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Report No. 537

Lubricant Testing in Small-scale Apparatus.

(Lecture delivered on the occasion of a meeting of the Lubricating Oil Panel at the Testing Station, Oppau on 26th Feb. 1943).

Synopsis: This report describes apparatus used in the testing of lubricants at the Testing Station Oppau.

The instruments employed to determine coefficients of friction under conditions of limiting friction show satisfactory agreement among themselves as regards the evaluation of lubricants. With measurements of the amount of wear the results are largely dependent on service conditions, in particular on the nature of material employed, on the temperature and on the roughness of the surfaces: consequnetly a uniform conclusion regarding the manner in which a lubricant influences wear is difficult to reach. With a number of esters a relationship between the frictional coefficient and wear may be established under certain test conditions: thus, oils producing little wear have high coefficients of friction, and vice versa.

The "Four Ball" machine and the Almen-Wieland apparatus are employed for the investigation of extreme pressure lubricants, and both machines throw light upon the process of seizure. The tests carried out with the two machines yield contradictory results.

The rapid progress made in mechanical science brings with it ever increasing demands on working substances, e.g. lubricating oil etc. The present war further increases the demand for quantity and quality and at the same time brings about greater difficulties as regards the supply of raw materials. The task confronting the oil chemist, is therefore not always easy and he requires suitable testing facilities in order to investigate the problems connected with his products.

The purpose of this lecture is to show the manner in which tests on lubricants are carried out at the Testing Station, emphasis being laid on the tests on lubricants on small scale apparatus.

When testing the lubricating properties of an oil one must be clear regarding the various phases of lubrication: these can be most easily demonstrated in a loaded journal bearing Diag. 1 is a graphical representation of the change in the values of the frictional coefficient at the bearing in relation to the number of revolutions made by the shaft, using three different oils of equal viscosity. It can be seen that with a large number of revolutions and otherwise similar conditions, the three oils produce equal coefficients of friction. In this case a comparatively thick lubricating film separates the shaft from the bearings, which film is capable of carrying all of the pressure on the bearing. In a manner of speaking the shaft is floating in the oil film, while the eccentricity of shaft and bearing is but small. If it were possible to increase the number of revs. to infinity, the bearing and journal would become concentric, giving the greatest possible strength to the lubricating film under that condition. If on the other hand the number of revs. is reduced, the shaft will tend more and more to come into contact with the bearing. At the same time there is a decrease in the coefficient of friction in the bearing until a point of inflection is reached, also known as the "Ausklink" point. Beyond that point the coefficient of friction rises rapidly to a maximum value when n=0, when the shaft is in actual contact with the bearing. This point of inflection is of particular importance. To the right of this point i.e. with higher speeds of revolution, we are dealing with a state of full fluid lubrication where the laws of hydrodynamics come into force, and wear does not occur. The value of the coefficient of friction is then only dependent on the viscosity of the lubricant, provided that mechanical conditions are constant, i.e. pressure between surfaces, number of revs. and shape of bearing are all the same. This is why oils of equal viscosity will produce equal coefficients of friction no matter what their remaining chemical and physical properties may be. In the region of the point of inflection the friction curves separate and form paths of their own. It is here that the lubricating power of the oil becomes noticeable, and this comes into full force in the region of limiting friction, when the viscosity no longer plays any part in the proceedings. In the region of partial friction (or partial lubrication), i.e. near the point of inflection fluid lubrication and boundary lubrication go on side by side under conditions of boundary lubrication, shaft and bearing are so close that the metal surfaces are separated by only a few molecular layers of oil. The lubricating action will be the more effective the more these layers, absorbed by the metal, adhere to the surface, thus giving it protection.

The state of affairs aimed at in practice is to work with the lowest possible coefficients of friction in the region of fluid lubrication, at the same time keeping away somewhat from the point of inflection, for the sake of safety: a state which it is quite possible to reach. By suitable construction of the bearing shell and particularly by suitable selection of the oil as regards viscosity it is possible to choose the most favourable region (see diag. 2), although the region of "mixed" and boundary lubrication can never be completely avoided. These stages of lubrication are passed through each time the mechanism starts or stops: similarly all oscillating and reciprocating movements take place in the region of boundary lubrication, especially at the end of each "oscillation" where the motion suffers a reversal in direction, thus leading to wear. In such cases the important factor is the lubricating power of the oil and it is therefore necessary to investigate how that can be measured.

Fundamentally speaking, two avenues of approach are available when testing lubricants: one can either use a piece of machinery largely corresponding to the practical case for which the oil is required, or one can construct special test apparatus suitably designed to take the necessary measurements. In the former case, for instance, a gear oil would be tested in a train of gear wheels, a gun oil in a machine gun, a torpedo oil in the mechanism of a torpedo, a cutting oil on a lathe, etc. Tests of this kind require great expenditure of material and labour, are apt to take a long time and do not necessarily yield reliable results as their accuracy is often impaired by circumstances beyond the control of the operator. Apart from that, such tests would hardly allow the nature of lubrication to be more closely investigated, while on the other hand they have the advantage of producing conditions peculiar to, or closely resembling those met with in practice.

The other method of approach employs test apparatus which is relatively simple, shoe test pieces can be easily produced and retain a large degree of uniformity, and which are both cheap and easy to handle. Such apparatus will yield quantitatively reproduceable results in a comparatively short time.

The disadvantage, here, lies in the necessity to digress rather far from practical conditions, so that it is frequently somewhat risky to apply the test results to actual practice without laying oneself open to criticism; moreover, this procedure may well cause the value of the lubricant to be wrongly assessed. Both methods of investigation have so far been adopted at the Testing Station: in latter years, however, preference was given to the development of small scale apparatus, i.e. instruments of the second type, because in that way alone could a proper basis be created for the investigation of lubricants.

According to their purpose, the instruments may be grouped under 3 headings:

1. Apparatus for the measurement of coefficients of friction, under conditions of boundary lubrication.
2. Apparatus for the measurement of wear
3. Apparatus to determine the efficiency of lubricants in the prevention of seizure.

It might be considered a good idea to measure the coefficient of friction, at boundary lubrication, in a machine running on normal bearings, e.g. crank shaft bearings: the curves obtained would be similar to those in diags. 1 and 2. In this case at any rate, the step from the test machine to practice would be very small. This advantage, however, is offset by considerable disadvantages. Wearing takes place in the region of boundary friction and this causes phenomena which put difficulties in the way of reliable measurements being taken. The choice, therefore, lies between foregoing the taking of such measurements and only working in the region of combined fluid and boundary lubrication, or being forced to renew the bearing frequently, accepting all that this entails in the way of inconvenience apart from the fact that the reproducibility of the results may well be unfavourably affected through such renewals. It is important to cut out any effects due to viscosity, for it may well happen that changes in the lubricating action can be traced down to changes in viscosity. This danger is very great when working in the region of "mixed" lubrication a fact which is particularly well illustrated in diag. 2.

The region of boundary lubrication in which measurements are to be made, is more readily attainable with small apparatus than with full-scale machinery, and for this reason at the Testing Station we use to a large extent apparatus containing test equipment which is readily obtainable. The types of apparatus employed here, are illustrated in diag. 3. In one piece of apparatus a chain is passed round a slowly revolving steel cylinder and loaded at one end, the arc of contact subtending an angle of 180°. Both chain and cylinder dip into the oil under test which can be electrically heated. The cylinder tends to pull the chain in th direction in which it is itself revolving, and this pull increases in strength as the slipperiness between the chain and cylinder decreases i.e. as the friction in the lubricant between chain and cylinder increases. The frictional forces set up can be measured by means of a balance, and the coefficients of friction can then be calculated. The second instrument, the Almen-Wieland machine, employs as test pieces a shaft of 6.3 mm dia. with a split bearing. The whole arrangement is immersed in oil and is loaded step by step by the addition of weights. The shaft, on turning, attempts to move both halves of the bearing in the direction in which it turns, and the peripheral force set up is measured on a balance for each addition of a weight; the coefficient of friction can then be calculated from this in each case. New test pieces are used for each test.

The third arrangement arose from the need (in order to avoid greater discrepancy between results) for test pieces possessing the smoothest surfaces possible, while at the same time they had to be easily obtainable. Ordinary steel balls, as used inball bearings, are employed here, running in conical cages made of a different metal. The coefficient of friction can be calculated from the torque set up on the disc. A new disc and ball are used for each test, while the disc., having been used once, may be re-ground for further experiments.

Some of the results with these three pieces of apparatus are shown in the following illustrations. Diag. 4 shows the change in the coefficient of friction for refrigerator oil in relation to temperature according to trials carried out in the chain apparatus. Test material 19 yields results which are about 10-15% lower. A mixture of both oils, however, does not give a curve lying half way between the two, but one which lies still further down the scale. This effect o mixing has been observed quite often, as in the case of fatty acid where a similar result was obtained when it was added to other oils. This particular instrument appears to be especially suitable for tests on lubricants used in the manufacture of cutting oils. 3 synthetic lubricants and rape oil added singly to regrigerator oil in quantities of 5%, and tests in the chain apparatus yielded results shown in diag. 4. In actual practice these lubricants were arrenged in an order of merit corresponding to the order of the friction coefficients as measured in the test: viz. lubricatn C better than B, B better that A, and rape oil best of all. From this it appears that the friction coefficients, as measured here, provide a certain standard of comparison in the case of cutting oils. Diag. 5 shows further results obtained with the three instruments and from this it can be seen that the differences that occur can be quite considerable. The behaviour of the sulphur ester during trials in the chain apparatus is noteworthy, giving a minimum value at about 55°C. The decrease indicated by the left-hand part of the curve is probably due to an increase in chemical activity with a rise in temperature; while the subsequent rise may possibly be caused by the gradual formation of a layer of sulphide on the tombac (pinchbeck) chain. A clearly defined mixture effect can again be observed in the case of a mixture of E 515 and S-Ester. The majority of lubricants produce a curve where friction increaseswith a rise in temperature, a notable exception being made by rape oil where the coefficient fo friction falls with the rising temperature. It is questionable, however, whether the change in temperature really is the cause of this: it rather appears as though the duration of the test, i.e. the time factor, has great influence. This point will be dealt with later on.

For the sake of comparison, the results obtained with the Wieland machine have been grouped alongside those obtained with the chain apparatus. For these tests the original bearings were replaced, by brass bearings (Aeterna VL 22) carrying a silver steel shaft. The test is carried out at room temperature, although a gradual temperature rise due to friction in the bearing is unavoidable. The curves represent the change in the friction coefficient with increasing load, and the 6 oils are placed in an order closely approximating to that obtained with the chain apparatus between 20° and 40°C. However, the friction coefficients obtained from the Wieland machine are all of a lower order than those given by the chain apparatus. This is explained by the fact that the Wieland machine does not work in the region of boundary lubrication to the same extent as the other instrument. Thus a certain part is still played by viscosity, a statement which is borne out by the fact that in the region of smaller load, viscous castor oil appears to be preferable to rape oil. On the other hand, with increasing load the bearing comes more within the region of boundary lubrication, the effect due to viscosity decreases in importance and the better lubricating effect of rape oil becomes evident.

Interesting results are also obtained with the third arrangement where a bearing ball rotates on a disc, and where the coefficient of friction becomes dependent on the time interval. E 515, E 426 and castor oil show little change in the value of the coefficient during a test lasting 1 hour, whereas in the case of S-ester and oils containing S-ester additives a rapid increase takes place followed by a decrease. Corrosion may be partly responsible for this. Interesting too, is the test on rape oil in which the value of the coefficient of friction decreases right from the start. This is presumably due to the strong wearing action which results in satisfactory running-in. The similarity between the curves obtained in this test with those based on the chain apparatus is striking, so much so that it may be reasonably suggested that the time factor has some bearing also onthe chain apparatus.

From these tests it follows that no definite value of the coefficient of friction may be given for any one oil, as these values as measured in the various instruments, never correspond. The reason for this must be sought in the use of differently shaped test pieces and varying materials, temperature, rubbing speeds etc. At best the oils may be arranged in a certain order of merit, and one should be pleased if agreement is obtained in that respect.

It is important to look at the significance of friction coefficients, as measured in the three instruments, in the right perpective. Actually the fact that there is a reduction in the resistance of engine parts in rubbing contact, due to lowered friction coefficients when a state of limiting friction exists, can be of importance only in certain exceptional cases: as a rule, the reduction obtained in the amount of power required to overcome friction is negligible. Low coefficients under conditions of limiting friction do, however, have some meaning in as much as there is probably a certain connection between adhesion and friction in the neighbourhood of limiting friction. It may be expected that an oil having low coefficients of friction, such as castor oil and rape oil, will protect sliding metal surfaces even under unfavourable conditions. The evaluation of a lubricant, however, must not be made solely dependent on the measurement of the friction but measurements of the amount of wear produced, must also be taken into account.

Fundamentally speaking distinction must be made between two types of wear. In one case we are dealing with a slow but gradual abrasion of the material, resulting in smooth metallic surfaces. In the other, wearing takes place with seizure, resulting in deep grooves which will soon make useless the engine part in question. Below the first type of wear will be considered:

A wear-producing machine was developed at the Testing Station for these tests, working on the following principle (diag. 6). Two drums fixed on a shaft are set in rotation by means of a motor equipped with reduction gear, via a connecting rod giving reciprocating motion. The drums are lined with steel strips, hardened and polished which serve as rubbing surfaces. Cylindrical wearing pins made of various metals are pressed against the underside of the steel strips, the load beingapplied by lever action. Both rubbing surface and wearing pin are immersed in the oil to be tested, which is itself surrounded by an oil bath , kept at constant temperature by electrically heated coils of wire. The wear on the pin causes the latter to shorten, and the amount by which it shortens is measured by means of a micrometer gauge fixed to the lever arm. A speed of 81 rpm; resulting in 162 strokes per minute, causes an average rubbing speed of 22.3 cms/sec. Diag. 7 shows a set of results obtained in these tests, carried out on the 6 oils already known from the tests on the friction instruments. The wearing pin was made of soft iron in one case, and "Aeterna VL 22" in the other. Particularly interesting is the wearing process as observed on the iron pins (right hand diag.). The amount of wear obtained with rape oil was by far the greatest, being more than 2 mm during 20 hours. Castor oil gives almost equally high values for the amount of wear taking place, but only at temperatures exceeding 65°C. On the other hand, E 426 shows exactly contrary behaviour, giving a large amount of wear at low temperatures, and a small amount at high temperatures. It is also noteworthy that the behaviour of S-ester and E 515 is quite similar, whereas a mixture of the two yields entirely different results. The similar shape of the wear curves just mentioned (i.e. those of S-ester and E 515) is only apparent; this is particularly true in the region above 100°C. When dismantling the apparatus it appeared that in the test on S-ester, at 130°C, the pin was not shortened to the extent indicated on the gauge, but that the considerably harder steel strip, which had been 0.2 mm. thick, had been worn down to the thickness of paper. No doubt this was no longer a purely physical action but mainly a chemical process. It would appear that the hardened steel strip is more prone to corrode than the soft iron of the pin. In the case of E 51.5, on the other hand, as on all the other numerous occasions when the test was carried out, no appreciable abrasion took place on the steel strip, wear being measurable on the pin only.

The same oils were subsequently tested for their wearing qualities under exactly similar conditions but using pins made of "Aeterna VL 22". According to spectroscopic analysis, Aeterna VL 22 consists chiefly of copper (51%) and zinc (42%), containing also small quantities of manganese (2%), aluminium (2%), iron (0.7%), tin (0.6%), silicon (0.5%), lead (0.4%) and nickel (0.3%). The results obtained with it are shown in diag. 7 (left hand side.) This shows that there is no connection whatever with the wearing action produced by iron, illustrated in the other half of the diagram. S-ester, either alone or with other substances, produces considerable wearing particularly at high temperatures, a fact which may be traced to the high chemical affinity existing between sulphur and copper. The amount of abrasion measured while using rape oil is moderate in this case and this also applies to castor oil, at least below 120°C, so that in the case of these lubricants, too, a change of material leads to quite different results. These tests indicate, therefore, that in wear tests the material employed plays a very important part, and that results obtained with one kind of material must not be applied to another. It may furthermore be concluded that low coefficients of friction do not necessarily mean that the amount of wear will be slight, on the contrary, the exact opposite is often true, as in the case of rape oil.

Diag. 8 illustrates results obtained with the same working substances and under the same conditions as those which produced the results of the previous diagram. The four oils tested belong to the group of aero engine oils, as regards their viscosity. K7 is a mineral oil SS 902 F 25 is a synthetic aero engine oil with an ester as additive, LK 2200 is an experimental oil, soluble in water, and M 620 is another experimental oil, soluble neither in water nor in petrol. The diagram shows that the change-over from one working substance to another produces little change with K 7 and M 620, in direct contrast to the two remaining lubricants which show a reversal of wearing effect. Considerable changes in the assessment of the lubricants with regard to wear are not produced by the use of different working substances only, but changes in the test conditions, e.g. the roughness of the rubbing surfaces, are sufficient to produce the same effect. The same 4 oils were tested in conjunction with steel strips which had been sandblasted and consequently showed a certain amount of roughness. The results are illustrated in diag. 9 and those obtained with smooth strips are placed alongside for the sake of comparison. With smooth strips the duration of the test was 20 hours, with roughened strips it was 20 minutes. It is particularly noticeable here that with rough strips K 7 produced a very small amount of abrasion, while that produced by M 620 and SS 902 F 25 was large. The reason for this difference of results is not yet fully understood: but it is not to be found, as might be imagined, in the ageing of the oil which is naturally not the same in both cases as the test periods differ in length.

It can be seen from this short survey that the problem of wear under lubrication has not yet been solved and that the greatest caution must be exercised if a lubricant is to be considered in the light of wear measurement.

A further wear measuring apparatus has been constructed in order to take the investigation of the problem a step further. As shown in diag. 10, a rigid stationary cylinder is forced against a rotating hard metal disc, the latter being lubricated by an oil drop-feed. The disc is run in contact with the drum for a predetermined time interval, 1 0 minutes as a rule, and on removal it will leave a cut of definite length, the size being different for each oil. Speed of rotation of the disc. and the load on the cylinder can be adjusted as required. The cuts are measured with a measuring microscope the volume ground out being calculated from the length: some of the results obtained with the apparatus are shown in diag. 11. 14 oils were tested with a load of 20 kg., at 210 rpm. and a test of 10 minutes duration, using cylinders made of different materials. The lubricants were arranged in the order of the results obtained on the steel cylinder, rape oil which produced the greatest cut, occupying last place. If the same experiment is carried out with cast iron, considerable re-shuffling takes place: although rape oil still occupies the last place, S-ester now occupies the first. With a brass cylinder BH 4 produces the deepest cut, a result in sharp contrast with that obtained when using steel. Castor oil, too, produces greater wear, and so once again does rape oil LK 2200, producing the smallest cut, occupies the first place. The greatest differences between the individual oils are demonstrated when using light metal. LK 22 00 and M 620 allow very strong grinding to take place; S- ester and SS 902 F 25 are next in order. In the case of bearing metal (tin and lead alloy) the sulphur content seems to increase wear, the lowest values being these obtained with M 620 and LK 2200. This diagram, then, shows quite clearly how different can be the behaviour of lubricants when acting on the various metals. Exactly how far these test results may be exploited for practical application is a matter for further investigation. Conclusions can probably be drawn, however, from the size of the cuts, about the suitability for cutting oil. Accordingly rape oil would be very efficient as a cutting oil, which of course it actually is, when used on steel and cast iron. BH 4 would seem to be especially suitable for bronze and M 620 or LK 22 00 for light metal.

This grinding apparatus is interesting also for other reasons. During tests on numerous esters at the "Leuna" works it was noticed that a certain connection existed between the coefficient of friction measured on the chain apparatus, and the size of the cut in the steel drum Diag. 11 shows 35 synthetic esters, and also rape oil and bone oil each oil being depresented by a point. It is seen that all these points fall within a certain part of the graph, stretching in an extensive narrow area from the region denoting a high coefficient of friction and little wear, to that denotoing a low coefficient coupled with much wear. It is beyond doubt that there is a certain law connecting the two: and the phenomenon can possible be explained as follows: good adhesion secures the presence of a protective oil film which reduces friction and thus leads up to low coefficients of friction. This adhesion on part of the lubricant appears to be so great, here, that with a large shearing force acting on the oil film, metal is torn from metal rather than oil from metal.

At the same time this abrasion helps, perhaps, to smoothe the surface, causing rapid running-in of rubbing metal surfaces, and thus to further reduce the value of the coefficient of friction.

In the tests described so far, a phenomenon occurs every now and then which is worthy of mention. It was observed in the wear machine that with the use of Aeterna or brass pins on smooth steel strips, the material may pass from the pins to the rubbing surface, forming an extraordinarily adhesive coating on the steel. When ever that takes place the test turns into a case of two similar metals rubbing against one another, which results in exceedingly high wear. A similar action has been observed in the Wieland machine, where particularly when dealing with substances soluble in water the shaft is coated with a thin layer of bronze, high friction coefficients being measured in consequence. The cause of this occurrence is probably of an electrolytic nature incidentally, this action was not only observed on test apparatus but also in actual practice, e.g. on the journal of the Cardan shaft in motor cars.

So much for the investigation of wear produced by slow metal abrasion. It has already been mentioned that wear coupled with scuffing is the more dangerous. This takes place especially where either the same materials, or at any rate materials of similar hardness, are in rubbing contact, as in the case of gear wheels. Tests of this kind will therefore apply first of all to gear oils, i.e. extreme pressure lubricants.

At the Testing Station the Wieland machine mentioned above is employed for these tests, except that the bronze bearing is replaced by one of very mild case hardened steel, with a shaft of unhardened tool steel ("original" bearing). The actual test is carried out in the same manner as that performed to find the coefficient of friction. The load is stepped up by the addition of weights until seizure takes place, indicated by a sudden kick of the friction indicator, and frequently by a wrenching action on the shaft. This gives the load at which seizure of the bearing causes failure of the lubricant. The value thus obtained is not readily reproduceable as in this case any slight unevenness of the surface may either impede or assist wearing very strongly.

Another instrument used for similar testing purposes is the "Four Ball" machine: the Testing Station has two of these available, one of its own construction and one built by the Rhenania-Ossag Works. The former is illustrated in diag. 13. The four spheres are of ½ inch diameter and their centres are arranged to form a tetrahedron. The 3 bottom spheres are clamped inside a cup-shaped vessel which contains the oil. The top sphere is attached to the foot of a vertical shaft which is rotated by a belt drive from an electric motor. The vessel containing the spheres contains electrical heating elements so that the oil may be tested at different temperatures. The temperature is measured with a thermo-couple pushed between the three spheres through the bottom of the vessel. In order that the torque transmitted to the three bottom balls may be measured, the vessel containing them presses on a rod which transmits pressure to an indicator recording the force applied at any one moment. The instrument is shown in diag. 14.

There are two ways in which the test may be carried out. Either the load is kept constant and the time taken till seizure occurs, is measured: or the load is increased starting from zero, and that producing seizure is determined. The former method is the one most frequently adopted. While using a previously determined constant test load the motor is switched on and a stop watch measures the time that elapses until seizure starts, an event which is indicated by a sudden sharp kick on the recording drum. In this manner the time required for seizure to commence can be determined at different loads and also at different temperatures. Results based on this method are shown in diag. 15. The substances tested were a synthetic lubricant (TP 57) containing several different additives namely: thio-isobutanol (sulphur product T), carbon tetrachloride and fatty acid. The effect of the first two substances is quite considerable, the time taken for seizure to start being, in part, four or five times as long as that relating to the pure oil. On the other hand, the effect of fatty acid is small. Unfortunately the results obtained with the "Four Ball" and Alemn-Wieland machines, respectively, are in no way in agreement, a fact well shown in diag. 16. When tested in the Almen-Wieland machine, fatty acid produced no seizure of the bearing, while in the case of M 469, an organic chlorine compound, the load causing seizure was established as 1710 kgs/cm^2, for which reason the test had to be discontinued. Both materials behave quite differently in the "Four Ball" machine. Depending on the load applied, the time taken for seizure to commence varies from 0.8 to 2.5 seconds in the case of fatty acid, and is about 10 times as long in the case of M 469. It should, however, be mentioned that with M 469 seizure is much more severe leaving a large badly worn area at the points of contact of the balls. Interesting, too, are the results shown in diag. 17. In the Almen-Wieland machine the addition of 0.5% benzoic acid to "Gargoyle" engine oil results in an approximately 2½-fold increase in the load at which seizure occurs. The same additive has on the other hand no effect during tests in the "Four Ball" machine. The disagreement between the two sets of results may be accounted for by the different test conditions: the loads and speeds applying to the "Four Ball" machine, being roughly 10-20 times higher than those of the Almen-Wieland machine. Another important factor no doubt is that of the materials used: in one case the test is carried out with balls made of exceptionally hard steel, in the other with shafts and bearings made of unhardened steel.

The same arrangement of the "Four Ball" machine can be used as an apparatus for testing wear a method of testing which is adopted by the Rhenania-Ossag Works for the invetigation of gear oils. Their version of the apparatus is largely similar to that of the Testing Station, though there are minor differences of detail in the design. In the test method adopted by the Rhenania-Ossag, the machine is run for 1 minute while under a certain load, and the diameter of the worn area on each of the three bottom balls is then determined. This test was carried out at different loads so that wear/load curves relating to each oil are obtained. The loads employed in these tests cannot be made as high as desired because beyond a certain load the temperatures developed at the points of contact of the balls are so high that mutual welding action takes place. Diag. 18 shows the results obtained with 6 oils already known to you. It is seen that Seester, straight as well as mixed with another lubricant, is outstanding. Not only is the diameter of the worn part reduced but welding action takes place only with very high loads. It is interesting to note that in this test lubricants like rape oil and castor oil do not distinguish themselves in any way.

The "Heereswaffenamt" (Department responsible for Armament Requirements for the Army) has adopted ~~this test as a~~ standard specification test for gear oils, prior to delivery. This test is of 1 minute's duration and demands that welding action should occur only with loads exceeding 200 kg. So that of the oils mentioned in the diagram only S-ester and E 515 + 10% S-ester would come up to this standard. The demands made on the oil in this test are exceptionally high and it appears doubtful whether a test carried out in such a manner, can be correlated with practice. Furthermore there is no connection between the period preceding seizure, as measured in the apparatus of the Testing Station, and the results based on the method adopted by the Rhenania-Ossag Works. This is made clear in diag. 19. As expected, aero-engine oil SS 970 R, tested according to both methods, failed when subjected to high loads. The addition of 2% EHS delayed seizure to an extent sufficient to make the time before seizure twice as long; on the other hand it had no noticeable effect on the wear diameter. The welding point could be raised from 150 Kg. to 200 Kg. The results obtained with an Army Winter-grade gear-oil are stated for the sake of comparison. According to one method, the results are almost the same as those obtained with straight SS 970 R, while in the Rhenania-Ossag method this winter-grade oil occupies the first place. Early seizure, therefore, is not necessarily accompanied by a large amount of wear in all cases. It is therefore not only a question of seizure taking place after a certain time, but also of the manner in which it takes place and the traces it leaves behind.

In the above I have given you a brief survey of the apparatus at present employed at the Testing Station for the testing of Lubricants. The demands made on ~~the~~ lubricants by the various machines are widely different, and so, in consequence, are the effects observed and the results obtained. Testing an oil in one machine only may perhaps enable one to pronounce some judgment on the oil, but any such judgment will be valid within very narrow limits. When, on the other hand, the investigation is extended so as to involve tests with several machines, as is done here, a jigsaw puzzle results with many pieces yet missing. In other words it is not yet possible, at present at any rate, to supply exhaustive information about the lubricating powers of a substance. The field can only be partly covered and an attempt be made to combine the many results obtained both with one another, and with practical conditions.

Diagram No.	Description
1	Lubrication in a journal bearing with 3 oils of equal viscosity ordinate: coefficient of friction abscissa: no. of revs/min. Position of shaft at different speeds of rotation zero small large ∞ Oil A produces very good) Oil B medium) Lubrication Oil C bad)
2	Coefficients of Friction of oils possessing equal lubricating power but different viscosity. (schematic diagram based on trials in journal bearings). ordinate revs/min. abscissa coefficient of friction

Diagram No.	Description
3	Arrangements for Friction Tests. left to right: chain on drum shaft and bearing ball on disc.
4	Friction Tests in the Chain Machine. Load on chain 400 grammes Peripheral Speed of drum 0.16 cms/sec. Ordinate : coefficient of friction abscissa : Oil temperature in ^{o}C.
5	Coefficients of Friction of 6 Oils in 3 different machines Ordinate: coefficient of friction left to right abscissa: oil temperature ^{o}C load Kg/sq. cm. running time minutes
6	Wear apparatus (see report No. 574)
7	Wear in Relation to Temperature, for various materials ordinate: shortening of pin abscissa: oil temperature Duration of Test 20 hours Load 142 Kg/sq. cm. No. of strokes/min 162 left: bronze pin on polished steel right: iron pin on polished steel
8	As No. 7
9	Wear, with different degrees of surface roughness: using an iron pin on a steel surface. ordinate) as No. 7 & 8 abscissa) left: polished surface, duration of test 20 hours right: rough surface, duration 20 mins. remainder of data as Nos. 7 &8 (except for test materials employed).
10.	Grinding Apparatus (see report No. 574)

Diagram No	Description
11	Wear produced on various metals by different oils. Ordinate: quantity ground out top to bottom: hard metal on steel cast iron " bronze " light metal " bearing alloy "
12.	Coefficient of Friction - wear ordinate: coefficient of friction (from chain apparatus at 50°C) abscissa: vol. of steel ground out.
13/14	"Four Ball" Machine (as constructed at Research Station) "Kugelhalter": oil vessel and clamp for balls. "Heizung" : heating coils
15	Behaviour of Engine Oils with additives in the "Four Ball" machine.
16/17	Comparison between "Four Ball" and Almen-Wieland Machines. Ordinate: left: friction force right: delay in start of seizure in secs. Abscissa: left: load in Kg/sq. cm. right: load in Kg.
18	Results obtained in the "Four Ball" Machine with the Rhenania-Ossag method. Ordinate: wear Abscissa: load ○ end of trial due to welding action
19	Results obtained with two "Four Ball" machines according to different test methods. Ordinate: left: delay in start of seizure right: wear Abscissa: left and right: load.