no grease whose "break-away" value at -60°C . is above 13 consistency units (likewise an arbitrarily fixed unit) can be considered resistant to low temperature. For the present, this value was selected as the limiting value. Further tests being made by DVL. will explain exactly why this limit was selected.

Data were also obtained about the influence of the cooling time. It was found that this influence was not apparent, whether the break-away occurred after a pause of 15 minutes, half-an-hour, or an hour at constant test temperature. If the "break-away" experiments were continued to the end, that is to say, terminated after being repeated five times, they were

generally followed by the kneading test, that is, the determination of dynamic consistency on a bearing which is running without interruptions. After determining the worked value and the time of cooling which followed it, the same "break-away" value was observed after a pause of 15 minutes as before working (Fig.5). In none of the cases investigated was a maximum value observed after various cooling times. Tests made on the same material on different days, under the same test conditions, gave the same values.

III. Results of Friction Resistance Tests (dynamic consistency)

In the investigations on greases 1 to 19, the curves for the friction resistances (dynamic consistency) generally gave a similar order of rating. For better comparison, a larger scale was selected for the points plotted on diagram 3. The test time for determining the friction resistances was 5 minutes with the bearing running without interruption. Curves 1 to 5 were in a different order to that of the break-off curves. The curve for grease 5 had the flattest slope and the lowest consistencies at -65°C . and -70°C . The curve becomes much steeper below -70°C ., than in the case of greases 3 and 4, which have equal consistency values at -65°C ., but different values again at -70°C . But taking into account that a much larger scale was used, the difference of 0.6 units between the lowest consistency value (grease 5) and the highest value (grease 2) cannot be considered very pronounced.

Comparing curves 1 to 5 with curves 6 to 19, the greatest difference is seen to be that between the angle of slope of the curves. Including No. 6, which had only a comparatively slight tendency to resist solidification at low temperatures, the greases are almost exclusively in the medium hard or hard region at temperatures below -60°C . This means that they can only be used under certain conditions, after working, at temperatures of -60°C ., and below. It can further be stated as regards these tests, that greases 1 to 5 on working can be used without limitation at -70°C ., and greases 6, 8 and 13 are serviceable under certain conditions at temperatures round -70°C . The other greases, however, fail completely at higher temperatures, grease 19, which is the least cold-resistant, being completely useless.

E. Evaluation of Test Results

I. Penetration.

It is not possible to rate the greases as to low temperature behaviour on the basis of values given by the penetrometer. This procedure makes it possible to draw conclusions about the degree of flow resistance of the greases, but does not admit of comparisons with low temperature behaviour in practice. Also, the consistency figures obtained by this process and those made with the DVL test apparatus do not agree. The time required for the penetration test is very great, since the greases must be re-cooled again and again.

A much better result was obtained with the test apparatus developed by DVL., which was evolved with practical conditions in mind, and gave reproducible results.

II. Starting resistances (static consistency)

The investigation of chilled greases which were run in a bearing having an interrupted run, showed "break-away" values which make it permissible to rate their resistance to low temperature on this basis. With this method it was possible to

measure the limit of low temperature dependability. This limit value was selected and fixed on the basis of the experience of DVL. It gives data about the failure of greases at certain temperatures. In practice, the resistances which are encountered in the steering gear when set in motion or in other bearings at low temperatures may not exceed a certain figure. If the steering gear is only slightly moved as is the case in flying straight for long distances, at low temperatures, it may jam hard through formation of crystals. This is a source of grave danger to machine and crew, which can only be reduced by using in the controls a cold-resistant grease which complies with every requirement. Unanimity has not in practice been reached as to the maximum force which is permissible for the freezing of the control details. On the basis of the experience they have gained in investigations on many greases, DVL laid down the figure of 13 units of consistency at -60°C . Further investigations will be directed towards discovering, whether this useful low temperature limit can be displaced upwards or downwards. It may be stated with certainty that greases 1 to 4 do not fail at extremely low temperatures, and do not offer a very great resistance to the free operation of the control parts.

III. Friction resistances (dynamic consistency)

When greases are thoroughly worked, the conditions are somewhat different. Here it is important to determine whether, when flow resistance is high and the break-off has occurred the gear parts rotate in a cavity which has been hollowed out, or whether the grease can again be re-circulated to the bearing, in consequence of its thin paste-like (soft) consistency.

In the first case one would be dealing with greases which have been given the designation "hard" or "very hard" on the basis of investigations made on them. The danger of dry friction is very great here, for to begin with only a part of the crystalline texture is broken. The period which elapses before the whole structure becomes a paste of grease and crystals will be very long. This makes itself evident in the working test from the fact that, after the "break-away" the curve falls rapidly, and then, however, the pointer of the indicator is violently arrested. From this moment onwards the curve only falls very slowly.

In the thinly paste-like greases the whole structure is destroyed immediately. The kneading very soon produces a paste of grease and crystals, which absolutely eliminates the danger of dry friction. This is observed on the recording instrument as a slow but steady falling of the indicator curve until a minimum is reached.

In conclusion one can say that greases 1 to 5, which are known to be outstandingly soft greases, can be used even at temperatures below -70°C ., even when from time to time the bearings are not running. The medium-hard and hard greases must, however, be fed into the bearings with a certain amount of caution.

F. Summary.

An original apparatus has been evolved for investigating greases, which

- 1) Requires comparatively small quantities of grease
- 2) Under certain conditions permits the temperature to be rapidly adjusted

- 3) Makes it possible to carry out continuous measurements during the run.

In this way a characteristic curve was established for the greases, based on the behaviour on "breaking away" and working for a long time, after cooling.

Consumers wish to restrict the large number of greases which are produced. The behaviour at extremely high temperatures, the stability on ageing, and the load capacity, were not investigated in the course of these researches. As regards the question of resistance to low temperature, it appears that it is quite possible by using the procedure suggested here to lay down the allowable values, and so to reduce the number of greases in use.

Literature

- 1) D. Holde, Kohlenwasserstofföle u Fette, 7th Edition, p.378 (1933)
- 2) ditto ditto ditto p.379.
- 3) Tentative method of test for Penetration of Greases and Petroleum ASTM Standards on Petroleum Products and Lubricants p.193. (Sept.1933)
- 4) Bericht der I.G. Farbenindustrie, Experiments with lubricants in the cold. Vers.Bericht. Nr.296. Techn.Prüfst.Oppau 200.

Table 1

Description of Grease	Flow Point	Drop Point	Ash %	Water %	Alkali No. mg.KOH.
1	61	68	1,04	0,5	0,178
2	73	80	1,24	0,15	0,011
3	68	137,5	0,43	0,0	0,252
4	81	89	1,99	traces	0,561
5	85	158	1,82	0,4	0,140
6	85	98	2,50	-	-
7	85	94	4,12	0,0	0,841
8	90,5	128,5	0,55	traces	-
9	88,0	94,5	1,65	"	1,290
10	82,5	93,5	1,83	"	0,791
11	-	-	-	-	-
12	85,0	100,0	3,48	1,0	0,522
13	62,0	69,0	1,34	0,4	0,101
14	-	75	4,0	4,0	-
15	77	150	1,10	1,0	1,6+)
16	120	145,5	1,57	0,1	0,196
17	95	120,0	0,97	traces	-
18	94	102,0	3,12	3,0	-
19	115+)	150+)	1,50+)	traces	-
20	-	38-51	0	0	0

+) Statement of producing firm.

- Fig.1. Richardson's penetrometer.
 Fig.2. I.G. apparatus for determining "break away" resistance.
 Fig.3. DVL Kneading Apparatus.
 Fig.4. Break-away values recorded in the DVL consistometer (Grease 19). Kneading test I73 was carried out in conjunction with the break-away tests.
 Fig.5. Kneading test (Grease 19) and subsequent break-aways after a pause of 15 minutes.
 Diagram 1. Penetration tests by the Richardson method.
 Diagram 2. Static consistency (break-away values)
 Diagram 3. Dynamic consistency (worked values).

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Rickert & Staab

Determination of the lead tetraethyl content of fuels by means of X-ray absorption

Synopsis

Previously the lead tetraethyl content was determined chemically. This generally took a lot of time and required chemical training. During the past year a simplified rapid method was developed in the Stuttgart Research Institute, which reduces the necessary time to 10 minutes.

The method recommended in the present report depends on the absorption of X-rays passing through a layer of leaded fuel. The manipulation is very easy.

Each lead determination takes about 1 minute. The method is particularly suitable for routine examination.

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Index of Symbols

$\% EF$	Percentage weight of ethyl fluid
αPb	" " " Lead
αBr	" " " Bromine
D	Thickness of Fuel Layer in cm.
ρB	Density of unleaded fuel, gm/cc
ρ	" " " leaded " "
$(\frac{\mu}{\rho}) B$	Absorption Coefficient of unleaded gasoline
$(\frac{\mu}{\rho}) EF$	Mass absorption coefficient of the ethyl fluid with exclusive reference to lead and bromine content
$(\frac{\mu}{\rho}) Pb$	Mass absorption coefficient of Lead
$(\frac{\mu}{\rho}) Br$	" " " " Bromine
J_0	Intensity of Radiation before the fuel layer
J_o	" " " " after passage through the leaded fuel
J_u	" " " " " " " " unleaded fuel

Introduction

The knock tendency of carburettor fuel limits the output of spark ignition engines. In general, the highest output may be expected shortly before the knock limit is reached when compression or boost pressure is increased. This creates the demand for fuels whose anti-knock values are as large and as constant as possible.

In order to obtain the desired octane number, the requisite amount of lead tetraethyl is added to the fuel in the form of ethyl fluid.

-2-

It is necessary to obviate the detrimental corrosive effect of the lead dioxide; the latter has a very high melting point (800°C) and is thus easily deposited in the combustion chamber. For this reason ethylene dibromide is mixed with lead tetraethyl in the ethyl fluid, in a definite, constant proportion. As a result lead bromide, $PbBr_2$, is produced during combustion. The melting point of lead bromide is 370°C and its removal by the exhaust gases from the combustion chamber is consequently facilitated.

The ethyl fluid used in aero-engines is composed thus:

Lead Tetraethyl $Pb(C_2H_5)_4$	61% by weight
Ethylene Dibromide	35.66% " "
Colouring matter, petroleum & other additions	2.92% " "
Density	1.755 gm/cc
Volume ratio of ethyl fluid to lead tetraethyl	1.531

The ethyl fluid used in automobile engines has the following composition:

Lead Tetraethyl	63.5 % by weight
Ethylene Dibromide	25.75% " "
Ethylene Dichloride $(CH_2)_2Cl_2$	8.72% " "
Colouring matter, petroleum & other additions	0.32% " "
Density	1.671 gm/cc
Volume ratio of ethyl fluid to Lead Tetraethyl	1.561

Up to now the content of lead tetraethyl in fuels has been determined by chemical methods, and until recently, one lead determination required a very long time. Only during the past year the time was reduced to about 10 minutes, while maintaining an accuracy of plus or minus 0.003 vol. percent.

A new method has now been developed at the F.K.F.S. This makes it possible to determine the lead content in still less time by means of physical measurements. According to a proposal by W. Gross, X-rays have been tried and have since been most usefully employed in material testing. The principle of the method is to use the absorption of X-rays by passage through certain thickness of fuel as a measure of the lead content of the fuel. The usefulness of this idea for lead determinations depended on whether it was possible to register differences in intensity of the X-rays by simple means and with sufficient accuracy. A measuring instrument of high sensitivity has been known for a long time. This is the Geiger-Müller counter which is very frequently used for physical investigations. But this instrument has not yet become suitable for industrial tests because it works too irregularly and because its manipulation demands too much experience. In the last few years, however, Trost has developed technical counters which have been applied to the testing of materials.

Essentially the counter consists of a cylindrical metal tube of diameter from a few mm. to a few centimetres. A thin wire, insulated from the tube by amber discs, is led through the tube axially. This arrangement is enclosed in a glass tube which is exhausted and then filled with a gas such as argon or alcohol vapour. A D.C. voltage of 1000 V - 1500 V is applied to the tube. The intensity of X-rays may be measured with this tube.

Experimental Arrangement

The experimental arrangement consisted of an X-ray installation and a counter with amplifier (Fig. 1). The small Kristalloflex X-ray outfit, made by Siemens and Halske, Berlin, was used with the Micro-50 Apparatus of C.H.F. Müller. The counter was an interference counter constructed at the Reichs X-ray institute, and was designed for investigation of the fine structure of the X-ray spectrum, and is able to measure X-ray intensities with high accuracy. The intensity is no longer obtained from impulse-counting which had been the usual method; instead the counter current is read on a milliamperemeter. This amounts to an enormous simplification and permits rapid comparison of intensities. The amplifying apparatus of the Reichs X-ray institute was used. It is built for

various ranges of sensitivity and inertia, which would not be necessary for the present simple absorption experiments.

For the sake of simplicity, the fuel was poured into a thin-walled beaker, which was placed between the X-ray tube and counter. Initially measuring cylinders of small diameters were used; but the stray radiation was found to have a bad effect. A lead screen mounted above the counter shielded the radiation which did not strike the counter. The two must not be displaced relatively to each other; otherwise part of the radiation striking the slit of the counter which is protected by aluminium foil, would be absorbed earlier, and comparison of successive measurements could not then be made.

The X-ray Absorption Curve for Fuels

At 22 kV and with a layer 15.6 cm. thick of T.C. Reference Fuel of density 0.713 gm/cc the variation of radiation intensity with concentration of lead tetraethyl was obtained with the experimental arrangement described above (Fig. 2). The same variation was obtained for other gasolines. It will be shown below that the same curve can be obtained by a simple theoretical consideration, which will also permit estimation of the influence of the nature of the fuel on the test results.

The reduction of intensity of the X-rays which is composed of losses due to absorption and losses due to scattering, is caused by the atoms themselves. It does not matter, therefore, whether an element is present as a compound, a mixture, a liquid or a solid. Only the number of atoms of the element concerned, counts. The reduction of intensity is measured by the absorption coefficient, μ , or the mass absorption coefficient μ/ρ where ρ is the density of the element in question.

If a layer of thickness D of an element of absorption coefficient μ is irradiated with a parallel beam of a definite wavelength, then the intensity of the radiation (the energy of radiation incident in one second on a plane 1 cm square at right angles to the direction of radiation) after passage through the layer is

$$J = J_0 e^{-\mu D} \dots\dots\dots (1)$$

where J_0 is the intensity before passage through the layer.

For mixtures and chemical combinations the expression becomes

$$J = J_0 e^{-\left\{ \frac{\mu_1}{\rho_1} \rho_1 + \frac{\mu_2}{\rho_2} \rho_2 + \dots\dots\dots \right\} D}$$

where $\frac{\mu_1}{\rho_1}$ etc. are the mass absorption coefficients of the elements which are contained in the substance at concentrations by weight ρ_1

It can be seen from this expression that in order to be able to determine the concentration of lead tetraethyl by means of the absorption coefficient of X-rays, the condition is that the product $\frac{\mu}{\rho} \rho$ for lead tetraethyl should have a certain minimum value as compared with $\frac{\mu}{\rho} \rho$ the corresponding values of the other constituents of the mixture. Since ρ only amounts to 0.3% by wt., μ for lead tetraethyl must be very large compared to the corresponding value for gasoline. This is actually the case; the gasoline is built up of atoms of low atomic number and the mass absorption coefficient is approximately proportional to $\lambda^3 Z^3$, where λ is the wave-length and Z is the atomic number.

Table I
Specific Reduction Coefficients of Several Elements

Voltage in volts	min $\frac{\mu}{\rho}$	H	C	O	S	Br	Pb
30900	0.40	0.46 x)	0.245	0.34	1.78	-	51.9
24700	0.50	0.44 x)	0.315	0.52	3.5	52	57
22000	0.56	0.44 x)	0.40	0.68 x)	4.82	43	76
19600	0.63	0.435	0.474	0.900	6.9	59	101

x) interpolated

The specific reduction coefficients of the elements of interest may be read off from Table I.

The analysis of the gasoline (J.C. Reference Fuel) gave the composition as 85.2% by wt. of carbon and 14.8% by wt. of hydrogen. Although one is dealing with a continuous spectrum i.e. a multiplicity of wave-lengths, one can use its shortest wave-length, λ_{min} , as an approximation, the other wave-lengths being absorbed to a much greater extent proportional to λ^3 . At 22 kV, λ_{min} equals 0.55 Å. For this value the specific reduction coefficient may be taken from Table I for carbon and hydrogen, and therefore the J.C. Reference Fuel, is

$$\left(\frac{\mu}{\rho}\right)_B = \frac{85.2}{100} \cdot 0.40 + \frac{14.8}{100} \cdot 0.44 = 0.408$$

Since the lead is not contained as such in the fuel, but is added in the form of ethyl fluid, the reduction of intensity of the X-rays by the ethylene dibromide must also be taken into account. As explained above ethylene di-chloride is also present in automotive fuels, but its effect is quite similar. The small additional amounts of carbon and hydrogen present in the lead tetra-ethyl and the ethylene dibromide may be neglected in comparison; similarly with any additions consisting of elements of lower atomic number.

The thickness of the layer D was kept constant for the various leaded fuels. A small alteration in the density by reason of the leadings was however taken into account.

The intensity of the X-rays after passage through the J.C. Reference Fuel with different concentrations of ethyl fluid, measured at D equals 15.6 cm, S_B equals 0.713 gm/cc and a working potential of 22 kV were these:

Amount of ethyl fluid in 1000 cc of fuel:

0 cc :	J =	J_0	0.51096
0.5 " :	J =	J_0	0.00619
1.0 " :	J =	J_0	0.00342
1.5 " :	J =	J_0	0.00192
2.0 " :	J =	J_0	0.00105

The curve obtained from these values has been plotted in Fig. 2. One could not have expected a better agreement with the experimental absorption curve, for the values employed in the calculation could not be determined with sufficient accuracy because the experimental arrangement was only set up for comparison purposes.

From the experimental curve, one may also observe the accuracy of the intensity measurements. The accuracy of the lead content determination by this method is shown to result, at a concentration of 0.015% by vol. of T.E.L. in an error of about 0.003% by vol. T.E.L. and at a concentration of 0.12% by vol. an error of about 0.005% by vol. T.E.L.

Measurements on gasoline samples of different densities and compositions

The gasoline samples differ in density and chemical constitution. It is essential for X-ray analysis that the proportions of carbon and hydrogen alter only very slightly (according to table II, column 2, from 85 to 87% by wt.) Such an alteration has little effect on the absorption of X-rays since the specific reduction coefficients of carbon and hydrogen only differ slightly (at 22 kV 0.40 for carbon and 0.44 for hydrogen)

a) Measurement of concentration of T.E.L. for equal layer thicknesses

For equal thicknesses of the layer it is evident that similar curves for ethyl fluid will be obtained with different fuels. For in equal volumes of fuel, equal parts of ethyl fluid by volume i.e. equal numbers of atoms of lead and bromine will be present if the concentration of ethyl fluid is the

same. This means an equal reduction of the intensity of the X-rays. (see paragraph 3). The same may be seen from a consideration of the intensity equation:

$$J = J_0 \cdot e^{-\left(\frac{100-\alpha}{100}\right) S D} \cdot e^{-\left(\frac{\alpha}{100}\right) S D} \dots (5)$$

where $\frac{100-\alpha}{100} S D$ is the weight of gasoline in gm.

and $\frac{\alpha}{100} S D$ is the weight of the ethyl fluid per unit of surface.

The second factor is proportional to the volume concentration of ethyl fluid if the terms of higher order are neglected. The first factor varies very little for various concentrations in the same gasoline.

The intensity of the unleaded gasoline i.e. for $\alpha = 0$

$$J_u = J_0 \cdot e^{-\left(\frac{100}{100}\right) S D}$$

is independent on the density, because of the constancy of D and $\frac{100}{100}$. This may also be seen from Table II, 4th column, where the calculated values of J_u/J_0 have been entered. The third column gives the experimental results.

Thus, starting with constant intensity, J_0 , the absorption curves in the intensity diagram must intersect the ordinate at different heights. These families of curves have been entered into Fig. III. It is only necessary to measure the density of the gasoline after carrying out the intensity measurements for the leaded gasoline, and read off the concentration of lead tetraethyl.

If the unleaded gasoline is available for a comparison experiment, then, by interpolating in the family of curves in Fig. III, the lead tetraethyl concentration can be determined directly without a density determination.

If a comparative measurement cannot be carried out it is assumed that the constants of the instrument remain the same, i.e. the same deflection of the millimeter is obtained for a given intensity of radiation incident on the counter. Experiment has shown that this is the case over a sufficiently long period of time.

b) Determination of the concentration of lead tetraethyl for constant weights.

For equal values $S D$, i.e. equal weights of unleaded gasoline per sq.cm., equation (5) indicates that the intensity of radiation J_u will be the same.

The results of the measurements have been entered in column 5, table II. These agree with the calculated values of column 6 to a sufficient degree of accuracy.

Again it is the second factor in equation (3) which mainly determines the reduction of intensity because the first factor alters only slightly with increasing lead content and alters similarly for all gasoline samples. Moreover for equal lead content α is approximately inversely proportional to the density S . Therefore different gasolines of different lead content will give curves in the intensity diagram which, though starting from the same point on the ordinate, have different gradients corresponding to the different densities.

In this method, as in previous ones, a weighing has to be done for the determination of the density. There is the advantage, however, that in order to obtain the point of intersection of the absorption curve and the ordinate one can make a comparative measurement with an unleaded gasoline which need not even have the same density. This latter method would be advantageous if one had an apparatus whose sensitivity does not remain constant over a longer period of time.

Consideration of various additions

a) Sulfur content

The sulfur content of aviation fuels must not exceed 0.05% by wt. The average value, however, amounts to 0.01 to 0.02% by wt.

Column 6 of table II gives the value of the ratio of intensities J_u/J_0 for J.G. Reference Fuel with an addition of 0.05% of sulfur measured for the same weight per sq. cm. It is about 2% less than the ratio for pure gasoline; thus it would just be noticeable in the measurements. It can be assumed, however, that no more than half this concentration of sulfur is present, and the sulfur can be neglected in most cases. If a measurement with the unleaded gasoline is possible, then the error introduced by the sulfur content would cancel out and an accurate determination of the concentration of lead tetraethyl can be made.

b) Peroxide

Peroxides are formed through long storage of fuels. They do not, however, amount to more than 1% by wt., which is equivalent to 0.29% by wt. of oxygen. This does not affect the measurements very much because the mass absorption coefficient of oxygen does not differ very much from that of carbon.

The intensity ratio J_u/J has been entered into column 6 of table II and calculated for the given concentration of peroxides in J.G. Reference Fuel. It will be seen that the value given does not even differ by 1% from the value for pure gasoline. The error is thus within the limits of experimental error.

Fuels containing Benzene and Alcohol

Alcohol or Benzene is sometimes added to the fuel in order to diminish its tendency to knock. Benzene contains 92% by wt. of carbon which is considerably more than for gasoline.

a) Benzene Content

The results of measurements carried out with a mixture of 60% J.G. Reference Fuel and 40% Benzene are shown in column 5 of table II. For equal weights no difference, as against pure gasoline, is found. For this concentration of benzene, calculation gives a value whose difference from the gasoline value is within accuracy of the experiment. For pure benzene one obtains an intensity ratio which exceeds that for normal gasoline by 3%.

b) Alcohol Content

Experiments point to a somewhat larger effect of oxygen content than would correspond to the calculation. The reason for this cannot be ascertained without further investigation. If alcohol is present one cannot determine the concentration of lead tetraethyl without a comparative measurement with unleaded fuel. On the other hand, it may be carried out without difficulty if the intensity J_u for the unleaded fuel can be measured, because the absorption curve for ethyl fluid always takes the same course.

Since alcohol, as opposed to gasoline dissolves in water, the alcohol may simply be extracted with water. Lead tetraethyl and ethylene dibromide do not separate with the alcohol. An increased concentration of lead will thus be found in the residual gasoline and the final result may easily be corrected. A simpler procedure is to replace the alcohol extracted with water by unleaded gasoline; the correct concentration of lead is then obtained directly.

Suitable Test Conditions.

The ratio of the intensities of radiation J_u and J after passage through unleaded and leaded gasoline respectively, is approximately

$$\frac{J_u}{J} = e^{\frac{0.160 \text{ g D}}{1.5} \left(\frac{n}{s} \right)_{EF}}$$

The determination of the concentration of lead tetraethyl becomes more accurate as this ratio increasingly differs from unity. The ratio increases with larger mass absorption coefficients of the ethyl fluid i.e. of lead and bromine. This will be the case if one uses longer wavelengths i.e. lower working potentials. It was for this reason that the low voltage of 22 kV was used.

J_u/J also increases with increasing $\alpha_s D$ i.e. the weight of ethyl fluid per sq. cm. This should mean that 100 one would do best to use a long column of fuel at the same concentration of lead, but this is not confirmed by experiment. The experimental maximum for J_u/J is at 22 kV and with a layer thickness of 16 cm. The reason for this is the scattered radiation coming from every point irradiated by the X-rays, and this scattered radiation increases with increasing height D . The distance of the tube is not important as long as it does not become too large.

Further Work

Up to now the arrangement used is still a laboratory apparatus. It may however be developed so far that it would satisfy all practical requirements. Without much difficulty it will be possible to construct a portable instrument for these examinations, for X-ray units are available which would satisfy the requirements and have dimensions 20 x 45 x 35 cm. One might have to add a voltage stabilizer in order to smooth the variations of the grid voltage. This need not occupy much space.

It will be possible to develop a small amplifier with a counter for the present purpose; this could be made simple to operate and of sufficiently constant sensitivity.

The advantage of such X-ray measuring equipment would be particularly important in places where large numbers of determinations have to be made. One determination does not take more than a minute and the concentration of lead tetraethyl may be read off from a milliammeter or a curve. Screening would make the radiations completely harmless.

If a mains point should not be available, one would have to generate voltage for the tube. The consumption of the valve is only about 1kW.

Summary

W. Gross proposed that by using the reduction of intensity of X-rays it should be possible to determine the concentration of lead tetraethyl in a fuel with an accuracy of 0.002 - 0.003% by vol. of T.E.L. He suggested using a counter and his method would require only a very short time, thus facilitating series measurements. Results of still greater accuracy are to be expected with an apparatus developed especially for the purpose.

The measurements may be carried out in two ways:

1. Measuring the absorption of the rays after they have passed through the leaded fuel while keeping to a definite thickness of the layer. After measuring the density the concentration of lead tetraethyl can then be found by reading off a chart.
2. Carrying out the measurements with a definite weight of fuel per unit of area. After determining the density the concentration of T.E.L. is again read off from a chart.

For these measurements the unleaded fuel need not be available. This is of considerable importance.

It is further shown that the effects of peroxides and the usual sulfur impurities may be neglected. A content of 40% benzene does not affect the results either. On the other hand, even a small concentration of alcohol is noticeable. If, however, one can carry out a comparative measurement with the unleaded fuel, the concentration of T.E.L. will again be measurable with

the accuracy indicated. The alcohol may also be extracted with water.

The further problem will be to develop a simple and robust instrument for practical use. This should not meet with any difficulties in principle.

Table II

Comparison of various fuels with equal thicknesses of the layer and with equal weights on unit area. The experimental data in column 3 and 5 represent divisions on the millimeter.

Column	1	2	3	4	5	6
Fuel	Composition	Density gm/cc	J_u/J_o @ equal thickness D = 15.6 cm. Meas. Calc.	J_u/J at equal wts. 10.55 gm/cm ² Meas. Calc.		
J.G. Ref. Fuel	85.2% C pl. 14.8% H	0.713	66 ± 0.7	0.0110	62 ± 0.7	0.0138
Rumanian Gasoline	85.5% C " 14.5% H	0.726	61.5 ± 0.5	0.0102	52 ± 0.7	0.0138
CV 2b Hitzacker	app. 87% C pl. 13% H	0.793	42 ± 0.5	0.0067	62 ± 0.7	0.0139
VT 706 b Hitzacker	" " "	0.791	41.5 ± 0.5	0.0067	61 ± 0.7	0.0139
60% J.G. Ref. Fuel plus 40% Benzene	87.9% C pl. 12.1% H	0.781			61 ± 0.7	0.0139
80% J.G. Ref. Fuel plus 20% Alcohol	78.6% C pl. 14.4% H pl. 7% O	0.727	40 ± 0.5	0.0080	48.5 ± 0.5	0.0112
Alcohol	52.2% C pl. 13% H pl. 54% O	0.799			18 ± 0.5	0.0050
Benzene	92% C plus 8% H	0.829				0.01435
J.G. Ref. Fuel J.G. Ref. Fuel with pl. 1% peroxide	0.29% O					0.0136
J.G. Ref. Fuel pl. 0.05% Sulfur	J.G. Ref. Fuel with 0.05% S					0.0135

Figure I

Experimental Arrangement

Figure II

Calculated and observed values J/J_o as a function of the concentration of lead (J.G. Reference Fuel)

J intensity before passage through fuel layer
 J_o " " after " " " "

Figure III

Ratio of intensities J/J_o as a function of the concentration of lead at equal layer thickness and varying density of the fuel ρ_B

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(3) Influence of varied valve overlaps on various fuels
in the DB 601 engine.

Before describing the results of the tests made to determine the influence of a changed valve overlap on an engine and various fuels, we should like to give a short survey of the effects of the valve overlap.

Whilst in carburettor engines the amount of valve overlap is limited because scavenging causes losses of fuel, it is possible with the fuel-injection system to apply valve overlaps extensively, and so to obtain considerable scavenging of the dead space. The extent of scavenging depends very much - apart from supercharging - upon the amount of the valve overlap. At a small valve overlap only a little air is passed through since the time interval when the inlet and exhaust valves are open together is rather small. But even with a small valve overlap the volumetric efficiency is increased quite considerably, since the compression at the end of the exhaust stroke caused by throttling without an overlap is eliminated. Partial filling of the dead space with air, and appreciable scavenging will be noticeable only when the valve overlap is approximately 80° . With increasing valve overlap the scavenging becomes quite considerable and there is also a cooling effect on the hot exhaust gas. These effects produce an increase of the brake horse power of the engine on the single cylinder test stand, where the compressed boost air is taken from a plant not driven by the engine itself. The increase in power is smaller in a main engine operating its own blower, since with an increasing air flow we have also an increase of the supercharger drive power and so a decrease of the brake horse power.

The scavenging of the dead space alters the thermal stress on the engine because the air flows past the hot inlet and exhaust gear, and so has a great influence on the tendency to detonation. In our tests here we did not deal with this question. We refer, however, to the extensive tests concerning the knock behaviour of the DB 601 engine with varied valve overlap and various fuels of the same and of a different octane number, already made by the Institut für Betriebsstoffforschung der DVL. Their results are being prepared for a report on this subject. In these tests with VT 702 + 0.12% TEL, the knock-limit curves were plotted as a function of the boost-air-temperature and valve overlap, and made it possible to explain the knock behaviour of the DB 601 engine.

The evaluation of the test data was undertaken in the light of the knowledge gained by the short survey given above. The fuel loops obtained at a boost-pressure of 1.15 and 1.3 atmospheres can be seen in fig. 19-21 for 5 different fuels. With a valve overlap of 40° crank angle in fig. 19, we see the already well known picture of power-increase with increasing latent heat of the fuel. Under the selected working conditions knocking in the engine did not occur. Figs. 20 and 21 show a similar power increase of these fuels at the same boost pressures with increasing latent heat. Later on we shall mention the power increase and the relation to the air-flow increase as a function of the overlap for the different fuels. At a valve overlap of 80° (fig. 20), it should be noted that, at a boost-pressure of 1.3 atmospheres, the engine has entered a rather large knock region which has increased in size at 120° valve overlap and here knocking occurs

even at 1.15 atmospheres, as shown by fig. 21. This phenomenon is really in contrast to the fact that an increased valve overlap produces a better scavenging of the residual gases and a better internal cooling of the engine, thus reducing its general temperature condition which must be regarded as partly determining the knock-behaviour. It is therefore necessary to relate the thermal load to the mean effective pressure, so that with regard to the increased volumetric efficiency of the engine we must reduce the boost correspondingly in order to obtain the same mean pressure. This, however, causes an increase of the knock-limit because of the scavenging effect and the consequent reduction of the thermal stress, when related to the same power. The corresponding values of the M.E.P. in the test engine are with increasing overlap:- 8.95; 11.4 and 12.2 Kg/cm² for optimum output with a boost pressure of 1.15 atmospheres and 80° boost air temperature. Hence it follows that under consideration of the plotted knock-limits we can obtain a M.E.P. of 11.4 kg/cm² still knock-free at an overlap of 80°, whilst at 40° overlap a smaller M.E.P. - viz 10.9 kg/cm² - is already within the knock-region, admittedly with a boost pressure of 1.3 atmospheres.

Speaking of the knock-region, mention should be made of a peculiarity of the DB 601 engine which according to our experience depends to a small degree upon the valve overlap, on the other hand, however, is strongly influenced by the boost-air temperature. With most engines, hitherto tested, the minimum of the knock-limit curve was reached at an air-fuel ratio of approximately $\lambda = 1.05$ corresponding at this point to the maximum of the temperature of the unburnt mixture residue. On the fuel loops this point corresponds to a power reduction of about 5% in the excess-air region. Actually, at a certain boost pressure, knocking was found to start in a small region in the neighbourhood of this valve. When, however, examining the knocking region of the DB 601 which is entered into for the first time at 80° overlap and at a boost-pressure of 1.3 atmospheres, we see that knocking begins only at a $\lambda = 0.87$ and covers the air deficiency region up to $\lambda = 0.6$. In the DB 601 this phenomenon (x) could be observed with all fuels, excepting the gasoline/ benzol and the gasoline/alcohol mixtures, as soon as the engine was brought to the knock-limit in the rich region by suitable enrichment and by a boost pressure still compatible with safety and reliability. So it appears that this phenomenon is caused only by the engine, and does not depend upon the kind of fuel. It passed off with increasing temperature. When taking into account the hypothesis of a poorer mixture distribution in the DB 601, we can give the following explanation:- First of all we should like to quote a passage of "Lindner"'s book:

"In the presence of non-vaporized fuel droplets in the mixture, Callender could find a considerable increase of peroxide formation and also at the same time a decrease of the reaction temperature as compared to the mixture with completely vaporized fuel content. Because of the enrichment of the mixture there are zones in the immediate neighbourhood of the droplets which are particularly favourable to the formation of peroxides. The lower the inlet temperature the greater the proportion of un-vaporized droplets at the start of compression".

These findings from an outside source and the "DVL"'s assumption of a poor mixture distribution of the DB 601 engine as well as the fact that the phenomenon decreased during the tests when the temperature rose, allow us to make the following statement:

- (x) This passage anticipates results from the experiments since completed about the influence on the knock-limit of various fuels by overlap.

First we refer to a diagram from the report still in preparation which we added to this report as fig. 22. This diagram shows the effect of temperature on the knock-limits of VT 702 in the DB 601, at an overlap of 40° . The poorer mixture distribution in the DB 601 is caused by the injection process, turbulence and structure of the combustion-chamber, and has a particularly marked effect in the rich region. Though the engine was not brought to knock at its otherwise most sensitive point on the mixture ratio range, namely $\lambda = 1.05$ at the given boost pressure, knocking occurred in the rich region on account of the poorer mixture distribution characterized by un-vaporized fuel particles. It goes without saying that with increasing boost air temperature the mixture distribution improves, and so the proportion of unburnt fuel particles decreases. Consequently, the conditions would be less favourable for the occurrence of knocking. The tests (fig. 22) confirm this assumption, since the boost pressure necessary to cause knocking becomes higher and higher, and on the other hand the minimum of the knock-limit curve in the rich region shifts more and more towards the rich end. From this we may deduce that with increasing boost air temperature the mixture distribution improves, so reducing the proportion of unburnt fuel particles and the curve therefore moves towards the rich region.

The curves shown in figs. 23 to 28 were chosen for further interpretation, and give, in terms of the injection quantity in $\text{mm}^3/\text{stroke}$: the brake horse power, the air-flow, the specific fuel consumption and the air-excess coefficient. The evaluation of these data took into account principally the power increase caused by the increased air-flow which was due to an increasing overlap, and also the power-drop with weakening the mixture. It was here very difficult to find points of an equal air-fuel ratio. Thus, the air-fuel ratio for maximum power on the consumption-loops moves, with increasing overlap, towards the weak region. This is explained by the fact that the method of calculation involved the whole air consumed by the engine. But we have to take into account that with increasing overlap a great deal of boost air passes through the engine as scavenge air without participating in the combustion. Therefore the air-fuel ratio in the engine differs from the result of the calculation which was based on the total air quantity. When the calculations are checked by the readings of the exhaust-gas meter, we obtain the same figures, since this instrument is also influenced by the scavenge air. Without complicated tests and without considering the proportion of the scavenge air, we used the following method: When comparing the power outputs we took the values at the points of maximum power; when comparing the power-drops we used equal intervals of excess air ratio from the point of maximum power.

The percentage increases in power and air-flow, obtained from the curves, are plotted in terms of the valve overlap in fig. 29 for VT 702, gasoline/alcohol and alcohol. As in the case of the power increase due to latent heat, we see also here a greater increase in power than is compatible with the air-flow increase, up to about 100° crank angle valve overlap. The reasons are the same as those quoted for the power increase due to the latent heat of the fuel. With a valve overlap of more than 100° and because of the greater time intervals, part of the boost-air passes as more scavenging air through the engine without taking part in the combustion. Accordingly from here onwards, the gain in power is less than should correspond to the air-flow increase. We may deduce from the course of the curve that a further increase of valve overlap would not lead to any considerable power gain. For, from an overlap of 100° onwards, further increase of air-flow with an already complete scavenged dead space, has only a cooling

effect on the interior of the cylinder. Consequently a smaller increase of power is the result.

The complete conformity of power and air-flow curves for the various fuels must be noted. With the VT 702 a greater power gain corresponds to a greater air-flow for this fuel, the other fuels with increased latent heat show a relatively smaller gain of power and air consumption. This is so, because at a valve-overlap of 40° the increased volumetric efficiency of the engine was caused by the higher latent heat with alcohol and its mixtures. With increasing valve overlap, as a result of the greater air-flow, the almost constant rise in volumetric efficiency due to latent heat no longer manifests itself in the same proportion. This applies only if - in accordance with our presentation - the difference in the volumetric efficiency of the individual fuels is related to the values at 40° valve overlap.

The power necessary for delivering the boost-air was not taken into account when comparing the power values. With allowance for the supercharger drive power supplied by the engine, somewhat less power increase with increasing valve overlap is obtained, since, with the same boost pressure, the supercharger drive power - which normally must be supplied by the engine itself - increases with increasing air-flow. Taking into account a supercharger of 0.6 efficiency, fig. 30 shows the blower m.e.p. values for a given boost pressure but at various air-flows. Based on this blower-power, we obtained the values shown in fig. 31, comparing them to the output which we obtained on the single cylinder test-stand with independently-driven blowers. A difference between the two power values, increasing valve-overlap, is clearly visible.

When comparing the engines BMW 132 and DB 601 as regards the form of scavenging and the amounts of residual gas at the same valve overlap, it was assumed that the test-bed arrangement gave worse scavenging with the BMW 132 and that therefore a greater quantity of residual gases resulted. One of the arguments in support of this assumption dealt with the greater power-drop of the BMW engine with the same mixture change when tested on the DVL test-stand, and attributed it to the incomplete scavenging, already mentioned, and to its consequence, viz reduced volumetric efficiency. Based on the tests made with various timings, it was possible to check the soundness of this assumption since with increasing overlap the scavenging of the engine improves. With this improvement of the scavenging and with the resulting decrease of the proportion of the residual gases, the power drop should decrease with the same variation of the mixture. Fig. 32 shows in similar form for the different fuels the power drop in per cent at 40° , 80° and 120° valve overlap. We mentioned already that the calculation of the air-fuel ratio is incorrect because of the scavenge air which passes through the engine when the overlap is increased and does not take part in the combustion. The different points of the excess-air ratio are moved towards the lean region by the fact that the air quantities were taken at too high a figure. That can clearly be seen from fig. 32, since the point of optimum power moves towards the region of greater air excess when the overlap increases. In consideration of the excess-air coefficients not agreeing with the real operating conditions, the power drop for the different points of the air-fuel ratio must be compared by counting equal λ -units, starting from the point of maximum power. If we compare in this manner points of the excess-air coefficient, we really obtain the result that with increasing overlap and the consequently improved scavenging of residual gases, the power drop decreases. E.g. with VT-702 and a boost pressure of 1.15 atmospheres and at a distance of 0.357

from the optimum power point measured on the excess-air ordinate, it is: 18.4, 14.0 and 11% with increasing overlap.

Scattered points obtained occasionally with other fuels could not dispute the result that the power drop decreases with increasing valve overlap. But here again we should emphasize that this way of explaining the differences in power was only taken from the experimental values on the DVI test-stands under the prevailing conditions and a generalization does not appear permissible without tests on similar main engines.

When examining the power drop with various fuels in fig.32, we see for the whole region that VT 702 with the same air-fuel ratio shows the smallest power drop of all the test fuels. This phenomenon was already explained earlier by the fact that this fuel showed the greatest volatility. Here we should like to point out that for long range aircraft the fuel should be selected from consideration of its power drop in the lean region. The engines of such aircraft are always set for cruising on the basis of a power drop, and a corresponding minimum specific fuel consumption, in order to obtain a large range. By selecting a fuel, causing the smallest power drop in comparison to other fuels, and so a higher output of the engine under otherwise the same working conditions, a small increase in the cruising power of the engine could be achieved.

Amongst other evaluations which might be of interest, we mention the measurement of fuel consumption as a function of the calorific value at a constant excess-air ratio for 80° and 120° valve overlap, and this is shown in fig.33 and fig.34. The conversion of those results to fuel consumption for 1 kg air per hour, already shown by fig.18, agreed with the latter values. So we may generally use fig.18 for the calculation of fuel consumptions for fuels of different calorific value at a known air-flow.

S U M M A R Y

The tests concerning the determination of the fuel properties, the influence of different fuels on various engines under the same operative conditions, as well as on one engine with varying valve overlap, gave us the following results:-

- The power is principally influenced by the increased air-flow with fuels of high latent heat. Small power variations are caused by the slightly different air requirements needed to produce the same heat energy. Furthermore, they are effected by alteration in the internal efficiency caused by change in the cycle temperatures, and finally by the quality of the mixture distribution.

Tests were made in connection with mixture formation on the assumption that - apart from the turbulence and other effects - it is influenced partly by the rate of evaporation of the fuel. With highly volatile fuels, because of their better performance in regard to alteration in the mixture strength, good mixture formation could be deduced.

Rate of Evaporation and boiling characteristics have not the same significance. We obtain a better evaluation of the starting behaviour of a fuel from its rate of evaporation. We also pointed out that the fuel having the smallest power drop in the lean region should be selected for the economic operation of the engine in order to obtain a great range.

The air-flow depends above all upon the latent heat of the fuel giving us a larger charge of the cylinder because of the resulting cooling down of the boost-air. In addition we have to consider the effect that fuels with high latent heat possess a lower calorific value, so that we must inject a larger quantity in order to reach the same power output.

~~The influence of the calorific value on the consumption in~~ a given operating condition was found, and a generally applicable formula was established for the fuel consumption per kg of boost-air in terms of the calorific value.

When comparing the BMW 132 and the DB 601 on the DVL single cylinder test-stands under the same operating conditions, we saw that the DB 601 has a greater air-flow in spite of its smaller capacity. The reason for this difference is partly the greater heating of the boost-air during the inlet process in the BMW air-cooled engine and thus poorer cylinder charging because of the volume increase. Besides, it could be assumed that in the different test-stand arrangements the charging was influenced by pressure vibrations in the boost-air and exhaust-gas manifolds which resulted in decreased scavenging of the dead space of the BMW 132-engine. The higher proportion of residual gases resulted during weakening or enrichment of the mixture, in a greater power drop than in the DB 601 engine. The influence of the residual gas on the power drop due to alteration in mixture strength could be observed in the tests with varying valve overlap, since with increasing overlap and the accompanying reduction of the residual gas quantity, the power drop was reduced.

The difference in the optimum output of the two engines under the same operational conditions, taking into account their different capacities, was attributed to a poorer mixture formation in the DB 601 engine.

The poorer mixture formation of the DB 601, which probably results in unvaporized fuel droplets at the end of the compression stroke, particularly in the rich mixture region, enabled us to explain the onset of knocking in this engine. In comparison to other engines, the minimum of the knock-limit curve of the DB 601 is to be found, over rather a large range of boost-air temperatures, in the rich region. When the boost-air temperature increases, the quality of the mixture formation improves, and the proportion of the unvaporized fuel particles in the rich region decreases. Therefore the minimum of the knock-limit curve moves more and more towards the region of extreme richness, and at the same time the permissible boost-pressure rises.

The knock-limit is influenced by increasing valve overlap because the thermal load decreases with increased scavenging. Therefore we can either obtain a certain knock-free power which is still within the knock region at a small valve overlap, viz. by increasing the overlap and by reducing the boost-pressure, or we can increase a power which is outside the knock region, by maintaining the boost-pressure and increasing valve overlap, without causing the engine to knock.

We obtained improved scavenging of the dead space and a corresponding power increase up to approximately 100° crank angle valve overlap. Beyond that a further overlap increase causes only additional scavenging, and therefore leads only to greater internal cooling of the engine and a relatively smaller power increase.

TABLE 1.

ENGINE - DATA.

Engine Type: BMW 132 N

Data:	Stroke:-	= 162 mm			
	Bore:-	= 155.5 mm			
	Compression-ratio:-	$\epsilon = 6.5:1$			
	Capacity:-	= 3.074 litres			
	Compression space:-	= 559 cm ³			
Valve Timing:-	Inlet opens deg.before T.D.C.	Inlet closes deg.after B.D.C.	Exhaust opens deg.before B.D.C.	Exhaust closes deg.after T.D.C.	
	20	77	76	21	
Fuel System:-	Pump:- Bosch PZ 2/120 V 1024 a 3 (Eccentric pump)				
	Nozzle:- Bosch DE 40 N60 M6				
Ignition System:-	Sparking plugs:- Bosch W 225 T 1				
	Magneto:- Bosch FI IR 36 FI IL 36				
Boost-air:-	Blower:- Klein, Schanzlin & Becker, 1.5 atmospheres				
	Air-heater: DVL 24 KW				
Coolant:-	Air				
	Blower Hermuel 22 KW 2900r.p.m.				
Exhaust lay-out:-	DVL ; / through surge tank to an extraction-fan.				
Brake-gear:-	AEG - generator type AW-PT 99.				

TABLE 1: Data of the test-bed and of the BMW engine.

TABLE 2

ENGINE - DATA

Engine type: DB 601 A

Data:	Stroke	= 160 mm
	Bore	= 150 mm
	Compression-ratio	$\epsilon = 6.5$
	Capacity	= 2.828 litres
	Compression space	= 517 cm ³

Timing: Valve overlap: crank angle of:	Inlet opens deg. before T.D.C.	Inlet closes deg. after B.D.C.	Exhaust opens deg. before B.D.C.	Exhaust closes deg. after T.D.C.
	24	56	52	16
	39	72	53	41
	71	56	69	49

Fuel System:-	Injection	
Pump:	Bosch PZ 2/100 V 402 (cam-pump)	
Nozzle:	L'Orange 6/38 9 - 2029 A	
Ignition System:-	Sparkign-plugs	Bosch W 260 T 1
	Magneto	Bosch FI IR 36 FI IL 36

Boost-air:-	Blower:- Klein, Schanzlin & Becker, 1.5 atmospheres 450 m ³ /h
	Air-heater: DVL 24.5 KW
Coolant:-	Water.
Pump:-	Odessa Machine Factory Type S 30/160 135 l/min
Exhaust lay-out:-	DVL, through silencer, extraction-fan.
Brako-gear:-	Siemens - generator type A 6 247.

TABLE 2: Data of the test-bed and the DB 601 engine.

Description:-		VT 702 + 0.12% TEL 405/40		25% Gas. lead free 75% Aircraft-Benzol 120/41		Toluene 346/40		55% Gas. lead free 45% Ethyl Alcohol 122/41		Ethyl-Alcohol 166/41		Methyl-Alcohol 166/42		C 1 + 0.08% TEL 212/41	
Received No:-	Supplied by:-	Ammonia Wms. Mersching		mixed by "Olex"		Benzol Works Berlin		mixed by "Olex"		Reichswalzg. Bln. Lichtenberg.		Scherling Bln. Adlershof.		"Wifo" Brktz. (Capt. Stas.)	
Specific Gravity at 20°		0.7206		0.8285		0.8670		0.7495		0.7890		0.7920		0.7446	
Refraction n _D 20		1.4021		1.4696		1.4940		1.3804		1.3608		1.3302		1.4010	
Water soluble components %		0		0		0		46		100		100		0	
Vapour pressure Reid atmospheres		0.435		0.215		0.0749		0.485		0.160		0.323		0.365	
Dist. Range		See fig. 3		See fig. 3		See fig. 3		See fig. 3		See fig. 3		See fig. 3		See fig. 3	
Corroding properties		Unchanged		Unchanged		Unchanged		Unchanged		See fig. 3		See fig. 3		Unchanged	
Cu-Al-Rivets 3 hours 50°C.		Unchanged		Unchanged		Unchanged		Unchanged		See fig. 3		See fig. 3		Unchanged	
Gum mg/100 cm ³		2.4		9.8		0		2.6		0		0		1.4	
Crystallization point °C		below -60		-19		below -60		below -60		below -60		below -60		below -60	
Iced content according to iodine method		0.12		0		0		0		0		0		0.08	
Iodine number (Hanus)		3.2		2.6		-		1.61		-		-		4.58	
Aniline - Point II.		60.2		58.4		-		59.4		-		-		65.8	
Aromatics + unsaturated															
Ket. Daniel - Weight %		Uns. 2.3 Ar. 19.7		Uns. 3.0 Ar. 22.3		100		Uns. 3.2 Ar. 23.3		-		-		11	
Naphthalene %		25.5		5.7		0		26.0		-		-		12.5	
Paraffin %		52.5		9.0		0		47.5		-		-		76.5	
C - content %		85.20		90.38		91.24		67.97		56.11		37.46		85.13	
H ₂ - content %		14.73		9.68		8.76		13.17		13.14		12.59		14.87	
O ₂ - content %		0		0		0		18.86		34.75		49.95		0	
C - H ratio		5.78		9.34		10.42		5.16		3.97		2.98		5.74	
I ₀ theory Air-requirements		14.85		13.7		13.46		12.1		8.98		6.46		14.89	
Lower calorific value		10457		9849		9739		8502		6436		4748		10479	
Octane number H.M.		92		88.5		109		88		93.0		99.0		97.0	

Table 3:- The fuel - data.

TABLE 4

Fuel	Vapour pressure according to Reid at 38° C		Molecular Weight.
	in mm Hg	atmospheres	
Water (distilled)	49	0.067	18.016
Toluene (pure)	55	0.0749	92.06
Ethyl alcohol	118	0.160	46.05
Benzol (pure)	166	0.226	78.05
Gasolene/Benzol	208	0.215	82.2
C 1	268	0.365	
VT 702/1	309	0.435	125
Gasolene/Alcohol	345	0.485	87.75
Ether	850	1.155	74.08

TABLE 4: Vapour pressure and molecular weight of various fuels.

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The Influence of the valve overlap on the knock-limit of various fuels in the DB 601 Engine.

Outline:- Fuels of various chemical compositions and of different octane number were examined in the DB 601 cylinder at 40°, 80 and 120° crank-angle valve overlap as to their detonation behaviour. The results showed that both the characteristics of the knock-limit curves and the anti-knock value were considerably influenced by altered valve timings. The decisive factors for this are the variation of the thermal internal stress and the different qualities of residual gases, which have, according to their composition, different effects on the fuels. The shape of the knock-limit curves differed from their usual form in the DB 601 under certain operating-conditions, and this could be explained by imperfect mixture formation in the relevant regions, and was also connected with the boost-air temperature and the valve overlap. The effect of various valve overlaps on the shape of the knock-limit curve of fuels could be compensated by a corresponding variation of the boost-air temperature.

The applicability of knock-limit curves to the same engine with different valve-overlaps is discussed. The effect of the results on the testing of fuels according to the DVL supercharge-method and its possible improvement are also mentioned.

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I Introduction

Apart from the other measures to raise the power of aero-engines, increased valve-overlap is employed. Its purpose is to decrease the proportion of residual gases by improving the scavenging of the dead space when supercharging. Thus the air quantity which can be admitted in the same cylinder volume, increases; on the other hand, with the same

mean pressure the thermal internal stress of the engine decreases. Apart from the power increase thus achieved a change in the behaviour of the engine as regards the fuel may be expected.

Numerous tests concerning the quantitative influence of alteration of the air-flow on the brake horse power have already been carried out, but the behaviour of fuels of different chemical constitution especially at the knock limit has not yet been unmistakably defined.

At present tests of aero-engine fuels according to the DVL supercharge method are carried out in the BMW 132 N cylinder at a valve overlap of 40° crank-angle. This valve overlap is no longer used in any of the current main engines. Recent engines have at least 60° overlap and sometimes considerably more increasing often up to 120°. Thus, if the valve overlap influenced the knock-limit noticeably, it is obvious that the DVL supercharge method, normally used for the evaluation of fuel, cannot be applied directly to practical cases.

The object of the present tests was to find out how far it was possible to apply the knock-limit curves, obtained by the DVL supercharge method with a small valve overlap, to main engines with higher valve overlaps. Apart from a knock-limit increase which might occur because of the decreasing thermal internal stress, it was desirable to examine the alteration of the knock-limit curve characteristics due to the valve overlap, under otherwise similar operating conditions.

Furthermore the tests were designed to show how the form of the knock-limit curve is influenced by a change of the boost-air temperature and the related effects of the mixture formation of the various fuels in the engine on the characteristics of the curve.

In order to examine a very wide range of chemically different fuels, 6 fuels of the most different composition were selected for the tests. A very great range of boost-air temperature was selected, since the extreme cases met with in practice had to be taken into account. As a starting point a valve overlap of 40° crank-angle was used, as this is the usual overlap in test engines for the DVL supercharge method. It was increased by stages up to 120° valve overlap. At present we need not expect greater values with main engines, since with further increase considerable difficulties in the operation of the engine are experienced. Besides, when further increasing the valve overlap, the small increase of indicated power is out of proportion, in view of the enlarged blower required with its greater weight and increased drive power.

II General Remarks on testing aviation fuels

Until lately engine-designers had no difficulty with the fuels at their disposal. The purpose of the gradual improvement of the working process by the increase of the compression-ratio, the increase of the volumetric efficiency by super charging and valve-overlap, the alterations in ignition-timing etc., was to increase the engine efficiency, to lower the fuel consumption and to increase the power. These measures increased the thermal stress on the engine, and it was found that the fuels then available no longer met the requirements of the engine. Besides the normal combustion of the air-fuel mixture another kind of reaction occurred, namely detonation-combustion or knocking.

Knocking in the engine - a hard and metallic noise - was recognisable without great difficulty by means of suitable knock indicating instruments. It was however, very difficult to explain the physics-chemical aspects of the knock-phenomenon. Several scientists, however, working on this problem, succeeded by elaborate and extensive tests to clarify the matter so as to enable us to explain with some degree of reliability the essence of the knock-process and its dependence upon fuels and operating conditions. As one of the first results it was found that the mixture in the engine changed from an originally controlled and slow combustion to a practically instantaneous reaction of the unburnt residual mixture. Bomb-tests showed the speeds of the flame propagation to be a few m/sec. These speeds are increased to 20 - 40 m/sec in the engine because of the turbulence of the mixture. Before the flame-front, traversing the combustion chamber at this speed, are the unburnt parts of the mixture. Their temperature and pressure rises because of the expansion of the burnt gases and because of the radiation and heat connection of the flame-front and of the burnt part of the mixture. Under certain conditions this may lead to a sudden reaction of the unburnt portion of the mixture. Here combustion velocities up to 900 m/sec are obtained.

The reason for this sudden reaction of the residual charge has not been fully explained. There are many theories. The assumption, that local overheating of the engine is responsible for the instantaneous reaction of the residual mixture cannot be confirmed. Photographs of the course of combustion in knocking engines showed that during consecutive working strokes the ignition centres of the charge residue. Where combustion was accompanied by knocking, were not always in the same place, which should be the case if overheated parts of the wall produce these ignition-centres and thus cause spontaneous combustion of the residual charge. Hot spots may perhaps be favourable to knocking but cannot be said to initiate it.

Another assumption is that the pressure effects caused by the flame-front lead to pressure-waves. Now it was said

that these pressure waves have no opportunity of fading out or spreading in the whole of the combustion-chamber. Rising flame velocity and increasing pressure may have the effect that the amplitude of one of the pressure waves become sufficient to bring the mixture residue which is already hotter as a result of the combustion process its self - to self-ignition. The observations, however, make it doubtful whether vibration phenomena are the real cause of the knocking.

A third assumption is that the main cause of the sudden reaction may be a slow reaction in the unburnt part of the gas mixture which is compressed and heated by the advancing flame-front. The experiments of Rassweiler and Withrow were very instructive in this respect. They showed that before the flame front the residual gas contains new ignition-centres which by flashing in all directions cause the residual charge to ignite almost spontaneously. One may therefore picture the knocking in the engine thus:- The sparking-plug initiates a flame-front which advances with a velocity depending on the quality of the mixture formation, the excess-air, the pressure and the temperature; and increases the pressure and temperature of the unburnt mixture. Thus a slow reaction or combustion is started in this part of the mixture which is increased with rising pressure and temperature and so may lead to self-ignition of the mixture. This sudden combustion produces a region of high pressure, the instantaneous increase of which in the combustion-chamber causes the hammer-like knocking noises when the gases strike the cylinder-walls.

This sudden reaction of the residual mixture and the peak pressure thus produced is detrimental to the operation of the engine. The great increase of the heat transfer causes a thermal overload on cylinder piston and valves. The consequence is a gradual power-drop with increasing temperature. If the knock continues it will damage the piston, the piston-rings, the cylinder-bore and the valves. To the thermal overload must be added the mechanical shock load of the pressure peaks with its effect on the engine components.

The most important criterion of the quality of fuels is their liability to detonation. It is therefore clear that the investigation and solution of the knocking problem as well as the measurement of the anti-knock value form the essential part of investigations on fuel quality. While the knock phenomenon has been related to operating conditions to a certain extent, and it is possible to determine the anti-knock value in special engines, e.g. by the octane-number, the DVL supercharge method etc., it is extremely difficult to obtain an anti-knock value of fuels which is generally applicable.

The great interest of fuel manufacturers in the solution of the problem of evaluating aero-engine fuels in engines intended for practical use is understandable. The engine

manufacturer is similarly interested, since the engine power is given and guaranteed for a fuel with a minimum knock value. The CFR method octane-number was quite good for the quantitative determination of the detonation characteristics in motor-car engines. But for the aero-engine it was found that no definite relation existed between the octane-number and the actual detonation characteristics in current engine cylinders.

The disadvantages of an insufficiently exact knock rating are not particularly great as far as automotive fuels are concerned. If a vehicle with a fuel of insufficient anti-knock value enters the knock-region the engine may suffer if in service for some time. This, however, means only some strain on the car owner's purse as far as civilians are concerned. For the Armed Forces there may be graver consequences. Not only because of additional repairs but also because of break-downs in supply, combat, transport etc.

The problem is entirely different for the aero-engine. If we have an aero-engine which gives its maximum power at take-off and if the air-fuel ratio is set on the basis of knock-free operation at a certain octane-number, it is probable that the engine will be severely damaged. For though a fuel has the required octane number, it has not necessarily a suitable anti-knock value under the existing engine conditions. In the relatively short time, during which the maximum power is required for take off, the thermal stress in these engines developed to a stage of very high power - has already reached its permissible limit. The additional effect of knocking combustion can be sufficient to cause the failure of the engine.

The greatest disadvantage of determining the detonation characteristics of fuels according to the CFR method is that the fuel is tested by a single-point evaluation. As under practical conditions fuels of the most varied chemical constitution are used, and they behave very differently according to various operating conditions, it is possible that in the aero-engine cylinder there are considerable differences between the octane-number found and the real anti-knock value.

A method which takes the prevailing operating conditions partly into consideration, especially the mixture adjustment, is the DVL supercharge method. Here the knock-region of the fuel is determined over a range of excess-air ratios in terms of the boost-pressure which leads to incipient knock. The tests are performed on a single cylinder test stand with a BMW 132 N aero-engine cylinder under specified test conditions. The relative knock-limits of various fuels in the BMW cylinder can then be noted.

The different susceptibilities of fuels to operating conditions - aromatics are very sensitive - make it clear that minor variations in engines even of the same type, slightly different test-stand arrangements and small changes in operating conditions cause considerable alterations of the knock-limit curve. In the same engine cylinder, however, the order of evaluation of the fuels used to remain the same. Therefore the position of the knock-limit curves of various fuels permit certain conclusions concerning their general behaviour. It is

found that the knock behaviour of various fuels differ from that of a reference fuel with the same excess-air and under the same operating-conditions. Apart from being able to state the approximate behaviour of a fuel, it is not possible to state the exact position of its knock-limit curves in another engine. In order to clear this matter up the DVL tested quite a number of aero-engine single cylinders as regards their knock behaviour with various fuels sensitive to temperature. From a number of test results fig. 4 shows the knock limit curves at 130° boost temperature for 12 different engines. An elaborate explanation of the test procedure and discussion of the results cannot be given here. This will be the object of the detailed reports which are still in preparation and also of the final report. A preliminary study of the tests, illustrated in fig. 4, shows, that the order of the fuel evaluation is partly reversed, apart from the fact that the general position of a knock-limit curve, its maximum and minimum, and their separation, differs in each engine. A preliminary study of the tests on the knock behaviour of fuels in various engines does not give very promising results, with regard to the question of how far the knock limit curves of the same fuel can be applied to engine of different types.

The advantages which would result if the knock-limit curves, obtained according to the DVL super charge method, could be applied to any given engine type are indicated by an example. Let us suppose that the knock-limit curve had been obtained in a clearly reproducible form for a fuel according to the DVL super charge method and at a certain temperature, a certain ignition timing and under precise operating conditions. By means of the combined curve of the engine, i.e. its boost pressure and speed classification, as well as by the temperatures of the boost-air, obtained from the outside temperature and blower speed, and perhaps by varying the ignition control, it would be possible to find out from the position of the knock-limit curve of the fuel and from its application to any engine type under consideration of the control curve, plotted against the excess-air coefficient of the engine, if the engine under the given circumstances could or could not be operated free from knock. For various reasons this would be highly desirable. It is relatively easy to find the knock-limit curve for the single cylinder engine at little expense and above all in very short time, but it is very difficult to do so for the main engine. The reason for this is, that in the main engine we cannot yet determine in a suitable manner the moment at which knocking sets in, and on this the super charge method of knock rating is based.

The method of obtaining the knock-limit curves on the single cylinder test-stand is excellent and cannot easily be surpassed as regards the simplicity of the method, since it does not necessitate any alterations of the engine. This method determined the start of knocking acoustically. It is obvious that this is impossible, with the main engine. Firstly the engine running on the test-stand is very noisy. Secondly the knocking noise heard might come from any one of the cylinders. The very exact determination of the beginning

of the knock according to the second DVL method proves difficult, since apart from the fixing of a quartz pick-up which necessitates a further drilling in the cylinder, the number of cylinders to be tested must be taken into account. As long as there is no exact method which satisfies simple test-stand arrangements and as the same time enables us to determine the start of knocking for each cylinder, the determination of knock-regions in the main engine remains rather a difficult matter requiring some skill and experience. It must be realised that, even with the closest observation of the cylinders connected with the knockmeter, a cylinder not under observation could be in the knock region. According to experience it need not be long before the piston burns through or suffers from other defects, usually as the result of heavy detonation. The method which A.W. Schmidt is developing for the purpose of determining knock in the main engine has considerably better chance of success. In this, the whole noise level of the engine is picked up by a microphone, and all frequencies not due to the knock vibrations are eliminated, so that the remaining impulses, amplified as necessary, can be recorded by a cathode ray oscillograph.

These difficulties would not arise if it were not necessary to investigate the knock behaviour of main engines by establishing the control curve on the basis of a certain fuel. In order to do this it should be possible to determine the operational position of the engine from the knock-limit curve of the fuel provided for the operation and the control curve of the engine itself.

Various reasons cause the displacements and the different positions of the knock-limit curves. We must distinguish between those, purely influenced by the operating conditions, and those caused by the mechanical arrangement. We consider as operating conditions those which change the position of the knock-limit curve and which have different effects i.e. the following - excess-air ratio, compression, boost-air temperature, ignition, engine speed etc. and finally the valve timing. The last item brings us to the influence caused by the mechanical arrangement. Here we have the following:- Shape and design of the combustion-chamber, arrangement and number of valves, use of conventional valves or sleeve valves, position of sparking-plugs and nozzles, design of the cooling surface etc. In practice it is quite difficult to separate clearly and distinctly the items mentioned above since often the alteration of one necessitates also the alteration of another.

It is quite possible by a systematic determination the effects of these factors to succeed in the following:- Within certain limits a knock-limit curve for one particular fuel may be applied to another engine under consideration of its different data and operating conditions, provided that the other engine type is not very different. In the simplest case we may imagine the application thus:- The knock-limit curve of a fuel for any one test engine, e.g. for the BMW 152 cylinder, is known not only as regards its position and extent but also as regards the factors which determine its position.

We should have to determine also the knock-limit curve on another engine with the same fuel. So long as we were able to explain clearly from these knock-limit curves the differences of their positions and forms by the different operating conditions prevailing in each engine and their effects on the knock behaviour, we could apply the curves to the other engine. When the knock-limit curve in the BMW 132 cylinder is given for another fuel we can determine its position for the other engine by consideration of the various data which influence this fuel.

During the continuous development of aero-engines to achieve a power increase with equal capacity, a part from other measures the increase of the valve overlap has been tried successfully. When the necessary alterations on the single cylinder test stand of the DVL were made on an engine type DB 601, and when the first knock-limit curves of known fuels were obtained with increased valve overlap, they exhibited a form which was considerably different from that hitherto seen and sometimes had no similarity whatsoever to the usual knock-limit curves. Therefore a larger series of tests suggested itself with the object of determining the influence of the valve overlap on the position and form of the knock-limit curve. Before describing the tests in detail it seems best to give a survey of the effects of the valve overlap on the behaviour of an engine in the knock-free region.

In an engine with valve timings at TDC set so that there is no overlap, the dead space above the piston is filled with residual gas. Even assuming that this residual gas has no influence on the boost-air entering during the induction process, volume which it occupies in the cylinder is lost to volumetric efficiency and thus to the power output. Under practical conditions we must add to this loss the fact that the residual gas heats the entering charge, which results in a further reduction of the charge as regards its weight, due to the increase of the boost-air volume. When the engine operates in the rich region ignitable residual mixture components may be brought to combustion when the boost-air enters, and again part of the charge is lost for the performance in the engine. It was an obvious step to keep the valves open at top dead centre by altering the timing for the inlet and exhaust and so cause partial or complete removal of the residual gases and scavenging of the engine. In carburettor engines the valve overlap reaches its possible maximum rather quickly owing to the fuel losses with scavenging. But with injection-engines it is possible to achieve an extensive dead space scavenging. Tests showed that at boost-pressures used nowadays, an almost complete scavenging of the dead space is reached at approximate 166° crank-angle. A further increase of the valve overlap results only in further scavenging of the engine.

The effect of overlap on an engine with supercharge is mainly a power increase. With increased overlap a higher mean effective pressure is obtained at the same boost pressure by virtue of the greater weight of the charging air contained in the same cylinder volume. As soon as the scavenging of the dead space is complete a further increase of

the overlap gives us only very little power-increase due to the scavenging of the engine and the consequent reduction of the thermal stress.

The thermal stress has some importance for the knock-limit in as much as hot spots in the cylinder influence the liability to detonation. Therefore the air, flowing past the hot inlet and exhaust valves, will cause a cooling of these parts, and so a reduced liability to detonation. Also the residual gas quantity becomes smaller and there is then no longer any heating effect on the boost-air, which again affects the knock-limit. Finally the reaction kinetic influence of the constituents contained in the residual gases must be taken into account. Here the stable components e.g. CO_2 , H_2O , H_2 and CO , and also the short-lived combustion products which in some form or other can have a chain promoting or an interrupting effect, and so influence the knock-limit.

In order to interpret the knock-limit curves obtained under certain operating conditions on the DB 801, and to explain their shape, which is totally different from that usually obtained, reference will be made to the factors which affect the shape of knock-limit curves.

From the explanations of the previous passages about the probable reasons for knock in the engine, the compression theory is the most probable one according to the present stage of knowledge. In this case the thermo-dynamic state of the unburnt fuel-air mixture is decisive. The factors which determine the temperature-limit which leads to self-ignition of the fuel in the unburnt mixture, are as follows:- Density and its alteration with time, temperature and its alteration with position and time, and finally the mixture composition and its variations.

Under the assumption of constant operating conditions the mixture composition may be taken as the greatest influence on the knock-limit. Difference in mixture composition gives a different end-temperature both through the alteration of the quotient Sp/Cv and through the alteration of the combustion temperature. Jost and his assistants made calculations concerning the temperatures prevailing. For a gasoline with a mean molecular weight of 100 and with a composition $(\text{CH}_2)_n$ the end temperatures were calculated by consideration of the dissociation of the combustion gases and of the exact variations of the specific heat. The following drawing shows the values for the end-temperature of the unburnt mixture as a function of the excess-air ratio.

(Diagram: Calculated end-temperature in terms of the excess air-ratio)

This calculation forms an essential starting point in further discussion on the extent of the knock-region. It does not, however, deal with all changes which occur with change in mixture composition.

The highest temperature of the unburnt mixture portion occurs at about $\lambda = 1.05$ as can be seen from the graph. In accordance with this the curves of a number of engines show that knocking starts in this region when boost pressure, the ignition or other operating conditions are favourable to the onset of knocking.

The temperature decrease in the rich region is considerably greater than that in the excess-air region. Therefore the knock-behaviour should be better in the rich region than in the lean region. The decreasing speed of combustion with increasing air excess, at otherwise constant operating conditions, apart from the direct effect of the mixture-ratio (heat content), leads to lower peak-pressures and therefore peak temperatures of the unburnt residue. This may perhaps explain the favourable effect of weakening the mixture on the knock-behaviour always assuming that the temperature of the unburnt mixture is the decisive factor for the knocking. The knock-limit curve according to the DVL supercharge method is not plotted like a fuel loop at a constant boost pressure but at different boost pressures which cause knocking at the corresponding mixture rates. But we may imagine that the knock-limit curve according to the DVL supercharge method was obtained in the following way:- From a number of fuel loops at different constant boost pressures, the points for the beginning and the end of knocking have been extracted and have been plotted against the excess-air coefficient. This would give us then the shape of a knock-limit curve according to the DVL supercharge method. The minimum is similar to the first onset of knocking in the fuel loop and is at $\lambda = 1.05$. In accordance with the fact that the knock region is reached earlier at higher boost pressures, the curve continues to rise on both sides of the minimum and shows the well known shape of a knock-limit curve. The different shape of the curves for the DB 601 under certain operating conditions, as well as the probable causes will be explained when we discuss the test results.

III - Test procedure :

1) General Remarks:- The engine speed of 1900 r.p.m. was chosen according to the same principles which governed the tests of a general nature on the DB 601 to find the changes in power or consumption, increase of the air flow etc. The speed of 1600 r.p.m. prescribed for the measurement of knock-limit curves according to the DVL supercharge method is outside the range of normal operating speeds of more recent engine types. The selected speed of 1900 r.p.m. is already closer to the normal speed range. The engine noise did not make it impossible at this speed to detect detonation. Also the mechanical stresses on the test-stand were kept within permissible limits. A further reason for choosing a higher speed was that the effect of the valve overlap on the cylinder charge depends considerably on the engine speed. The higher the speed the more nearly is the effect on the volumetric efficiency determined only by the time interval.

The range of the boost air temperature between $+ 30^{\circ}$ and $+ 190^{\circ}\text{C}$ was sufficiently great to cover all temperature regions met with in practice. When running an engine with a low ratio blower the boost-air temperature - even near the ground with large variations of the external temperature from the Standard atmosphere - will probably not be below $+ 30^{\circ}\text{C}$. On the other hand even on the assumption that the engine is operated near ground level with altitude control because of defects of the blower couplings or because of other failures, an increase of the boost-air temperature above $+ 190^{\circ}\text{C}$ with high altitude or 2 stage blowers, need not be anticipated.

The reason for fixing the ignition time was to keep the knock-limit curves free from any additional influence due to ignition timing. It was kept constant for the whole range of valve overlaps and for all fuels at 35° before top dead centre.

VT 702, the reference fuel for the knock-limit test, gives its optimum performance at the above mentioned ignition advance at a boost-pressure of 1.3 atmospheres. The other fuels, with the exception of the alcohol mixture, have values for the ignition at optimum performance similar to those of the VT 702. Gasoline-alcohol requires a further ignition-advance for optimum performance. Alteration for the operating conditions also influences the ignition-timing. In this case the variables would be the boost pressure, the boost-air temperature, the valve overlap and the mixture composition. Apart from the fact that it would have been beyond the scope of this experimental work to investigate each item previously mentioned with regard to its influence, on the ignition timing, so many different ignition timings would be obtained that in practice a special valve timing would be required for each single measurement.

2) Engine conditions

The tests were made in a DB 601 single cylinder unit with a compression-ratio of $\epsilon = 6.5$. The valve timing and thus the valve overlap was altered by exchanging various camshafts and by a suitable selection of different rockerarms and tappets. The individual camshafts gave the large differences in the valve overlap. The alteration of the distance between cam and roller from the pivot of the rockerarms permitted smaller variations in the valve timing. In this way even integral values of the valve overlap were obtained. The choice of the DB 601 for the tests was very fortunate. We found that the knock-limit curves in the rich region could be plotted very close to the ignition limits of the fuels so long as the operating conditions and the maximum quantity delivered by the injection-pump permitted it. Even in this extremely rich region failure of the engine was not experienced in spite of a power-drop which was very considerable at times. This gave the opportunity of making some interesting observations on the knock behaviours in these regions as a consequence of the mixture formation and distribution. Also in the lean region the engine ran smoothly for quite a large range of air excess. This made possible accurate measurements of all required variables.

It is easier to keep the cylinder-head temperature constant in an engine with a liquid cooling system than in an air-cooled engine. By varying a little the quantity of the circulating coolant and by alteration of the inlet temperature an almost constant coolant outlet temperature could be maintained. This had the advantage of permitting easy reproduction of the knock-limit curves which is normally not possible. Points plotted later were on the curve within ± 10 mm. Hg boost-pressure.

The engine ran altogether for 200 hours during the tests. Slight breakdowns occurring during this time were mainly due to the accessory equipment. After the removal of each camshaft the cylinder was taken off; the piston and the rings examined and the valves ground in. Apart from the sparking-plugs no parts were replaced. After the end of the tests all the engine and test-stand components were in good condition, all piston-rings were free, without much carbon in the grooves. This was mainly due to the use of P 16 as a lubricant. Its outstanding quality is, that it practically leaves no deposits. Fig. 1 shows a piston at the end of all tests.

During the tests the state of the engine was checked by a control point taken at the same boost-pressure and boost-air temperature and with mixture adjusted for maximum power. Throughout the tests no drop in power was measured which would have interfered with the accuracy of the results.

The ignition point is controlled continually in the DVL test-stand by the installed ignition control. We checked the valve timing and adjusted valve clearance at the beginning and end of each series of tests. Frequent pressure tests of the boost-air pipes for gas-tightness guaranteed accurate measurements of the air quantity.

The whole of the test-stand and the construction of the plant were arranged in the well known manner. This is shown in fig. 2 so that a special description is not necessary. Table 1 gives engine and test bed data.

3) Fuels:-

It was desirable to obtain knock-limit curves of the utmost variety by using fuels of a different chemical composition and anti-knock value. Therefore the fuels were sub-divided into 2 groups. The first group contained fuels with approximately the same octane number and of as varied a chemical composition as possible, which were also used by the DVL for other tests. The fuels were as follows:-

	Octane Number
VI 702 + 0.12 lead	92
Gasoline/benzol blend	88.5
Gasoline/alcohol blend	88.0

The second group contained fuels with octane numbers differing by ± 10 units. This requirement was incomparable with similarity in chemical composition. A larger proportion

of aromatics - which are very much influenced by operating conditions - could be avoided by a suitable selection of the fuels. The following fuels were available:-

	Octane number
VT 706 5/707 blend	75
VT 702/1 + 0.12 lead	88
C1 + 0.09 lead	97

These fuels were closely examined as to their chemical and physical properties before the tests were begun. Particularly important was the determination of the elementary analysis and of the resulting theoretical air requirement L_0 . Table 2 shows the data for the fuels and fig. 3 the boiling curves. The method for the analysis of the fuels was determined in accordance with Instructions for Aero-Engines, Test regulations for Aero-Engine fuels, October 1940.

Table 3 shows the data for the synthetic oil P 18 which was used for the tests.

XV. Test Results

1) Survey

The knock-limit curves obtained by taking into account all the points mentioned above for the test procedure, formed the basis for investigations. The knock-limit curves are plotted in the following graphs for all fuels tested, and for all boost-air temperatures which could produce knocking within permissible limits. The knock-limit curves for the DVL reference fuel VT 702 + 0.12 lead with valve overlaps of 40°, 80° and 120° crank-angles are given in figs. 5 to 7. In order to obtain a better idea of the effect of the valve overlap the same method of plotting the knock-limit curve is used for the different valve overlaps. E.g. fig. 5 shows the permissible boost-pressure plotted against the excess-air coefficient for the various boost-air temperatures; fig. 6 shows the M.E.P., and fig. 7 the boost pressure plotted against the injection quantity of the fuel in mm $3/\text{cycle}$. For the two strongly temperature sensitive fuel blends of equal octane number the knock-limit curves are shown in the same way in figs. 8 to 10 for the gasoline/benzol blend. Fig. 11 to 13 show them for the alcohol blend.

The knock-limit curves of fuels of different octane number are plotted in figs. 14 to 16 for the blend VT 7065/707. They are shown in figs. 17 to 19 for VT 702/1 and for C, in figs. 20 to 22.

In some graphs there are points which are not connected by a curve. These points occurred once during the test in question. They could not be repeated or in some other way did not agree with the normal course of the curve. But this phenomenon could be observed only with the gasoline/benzol blend at high boost pressures and with the VT 702 at the highest boost-air temperatures high valve overlap. Fig. 8 shows the knock-limit curves for the gasoline/benzol blend at 160° and 180° boost-air temperature with 90° valve-overlap. The knock-limit curve for 190° boost-air temperature was obtained from

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clearly reproducible measuring points. At 160°C boost-air temperature, the engine entered the knock-region during one series of tests and quite improbable experimental values were obtained. On the following day the engine could under no circumstances be brought into the knock region at 160°C. When the ignition was changed or the boost-air temperature was increased the engine promptly started to knock, which stopped each time as soon as the conditions necessary for the determination of the knock-limit curve were restored. The same effect occurred with the gasoline/benzol mixture at 120° valve overlap and 160° boost-air temperature. Here measuring points on different days compared well at single air-fuel ratios but showing intermediate regions of knock-free operation. The position of the measure-points and the manner in which they were obtained no longer justified the plotting of a knock-limit curve. Fuels with a high benzol-content also presented difficulties in the determination of the onset of knock in other tests. Frequently, scattered points were obtained, which were not reproducible. Unfortunately we could not make extensive experiments concerning this absence of the knock phenomenon, since the mechanical stress on the engine was so great because of the high super-charge that the engine could be subjected to it only for a short time in the interest of the preservation of the test-stand and the cylinder. Discrepancies with VT 702 could be found only at 120° valve overlap and 160° boost-air temperature. The curves plotted in the graphs come from 3 series of tests. They show complete agreement of the measure points within very narrow limits and so appear to be justified. The points outside the knock region for VT 702 and VT 702/1 were obtained in a similar way. They could only be obtained when the number of knock impulses was smaller than the usual average for the evaluation of the onset of detonation, and the engine had to be brought from the knock-free region to the knock-limit. Apart from these 2 exceptions there were no other discrepancies during the tests. All other curves and test points could be repeated at any time. The interpretation of the test results was carried out in the following way: - At first tests were made to explain the shape of the knock-limit curves in the DB 601. This led to the determination of the effect of the valve-overlap on the shape of the knock-limit curves. Finally the change of the thermal stress and the decrease of the residual gas quantity at increasing valve overlap and their effects on the knock behaviour generally, were examined.

2) The knock-region in the DB 601.

In the general discussion of the causes for the onset of detonation it was pointed out that under otherwise constant operating conditions, with variation in excess-air coefficient - as is the case when plotting the fuel loop - knock occurs first at approximately $\lambda = 1.05$. In a great number of tests on various engines under corresponding conditions this was in fact the case, and the minimum of the knock-limit curve was at this point. In the knock-limit curve of the DB 601, however, the minimum occurred away from the region of $\lambda = 1.05$ and sometimes partly reached the extreme

rich region. In characteristic cases the knock-limit curves had their minimum at $\lambda = 0.6$ and from that point showed a nearly linear increase with increasing excess-air.

In connection with an earlier series of tests to determine the influence of fuels on various engines, the present tests provided sufficient material to explain this phenomenon, for in comparing various engines, it was found that the liquid cooled DB 601 cylinder has a poorer mixture formation.

This is due to the injection process the turbulence and structure of the combustion-chamber and temperature state in the engine and takes effect particularly in the rich region. Unvaporized fuel particles may be present in droplet-form. In order to explain the knock-behaviour a passage from a book by Linde is quoted:-

"In the presence of non-vaporized fuel droplets in the mixture, Callendar could detect an increase of peroxide formation and at the same time a decrease in reaction temperature as compared to mixture with completely vaporized fuel. As a result of enrichment of the mixture there are zones in the immediate neighbourhood of the droplets which are particularly favourable to the formation of peroxides. The lower the inlet temperature of an engine the greater the proportion of unvaporized droplets at the start of compression. Paraffinic fuels are influenced most, aromatics least. The products of the reaction are mainly aldehydes and acids. There is no peroxide formation with benzol because of its resistance to decomposition. With alcohol the molecular combination is loosened by the inclusion of oxygen, and the further oxidation requires only little energy of activation so that the resulting products of oxidation because of their low energy of dissociation do not lead to rapid reactions which can produce knocking."

These findings and their application to the results obtained with the DB 601, made it possible to explain the phenomenon we observed. The poorer mixture formation in the DB 601 is particularly effective in the rich region and there are unvaporized fuel particles in droplet-form. The usual knock-limit curve of engines falls from the excess-air region with a certain inclination depending on the kind of fuel, the engine and the operating conditions, to a point in the region of $\lambda = 1.05$ and from this point rises again. In comparison with this, with a knock-limit curve of the DB 601 at a low boost-air temperature, the declining branch of the curve is in the rich region. With increasing mixture strength the portion of unvaporized fuel particles becomes greater and thus the possibility of the formation of peroxides. The knock-limit curve does not therefore rise in a normal way from the usual minimum on account of the temperature drop of the unburnt mixture residue, but continues to fall. After the curve has reached its lowest point it usually shows an almost vertical rise. With higher boost-air temperature again a falling curve in the lean region is again obtained, indicating that the mixture formation is improved.

The higher cylinder temperature decreases the proportion of unvaporized fuel particles and therefore the minimum of the knock-limit curve moves further towards the rich region. When the boost-air temperature, and thus the temperature in the interior of the cylinder is increased further, the knock-limit curve rises from the point $\lambda \sim 1.05$ since over a certain range of the excess-air ratios there are no longer any unvaporized fuel particles present because of the increased temperature. They occur again only when the mixture is further enriched. Again a decline of the knock-limit curve occurs in the extreme rich region down to a second minimum from which the vertical ascent in the extreme rich region takes place. The change of the minimum point with boost-air temperature for VT 702/1 and C1 has been plotted in fig. 23 for the whole experimental range, viz. at 80° and 120° valve overlap. Considering the difficulty of determining exactly the proper minimum of the knock-limit curve in the engine, the scattering of the points is very small.

From a number of knock-limit curves which showed the displacement of the minimum due to the mixture formation and also the change in the shape of the knock-limit curve, a family of curves for the whole range of the boost-air temperatures was plotted in fig. 24 in a three dimensional representation. The knock-limit curves are shown for the fuel C1 + 0.08 lead at 40° valve overlap. At boost-air temperatures of 30° and 50°C the vertical rise at the rich end occurs following an almost linear course of the curve from $\lambda = 1.2$ to a minimum value in the rich region. The knock-limit curve at 80° shows a small bend first at $\lambda \sim 1.05$. Then after a small discontinuity indicating a tendency to rise, it continues to decline to the lowest point in the rich region. At 100° boost-air temperature the knock-limit curve shows first a definite minimum at $\lambda \sim 1.05$. Then, after a short rise there is an almost linear decline to a second minimum. Here remaining irregularities in the mixture formation due to the presence of unvaporized fuel particles counteract the rise of the knock-limit after $\lambda = 1.05$. Again there is a second minimum of the knock-limit in the rich region followed by the steep rise. From 130° boost-air temperature onwards the knock-limit curves show the usual rise on both sides of a minimum value in the region of $\lambda \sim 1.05$. The decline of the curve after the peak value in the rich region, is explained by the increasing presence of unvaporized fuel particles due to the extreme richness of the mixture. This particular representation in fig. 24 shows very clearly the mixture composition as a function of the boost-air temperature and its influence on the knock-limit curve, the same phenomena may be observed with all the other fuels with the exception of the gasoline/benzol and the gasoline/alcohol blends.

The passage quoted pointed out that the behaviour of aromatic fuels is least affected by the presence of fuel droplets in the mixture. In fact, under conditions still comparable with the reliability of the engine the minimum of the knock-limit curves of the gasoline/benzol blend - a highly aromatic fuel - is always in the region of the usually observed value of $\lambda = 1.05$. But this does not prove that aromatic

Fuels with corresponding enrichment and increase of the boost pressure do not show a second minimum somewhere in the region of fuel excess. The fuels used for the tests had different aromatic contents. C₁ has the smallest content, viz. 11%. Next comes VT 702, then the mixture VT 706/707 and finally gasoline/benzol with an aromatic content of 85%. Thus it was possible to investigate the position of the minimum boost point at a constant boost-air temperature in terms of the aromatic content. Fig. 25 shows the values of the excess-air coefficient for the minimum of each knock-limit curve in terms of the aromatic content for the various boost-air temperature and valve overlaps for the fuels mentioned. From the fuel C₁ with the smallest aromatic content and with the minimum point farthest in the rich region, with increasing aromatic content, the minimum is displaced more and more towards the weak region, until with the gasoline/benzol blend the usual minimum at $\lambda = 1.05$ is recorded. This permits the assumption that in the presence of unvaporized fuel particles, the formation of peroxides really depends upon the aromatic content of the fuel, and that this peroxide formation becomes less and less manifest with increasing aromatic content. It ceases altogether with almost pure aromatic fuels.

The factors which determine the knock behaviour of alcohol have already been mentioned. In spite of the presence of unvaporized fuel particles, these do not influence the knock limit decisively. Also, the minimum of the knock limit curve is only little affected by the temperature of the boost-air and is always in the region of $\lambda \sim 1.05$.

The previous discussions mentioned several times a steep rise of the knock-limit curve in the extreme rich region which could be observed with some fuels. Considering any case graph which shows plotted against the excess-air coefficient the knock-limit as boost pressure in mm Hg, e.g. for the fuel VT 702, this steep rise of the curve is displaced farther towards the rich region as the temperature rises. If, however, the curve is plotted for the same fuel against the injection quantity in mm³/cycle, the corresponding points for all boost-air temperatures lie on one curve. This means that the engine in this part of the rich region independently of the boost-air temperature, at the same boost-pressure and injection quantity, enters the knock-region. Consequently the knock-limit is displaced more and more into the rich region when the boost-air temperature rises and so reduces the volumetric efficiency. So long as the engine was working in this part of the knock-limit curve, a relatively further small enriching led to an almost immediate power-drop connected with failure of ignition. From these two phenomena it may be deduced that in this rapidly rising part of the curve in the rich region the knock-limit and the ignition-limit of the fuel are close together in this engine. The following observation supports this assumption: - The ignition-limits become wider with the increasing temperature of the system. In the present case, the steep part of the knock-limit curve - considered as the ignition-limit - moves more and more towards the rich region with increasing boost-air temperature.

3) The influence of the valve overlap on the characteristics of the knock-limit curve.

In the following discussion of the results which deal with the general form of the knock-limit curves only the changes in the characteristics of the curve itself, will be discussed. The variation of the general position of the curve, is reserved for a special chapter of this report, but it was not always possible to avoid anticipating some details in order to explain certain processes.

From consideration of the general form of the DB 601 curve, the considerable effect of the boost-air temperature was observed, i.e. the temperature state of the mixture which determines the mixture formation. On the other hand, earlier tests showed that the valve overlap at a given M.E.P., alters the thermal interval stress of the engine. It was obviously desirable to find out if there was a relation between these two different operating conditions, and what was their effect on the engine. In one case the increase of the boost-air temperature increases the compression temperature and consequently the temperature of that part of the unburnt mixture before the flame front which has a tendency to knock. This causes e.g. earlier knocking under otherwise constant operating conditions. The scavenging of the dead space improves with increasing valve overlap, and the decreased proportion of residual gas and the possible scavenging of the cylinder lower the overall temperature. This lowers the compression temperature at the same boost-air temperature in comparison with an engine with small valve overlap. Therefore the conditions for the onset of detonation are no longer the same and the shape of the knock-limit changes.

It is well known that change of the boost-air temperature changes the characteristics of the knock-limit curve. On the other hand a similar change of the shape of the knock-limit curve may be produced by changing the valve overlap by a certain amount. If a relation is established between these two factors influencing the shape of the knock-limit curve the effect of valve overlap may be balanced by a corresponding alteration in the boost-air temperature.

The influence of the residual gas on the heating of the charge must also be considered and furthermore the kinetics of reaction. The stable residual gases e.g. CO_2 , H_2O , CO and the short-lived products of the combustion process can in some form or other have a chain introducing or interrupting effect. It must be assumed however that the general shape of the knock-limit curve is influenced mostly by the vaporization of the fuel and its effects on the mixture formation, as already pointed out. It may therefore be assumed that the reaction kinetic effect of the residual gas influences the form of the knock-limit curve to a lesser extent, and affect chiefly its position.

Therefore the tests were interpreted in this sense. Without considering the height of the knock-limit curves, those of similar shape were selected and compared. Fig. 26 shows such curves for the various valve overlaps and for the fuel VT 702/1 + 0.12 TEL. Attention has been paid to the course of the knock-limit curves, to the relative position of the two minima and to the direction of the curve between these two points. This graph shows that almost the same shape of the curve is obtained by the following values:-

Valve overlap:-	Boost-air temperature:-
40° crank-angle	80°C
80° crank-angle	160°C
120° crank-angle	190°C

Therefore the increase of valve overlap from 40° crank-angle to 80° crank-angle would be equivalent to a boost air temperature increase of approximately 80°C. A further increase from 80° crank-angle to 120° crank-angle could be compensated by a temperature change of about 30°C.

The irregular jump in temperature for each valve overlap increase can be explained by the fact that the effect of the change in valve overlap from 40° to 80° is considerably greater than the further increase from 80° to 120°. The same effect could be observed during tests to investigate the change in power and air-flow when using various fuels, viz. that a further increase of an already great valve overlap gives relatively little improvement. We see again that as soon as that value of the valve overlap is reached which results in an almost complete scavenging of the dead space, a further increase of the valve overlap no longer reduces the thermal internal stress to the same extent.

For the other tested fuels the same evaluation was made to find out the numerical changes of the boost-air temperature which compensate the effects of valve overlap increase. Fig. 27 shows the knock-limit curves for various valve overlaps with their corresponding boost-air temperatures for the fuel C1 + 0.02% TEL. For this fuels curves are plotted which at each temperature show finally a linear knock-limit curve over the whole range of the excess-air coefficient with the exception of the steep rise in the rich region. It was not possible to show curves which correspond to one another and also have similar positions of the maxima and minima, since this fuel with high anti-knock value could sometimes not be tested over the whole range as the stress on the engine had to be taken into account.

In Fig. 28 are given for the mixture VT 7035/707 those knock-limit curves which have similar characteristics. For the first time, the knock-limit curves were distinctly separate from one another. Also, the boost-air temperature differences required to compensate the valve overlap change from 40° to 80° crank-angle, decreased from 80°C to 60°C.

In Fig. 29 and Fig. 30 are curves for the two remaining fuels, viz. the blends of gasoline/benzol and gasoline/alcohol.

Here it was not possible to relate the curves to one another by virtue of their similarity. Reference to fig. 8 and fig. 11, which contain all knock-limit curves of these fuels, shows that the shape of the knock-limit curves is almost independent of the valve overlap. This fact in itself is not new. Comparison of knock-limit curves plotted at various boost-air temperatures, shows great differences in their positions according to whether they were plotted against p_r or p_m . The alteration of the slope of these knock-limit curves is insignificant compared with the alteration in height. During the tests one has to bear in mind the fact, that with large valve overlaps we obtain values of the excess-air ratio which do not agree with the real engine conditions. Therefore the slope of the knock-limit curves is no longer to be taken into consideration as a measure for the influence of the temperature. This is why the two highly temperature-sensitive fuels, viz. the gasoline/benzol and the gasoline/alcohol blends, were assessed according to their corresponding heights and plotted in fig. 29 and fig. 30. Even with the small range of results available for the comparison it appears that the effect of the valve overlap on the knock limit can be compensated by a corresponding alteration of the boost-air temperature.

4) The influence of valve overlap on the anti-knock value of fuels.

While in the previous chapter how the change in shape of a knock-limit curve with increasing overlap, was discussed, in this section the variation of the knock-limit itself will be investigated.

The factors which, with changed overlap, influence the position of the knock-limit are, in this case:- The boost-air temperature, the scavenging of the dead space, the alteration of the thermal internal stress and the residual gas quantity with its thermal influence and its effect on kinetics of reaction. It is of course extremely difficult to separate these effects. For there is in most cases an influence of several of the factors mentioned, and the change of one factor necessarily causes changes one or several of the other factors at the same time. We can assess the test results therefore only by taking those factors into account which have the greatest effect, at the same time pointing out that other factors also contribute. Therefore it will not be possible to give a value which is generally applicable to all fuels, and which expresses clearly the alteration of the knock-limit curve with the valve overlap.

The influence of the valve overlap on the knock-limit was assessed in the following ways:- For the individual values of the excess-air coefficient were plotted the corresponding value of the boost pressure on the knock-limit curve and the prevailing mean effective pressure as functions of one another. A comparison of points of equal excess-air coefficient then shows how the knock-limit changes with the valve overlap.

It appears appropriate to explain the process outlined above with the aid of fig. 31 which illustrates the evaluation for all fuels. The points of equal excess-air coefficients

with their corresponding boost-pressure and M.E.P. values, obtained from the knock-limit curves, are plotted for all valve overlaps and all fuels, at a boost air temperature of 150°C , which is the reference temperature of the DVL supercharge method. This method of evaluation has of course the disadvantage that these points of equal excess-air coefficients do not reproduce the real mixture composition correctly. First of all, the scavenging air quantity increases with increasing valve overlap because of the way in which the air flow is measured. Therefore the excess-air ratio is too large in comparison to the actual mixture composition and the points are displaced towards the lean region. Secondly there is an additional error which is due to the way in which the knock-limit curves are plotted. For the boost-pressure is changing all the time during the plotting of such a curve and so also is the scavenging air quantity, so that the individual points have different errors. When it was tried to base the evaluation equal injection quantity, similar difficulties arose. Here the mixture composition changes according to the residual gas remaining in the cylinder with equal injection quantity and varying valve overlap. This again means comparing points of different power-drop.

With consideration of these disadvantages the interpretation of fig. 31 gives the following result:- The increase of the valve overlap from 40° to 80° increases the knock-limit considerably with all fuels even taking wrongly calculated excess-air coefficient into account. A further increase of the valve overlap up to 120° crank-angle gives for some fuels a further small increase of anti-knock performance, with others, however, there is no further improvement or even a decrease of the knock-limit. The fuel V7 702/1 shows very clearly how the knock-behaviour changes with the valve overlap. Here points of almost equal air-fuel ratio could be joined by a straight line as shown in fig. 31. With valve overlap of 40° a M.E.P. of 10 kg/cm^2 is obtained at the knock-limit with a constant boost-pressure of 1020 mm Hg. , while at 80° 12.3 kg/cm^2 and at 120° 13.5 kg/cm^2 is obtained.

The same evaluation is made in fig. 32 for the same fuels with a boost air temperature of 160°C . Here too the individual knock-limits of the fuels show a considerable increase up to 80° valve overlap. Beyond that the anti-knock value of the fuel in question increases relatively little or even decreases.

In order to explain this rather unexpected phenomenon, an attempt was made to relate actual points of equal mixture composition. For this purpose it seemed best to compare the individual minima of the knock-limit curves at high boost-air temperature. The position of the minimum of the knock-limit curve and its dependence on the boost-air temperature and the valve overlap has already been discussed. These considerations showed that the onset of knocking occurred at high boost-air temperatures near the stoichiometric mixture ratio regardless of the kind of fuel. That means that the percentage power-drop is almost the same at these points and that they can be compared directly.

In accordance with the principles outlined above, fig. 33 shows the change of the knock-limit with valve overlap for 180°C boost-air temperature and fig. 34 for 190°C. An increase of knock-limit up to 80° valve overlap is shown with all fuels. Beyond that, the tendency of the individual fuels differs. The fuels VT 702 and VT 702/1 still show an appreciable increase of the anti-knock value. Though the boost pressure increases only very little or even decreases there is an increase of the M.E.P. obtainable at the knock-limit. No noticeable increase occurs with the blend 706/707. The gasoline/benzol and gasoline/alcohol blends however, show, a drop in anti-knock value with the high valve overlap.

It is quite difficult to explain this phenomenon considering that there was not much test material and that this was obtained only from one engine. The general statement concerning the influence of the increasing valve overlap on the knock-limit curve was that the altered thermal internal stress and the reaction kinetic effects of the residual gases are of importance. The tests show that when the valve overlap is altered from 40° to 80° crank-angle the thermal internal stress must considerably decrease since with the same boost-pressure a corresponding increase of the M.E.P. is possible at the knock-limit. Under certain circumstances the boost-pressure may be increased still more without exceeding the knock-limit. The decreasing proportion of the residual gases can be noticed in this region of the valve overlap by the reduced heating of the boost-air. In addition there is the cooling affect of the scavenging air. It cannot be established with certainty how far the influence of the residual gases on the kinetics of reaction extends to the knock-behaviour in this region. All fuels showed an increase of anti-knock performance when the valve overlap was increased up to 80° crank-angle. Since a varied valve overlap may be compensated by a corresponding alteration of the boost-air temperature, it is apparent that fuels of a lower temperature sensitivity have a smaller, and fuels of a high temperature sensitivity a higher increase of their anti-knock performance.

It is clear that a further increase of the valve overlap to 120° crank-angle is followed by a further decrease of the thermal internal stress. This should therefore lead to a further increase of the anti-knock value for all fuels. Reference however, to fig. 33 and fig. 34 shows that the effects of the valve overlap are irregular. The fuels of low temperature-sensitivity still show an increase of their anti-knock value resulting from the decreasing thermal internal stress. But the fuel blends of a high temperature sensitivity which should gain most from a decrease of the thermal internal stress, have unexpectedly lost some of their anti-knock value. Therefore it may be concluded that the residual gas has quite an appreciable effect on the kinetics of reaction influencing the knock-behaviour favourably so that fuels highly sensitive to temperature are also affected by this factor. In the present case, i.e. at a valve overlap of 120° crank-angle residual gas quantities are no longer of any importance. Therefore the favourable influence on the knock-limit does not exist. VT 702 with a small aromatic content showed an increase of the anti-knock value at 120° valve overlap;

the 706/707 with a higher aromatic content had its knock behaviour unchanged; the gasoline/benzol blend with the highest aromatic content showed a decrease of the knock-limit. At 80° valve overlap an increase of the anti-knock performance took place, caused not only by the small thermal internal stress, but also by the residual gas and its influence on the reaction kinetics. At a valve overlap of 120°, however, the change in the knock-limit is due to the further decrease of the thermal internal stress and to the absence of residual gas. An increase or decrease of the knock-limit then depends only on the kind of fuel used.

5) General effect of the valve overlap on the knock-behaviour.

This chapter gives a short survey of the effects of valve overlap on the knock-behaviour of fuels, taking into account the individual factors involved. This is followed by a few hints on how the DVL supercharge method could be adapted to the operating conditions of modern main engines.

It must be emphasized, however, that all tests were made with a liquid cooled engine, and therefore it will not be possible to apply these test results exactly to an air-cooled engine. On the whole the results will be the same but it is just possible that slight deviations will occur, because the temperature in an air cooled engine is considerably higher. Tests now in process concerning the influence of the valve overlap in an air cooled engine are the logical continuation of the tests for the DB 601. When these tests are ended it will be possible to find out exactly how far the results coincide.

The tests showed that the valve overlap has a very marked influence on the knock-behaviour of fuels. The changed thermal internal stress together with the different residual gas proportion does not only alter the characteristics of the knock-limit curves but also the general position in height, i.e. the anti-knock value of the fuel. It was possible to determine clearly and exactly the influence of valve overlap variations on the characteristics of knock-limit curves of fuels which are not too strongly susceptible to temperature. These characteristics depend upon the temperature and upon the mixture formation. When the knock-limit curves are obtained for one fuel and for one valve overlap over a large range of boost air temperature the shape of the knock-limit curve may be predicted at a given boost-air temperature for another valve overlap without reference however, to its height.

A satisfactory solution could not be found for fuels of a high temperature sensitivity, viz. for blends with a high aromatic or alcoholic content. Since with these fuels the mixture formation as affected by boost air temperature has almost no influence on the characteristics of the curve the compensation for variations of boost-air temperature by alterations in valve overlap cannot be established. A variation of the valve overlap with these fuels causes only a variation of their anti-knock value by altering the height of the knock-limit curve.

As regards the alteration of the anti-knock value of various fuels by means of valve overlap, the effects on individual fuels did not show any definite relation to their chemical composition. When the valve overlap is increased from 40° to 80° crank-angle there is usually an increase of the anti-knock value. It did not matter if the knock-limit curve was plotted against the permissible maximum boost-pressure or against the M.E.P. With the general increase of the anti-knock value of all fuels, the order of evaluation of the individual fuels at the same boost-air temperature remains at least approximately the same so long as the valve-overlap is varied within the range of 40° to 80°.

When the valve overlap is still further increased the change of the anti-knock value becomes quite different. The different behaviour of the individual fuels as regards the anti-knock value, does not yet permit at present any clear cut conclusions as regards the order of evaluation. This change in rating depends upon the fuel composition and varies from increase via constancy to a decrease.

The following factor has to be taken into account for fuels which are less temperature-sensitive:- The reduction of the volumetric efficiency with increasing boost-air temperature and the increased thermal internal stress, at a large valve overlap balance each other for a considerable temperature range and for that region of the excess-air ratio which must be considered for practical operating-conditions, so long as we take the M.E. P. as a criterion. Fig. 35 shows such an evaluation for the fuels C1 and VT 702/1. The separation of the p_{me} knock-limit curves was taken from fig. 18 and fig. 21 and plotted at 50 and 100°C boost-air temperature for each individual valve overlap. The knock-limit curves of these fuels plotted for the intermediate values of the boost-air temperature of 50°, 80° and 100°C are within this temperature range when plotted against p_{me} . With increasing valve overlap the difference of the obtainable p_{me} values diminishes, and the curves within that region of the excess-air ratio which is relevant for practical operation, almost coincide at 120° valve overlap. So the measurement of fuels which are less temperature-sensitive based on the M.E.P. obtainable at the knock-limit, at various boost-air temperatures, would serve no further purpose with the large valve overlap.

According to our present test results it appears that the anti-knock value of fuels with high temperature-sensitivity deteriorates from a certain valve overlap onwards. This is at about 130° crank-angle. But their anti-knock performances at 120° valve overlap is still better than that which was obtained at 40° valve overlap when tested according to the DVL supercharge method. But under these circumstances it does not seem desirable to test aromatic fuels under altered supercharge conditions, e.g. with a valve overlap of 80°, since it may be expected in engines with a higher overlap that the knock-limit is reached earlier. This cannot be finally established at present, since in modern main engines there is not only the increase of the valve overlap but also an increase of the compression and tests have been started to find out the influence of compression at large valve overlaps.

A further argument against the change of the valve overlap to 80° crank-angle in the DVL supercharge method under otherwise the similar-conditions is the necessity of testing aromatic fuels at boost-air temperatures occurring in practice. This leads to such high boost-pressures to get the engine to knock, that the increased mechanical stress makes it doubtful if the test-stand would be reliable for prolonged testing.

The question is, whether it would not be better to test aero-engine fuels especially for actual operation, in the single cylinder of the engine type in question and under the operating conditions relevant to each particular case. Tests at present show that the knock-limit curves cannot be applied exactly to predicting the behaviour of given fuel in any given main engine under any given conditions after testing in an individual single cylinder engine. The results obtained by the DVL supercharge method are doubtless very significant for the evaluation of fuels; their applicability, however, to main engines is rather doubtful so long as conditions are met which vary a great deal from those of the DVL supercharge method and which are known to have a considerable influence on the knock-behaviour of fuels. The observation that the less temperature sensitive fuels at high valve overlap show an increase of the anti-knock value from rich to weak mixtures leads to the following conclusion:- Whilst up to now the remedy for the onset of knocking at take-off was enrichment of the mixture, this measure would cause the contrary effect in liquid cooled engines with a high valve overlap. The course of the knock-limit curve, e.g. of VP 702/1, in fig. 18 shows clearly, that at 120° valve overlap and up to 180° boost-air temperature an enrichment of the mixture would only result in greater knock tendency. In these cases weakening of the mixture might be a remedy as long as the permissible power-drop was not exceeded.

The extensive tests and the test data given here should also assist the work of some investigators who are attempting to calculate the effect of operating conditions on knock-limit curves and also their applicability to practical conditions.

Summary

The tests on the influence of the valve overlap on the knock-behaviour of fuels of different chemical composition had the following results:-

The DB 601 engine showed for fuels with a low temperature sensitivity a peculiar knock-region under certain operating conditions, e.g. with a high valve overlap or low boost-air temperature. The curves show from their minimum in the rich region a continuous increase of the anti-knock value, and so differ considerably from the usual knock-limit curves obtained by the DVL super charge method. This phenomenon is caused by the mixture formation. The presence of unvaporized fuel particles in the form of droplets and the resulting increase of peroxide formation could be proved to be dependant upon the boost-air temperature and the valve overlap. The increasing

boost-air temperature or decreasing valve overlap improved the mixture formation which caused the minimum in the rich region to be displaced slowly, and the knock-limit curves took the shape familiar to other engines. This phenomenon was not observed when using temperature sensitive fuels, benzol and alcohol blends, since the conditions causing the onset of knocking in the rich region are absent.

The characteristics of the knock-limit curves, which depend upon the mixture temperature and the resulting mixture formation, and their reaction to the influence of varied valve overlaps, could be determined in their order of magnitude. The effect of the thermal internal stress, decreasing with increased valve overlap, on the shape of the knock-limit curve can be compensated by a corresponding increase of the boost-air temperature. The increase of the valve overlap from 40° to 80° crank-angle can be compensated by increasing the boost-air temperature by about 80°C . The further increase of the valve overlap from 80° to 120° crank-angle is equivalent to a temperature increase of the boost-air of approximately 50°C . The variation of the height of the knock-limit curve was not considered in this connection.

The influence of the anti-knock value of fuels depends upon their chemical composition and upon the degree of the valve overlap. Fuels with a small content of temperature-sensitive components showed an increase of the anti-knock value for the whole range of the tests. Mixtures with a high benzol- or alcohol content which are consequently more temperature-sensitive no longer react uniformly. When the valve overlap was changed from 40° to 80° a considerable increase of the anti-knock value was generally observed. A further increase of the valve overlap had either no influence or produced a decrease of the anti-knock value. This depended upon the amount of temperature-sensitive components in the blend.

There are limited possibilities of adapting the DVL supercharge method to the operating-conditions in modern main engines. It seems possible that with a small difference in valve overlap the order of the fuel evaluation is preserved. An extensive change of the DVL supercharge method which takes into account the changed operating conditions of modern main engines, such as a larger valve overlap, higher compression etc., must be postponed until every influence mentioned above has been investigated.

Literature

- (1) F.A.F. Schmidt:- Internal Combustion-Engines. Thermodynamic and experimental principles with special reference to aero-engines.
- (2) C.B. Veal:- The Evaluation of aviation fuels in aero-engines. SAE Journal Vol. 5
- (3) W. Wilke and F. Jantsch:- The qualities of aviation fuels and their testing. Ring-book of aviation research IV C 12.

- (4) F. Dreyhaupt:- The position of research on the knocking of gasoline engines. ATZ 1941, vols. 21 and 23
- (5) J. Fost:- Explosion- and combustion processes in gases. Ed. Springer, Berlin 1939.
- (6) A.W. Schmidt:- Investigation of the knocking noise in gasoline engines with electro-acoustic meters. Deutsche Kraftfahrtforschung, Vol. 33
K. Generlich
- (7) H. Rögner:- Observations on the problem of fuel characteristics. Report of the physico-chemical Institute of Leipzig University, 1940.
- (8) K. Franke:- Influence of various fuels and valve overlaps on engines, DVL-Report.
- (9) H. Rögner Tests on self-ignition and combustion of hydrocarbons. Report of the physico-chemical Institute of Leipzig University 1941.
and v. Weber:-
- (10) F.A.F. Schmidt: Theoretical investigations and tests on ignition-lag and the knock process VDI-Research-vol. 592.
- (11) W. Lindner:- Ignition and combustion of gas-and fuel vapour mixtures. VDI. Ed., Berlin 1931
- (12) H.L. Callendar: Engineering 125 (1927) quoted in W. Lindner's book
- (13) D.R. Pys:- The Internal combustion-engine, translated by Wettstätt Ed. Springer, Berlin 1933
- (14) Construction Regulations for aero-engines BVM October 1940.
Test Instructions for aero engine fuels
- (15) F. Seeber:- Recent procedure in fuel testing, Luftfahrtforschung 1939, vol. 16.

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TABLE I

Enging-Data

Engine Type:-DB 601

Data:- Stroke:- = 160 mm
Bore:- = 150 mm
Compression:- = 6.5
Capacity:- = 2.828 litres
Compression-volume:- = 517 cm³

Valve Timing:-	Inlet opens °before T.D.C.	Inlet closes °after B.D.C.	Exhaust opens °before B.D.C.	Exhaust closes °after T.D.C.
Valve overlap:-				
40° crank-angle	24	56	52	16
80° crank-angle	39	72	53	41
120° crank-angle	71	56	69	49

Fuel system:- Injection: Begin of Delivery 26° after T.D.C.

Pump:- Bosch PZ 2/100 V 402 (cam-pump)

Nozzle:- L'Orange 6/389 - 2029 A

Ignition system:-

Sparking-plugs :- Bosch W 260 T 1

Magnets :- Bosch F1 1R 36
Bosch F1 1L 36

Boost-air:-

Blower:- Klein, Schanzlin, & Becker 1.5 atmospheres
450 m³/hr.

Air heater:- DVL 24.5 KW

Coolant:- Water

Pump:- Odessa Machine Factory Type S 30/160 135 l/min

Exhaust lay out:- DVL, through silencer, extraction fan

Brakegear:- Siemens- generator type A 6 247

Table 2
The Fuel Data

Description	VP 702 + 0.12 TEL	25% gasoline lead-free 75% aircraft benzol 120/41	53% gasoline lead-free 47% ethyl- alcohol 122/41	75% VP 706B 25% VP 707	VP 702/1 + 0.12 TEL	C1 + 0.08 TEL
Received No.	405/40			240/41	196/41	213/41
Supplied by	América Works Mergsburg	mixed by "Olex" mixed by "Olex"		mixed by DVL	"WIP" Hitzacker	"Wite" Brockwitz (captured stores)
Specific gravity @ 20°C	0.7205	0.8235	0.7435	0.7760	0.7216	0.7146
Refraction n _{D20}	1.4024	1.4585	1.3904	1.4354	1.4028	1.4010
Water soluble components, %	0	0	45	0	0	0
Vapour pressure, Reid atm.	0.435	0.215	0.465	0.385	0.435	0.385
Boiling curve	see fig. 3	see fig. 3	see fig. 3	see fig. 3	see fig. 3	see fig. 3
Corrosive properties, Cu, Al-ticks 3 hrs. 50°C	unchanged	unchanged	unchanged	unchanged	unchanged	unchanged
Gum, mg/100 cm ³	2.4	0.6	7.0	1.2	0.6	1.4
Crystallization point, °C	below -60	-19	below -60	below -60	below -60	below -60
Lead content, iodine method	0.12	0	0	0	0.118	0.08
Iodine number (Hanus)	3.2	2.6	1.61	1.90	2.24	4.38
Aniline point II	60.2	59.4	59.4	51.0	56.6	65.8
Aromatic & unsat. comp., wt. %	Uns 3.3 Ar 19.7 Uns 3.0 Ar 82.3 Uns 3.2 Ar 23.5	5.7	26	44	10.7	11
Naphthene, %	25.5	90.88	69.70	35.4	65.82	12.5
C-content, %	83.80	9.0	47.5	20.5	49.4	35.13
Paraffin, %	14.73	9.68	14.0	12.35	14.75	76.5
B ₂ -content, %	0	0	16.30	0	0	14.87
O ₂ content, %	5.78	9.34	4.83	7.11	5.77	5.74
C-H ratio	14.53	13.7	12.1	14.3	14.82	14.89
Lowest calorific value	10657	8849	8502	10195	10537	10479
Octane number, M.M.	92	88.5	88	75	88	97

" 30 "

TABLE 3

Characteristics of the Lubricant

Description:-	P 16
Received No:-	399/40
Supplied by:-	I.G. Farbenindustrie, Ludwigshafen
Specific gravity at 20°C	0.885
Refraction n_{D20}	1.4897
Viscosity at 20°C, E	239
" at 50°C, E	28.3
" at 100°C, E	3.76
Pole height	1.37
Flash-point °C	230
Flame-point °C	266
Setting-point	-12
Acid number mg KOH	0.08
Saponification-number mg KOH	0.013
Asph halt %	0
Ash %	0.002

- Fig. 1 :- The piston at the end of the tests.
(Running period approximately 200 hours)
- Fig. 2 :- Full view of the test stand with the DB 801 cylinder
- Fig. 3 :- Boiling-curves of the fuels
- Fig. 4 :- Knock-limit curves of various engines with various fuels
- Fig. 5 :- Knock-limit curves of VT 702 + 0.12 lead as a function of boost pressure and excess-air ratio for various boost-air temperatures and 40°, 80° and 120° valve overlap
- Fig. 6 :- Knock-limit curves of VT 702 + 0.12 lead in terms of M.E.P. and excess-air ratio for various boost-air temperatures and 40°, 80° and 120° valve overlap.
- Fig. 7 :- Knock-limit curves of VT 702 + 0.12 lead in terms of boost-pressure and injection quantity/cycle for various boost-air temperatures and 40°, 80° and 120° valve overlap.
- Fig. 8 :- Knock-limit curves of the gasoline/benzol mixture in terms of boost pressure and excess-air ratio for various boost-air temperatures and 40°, 80° and 120° valve overlap.
- Fig. 9 :- Knock-limit curves of the gasoline/benzol blend in terms of M.E.P. and excess-air ratio for various boost-air temperatures and 40°, 80°, and 120° valve overlap.
- Fig. 10 :- Knock-limit curves of the gasoline/benzol blend in terms of boost-pressure and injection quantity/cycle for various boost-air temperatures and 40°, 80° and 120° valve overlap.
- Fig. 11 :- Knock-limit curves of the gasoline/alcohol blend in terms of boost-pressure and excess-air ratio for various boost-air temperatures and 40°, 80° and 120° valve overlap
- Fig. 12 :- Knock-limit curves of the gasoline/alcohol blend in terms of M.E.P. and excess-air ratio for different boost-air temperatures and 40°, 80° and 120° valve overlap.
- Fig. 13 :- Knock-limit curves of the gasoline/alcohol blend in terms of the boost-pressure and injection quantity/ cycle for various boost-air temperatures and 40°, 80° and 120° valve-overlap.

- Fig. 14 :- Knock-limit curves of the 706 b/707 blend in terms of the boost-pressure and excess-air ratio for various boost-air temperatures and 40°, 80°, and 120° valve overlap.
- Fig. 15 :- Knock-limit curves of the 706b/707 blend in terms of M.E.P. and excess-air ratio for various boost-air temperatures and 40°, 80° and 120° valve-overlap.
- Fig. 16 :- Knock-limit curves of the 706b/707 blend in terms of boost-pressure and injection quantity/cycle for various boost-air temperatures and 40°, 80° and 120° valve overlap.
- Fig. 17 :- Knock-limit curves of the "VT 702/1 + 0.12 lead" blend in terms of boost-pressure and excess-air ratio for various boost-air temperatures and 40°, 80° and 120° valve overlap.
- Fig. 18 :- Knock-limit curves of the "VT 702/1 + 0.12 lead" blend in terms of M.E.P. and excess-air ratio for various boost-air temperatures and 40°, 80°, and 120° valve overlap.
- Fig. 19 :- Knock-limit curves of the "VT 702/1 + 0.12 lead" blend in terms of boost-pressure and injection quantity/cycle for various boost-air temperature and 40°, 80° and 120° valve overlap.
- Fig. 20 :- Knock-limit curves of the "C₁ + 0.08 lead" blend in terms of boost-pressure and excess-air ratio for various boost-air temperatures and 40°, 80°, and 120° valve overlap.
- Fig. 21 :- Knock-limit curves of the "C₁ + 0.08 lead" blend in terms of the M.E.P. and excess-air ratio for various boost-air temperatures and 40°, 80° and 120° valve overlap.
- Fig. 22 :- Knock-limit curves of the "C₁ + 0.08 lead" blend in terms of boost-pressure and injection quantity/cycle for various boost-air temperatures and 40°, 80° and 120° valve overlap.
- Fig. 23 :- Variation of the minimum of the knock-limit curve in the rich region for "VT 702" and "C₁" in terms of the boost-air temperature.
- Fig. 24 :- Knock-limit curves of C₁ + 0.08 lead at 40° crank-angle valve-overlap in terms of excess-air ratio, boost-pressure and boost-air temperature.

- Fig. 25 :- Variation of the minimum of the knock-limit curves in the rich region in terms of the aromatic content of the fuels.
- Fig. 26 :- Compensation of the effect of the valve overlap on the knock-limit curve of "VT 702/1 0.12 lead" by the alteration of the boost-air temperature.
- Fig. 27 :- Compensation of the effect of the valve overlap on the knock-limit curve of "C1 + 0.08 lead" by the alteration of the boost-air temperature.
- Fig. 28 :- Compensation of the effect of the valve overlap on the knock-limit curve of the "706b/707" blend by altering the boost-air temperature.
- Fig. 29 :- Compensation of the effect of the valve overlap on the knock-limit curve of the gasoline/benzol blend by altering the boost-air temperature.
- Fig. 30 :- Compensation of the effect of the valve overlap on the knock-limit curve of the gasoline/alcohol blend by altering the boost-air temperature.
- Fig. 31 :- Boost-pressure and corresponding M.E.P. at the knock-limit for various fuels at 150°C boost-air temperature.
- Fig. 32 :- Boost-pressure and corresponding M.E.P. at the knock-limit for various fuels at 160°C boost-air temperature.
- Fig. 33 :- Alteration of the anti-knock value at the minimum of the knock-limit curves ($\lambda \sim 1.05$) by the valve overlap at 160°C boost-air temperature.
- Fig. 34 :- Alteration of the anti-knock value at the minimum of the knock-limit curves ($\lambda \sim 1.05$) by the valve overlap at 190°C boost-air temperature.
- Fig. 35 :- Reduction of the separation of the P_{me} knock limit curves in the region of 30° to 130° boost-air temperature with increasing valve overlap for fuels of low temperature sensitivity.

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The influence of various oils on the knock limit curve of aromatic fuels

by Franks

Synopsis: It was proposed to investigate the influence of three different lubricating oils on the knock-limit curve under the operating conditions of modern main engines. The reasons for the choice of oils and fuels used in the experiment are adduced; and the test arrangement is also described. Lubricating oil affects the position of the knock-limit curve as the aromatic content of the fuel rises. The effect of the lead addition did not change.

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I. Introduction:

The influence of different oils on the position of the knock-limit curve had been determined by a series of experiments at the DVL according to the currently used DVL supercharge test method for aviation fuels. It was apparent that an effect is produced only on fuels with a high proportion of aromatic components. The experiments themselves were carried out according to the DVL supercharge method in an air-cooled BMW 132 single-cylinder.

The conditions of operation in modern main engines differ considerably from those in the DVL supercharge method. It therefore seemed expedient to repeat the previous experiments under operating conditions such as may be expected sometime hence and in an engine of more recent design. The choice for the test engine fell on a liquid cooled DB 601 cylinder of high compression ratio and large valve overlap. This engine was mounted on the DVL single-cylinder test stand.

The experiments themselves were carried out with a number of different leaded and unleaded fuels containing aromatic compounds. The experiments were meant to disclose whether the dependence of the knock limit on the type of oil appears in the same way under the changed conditions as it did in the BMW 132-N engine.

II. Experimental arrangement:

1. Test stand

The DB 601 single cylinder unit was employed as a test-engine. It was mounted on a new and reinforced DVL single cylinder test stand. In order to realize the experimental conditions demanded by the test programme, a cam-shaft giving a large overlap was employed. An overlap of 120° crank angle was then attained by a suitable choice of the rocker arms and tappets. The higher compression ratio was obtained not by a lowering of the adjustable test stand table but by fitting a suitable piston. The data sheet (table 1) gives the values of valve timing and compression ratio attained by means of these alterations. Other engine data are also given as well as the details of the test-stand, the dynamometer, accessory units and components of the test-stand. The amounts of fuel and air, the power output and other data were determined in the usual way. The onset of knocking was determined acoustically.

2. Details of the Test procedure:

The reproducibility of knock limit curves for the DB 601 cylinder was good and the spread of results comparatively small. All the same a number of

special points had to be considered in order to avoid undesired effects on the knock limit curves.

The cylinder chosen for the experiments had already been operating for some time. Displacements of the knock limit curve with longer periods of running were thus not to be expected. The power of the engine was checked repeatedly during the experiments by running it at some definite control point. A power drop large enough to affect the accuracy of the experiments could not be observed, the control point being reached every time to within ± 1 H.P. Further control of the engine consisted of checking the valve timing before and after each change of oil and also checking the ignition timing.

From the operational side, constancy of the state of the engine could be established with comparative ease. The pressure of the oil as well as its inlet and outlet temperatures could be kept constant within very narrow limits. This, in conjunction with a constant engine speed, guaranteed a constant amount of oil in circulation. Similarly it was possible to keep the temperature of the cylinder constant by means of small alterations in the amount of cooling water circulating. As in the experiments carried out previously for the BMW 132 engine the following were found expedient: suitable pre-treatment of the piston rings, keeping the running time approximately constant for each test, and particular attention to the actual changing of the oil. Experiments had been carried out in the DVL on the amount of wear of the piston rings in relation to the type of oil and the running time. These showed the necessity of taking this factor into account. The possibility existed that the result of the last oil examinations might be falsified by the wear of the piston rings with long test periods. Accordingly for each new series of tests, i.e. for each type of oil, a new set of piston rings was used, each set being fitted to give the same side clearance, ring gap and tension.

After finishing a test series with one oil, the oil was run out while the test stand was warm; a larger amount of the next oil was run in immediately afterwards. The engine was then motored for some time with this oil so that the whole oil circuit was flushed and the oil then run off. The running surface of the cylinder was examined after dismantling: the used piston rings were taken off and the grooves cleansed of any residues. The piston was then provided with new rings which had been prepared in the manner described above. After the test stand had been reassembled, the next oil to be tested was introduced.

When all the points mentioned above were observed, everything possible had been done to attain a constant operational and thermal state of the engine. This should eliminate any unwanted effects on the knock limit.

3. Kinds of oil and fuel

The oil samples selected for experimentation were chosen without regard to their applicability or production. The only point of view considered was what deviations occurred in the various oils on the basis of the investigation already carried out with the BMW 132 N engine. First of all, a reference oil was chosen, namely Intevep Grönring, which is the oil required by the fuel test according to the DVL supercharge method, or an oil equivalent to it on the basis of the effect on knock determined in the previous tests, e.g. Aero Shell 100. Of further interest are the two kinds of oil which gave greatest deviations from the normal knock limit curves. These were Rotring, which gave a higher position of the knock limit curve, and Stenavo 100 which produced the largest reduction of the anti-knock value. All other oil samples tested in the experiments mentioned above gave results lying within the range defined by these three or four oils. For this reason there was no need to consider them any further. The constants of the oils used, viz. Rotring, Aero Shell 100 and Stenavo 100, are contained in table 2.

Whereas it was feasible to reduce the number of oils in the programme, the number of fuels tested had to be increased in consideration of a number of points which had not been completely elucidated in the previous tests. Among these points was the knock sensitivity of the fuel, depending on the proportion

of aromatics, referred to the various oils. Also the influence of various oils on the lead susceptibility for highly aromatic fuels. Some leaded and unleaded fuels of intermediate aromatic content were used as well as the fuel VT 702 + 0.12 lead of low aromatic content, and the gasoline-benzol blend of high aromatic content.

The aromatic content, the amount of lead and other analytical data are contained in table 3.

III. Experimental results

The knock limit curves for the several fuels are given in figs. 1 to 5. These show the knock limit curves for one fuel with each of the various lubricating oils. Fig. 1 shows the results obtained for the fuel lowest in aromatics, VT 702 + 0.12% lead.

The boost air temperature was 130°C and the runs include the whole practical range of excess air ratios. Appreciable effects on the knock limits by the type of oil could not be observed: this applies to the range of air excess number concerned in the normal operation of the engine as well as to the extreme lean and rich regions in which operational conditions normally have large effects on the knock characteristic.

The two following fuels of nearly equal aromatic content, the blend VT 706b/707 unleaded and C3 + 0.12 lead have been plotted in figs. 2 and 3. All that can be said on the knock limit curves shown here which differ in shape from the usual knock limit curves is that they are determined by the special conditions of the test. For the present investigation only the effects of the several oil samples were of interest. Their influence can already be recognized to a small extent. The next fig. 4 shows differences in the several knock limit curves for the fuel CV2b which has a still higher aromatic content. Unfortunately points could not be obtained with Rotring lubricating oil for the reason that a fault occurred shortly after starting.

The knock characteristics for the fuel with the highest aromatic content, the gasoline-benzol blend, are given in fig. 5. In the region of the minima a distinct difference in the height of the curve according to the lubricant was noticeable. This result is similar to that obtained when experiments were carried out for the determination of the effects of oils in an air-cooled engine under the conditions of the DVL supercharge method. The order of magnitude of the effect is also the same and for the two extreme oils, is about 90 mm.Hg boost pressure. For comparison purposes the knock limit curves of the gasoline-benzol blend for the BMW 132 N engine with the same lubricating oils have been plotted in fig. 6. With highly aromatic fuels a displacement of the knock limit according to the oil type takes place. This is confirmed by these almost identical results obtained under very different operational conditions and for different engines.

It has already been stated that fuels of various aromatic content were available for carrying out the experimental programme. It was therefore expedient to determine quantitatively the influence of the aromatic content of the fuels in relation to the effect of the oils on the knock characteristic. An evaluation has been attempted for this purpose in fig. 7. The knock limit curve with Aero Shell 100 has here been taken as a reference. The approximate deviations of the antiknock value (expressed in mm Hg. boost pressure) found when the other oils were used have been plotted against the aromatic content of the fuels. One meets with some difficulty when attempting to determine consistent values for the displacement of the several knock limit curves: this is due to the variations in the shape of these curves. Only the region of excess air ratio $\lambda = 1.05$ could be considered, thus being the region where small alterations of the operating conditions produce the largest deviations of the knock limit. The selection of points in this region, however, is difficult for some fuels: especially for unleaded blend of VT 706b/707 and CV2b which has a low antiknock value. The shape of the curve is influenced by exhaust gas dilution during the overlap period and is not dependent purely on operation conditions.