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INVESTIGATION OF LUBRICANTS UNDER BOUNDARY FRICTION

By E. Heidebroek and E. Pietsch

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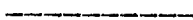Vol. 12, No. 2, March-April 1941

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I. INTRODUCTION

The numerous reports (references 1, 2, 3, 4, 5) of the Fuel Research Laboratory of the Dresden Engineering School, on the condition of oil films between lubricated surfaces of a variety of shapes have shown a consistently increasing need for the study of the conditions of what is termed the "boundary friction," which, considered on the basis of hydrodynamics, seems to occur much more frequently than the condition of "free floating friction" produced by a particular flow process. By "boundary friction," in this instance, is meant the real lubricating condition between nominally smooth surfaces in which the sliding or rolling surfaces attain a degree of contact for the contact surfaces to exert a strong influence on the entire lubricating film. This influence is principally an orientation effect on the molecules. This, along with the existence of irregularities on the surfaces that are large relative to the film thickness, makes the hydrodynamic laminar-flow dynamic-viscosity theory inapplicable.

Considering that surface roughness can seldom be reduced below 2 microns by engineering methods, the condition of boundary friction must occur with all rolling surfaces of poor finish and shape. Even with carefully constructed journal bearings this condition exists in the region where the lubricating film is thinnest.

Physico-chemical research has already furnished considerable data on the conditions in the boundary layers and the attendant polar orientation effects. At present, the problem of determining the magnitude of the adhesive forces of the oil molecules with simple apparatus is being studied; and the development of the concept of viscosity as being a measure of the internal friction in

relation to the molecular structure of the oil is under way. Incompletely understood thermodynamic processes are also involved, since every transfer of force between lubricated surfaces is accompanied by energy transformations (irreversible), which are of considerable strength compared with the small extent of the lubricating film, and whose exothermic nature, that is, release of heat, is far from being understood.

Numerous observations of such lubricating processes within range of boundary friction on journal bearings (reference 6) and gear tooth profiles (reference 7) have strengthened the supposition that it should be possible to study the attendant phenomena with engineering methods and equipment. These considerations formed the basis of the present studies, which have led to the discovery of relations governing the suitability of bearing surfaces and the concept of "lubricating quality."

II. PROBLEMS

The path of an element of area on one surface moving relative to another is made up of two principal types of motions; namely, tangential and normal, with respect to the other surface. A thin lubricating film of orientated molecules is then subject to either a shear stress or a tension or compressive stress, or a combination of both.

By using two plane "comparative plates" pressed strongly together in an oil bath, it must be possible to measure the tensile and shear stresses accompanying tangential and normal relative displacement of the plates and to determine any relations governing the effects of material, oil, surface condition, etc.

III. EXPERIMENTAL EQUIPMENT

The layout of figure 1 was made with very simple equipment. The base plate (a) was a heavy steel casting with carefully matched and polished surface, set in a frame (r). This plate served at the same time as bottom of a flat vessel containing the different test oils. The base plate itself was placed in an oil bath, the temperature of which was regulated by a heating resistance (w).

The top plates (b) were made of various materials having special surface treatment. The area varied from about 10 to 25 square centimeters, depending upon the purpose of the test.

The test oils comprised the lubricants listed in table 1. The plates (b) were fastened at several points and linked with the scale beam of a decimal balance. By suspension on a system of symmetrical levers a uniform distribution of the tensile force was obtained.

The shearing motion was produced by weights pulling on a string connected to the upper plate over a roller (g). The force producing the boundary film, was applied by a weighted lever, which was always removed before the actual measurements were made.

IV. MEASUREMENTS

The temperatures of the heating and test oil were taken with the two thermometers t_1 and t_2 (fig. 1).

Compressive, tensile, and shear forces were determined by weighing the applied weight and multiplying by the lever ratio. The friction in the ball bearing guide pulley (g) was disregarded. Time elapsed was measured with a stop watch.

V. RESULTS OF TESTS

1. General observations.- While the weight-loaded top plate was pressed against the bottom plate, covered initially by 2 to 3 millimeters of oil, the top plate was moved back and forth over a few millimeters by hand. It was found that the sliding friction was quite small, at first, despite a loading which is equal to a compressive stress of 12.5 kg $\approx$ 0.5 kg/cm². After some time the motion increased rapidly and the plate suddenly stuck. After that, it required comparatively great force to slide it even after removal of the compressive load.

The almost instantaneous change from light tangential motion to "sticking" makes it seem probable that this peculiar "contact condition" represents a special case of boundary friction which, by reason of a time-associated

molecular orientation process of the oil, requires a measureable length of time before becoming effective.

Unless otherwise specified, the measurements of the tensile and the shear stresses were always taken under contact conditions.

2. Tensile test and tensile law $\sigma_z t_z = \eta_z =$ constant.- The original plan was to determine the adhesive forces between the plates by loading the tensile test device with additional weights until the contact members separated. In doing this it was found that the tensile forces P_z were a function of the time in which the separation was allowed to take place. So the test method was modified to the extent that a specified tensile force P_z was set and the time interval t_z required to separate the top plate, (that is, of the oil film) was determined.

Figure 2 shows the result of such a test series for a square bronze plate (50 X 50 mm²) and lubricant A (reference temperature 22° C). The forces per unit area (1/m²) are plotted against the separation time interval t_z.

The hyperbolic similarity of the ensuing curve indicated that a corresponding law must hold. This was proved by hundreds of experiments. The law of separation is then

$$\sigma_z \ t_z = \eta_z = \text{constant} \left[\frac{kg \cdot s}{m^2} \right] \qquad (1)$$

The separation tests represented in figure 2 always give an equilateral hyperbole under constant test conditions.

The constant obtained η_z has the dimensions of dynamic viscosity (kg s/m²) and is termed "separation viscosity" since it is directly related to the viscosity as normally measured with a viscosimeter as will be shown later on.

3. Shearing test and shearing law $\tau_s \ t_s = \eta_s =$ constant. The attempt to free the plate without loading in tangential direction from the contact condition disclosed the existence of a similar hyperbolic law, since the tension weight P_s exerts, contrary to Newton's law $\tau = \eta \ dv/dy$ a suddenly incipient sliding motion only after a well-defined time interval t_s.

Figure 3 shows the results of the shearing test on a round steel plate (55 mm diameter) and oil C at t = 20° C. The shearing stress $\tau_s(kg/m^2)$ was plotted against the loosening interval $t_s(s)$, which again afforded the hyperbolical curve. In more than 100 duplications of this test under contact conditions and constant temperature, the equation

$$\tau_s \, t_s = \eta_s = \text{constant} \left[\frac{kg \cdot s}{m^2} \right] \tag{2}$$

(shear law) applies.

Here also the equivalence with the dynamic viscosity could be proved; hence this constant is properly termed "shear viscosity η_s."

4. Compression test and compression law $\sigma_d \, t_d = \eta_d = $ constant.- These tests were intended to show how the contact-producing time varied with the contact load P_d. Tests with a steel plate 55 millimeters in diameter gave a similar law of the form

$$\sigma_d \, t_d = \eta_d = \text{constant} \left[\frac{kg \cdot s}{m^2} \right] \tag{3}$$

The constant η_d is called the "contact-producing viscosity."

5. Extension of separation and contact-producing tests.- The tests were made to investigate the case in which the compression load is removed and the separation tensile load is applied before the contact condition is reached. Quantities discussed relative to tests under these conditions are primed. Comparative tests, at constant temperature with several compressive loads and load application time, show a relationship between separation viscosity η'_z and compression viscosity η'_d.

For each compressive load P'_d a curve of t'_z the separation time, is plotted against t'_d, the compressive load application time (fig. 4). The compressive loads varied from 2.85 to 24.1 kilograms. All the curves terminate in the "contact line," proving once again that the contact condition is attainable with any compressive load. (The index ' signifies that the measurements did not result from the final contact condition.)

But once the contact condition is reached the loading
weight and the loading period producing it have no effect
on the subsequent separation and shearing tests.

The data of figure 4 is replotted in figure 5, showing
the relationship between the compressive load application
time t'_d and the compressive load P'_d which give a
constant separation time t'_z when a 2 kilogram separation
force is used. The separation time t'_z is the parameter
of the family of curves in figure 5. Since the separation
force was kept constant $P'_z = 2$ kg, the separation viscos-
ities η'_z are directly proportional to the separation
times $t'_z (\eta'_z = t'_z P'_z/F = \text{const.})$. Corresponding to
each η'_z value is an oil film thickness that exists when
the separation load is applied. Since for each η'_z there
is one t'_z then t'_z corresponds to the same oil film
thickness. The plots are therefore P'_d versus t'_d for
constant oil film thickness. From the shape of the curves
the hyperbolic law is seen to apply and, therefore,
$\sigma'_d t'_d = \eta'_d$ = function of oil film thickness at constant
temperature. Similarly, it appears reasonable to write
$\sigma'_z t'_z = \eta'_z$ = function of film thickness at constant tem-
perature. So, if a relationship can be established between
the average oil film thickness and η'_z or η'_d this ap-
paratus can be used to compare oil film thicknesses in
cases where the roughness protuberances on one surface are
close to those of the other.

Figure 7 shows the η'_z values against the η'_d
values for this test series. It was found that the com-
pression viscosities η'_d are always greater than the sep-
aration viscosities η'_z. In other words, since η'_d is
greater than η'_z a greater force is necessary to produce
a given oil film thickness in a given time than to separate
the surfaces in the same length of time starting with the
same film thickness. This indicates that the process of
compression is not strictly the reverse of separation.

It should be noted that in the tests corresponding
to figure 4, etc., the difference in plate spacings was
no more than a few microns as determined by means of a
lever gauge ($1 \mu = 1$ mm deflection).

For film thicknesses greater than those corresponding
to the contact condition there is no time lag between the
application of a shearing stress and the resulting slipping.
There sliding velocity is probably not the one predicted by

the ordinary viscosity law $\tau_s = \eta \, dv/dy$ where η is the dynamic viscosity v is the slip velocity, and y is the film thickness. Therefore, in contradistinction to the compression and separation law the shear law holds for contact condition only.

   6. Validity of laws set down by equations (1) to (3).- The separation law (equation 1) holds, as has been proven, within very wide limits. Tests with tensile forces P_z of the order of magnitude of only a few grams took several days for the separation to occur. On the other hand, the same film thickness supported as much as 50 kilograms for a short period of time.

   The compression law is also universally applicable as long as the compressive forces are in the position to overcome the buoyancy of the oil. Two plates - one on top of the other - left in the oil bath, reached the contact condition by themselves after days or weeks; while very great compressive forces were required to obtain the contact condition in a short time.

   The validity of the shear law could be proved only for applied forces greater than some minimum value of P_s. But it is assumed that the contact condition can be broken by shearing forces less than this minimum P_s in accordance with equation (2), in which case the applied force will be too small to show a perceptible slip. This could be shown by allowing the small shearing load to be applied for a length of time given by equation (2) and then increasing the load above the minimum P_s. Slip started immediately, showing that the first small load had broken the contact condition.

   7. Contact condition and cohesive forces.- That the contact condition is marked by exceptionally great cohesive forces between the contact plates was proved by the following experiment: After pressing the contact plates together the shear test in which outside forces act only in tangential direction was initiated. The travel of the movable plate was restricted to 2 to 3 millimeters by a stop, a distance too small to permit an oil-wedging effect to move the plates farther apart. Just as soon as the contact condition was broken by the shearing load, a tensile load was applied and the separation viscosity η_z determined. In every instance, a drop of about 35 percent of the η_z values compared to the η_z taken from the contact condition was obtained.

This seems to indicate that the oil film molecular
orientation characterizing the contact condition and hence
the nature of the contact itself is changed by the shear-
ing motion. The particular kind of orientation responsi-
ble for this contact condition remains a problem for re-
search in molecular physics. Theoretically it has been
established by Hardy (reference 8) that such orientation
lasts a certain time (up to one hour).

8. Scatter of test points.- Because of the crude lab-
oratory apparatus in use it had been originally intended
to design a special precision instrument after the prelim-
inary tests, to assure a greater degree of accuracy. But
the small amount of scatter of the test points in the
first tests prompted the continuation with the present
equipment.

The scatter of the test data is attributable to minor
temperature fluctuations, vibrations, and slight dust im-
purities in the oil film. In addition, the relative posi-
tion of the surface protuberances (roughness) on the con-
tact plates was not always the same for different tests.
This resulted in a different oil film thickness distribution.

VI. SEPARATE INVESTIGATIONS

1. Effect of surface condition.- From the foregoing
it is readily apparent that the condition of the contact
surface has an effect on the separation tests. The size
of the surface protuberances will depend upon the degree
of finish given to the surfaces. The average oil film
thickness between plates in contact will be greater for
rough surfaces than for the smooth ones.

Assuming, accordingly, that each average film thick-
ness defines a certain η'_z or η'_d value, it follows
separation and compression viscosities are greater for
smooth surfaces in contact than for rough ones. A simple
experiment proved this assumption in every respect. The
separation viscosity of a steel plate under constant oper-
ating conditions was obtained, taken as an average value
from ten separate tests, starting with finely eneried
surfaces. In succession the surfaces were treated with
coarse emery paper, filed with a smooth file and lastly
with a rough file, and an average separation viscosity de-
termined for each case. The results (average values)

which show the effect of the surface finish plainly, are
compiled in figure 8.

A series of tests with silicon and steel plates of
different degrees of roughness as measured by the Schmaltz
light-intersection method (reference 8) developed by the
Zeiss company revealed that an average roughness of 2μ
produced a measurable difference in separation viscosities
η_z (fig. 9), and certain relations governing the surface
effect between roughness and separation viscosity are ob-
servable notwithstanding the scattering of the test points.

With the dependence of η_z on surface roughness known
for a reference oil the separation viscosity determination
gives a method for estimating the surface roughness of any
pair of plates of material similar to those for which a
calibration has been made.

2. The effect of matching surfaces and lubricant.-
The important question of surface material in lubricant
matching, sliding, and rolling processes is fundamental
in the problem of lubrication. Although the importance
of this point has been known for some time, our present
state of knowledge is largely empirical.

Proceeding from the conception that the effect of the
oil in the lubricating boundary is not a specific property
of the oil but is due rather to the interaction between
the bearing surfaces and the lubricant, the effect of vary-
ing the bearing surfaces with a given oil should be notice-
able in the separation viscosity measurements. With this
in mind, a large number of tests with a variety of contact
plates was made, the results of which are reproduced in
figure 10. A great deal of difficulty was experienced in
preparing these surfaces to the same degree of roughness
so that this factor would not influence the results. So,
after machining the surfaces they were polished for some
time by hand with a finest emery paper, although it should
not be assumed that this treatment results in identical
surface for all materials.

Because of the susceptibility of such comparatively
coarse experiments to surface roughness and oil film
temperature fluctuations which is appreciable in the
room temperature range (figs. 15 to 18), this effect was
removed by tests similar to those plotted in figure 9
(test temperature 45° C).

The effect of the contact-surface material is evident.
The experiments should be continued in order to establish
a correlation between the practical behavior of a material
in service and its separation viscosity. This would af-
ford a simple test method for suitable lubricant-surface
matching which would be of the greatest importance in
practice.

3. Effect of size of upper contact surface.- A com-
parison of the separation viscosities measured for iden-
tical plates of different surface area indicates that the
separation viscosity per unit contact area is independent
of the surface area as long as any one edge length (or
diameter for round plates) does not assume too low a value.

Figure 11 shows, by way of illustration, the separa-
tion viscosity per unit area η_z plotted against the unit
separation force $\sigma_z = P_z/F$ for identical square plates of
50, 40, 30, and 20 millimeters edge length. Whereas the
η_z data for the 50 and 40 millimeters lengths are practi-
cally identical and show little difference, even for the 30 ×
30 square millimeters plate, the η_z value for the 20 milli-
meters plate is considerably below them. The explanation
for this is that the apparatus is not sensitive enough
when small forces are involved, and also that then some
plate-edge effect exists which becomes appreciable when
the ratio of plate perimeter to plate area exceeds a
certain value. This edge effect is probably a zone of
lower cohesive forces.

If, as indicated in figure 11a, this zone of lower
cohesive forces is b_1 (mm) wide, and the plate edge length
is a (mm), then the area of this zone is $F_1 = 4(ab_1 - b_1^2)$.
The remaining plate area is $(a^2 - 4(ab - b_1^2)$. The ratio of
better cohesive force area to area of lower cohesive forces
is

$$\frac{a^2}{4(ab_1 - b_1^2)} - 1$$

from which it becomes apparent that (at constant width b_1)
the effect of the edge zone increases continuously with
decreasing contact area (a^2).

For this reason the separation law $\sigma_z t_z = $ constant
was confirmed for contact plates of various sizes, except
that the constant factor η_z for very small plates is
different from those measured for large plates.

large

The fact that for sufficiently large contact plates the separation viscosities η_z or η_s have constant values independent of the plate area precludes the hydrodynamic interpretation of the separation process as a "flow phenomenon;" although it does apply to cases where the separation between plates is very large. The integration of

$$P = \frac{3\pi}{2} \frac{\eta}{h^3} V R^4 \quad \text{(Gümbel-Everling law)}$$

with respect to time, gives for the contact compression time

$$t = \frac{3/4 \, R^2 \, \eta}{\sigma \, h^2}$$

but as it retains the factor of plate size, its application cannot be extended to cases where the contact conditions occur.

4. Effect of temperature and type of lubricant.-
(Relation to dynamic viscosity η) With an apparatus similar to figure 1 using a steel contact plate, a number of oils were tested in separation and shear at various temperatures. The measurements were not begun until temperature equilibrium was considered established between the upper and lower plate and the oil; so that it could be safely assumed that the dynamic viscosity of the oil in the lubricating film between the plates was the one corresponding to the temperature measured and plotted in figures 12 to 18.

When plotted against temperature the η_z and η_s curves show the same characteristics as does the dynamic viscosity. The results merely differ from η by a constant factor $\psi = \eta_z/\eta$ or $\psi_s = \eta_s/\eta$ so that the test points of both series could be immediately applied at the same scale to the viscosity curves of figures 12 to 18. The order of magnitude of η_z or η_s differs, apart from a numerical factor, from η by the dimension 10^6.

The separation and shearing viscosities are proportional to the dynamic viscosity and in this respect the apparatus used is a new viscosimeter.

The dimensionless temperature correlation factors, ψ_z and ψ_s (separation and shear factors) are constant

for each oil but vary from oil to oil. They may serve as characteristic numbers by which a contact system (top plate - boundary layer - bottom plate) can be rated.

That the separation and shearing viscosities depend on factors other than the dynamic viscosity can be readily proved by measuring η_z and η_s for two different oils at temperatures that make their respective dynamic viscosities equal. It was found that η_z and η_s differ markedly according to the type of oil in spite of the equal viscosities. The data by Büche (reference 9) concerning the different action of oil samples of similar viscosity are readily confirmed.

5. Correlation of separation and shearing viscosities.-
The test data of figures 12 to 18 can be combined into one relation

$$v = \frac{\psi_z}{\psi_s}$$

For reasons of comparison, factor v was equated to

$$v = 2 \, \frac{m_0 + 1}{m_0}$$

whence

$$m_0 = \frac{2}{\dfrac{\psi_z}{\psi_s} - 2}$$

with v and m_0 assuming the values as follows:

Oil	A	B	C	D	E	F	F$_1$	Mean value
v	15.	16.3	15.4	16	15.4	15.9	16.25	15.75
m_0	0.154	0.140	0.149	0.143	0.149	0.144	0.140	0.146

Since ψ_z and ψ_s are characteristics for tensile and shear stresses of the oil, a comparison with corresponding factors of solid bodies can be made.

A similar formula for solid isotropic bodies is

$$\frac{E}{G} = 2 \, \frac{m + 1}{m}$$

where E is Young's modulus and G the shear modulas.

The dimensionless quantity m (Poisson's ratio) ranges between 3 and 4 and amounts to about 10/3 for metals, according to Bach (reference 10).

Hence the following inferences:

Roughly approximated, the m_o values are comparable with Poisson's ratio m . The ratio between tensile strength and shear strength of viscous oils under contact conditions is several times greater than that for solid bodies. In the latter the orientation of the crystals is fixed; in liquids it is flexible and under contact conditions assumes a form which is similar to the state of "fixed structure" as applied to materials of highly plastic molecular properties.

The extent of the validity of this relation to other viscous fluids (Newtonian fluids) or colloidal mixtures, etc., remains to be demonstrated.

For the oils in question, the v and m_o values are fairly close together; subsequently tested oils showed greater differences.

Various researchers, such as Debye and Kyropoulos (references 11, 12) ascribe quasi-crystalline properties to the viscous films on the basis of dielectric investigations. The relations obtained in this work on the strength of thin oil films in surface contact argue in favor of such a concept and permit, in a certain sense, the application of conventional strength considerations of solid substances to the strength of oil films under contact conditions.

6. Behavior of grease in separation and shear tests.- Experiments with greases of high consistency indicate that for very long applications of a compressive load or for great forces P_d a contact state similar to that of oil is reached which can be broken by the application of any shearing or separation load, however small. But the unusual amount of scatter of the test data with the present set-up has afforded no definite information. It also may be attributable to the response of grease to mechanical stresses, as is claimed by Schröter (reference 13).

VII. IMPORTANCE OF THE FOREGOING RESULTS IN

LUBRICATING AND WEAR PROCESSES

Attempts to define the viscosity of fluids or gases by the separation of two previously close surfaces go back several years. Michell in his patent No. 364,236 of 1920 describes a device in which a ball is pressed flat against the bottom of a pan filled with the test liquid and the time of its separation from the pan into a free ball is recorded. Similar methods are described in the English patent No. 262,539 and in U. S. patent No. 2,070,862. The latter includes the use of flat plates. Stefan's experiments (reference 17) on "apparent adhesion" may also be mentioned in this connection. But every one of these methods works in the purely hydrodynamic range, that is, they fail to continue the application of the compressive forces for a sufficient time to produce the contact condition. They were ignorant of the relations governing the compressive period, the compression force and separation viscosity, and the difference between separation and shearing viscosities described in this paper. (At the release of a ball from a corresponding counter surface, normal and tangential motions occur at the different parts of the surface.) As a result only the "hydrodynamic viscosity" was measured.

That properties other than hydrodynamic viscosity are involved in the dimensionless factors ψ_z and ψ_s as obtained from separation and other tests made under contact conditions becomes evident from a comparison of the ψ_z and η values in figure 19, where all values are referred to oil A as a unit. Admittedly, the highly viscous oils usually have higher separation viscosities, but the ratios of the ψ_z's for different oils bears no relationship to the corresponding dynamic viscosity ratios. Bringing the comparative oils to the same viscosity η by appropriate temperature control still gives different ψ values. These values represent a typical constant for the oils, and are important in those cases where the oil film is subject to tension, compression, and shear stresses in which the occurrence of the contact condition is likely. This happens, for instance, in many rolling motions where the rolling surface elements come to rest under contact conditions, as well as in reciprocating sliding motions (piston at dead center, etc.).

On gear teeth such a process occurs in the pitch circle. The compression period at the time the gear teeth point of contact is on the pitch circle, where a pure rocking motion exists, is very short, but the compression load is very high. At separation the stress can become very high according to the law $\sigma t = constant$ and minute metal particles can be torn from their bond by the oil molecule.

This process was qualitatively demonstrated by the following experiment (fig. 20):

A guided steel plunger (s) is pressed by a strong spring (f) against an eccentric (e) connected to shaft (w) of a small electric motor. The plunger serves as upper contact surface and makes about 2000 strokes per minute the same as the motor. A base plate (g), vertically adjustable, was so arranged that at bottom dead center of the movable contact surface a very minute light slit between the plates remained. (The available apparatus made an exact measurement of the slit impossible.) A thin oil film was deposited on the bottom plate and the plunger was set in motion. The least "metallic" contacts were instantly recognized by loud knocking noises as confirmed after the tests. Because of the smooth running of the apparatus during the endurance test, bouncing on the bottom plate was not considered to have occurred. Photoscopic examination revealed the formation of an oil cone due to the fact that the oil clung to the rapidly moving plunger up to top center where the oil filament very often broke, but during collapse was intercepted by next plunger stroke before it had completely flattened out again (figs. 21-24).

Even though the oil strain in the lubricating film did not altogether correspond to the conditions of the contact separation tests, the endurance run was made and checked after every three hours of operation. Wear phenomena were observed after about 20 hours, equivalent to about 2.4×10^6 separation processes. The erosion showed in the form of a small crater on the spherical plunger surface (fig. 25) and on the flat base plate (fig. 26). Small, conspicuous erosion spots scattered outside of the principal zone, are indicative of a gradual enlarging of the crater zone with operating period. The test was run again but this time with a flat plunger tip (2 mm diam.). In this case cavities started after 14 hours (corresponding to 1.7×10^6 strokes). Craters formed appeared the same as those shown in figures 25 and 26.

Finally, a check run was made in which the plunger was bounced on the base plate producing a metallic knock. In a few seconds a sharply defined impact area was visible of about the same size as the previous erosion zone, but in contrast to it there was marked oxidation.

The alternating tension-compression stresses on surfaces is very much like the usual phenomena accompanying cavitation, and it is quite likely that, by exceeding the vapor pressure of the oil, the formation and decay of steam bubbles assist in the oxidation process. Such micro-pitting is of a different nature than Föppl's coarse breaks (macro-pitting), resulting from Hertzian tensions. The former appear where the latter do not, and are undoubtedly caused by the oil film (references 14, 15).

If the journal in a journal bearing remains inoperative for some time rotating the shaft from rest requires considerable force, as is observed on the large bearing testing machine of the laboratory. Following the destruction of the contact state the resistance drops immediately. The erosion of ball bearings - "false-brinelling" so-called in Sweden - on truck engines as a result of jerks during transport on railroad cars belongs to this class of phenomena and so does the sensitivity of many thrust bearings to alterate impacts.

Experiments intended to correlate the previously developed characteristics ψ of different oils with their behavior in practical operation were next carried out on gear wheels by means of the testing machine described by Dietrich (reference 7), and as reported elsewhere (reference 16). By giving a gear wheel a fixed amount of lubricant the life of the individual oils can be determined. For a large number of oils the life periods ξ appear proportional to $\sqrt[3]{\psi_z}$ as a first approximation. In addition it disclosed the notable fact that in the region of narrowest boundary film involved here, the oils of greatest viscosity manifest the lowest frictional forces and vice versa. Important elastic properties are also observable. In tests on journal bearings under boundary layer friction conditions (reference 6) the effect of matching shaft-oil-bearing bushing is very well shown in the varied load capacity of the bushing. Other tests show noteworthy properties of oils of certain structure to the effect that high friction values are associated with low temperature rises and vice versa.

The experiments are continued on a wide scale with a large number of oils of systematic molecular structure, with particular reference to the typical loading conditions met in practice. The hydrodynamic viscosity and the previously defined characteristics ultimately go back to the same root, the molecular structure of the oil. Investigations of the mechanical properties of materials in the state of "fixed structure," the condition of contact, constitute a valuable complement to parallel chemical-physical research.

SUMMARY

In the very narrow boundary layers between lubricated surfaces a peculiar state of structure of the oil films arise which gives them a quasi-crystalline property. In this state tensile strength, compressive strength, shear strength, and working capacity can be determined and correlations established in terms of engineering quantities, which are important in discussing the lubricating capacity of the tested lubricant.

Translation by J. Vanier,
National Advisory Committee
for Aeronautics.

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TABLE I. SPECIMEN LUBRICANTS

No.	Iden-tifi-cation	Brand	Manufacturer's data label	Condition of lubricant at room temperature (22° C)
1	Oil A	Rhenania Ossag B C 8	Oil for speeds over 1500 rpm	Clear, bright yellow, low viscosity.
2	Oil B	I.G.Farbenind. oil I	Pure hydrocarbon oil, blended (ethyl ester)	Clear, dark brown, low viscosity.
3	Oil C	I.G.Farbenind. oil II	Pure hydrocarbon oil, blended (ethyl ester)	Clear, reddish brown, low viscosity.
4	Oil D	I.G.Farbenind. oil III	Pure hydrocarbon oil, blended (sulph. com.)	Turbid, yellow brown oil with slightly higher viscosity - deposits gray, opaque liquid for some time.
5.	Oil E	I.G.Farbenind. oil IV	Pure hydrocarbon oil	Clear, honey yellow oil of medium viscosity.
6	Oil F	I.G.Farbenind. oil V	Pure hydrocarbon oil	Clear, yellow brown oil with very high viscosity and gluey behavior (great adhesive effect). Oil can be pulled in long threads.
7	Oil F_1	I.G.Farbenind. oil VI		Oil of similar appearance and behavior as F but with even higher viscosity.

a, Base plate
b, Top plate
c, Heating oil
d, Oil sample
g, Pulley
r, Frame
t_1, t_2, Thermometers
e, e', Position of compression loading lever during compression and during separation and shear tests

f, Connecting rods for applying separation load
P_z, Separation force
P_s, Shear force
P_d, Compression force
w, Electric resistance (heating)

Separation test

Shear test

P_z

P_d

P_s

= 220 V
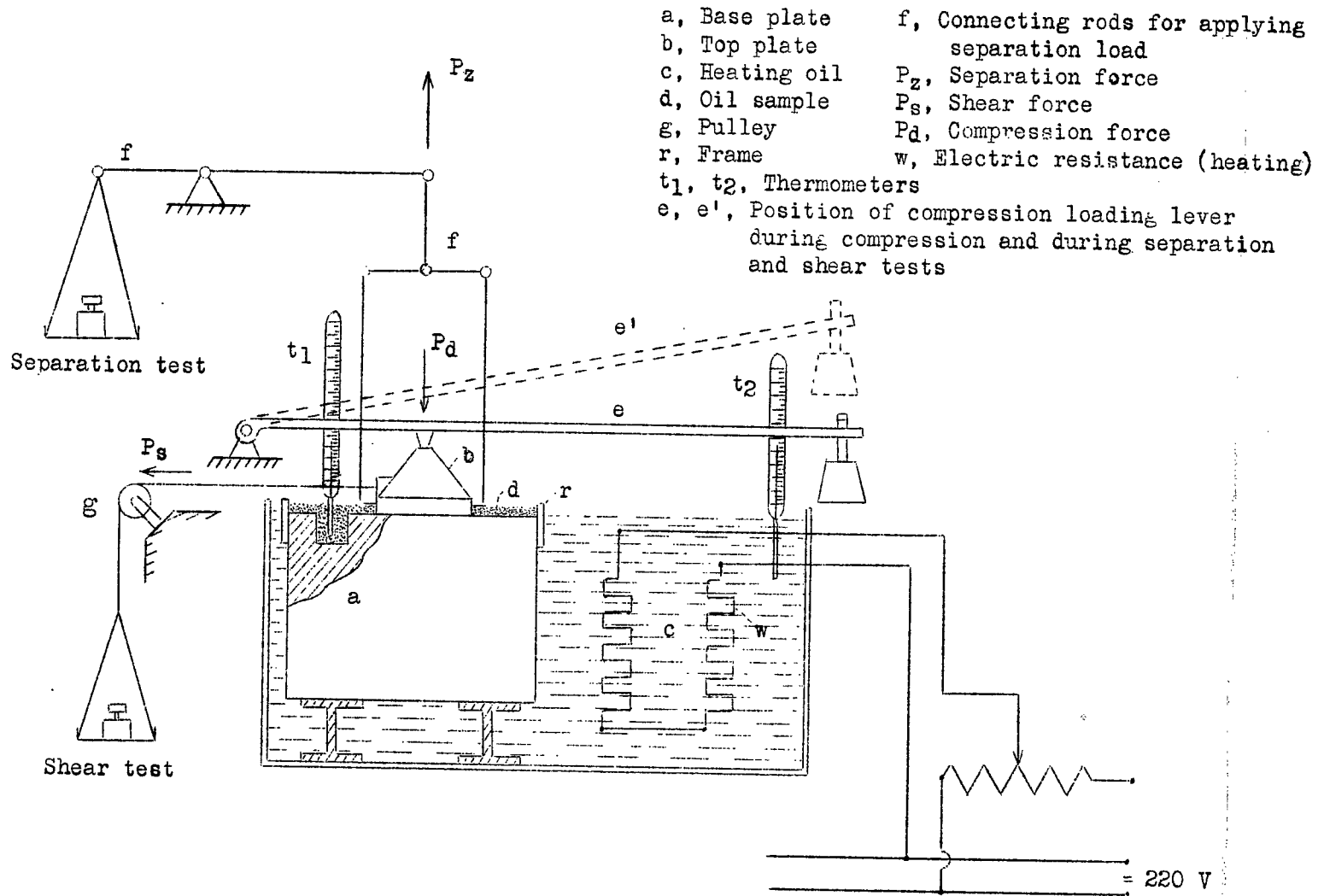
Figure 1.- Diagrammatic sketch of experimental apparatus.

Fig. 1
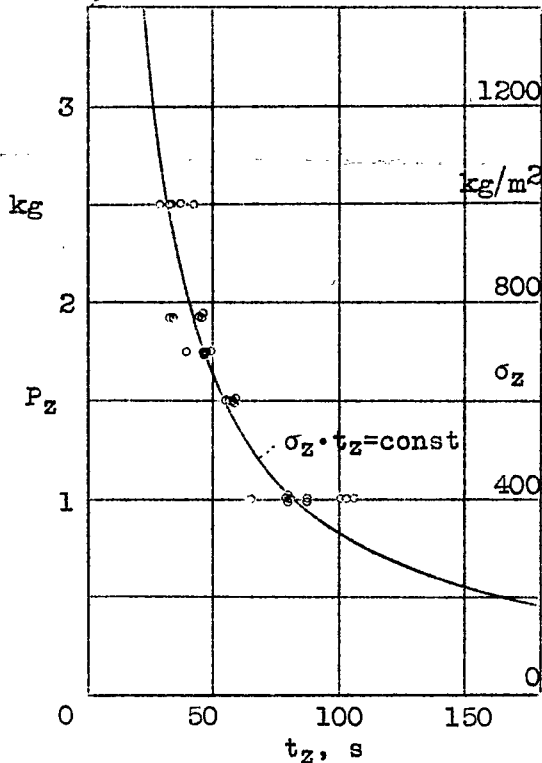
Figure 2.- Separation law $\sigma_z \cdot t_z = \eta_z =$ constant. Bronze surface against cast iron surface, oil A at 22°C (see table I)

Figure 3(upper right).- Shear law $\tau_s \cdot t_s = \eta_s =$ constant. Steel surface against cast iron surface, oil C at 20°C (see table I).
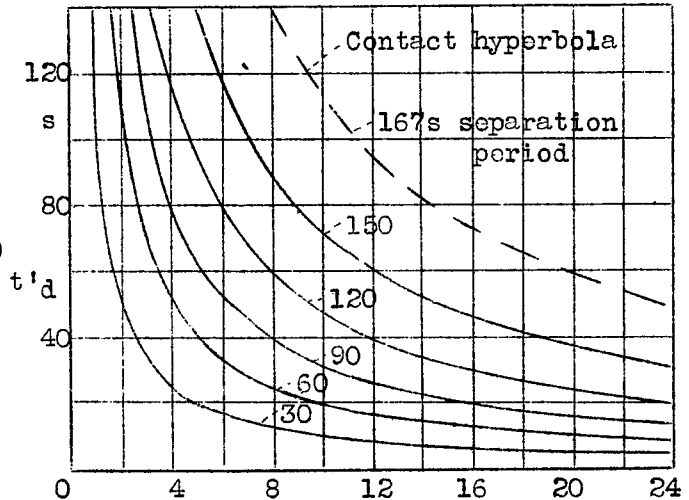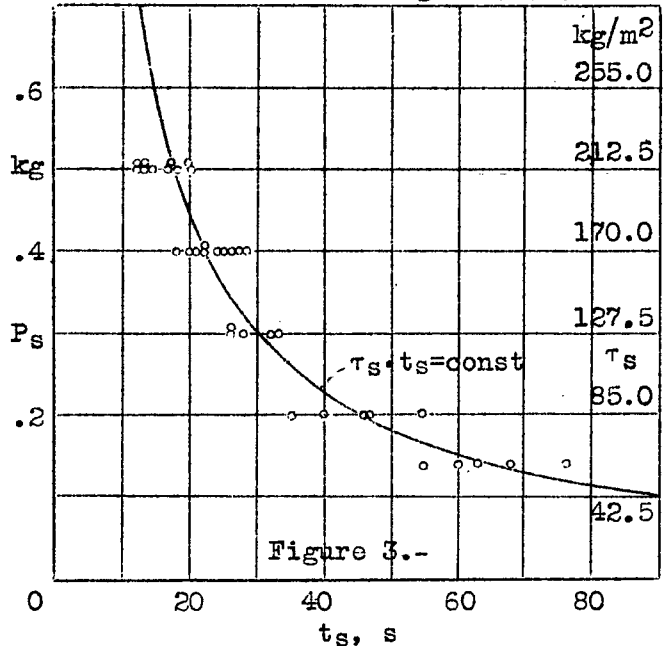
Figure 5.- Compression periods t'_d plotted against compression load P'_d for various separation periods at constant separation load of 2kg.
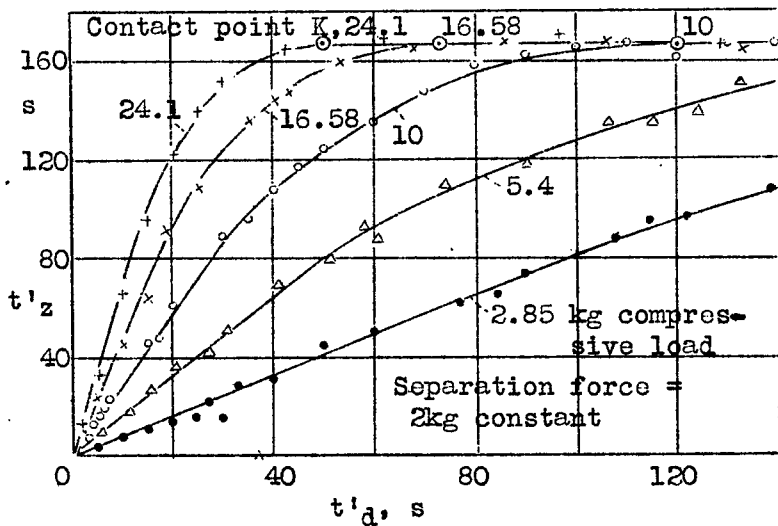
Figure 4.- Development of contact points from separation times (t'_z) and compression times (t'_d), oil B, at 21°C (see table I).
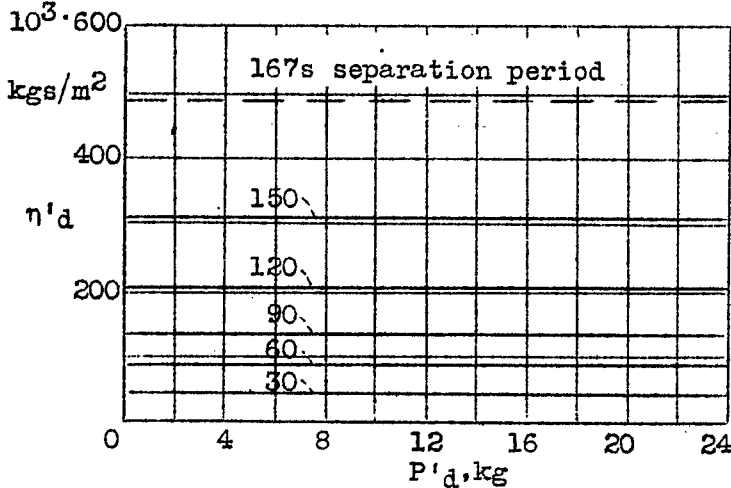
Figure 6.- Compression viscosity η'_d plotted against compression load P'_d for various separation periods at constant separation load of 2kg.

Figure 7.- Separation viscosity η'_z against compression viscosity η'_d.
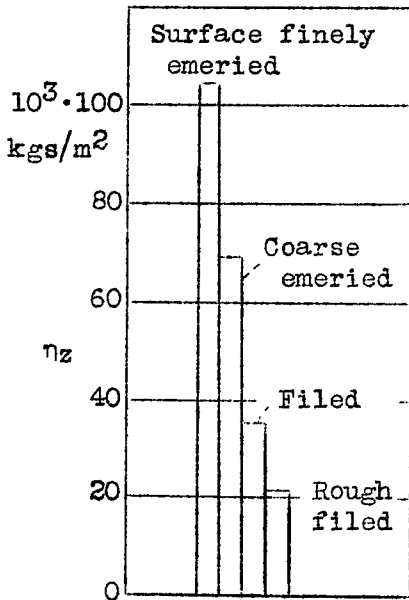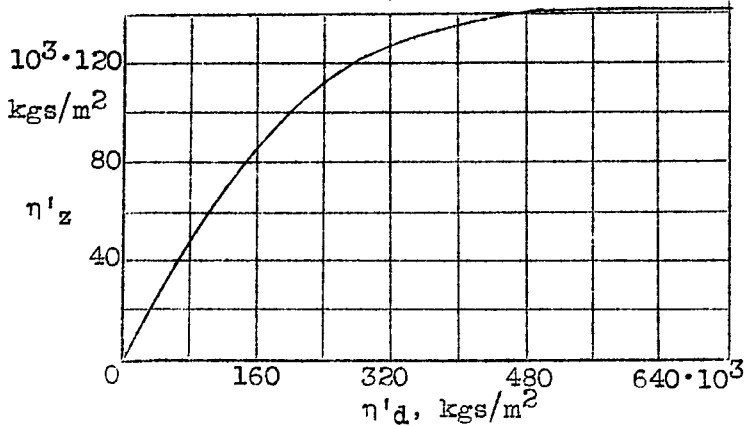
Figure 8.- Effect of surface roughness on separation capacity.

Figure 9.- Effect of matched surface material and average surface roughness (the numerals I to IV indicate roughness of plates paired). Paired: steel or silicon plates against cast iron plate.

$10^3 \cdot 140$

kgs/m^2

120

100

η_z

60

40

20

0

1,Babbit metal at 22° C
2,Bronze   " 24° C
3,Lautal   " 22° C
4,Plastic 1   " 22° C
5,Plastic 3   " 25° C
6,Plastic 4   " 21° C
7,Plastic 6   " 24° C
8,Plastic 8   " 22.5° C

3

6
1

2
7 4
8

5

400   800   1200   1600

σ_z, kg/m^2
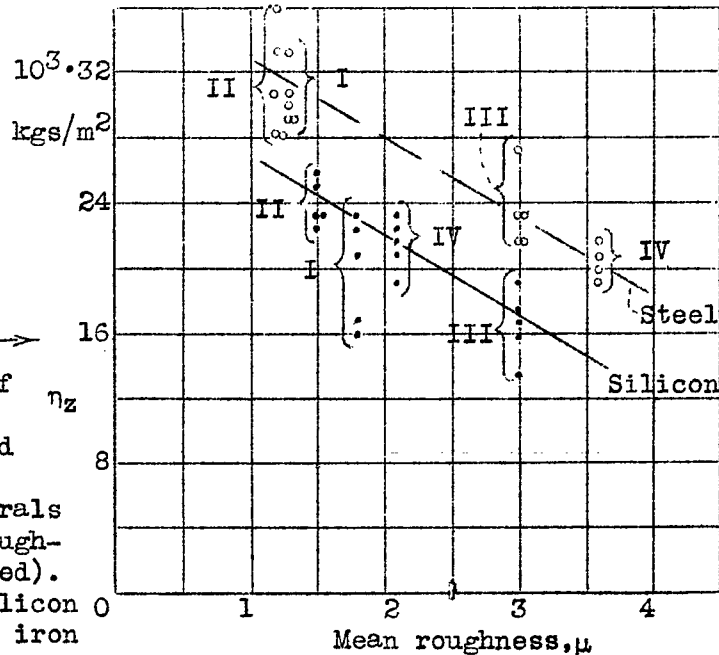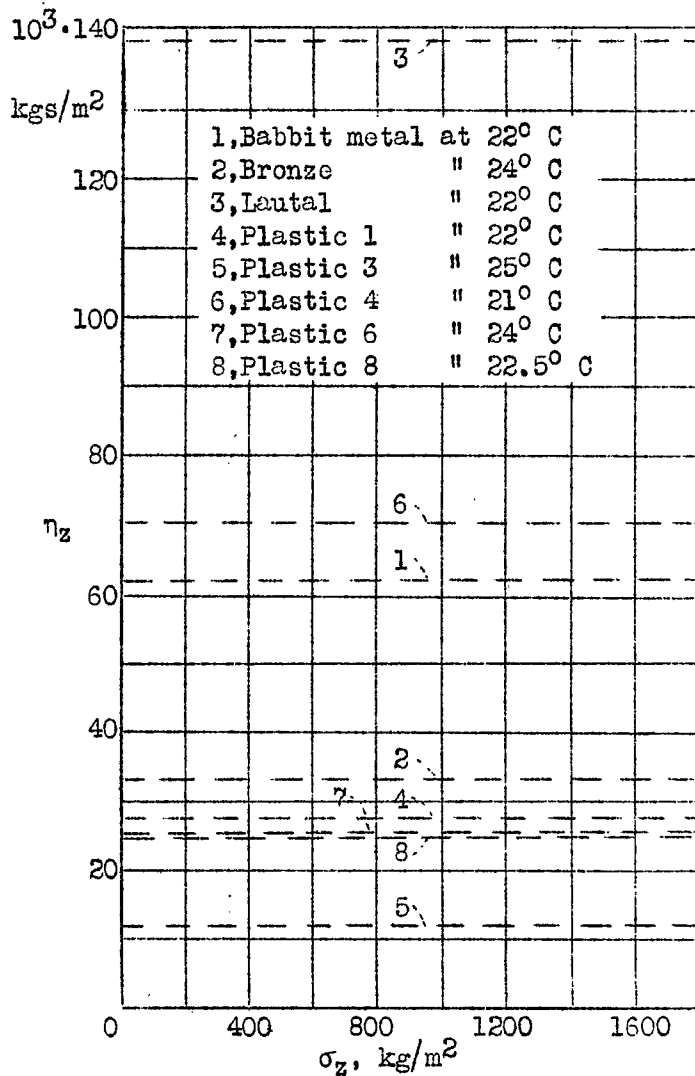
Figure 10.- Separation viscosity η_z of various
materials, oil A (table I).

$10^3 \cdot 80$

kgs/m^2

60

η_z 40

20

0   400   800   1200   1600

σ_z, kg/m^2
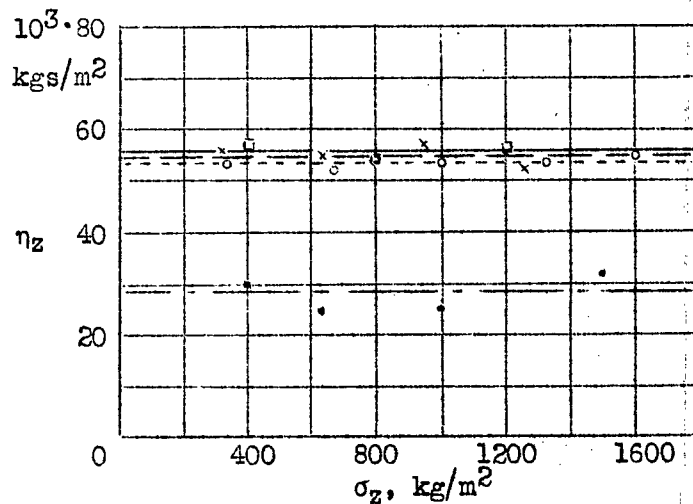
Figure 11.- Effect of plate size, aluminum
vs cast iron, oil E at 45°C
(see table I).

Plate size
□————□ 50×50mm^2
×——— × 40×40 "
o------o 30×30 "
●— ——● 20×20 "

b_1

a

a
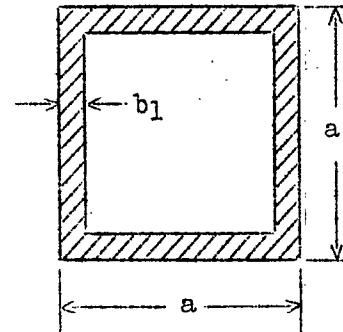
Figure 11a.- Zone b_1 of
lower
cohesive forces along
perimeter of upper
contact plate.
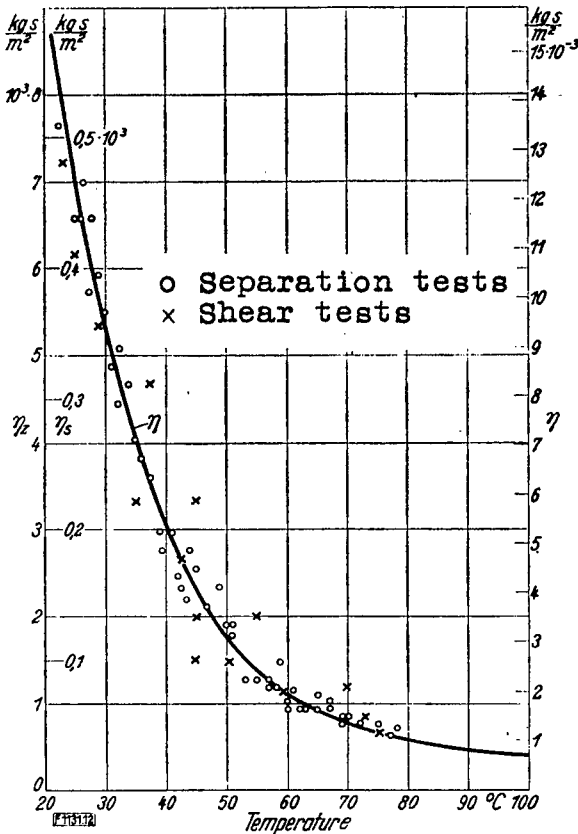
Figure 12.- Oil A
$$\psi_Z = 0.568 \times 10^6$$
$$\psi_S = 0.038 \times 10^6$$

Figure 13.- Oil B
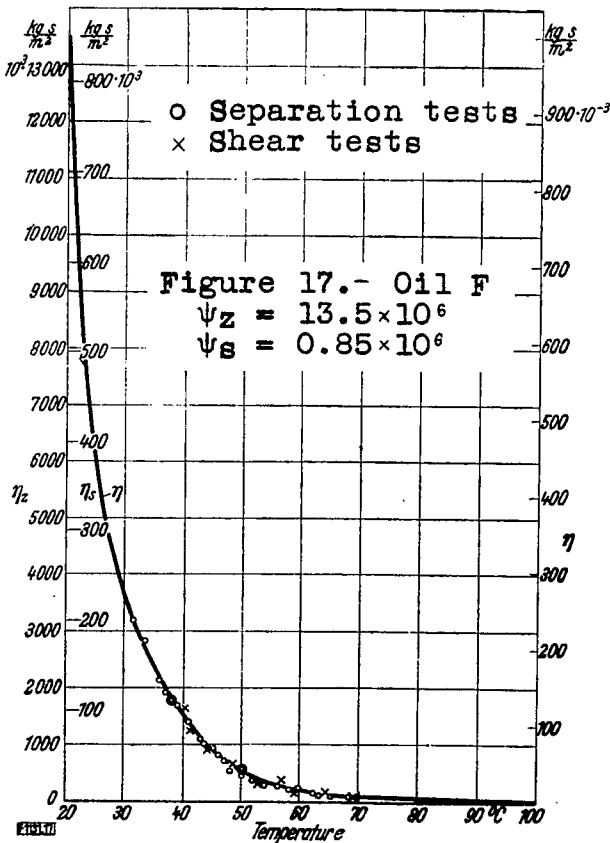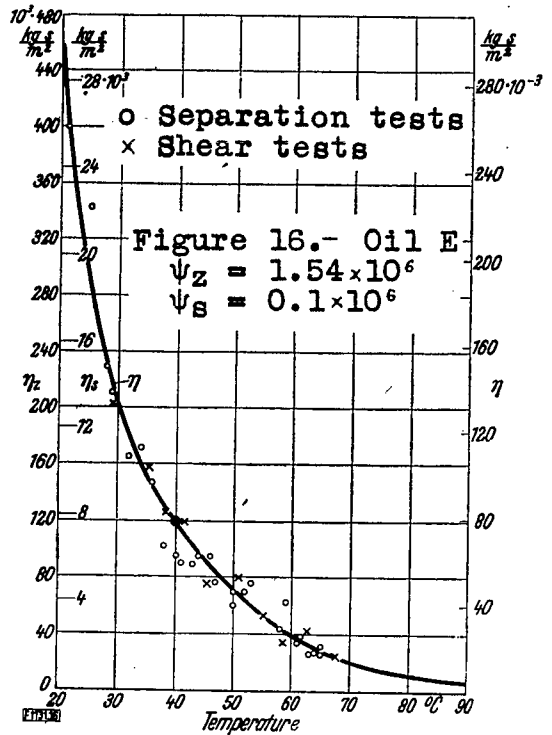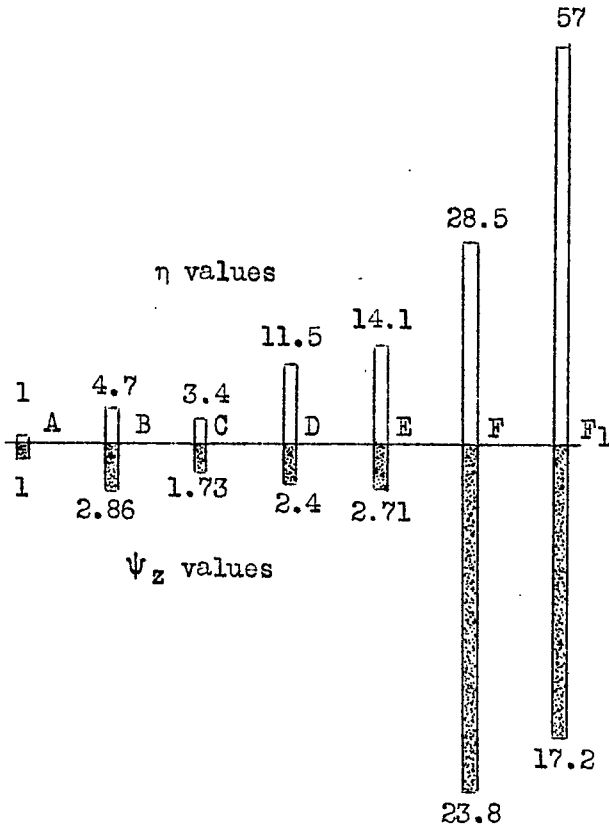$$\psi_Z = 1.63 \times 10^6$$
$$\psi_S = 0.1 \times 10^6$$

Figures 12 to 18.- Dynamic
              viscosity η,
separation viscosity η_Z,
and shear viscosity η_S
plotted against temperature
for different oils.(The η
curves were obtained with
the Vogel-Ossag viscosimeter.
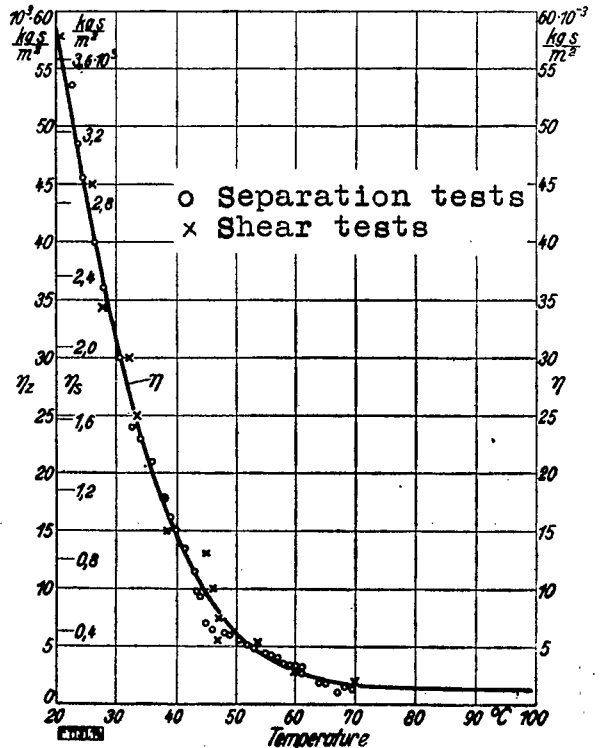
Figure 14.- Oil C
$$\psi_Z = 1.0 \times 10^6$$
$$\psi_S = 0.065 \times 10^6$$

Figure 15.- Oil D
$\psi_z = 1.36 \times 10^6$
$\psi_s = 0.085 \times 10^6$

o Separation tests
× Shear tests

Figure 16.- Oil E
$\psi_z = 1.54 \times 10^6$
$\psi_s = 0.1 \times 10^6$

o Separation tests
× Shear tests

Figure 17.- Oil F
$\psi_z = 13.5 \times 10^6$
$\psi_s = 0.85 \times 10^6$

o Separation tests
× Shear tests

Figure 18.- Oil F_1
$\psi_z = 9.75 \times 10^6$
$\psi_s = 0.6 \times 10^6$

η values

57

28.5

11.5 14.1

1   4.7   3.4
A   B   C   D   E   F   F₁
1
        2.86   1.73   2.4   2.71   17.2

ψ_z values

23.8
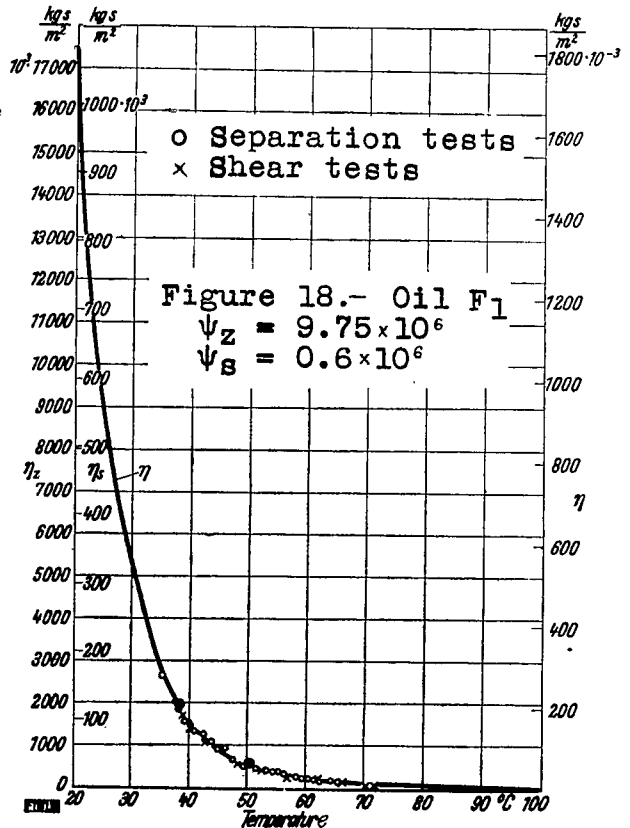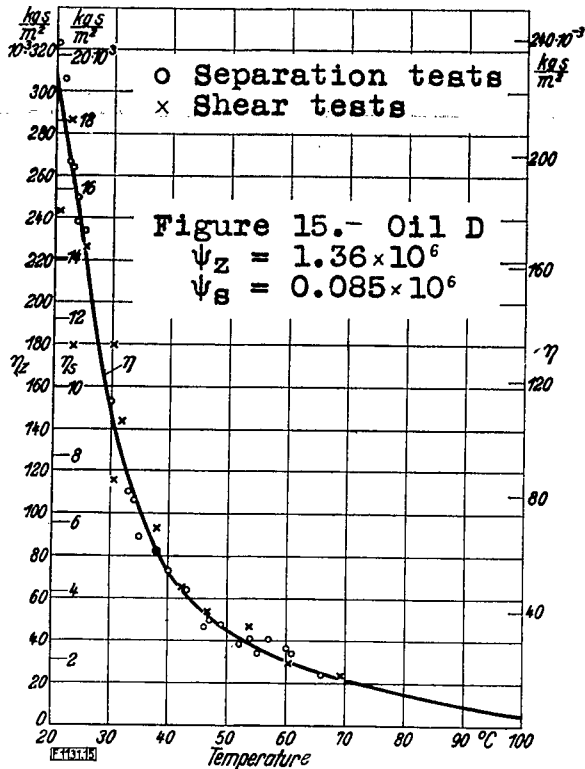
Figure 19.- Comparison of ψ_z and η values,
η refers to 30° C temperature,
ψ to oil A as unit.

Figure 20.- Apparatus for
separation
process endurance run.
s, steel plunger
f, spring
e, eccentric
w, motor shaft
g, base plate
    wetted with oil
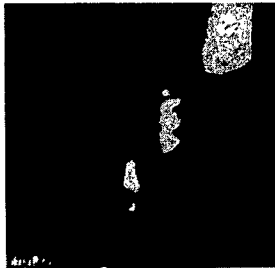
Oil
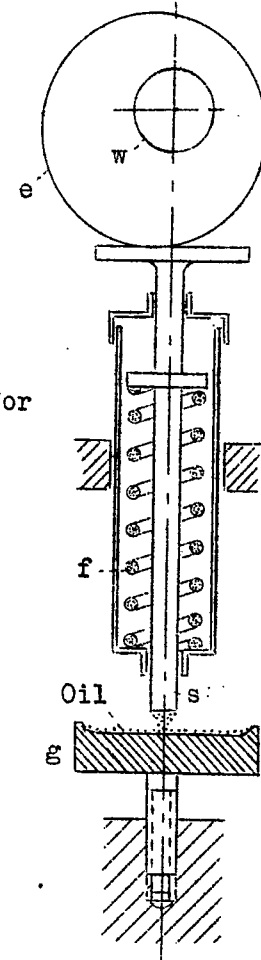
Figure 21.-
Lowest
position
of
plunger
(dips
in oil).

Figure 22.-
Medium
position
of
plunger,
up stroke
(oil
entrained
with it).
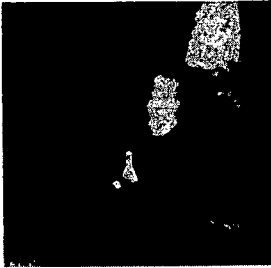
Figure 23.-
Top
position-
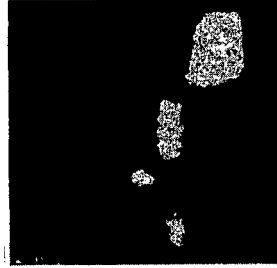oil cone
breaks
away
from
plunger.

Figure 24.-
Medium
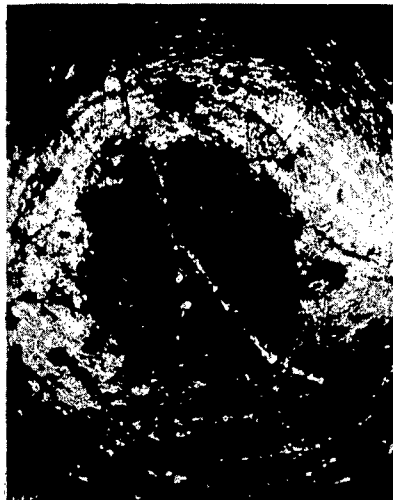position,
down
stroke
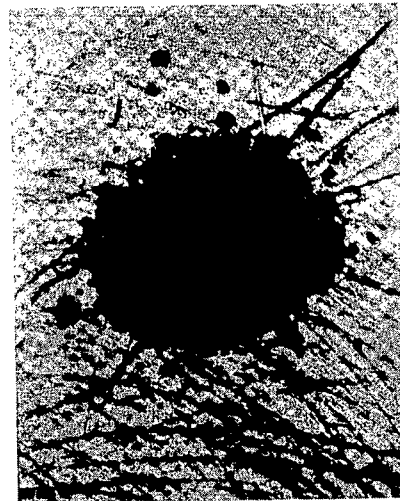(oil
cone is
pressed
flat).

Figures 25,26.-
Cavities formed
on plunger and
on top and
bottom plates.
The long cracks
in the centers
are formed by
a detector
needle.

Figure 25.-
Cavities on
plunger.

Figure 26.-
Cavities on
base plate.