REEL-C 4825

A.T.I 102110

NRL REPORT 3709

A STUDY OF THE FOUR-BALL WEAR MACHINE

W. C. Clinton

September 1950

Approved by:

Dr. W. A. Zisman, Head, Lubrication Branch
Dr. P. Borgstrom, Superintendent, Chemistry Division

NAVAL RESEARCH LABORATORY

CAPTAIN F. R. FURTH, USN, DIRECTOR

WASHINGTON, D.C.

DISTRIBUTION

CNO	2
ONR	
Attn: Code 425	5
BuAer	
Attn: Power Plant Div., Code PP	5
Attn: Airborne Equipment Div., Code AE	5
Attn: Code TD-4	1
BuDocks	
Attn: Res. & Dev. Section	3
BuOrd	
Attn: Code Re1b	5
Attn: Code Re6c	3
BuShips	
Attn: Code 331	10
CO & Dir., USNEL	2
CDR, USNOTS	
Attn: Reports Unit	2
CO & Dir., USNEES	3
CDR, USNOL	2
SNLO, USNELO	2
CDR, NAMC, Philadelphia	3
Office of the Chief of Ordnance	
Attn: Ord. Res. & Dev.	3
OCSigO	
Attn: Ch. Eng. & Tech. Div., SIGTM-S	1
CO, SCEL	
Attn: Dir. of Eng.	2
CG, Army Ground Forces	
Attn: Fuels and Lubricants Section	3

Wright-Patterson AFB	
Attn: Materials Laboratory	3
Attn: Ch., Electronics Subdiv., MCREEO-2	1
Attn: MCREXM-2	1
Attn: BAU-CADO	1
Attn: CADO-E1	2
Dir., NACA	
Attn: Sec. Subcomm. Lubrication and Wear	15
Atomic Energy Commission	
Attn: Clinton Laboratory	2
Attn: Mr. B. M. Fry, Library	3
Government Cooperative Committee on Lubrication	
Attn: Mr. C. M. Murphy, Permanent Sec'y.	15
Office of Tech. Services, Dept. of Commerce	2
Div. of Public Documents, GPO	
Attn: Library	1
RDB	
Attn: Information Requirements Branch	2
Attn: Navy Secretary	1
Naval Res. Sec., Science Div., Library of Congress	
Attn: Mr. J. H. Heald	2

UNCLASSIFIED

ATI 102 110 (COPIES OBTAINABLE FROM CADO)

OFFICE OF NAVAL RESEARCH, NAVAL RESEARCH LAB. WASH., D.C.
(NRL REPORT 3709)

A STUDY OF THE FOUR-BALL WEAR MACHINE

W.C. CLINTON SEPT'50 52PP PHOTO, TABLES, DIAGRS, GRAPHS, DRWGS

MACHINE ELEMENTS (14) BEARINGS - FRICTION TESTS
BEARINGS (2) BEARINGS - LUBRICATION

UNCLASSIFIED

CONTENTS

ABSTRACT

An investigation has been made of the effects of load, temperature, time, speed, and viscosity upon wear in the four-ball wear machine. These variables were found individually as well as collectively to affect the rate of wear. Reproducibility of results was adequate for some research and development purposes.

Wear-load curves of a group of petroleum, diester, polyglycol ether, and silicone lubricants were determined at 140°F and at 266°F. Many of the characteristics of the wear-load curves could be explained in terms of the viscosity, the temperature, and the polar material present or generated at the sliding surfaces. Less wear was generally obtained in the presence of adsorbable impurities. Pure hydrocarbons and silicones were shown to be extremely poor lubricants in the absence of chemically active addition agents. Phenylation of the silicones increased wear at all loads and temperatures. Pure diesters and polyglycol ethers containing an antioxidant were comparable to white mineral oils.

PROBLEM STATUS

This is an interim report on this problem; work is continuing.

AUTHORIZATION

NRL Problem C02-12R
NR 402-120

A STUDY OF THE FOUR-BALL WEAR MACHINE

INTRODUCTION

Accompanying the development of lubricants fortified to resist the wearing, scoring, and seizing which are certain to occur when ordinary mineral oils are employed in highly loaded bearings and gears, a large variety of machines have been designed to evaluate or compare these special lubricants. Among the more promising of the wear machines is that employing the now-familiar four-ball bearing. This principle was first employed by Boerlage (1)* in his design of a routine extreme-pressure wear tester. The basic elements are illustrated in Figure 1. The four balls form an equilateral tetrahedron. The three lower balls are locked immovably by a conical ring forming a three-point contact cradle for a fourth ball which is held rigidly in a cup-shaped end of a drive shaft which is free to rotate about a vertical axis. Through leverage, pressure is applied to this pyramid immersed in the oil under test. During a test, circular scars are worn in the surface of the three lower balls. The degree of wear is usually expressed as the average diameter of these scars. Boerlage's instrument and subsequent adaptations are very rugged and sturdy machines, capable of measuring wear from unit pressures of approximately 170,000 psi to over 900,000 psi. Only the most highly fortified extreme-pressure lubricants are able to withstand the latter pressure without causing welding of the four balls.

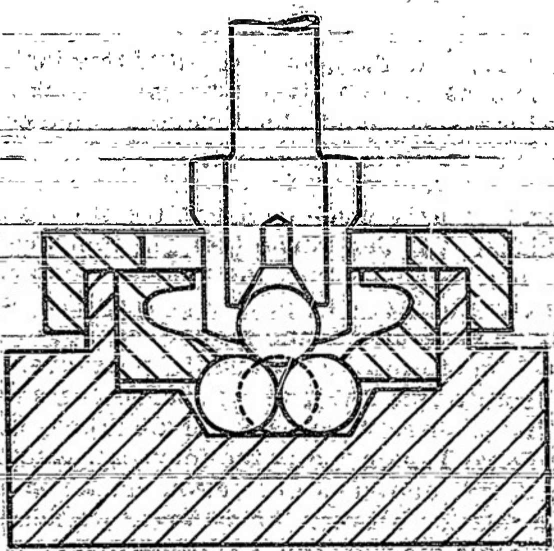


Figure 1 - Four-ball principle

* Numbers in parentheses refer to Bibliography at end of report.

Boerlage has described a one-minute test procedure for this four-ball machine (1), and the literature is replete with results obtained by other investigators who have used this method. Briefly, it consists of determining at a given speed the highest pressure that a given oil will stand for a run of one minute without permitting the balls to sieze. Boerlage has studied the effect of speeds, temperatures, and length of time of test. Among the more active investigators who have employed Boerlage's machine and test procedure are Clayton (2-6), Van Dijck and Blok (7), Davey (8-12), Kemmerer and Garton (13), Van der Minne (14), and Krienke (15).

The literature discloses many other methods of evaluation, all of which have their advocates. Blok has proposed a "Seizure-Delay" method of test (16) which considers only the maximum load a lubricant will carry for 2½ seconds without seizing. Clayton (4) has suggested an even shorter time of operation, and Kemmerer and Garton (13) have advocated a five-minute duration test at a specified load for truck hypoid lubricants. Clayton has very actively studied extreme-pressure lubrication with the four-ball machine. He has investigated the effect upon the breakdown load and wear diagrams of applying the loads in a continuous manner (as in the SAE machine (5), and also the effect of speed and the rigidity of ball chucks (5). His published results include a wide variety of well-known wear preventives in mineral oils and such unlikely and diverse lubricants as kerosene and golden syrup.

Many important studies of chlorinated and sulphurized compounds have been made by Davey (8), who came to the conclusion that the mechanism by which chlorinated compounds functioned as extreme pressure (E.P.) lubricants was governed by the ability of the chlorine atoms in the compound and the degree of "chlorine saturation." The E.P. properties are due to liberated atomic chlorine which forms an addition product with the metal surface yielding low wear; the formation of hydrogen chloride will lead to corrosion and high wear. However, Baxter, Snow, and Pierce (17) reported an increase in breakdown load for both inhibited and uninhibited lubricants when the balls were pretreated with hydrochloric acid.

Most investigations were limited to steel sliding on steel, but results with bronze sliding on bronze, steel sliding on bronze, and bronze sliding on steel have been reported in the literature.

Consideration has been given to the actual worth of this instrument as a prognosticator of the expected service performance of a given lubricant. Blok (16) and Kemmerer and Garton (13) have presented measurements which showed some correlation with actual service.

Many of these investigators have made comparative studies of the four-ball machine versus other testing machines. Van der Minne (14) has compared the behavior of extreme-pressure lubricants in the four-ball machine, the Timken Tester, the Floyd Tester, and the SAE machine. The remarkable differences in ratings obtained, were attributed largely to differences in temperature generated at the sliding surfaces of the various testers, the heat generated being a function of the velocity and the pressure. Chemically active compounds showed up best in testers like SAE and the four-ball machines at high loads. Lubricants which were believed effective because of adsorbed polar compounds, showed up most effectively in the Floyd Tester and in the four-ball machines at low loads. The explanation offered was that the coefficient of friction remained low and less heat was generated. The lack of correlation between the different machines was also demonstrated by Blok (16), who also attributed the variation to differences in temperature conditions between the testers. He believed that by applying his seizure-delay method the effect of bulk heating could be eliminated in the four-ball machine and the effects of the temperature flash be brought out. It would appear from his results that better correlation between the four-ball machine and a four square set-up Chevrolet Master de Luxe 85-hp hypoid gears is obtained than with the other testers.

The usefulness of the four-ball principle is not limited to the study of wear and seizing under high unit pressures. Being a very flexible tool requiring little lubricant, it has been successfully adapted to the study of friction by Boerlage and Blok in a sensitive instrument which they called the "Four-Ball Top" (18). The apparatus measures the coefficient of friction at low sliding velocities and uses, as its base, essentially the same mechanism as that shown in Figure 1, except that the fourth ball is inserted in a properly balanced and weighted top. The top is free to spin about a vertical axis on the support formed by the three clamped lower balls. The pyramid is immersed in the lubricant under test and a definite initial angular momentum is given the top by means of a falling weight and pawl arrangement. The coefficient of friction may be calculated by measuring the time required for the frictional force to stop the weighted top attached to the upper ball.

The friction studies made with the "Four-Ball Top" by Beeck and co-workers (19, 20) led to their conception of "quasi-hydrodynamic" lubrication. The term was chosen because it apparently defined the results they obtained with two groups of lubricants. One group consisted of uninhibited lubricants, and the other consisted of the same lubricants, but, inhibited with various free fatty acids. They found that, at an angular velocity of the order of 0.4 to 0.5 rps, the coefficient of friction was very low with the inhibited lubricants, and that, at a critical velocity, it increased to a steady level as the top decelerated. However, the coefficient of friction, at the same angular velocity, steadily increased with the uninhibited lubricants, approaching values usually associated with boundary lubrication.* They believed that a film was induced or wedged under the four balls at certain critical velocities by the free fatty acids. If such a film was formed, the electrical resistance between the points of contact of the balls should increase at this critical velocity. Therefore, measurements were made with a modified four-ball top (19), the balls of which were insulated so that the electrical resistance could be measured between one lower ball through the top rotating ball and back to a second lower ball. Uniformly decelerating motion in this case was provided by an electric motor, which was disengaged at any desired rpm by a special clutch. The electrical resistance measurements showed that concomitant with a sudden decrease in the coefficient of friction there was a high increase in the electrical resistance between the sliding surfaces. Since this was fair proof of the existence of fluid film lubrication, it was believed that the conditions existing at the points of contact resembled hydrodynamic conditions—hence the name "quasi-hydrodynamic" lubrication.

Beeck and co-workers (20) utilized this modified motor-driven top for measuring wear at unit pressures and velocities that do not cause actual seizing and galling of the moving surfaces. Although Boerlage's E.P. machine (1) theoretically should be able to accomplish the same thing, it has been found too rugged and insensitive for accumulative wear studies at low loads. Beeck et al. (20) ran the motor-driven top for a period of two hours at a constant load, and determined wear rates by measuring the amount of iron abraded into the lubricant. This they believed to be a more sensitive measure than that of the average wear-scar diameters. They also developed another method for measuring wear by employing steel balls plated with thin and uniform layers of a particular metal under investigation. The degree of wear was determined by the time required to wear through the plated metal to the steel beneath. Through such studies of wear the investigators were able to arrive at their "eutectic" theory of wear prevention which was based upon the fact that some elements like phosphorus form eutectic mixtures with various metallic elements. Apparently,

---

* "Boundary Lubrication," as used in this report, is understood to designate any kind of lubrication in which direct contact exists between the rubbing surfaces.

the lower melting point of these mixtures has a polishing effect upon the rubbing surfaces which lowers unit pressures and hence reduces wear.

The instruments and techniques employed by Beeck and co-workers were not found readily adaptable to routine work in the same laboratory under conditions that approximated those in actual machinery. Accordingly, Larsen and Perry (21, 22) modified the original Boerlage E.P. machine in an attempt to produce a more flexible, routine wear tester which, through control of the many variables that influence wear, would give good correlation with service. Their design has been adopted by a number of investigators who have either duplicated their apparatus, (as has been done in the work reported here) or have employed the model manufactured by the Precision Scientific Co.

Essentially, the Larsen-Perry version is an adaptation in miniature of the original machine designed by Boerlage (1). In contrast to the sturdy construction and insensitivity at low loads of the latter, their miniature tester is rather delicate in construction and responds with good sensitivity to applied loads as low as 0.1 kg. It is provided with controls for speed and temperature, and it is capable of measuring both wear and friction.

Most machines operate at loads considerably below those at which seizing or galling of the moving parts takes place. The Larsen-Perry wear tester attempts to simulate those conditions, since operation is confined to unit pressures which, with uninhibited motor oils, do not cause violent seizing or welding of the test specimens. At those unit pressures it is assumed that the region of lubrication encompassed extends from mild boundary conditions (direct contact between the rubbing surfaces) to thin-film hydrodynamic lubrication. Under true boundary conditions, the coefficient of friction is entirely independent of both velocity of sliding surfaces and viscosity of lubricant. Under hydrodynamic conditions, moving surfaces are separated by a fluid film so that the coefficient of friction is a function of both the velocity of the moving surfaces and the viscosity of the lubricant. The wear machine—in contrast to the E.P. machine, which is assumed to be operating always under boundary conditions—is assumed to be operating in the hydrodynamic region at low loads and in the boundary region at high loads. Figure 2 shows the load range of each of these machines.

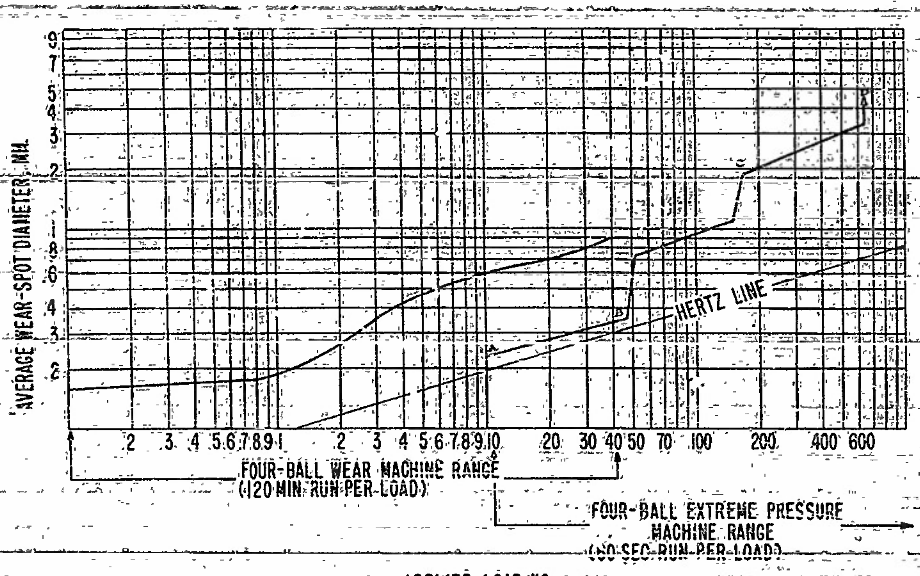


Figure 2 - Load range of the four-ball wear machine and four-ball-machine pressure

In a group of reports (21, 22, 23, 24, 25, 26) Larsen, Perry, and Webb have discussed the effects of temperature, speed, load, viscosity, time, and hardness of balls upon wear. They have shown that the machine is capable of producing fundamental data on wear and friction. For example, they demonstrated (22) that free fatty acids are effective wear-reducing agents, and that compounds like esters and ketones are not.

Their studies constitute a valuable background for anyone wishing to employ the apparatus for research, development, or the routine testing of lubricants.

A comprehensive review of all pertinent work would be too lengthy for inclusion here. However, references to many other papers are included in 28 to 47 of the Bibliography. This report will be concerned with laboratory studies of the reproducibility and the variables: load, temperature, viscosity, speed, and addition agents which affect wear in the Larsen-Perry version of the four-ball machine. A carefully selected group of fluids of present day interest in the field of lubrication has been studied also and the results are included.

EXPERIMENTAL METHODS AND EFFECT OF VARIABLES

Apparatus

Three identical four-ball wear machines were built at this Laboratory from blueprints and specifications kindly supplied by the Shell Development Company of Emeryville, California through Dr. R. G. Larsen. They are capable of measuring both wear and friction at controlled temperatures, speeds, and applied loads. Figure 3 shows a completely assembled unit and Figure 4a shows its basic elements.

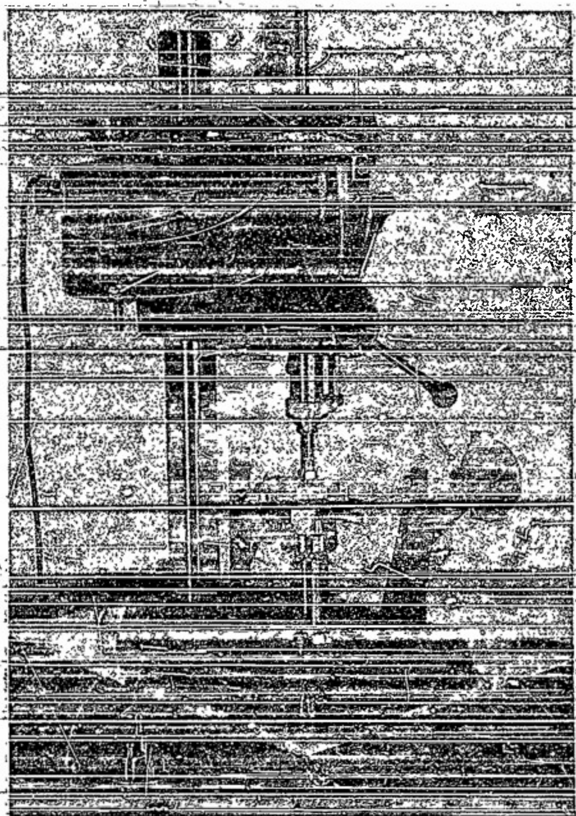


Figure 3 - Completely assembled unit

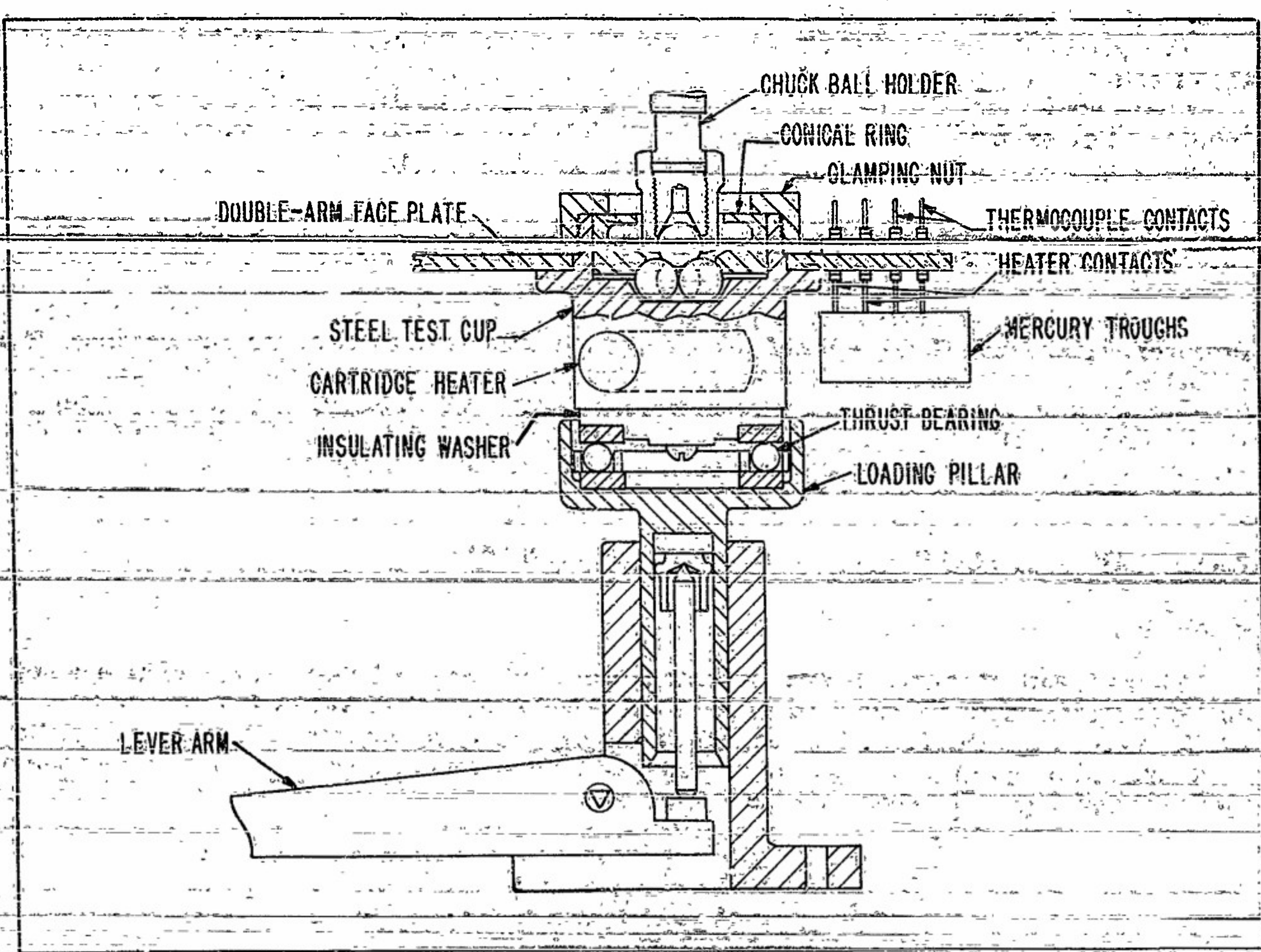


Figure 4a - Basic elements of unit

Each machine is built around a heavy-duty, bench-model drill press whose spindle is driven at 700, 1200, 2400, or 4800 rpm by a pulley arrangement with a 1/2-hp motor mounted on the shoulders of the drill press. Attached to the spindle assembly is a chuck ball-holder which firmly holds a 1/2-inch test ball. This ball rotates against three 1/2-inch stationary balls completely submerged in the test lubricant. These stationary balls, clamped immovably in a steel test cup by a conical ring and clamping nut, form a cradle in which the chuck ball rotates about a vertical axis.

The test cup rests on a self-centering thrust bearing mounted on a loading pillar. The thrust bearing permits the test cup to move freely in a horizontal position so that self-alignment of the four test balls is attained. An iron-constantan thermocouple and cartridge-type heating unit is embedded in the base of the test cup. Attached to the rim of the test cup is a double-arm face plate. One arm contains four electrical contact points which dip into separate mercury troughs. This arrangement permits frictionless electrical contact with the thermocouple and heater. Attached to the other arm of the face plate is a calibrated steel spring which is used for measuring the torque between the upper rotating ball and the three lower stationary balls. Heat loss between the metal-to-metal contact of the loading pillar and test cup is minimized with an insulating washer screwed to the bottom of the test cup.

Pressure between the rotating ball and the lower three stationary balls is created with a weight tray and level arm system whose thrust is transmitted up through the loading pillar.

In operation the torque between the test balls is determined by measuring the extension of the calibrated steel spring attached to the torque arm on the face plate. The frictional forces involved are illustrated in Figure 4b. The torque exerted on the three locked lower balls may be expressed as

$$T = f \times \frac{3\,PR}{\sqrt{6}}$$

where

T (kg/mm) = Frictional torque

P (kg) = Applied load

R (mm) = Distance from the center of the contact surfaces on the underlying balls to the axis of rotation

f = Coefficient of friction.

However,

$$T = FL$$

F (kg) = Force exerted on the indicator spring

L (mm) = Length of the total lever arm.

Also,

$$F = Dc$$

D (mm) = Measure of the spring extension

c (kg/mm) = Spring extension constant.

Hence,

$$FL = f \times \frac{3\,PR}{\sqrt{6}}$$

$$f = \frac{\sqrt{6}\ FL}{3PR} = \frac{\sqrt{6}\ DcL}{3PR}.$$

Although the spring extension D may be expressed directly, the machines employed were provided with a revolution counter and gear system as a quick means of measuring the spring extension.

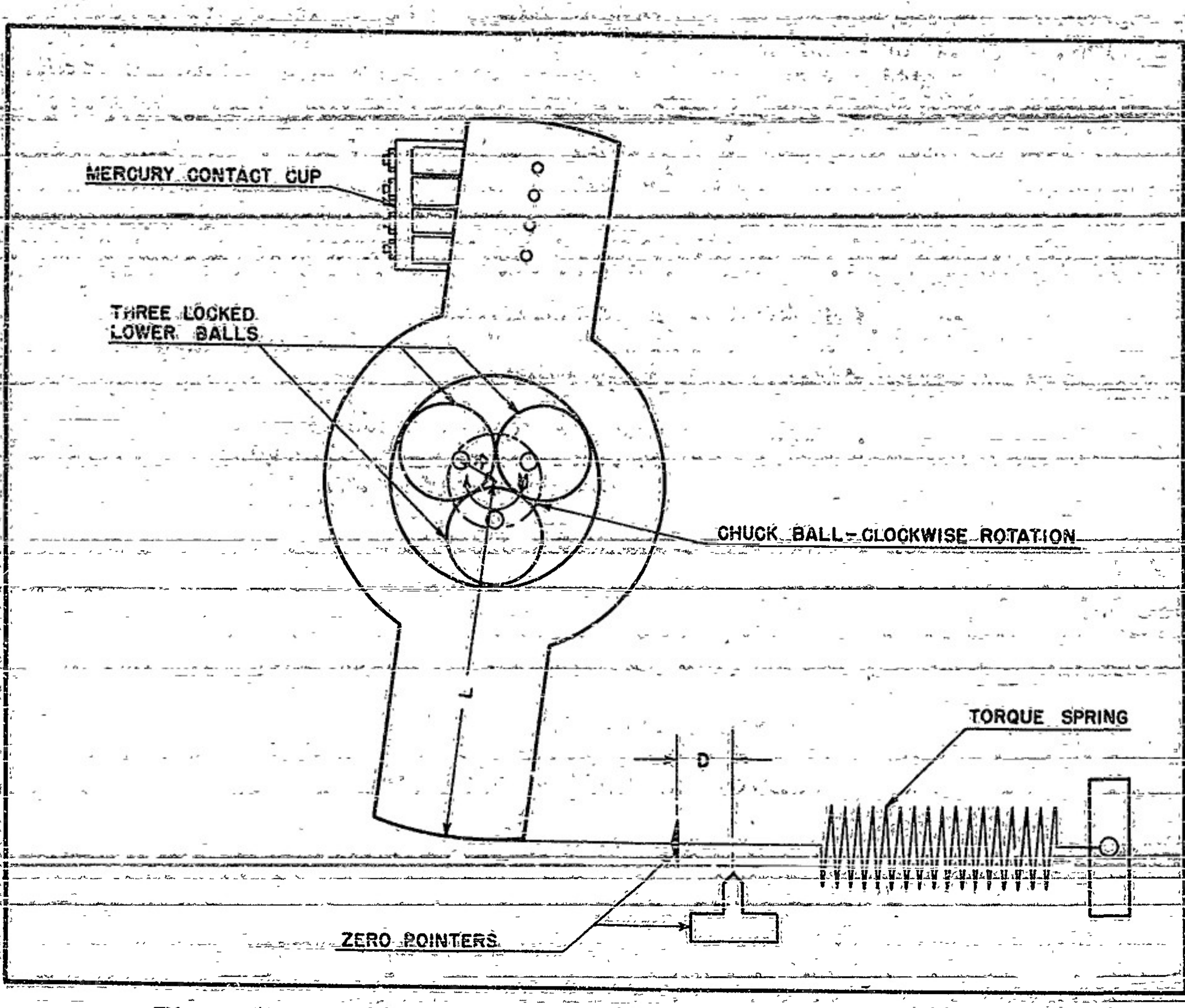


Figure 4b - Frictional forces involved in the four-ball wear machine

The four 1/2-inch balls form an equilateral tetrahedron. The area of contact between each of the three lower balls and the upper rotating ball depends upon the applied load and the elastic properties of the balls. This area can be calculated by means of the Hertz equation. According to Hertz (48) the diameter (d) of the area of contact between two spherical surfaces having the same elastic properties may be expressed as follows for 1/2-inch hard steel balls:

$$d = 87.3 \times 10^{-3} \sqrt[3]{P}$$

where

d (mm) = Wear-scar diameter

P (kg) = Applied load.

This assumes a value of 0.3 for Poisson's ratio and a value of 2.10 x 10^6 dynes/sq cm^2 for Young's modulus.

When wear occurs actual metal will be cut away and the area of contact will be larger than the area of the Hertz deformation. The pressure between each of the three stationary balls and the rotating ball at the end of a test can be calculated since the applied load is known and the contact area can be measured. The mean specific pressure based upon the geometry of the equilateral tetrahedron may be expressed as follows:

$$M_p = 0.52 \frac{P}{d^2}$$

where

M_p(kg/mm^2)	=	Mean specific pressure
P (kg)	=	Applied load
d (mm)	=	Average wear-scar diameter.

Procedure

All experimental work described in this report, except for the studies on wear-scar deposits, was done with SKF, Grade I steel balls.* In commencing a measurement, four new balls were degreased by washing them several times in hot benzene before locking them in their respective positions in the apparatus. The test cup and chuck ball-holder were also cleansed in boiling benzene. After the test balls were locked in position, a fresh 10 to 15 ml portion of the lubricant to be tested was poured into the test cup. The test cup was then placed on the loading pillar and the spindle with the rotating ball was lowered into position. The torque spring was then attached to the torque arm of the test cup. Full heat was applied until the test temperature was reached. It was then decreased with a "Variac" transformer to such a value as experience had shown would maintain the temperature. The weight tray was next loaded with the necessary weights and the motor started. At the end of 120 minutes the motor was stopped, the test cup removed, and, without removing the balls, the wear scars were measured with a bifilar microscope of 72X power. The balls were not removed from the test cup prior to the measurements because the small size of the wear-spot makes it virtually impossible to find the scars. Usually the scars are round, but the vertical axis of the microscope and the inclination of the wear-scar spot make them appear elliptical. The major axis of the scar seen in the microscope was taken as the measure of the wear-scar diameter (d). The average of the scar diameters on each of the three lower balls was considered a measure of wear. The diameters were plotted against their respective applied loads on log-log coordinate paper. These coordinates were selected because the wide range of loads investigated as well as the range of wear diameters encountered would necessarily result in very bulky and unwieldy graphs on rectangular coordinates.

Load and Temperature Effect

A series of tests were made with the highly refined, white mineral oil (Figure 5) at the selected temperatures of 140°F, 266°F, and 356°F. This mineral oil was a UXP1 petrolatum

---

* When needed, other test specimens such as stainless steel, mild steel, brass, bronze, monel metal, and aluminum are commercially available.

manufactured by the Kuhne-Libby Co. of New York City. The temperatures were selected for several reasons. It was found that one of the lowest temperatures most easily maintained with "Variac" control was 140°F. The higher temperature of 266°F was chosen because it was not unreasonable with respect to some actual operating conditions and also because data from Larsen et al. was available at that temperature. The effect upon wear obtained at these two temperatures made it desirable to investigate the effect of still higher temperatures. For this purpose the temperature of 356°F was selected. The speed at each temperature was 700 rpm. The sample used was freed of adsorbable impurities before testing by repeated percolation through adsorption columns packed with layers of activated fuller's earth and silica gel. A drop of this fluid did not spread on the clean surface of water maintained either at pH 3 or pH 11. The nonspreading of this percolated fluid was indicative of high purity with respect to hydrophilic adsorbable impurities (49, 50, 51). The results obtained with steel rotating against steel are shown in Figure 5.

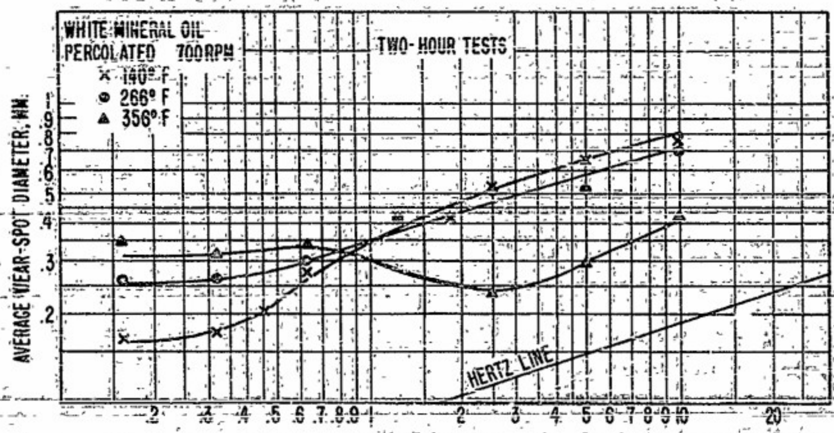


Figure 5

The degree of wear shown by the curves is evaluated at any given load by comparing the wear-scar diameter with the Hertz diameter of elastic indentation at the same load. The Hertz diameter is the diameter of the flattened area of the contacting surfaces before wear has occurred. The relationship between the Hertz diameter and the applied load is an exponential equation which produces a linear relation on logarithmic coordinates for a series of Hertz diameters and their respective loads. This linear relation (Hertz line) for hard steel balls has been included on all wear-load graphs illustrated in this study.

At 140°F it is seen that wear is very low from 0.16 to 0.46 kg, probably the result of a great deal of the load being supported by a fluid film. Any sliding surfaces may experience some degree of hydrodynamic lubrication. It should be expected therefore that an increase in the temperature would show an increase in wear because of the viscosity decrease. That this is the case at these low loads is illustrated by the expected increased wear at 266°F and the still greater increase at 356°F. However, Larsen has demonstrated that at still higher temperatures some lubricants reverse this trend and show a reduction in wear at these low loads (24). A simple significance cannot be attached to this fact, since at the high temperature at 446°F used in his work significant oxidation and other chemical changes in the oils and additives can be expected to have occurred and confused the interpretation of the experiments.

At higher loads the effect of temperature appears to be the reverse of that at lower loads. With an increase of load it would be expected that, in the absence of oxidation products able to adsorb on or react with the steel, the rate of wear would normally increase irrespective of the oil temperature in the test cup. However, the results show a decrease in wear at higher loads with an increase in temperature. This decrease is believed by Larsen et al. (24) to be due to increased corrosion of the iron, which tends to remove the asperities, i.e., the oil acts as a chemical polishing agent.

Viscosity Effect

In accordance with the hydrodynamic calculations of Howlett (44), fluid films of liquids at normal viscosities cannot exist between the sliding contacts of the balls in the wear tester. However, the results of the NRL viscosity studies indicate that a change in viscosity does have an effect upon the wear-load curves. Figure 6 shows the wear-load curves obtained with "percolated" white mineral oils of divergent viscosities. The viscosity-temperature curves of these oils, A and B, are graphed in Figure 7. Each wear scar is the average wear diameter after 120 minutes of operation at 266°F and 700 rpm. At nearly all loads less wear is obtained with the more viscous fluid, A. At the highest loads (10-20 kg) a decrease in wear with the load is shown for both fluids. Since an increase in load there is a corresponding increase in temperature at the point of contact, it is possible that the oil itself acts as a wear preventive at certain critical temperatures through the formation of wear-resistant oxidation products. However, the results show that to some degree hydrodynamic lubrication does exist between the balls at loads below 10 kg.

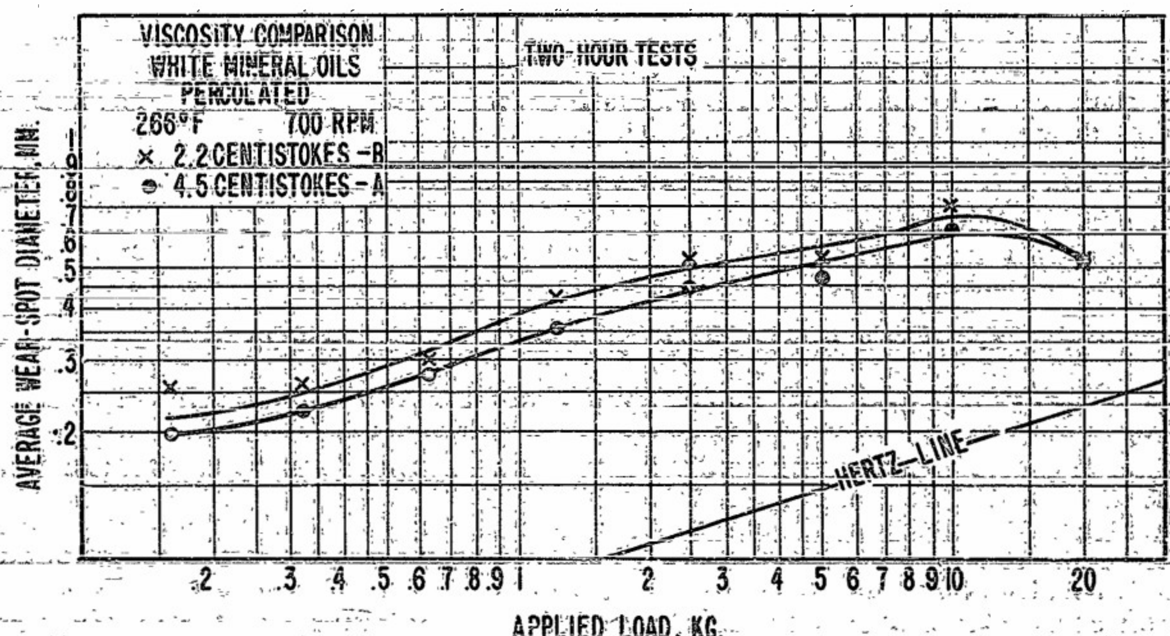


Figure 6

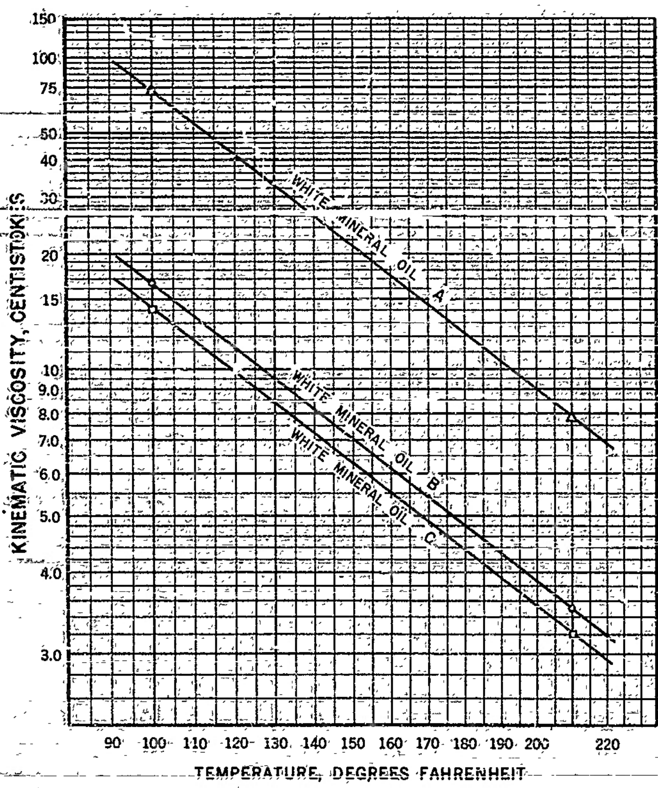


Figure 7 - Viscosity-temperature chart

Data obtained with three pure, additive-free diester oils—di-undecyl sebacate,* di-(2-ethylhexyl) sebacate, and di-n-butyl sebacate (52, 53)—would lend some support to the existence of fluid-film lubrication. Wear-load curves for these fluids based on wear scars after 120 minutes of operation at 140°F and 700 rpm are shown in Figure 8. The viscosity-temperature behavior of these fluids is given in Figure 9. It will be seen that there is a significant decrease in wear with an increase in viscosity from an applied load of 0.3 to 2.5 kg. At higher loads (5 to 20 kg) the effect of viscosity is less marked.

Attention is called to the dotted portion of the curves between 2.5 and 5 kg. They were dotted in that load region to indicate that reproducibility was very poor at all loads greater than 2.5 kg and less than 5 kg. This is not at all unusual with the four-ball machine. For example, the wear-load curve of an extreme-pressure lubricant illustrated in Figure 2 is typical of curves obtained with the Boerlage extreme-pressure machine. All experimenters with this machine are familiar with the unstable regions of lubrication found under similar conditions. The instability is caused by seizing of the metal. At all loads between points B and D the seizing of the metal is easily identified by one or more sharp surges of the friction-indicator arm during the time of test and also by the wear scars, which will show deep scoring. Between points B and C it is impossible to reproduce the wear scars with any degree of accuracy. At all loads above point C, reproducibility is very good although seizing leading to actual welding of the four balls does occur. Wear under these conditions of high load and high contact temperature is accompanied by seizing of macrodimensions

* Also known as di(1-methyl-4-ethyloctyl) sebacate

which is easily observed. Seizing of microdimensions may be responsible for the unreproducible dotted portions of Figure 8. During a test on the wear machine there are generally no sharp surges of the friction-indicator arm in those regions nor are there any differences in the appearance of the wear scars for those obtained in regions which show good reproducibility and those obtained in regions of poor reproducibility. Regions of unreproducibility are not suspected until a complete wear-load curve has been obtained. The spread of such a region may be broad and its limits ill defined. Sometimes, however, it is sharp and well defined (Figure 39). Langen et al. (24) also found wear-load curves which were similar to those of Figure 8. They called the dotted portion of the curves "breaks" because the general trend of the curves is broken at the loads included in the dotted portion. They believed that the breaks were determined by the temperature of the rubbing surfaces and that a break in the curve indicated that the contact temperature was so high that the metal softened to the point of failure; with the destruction of the initially smooth surfaces, a period of very high wear followed. They make reference also to the fact that two or more breaks may occur on a wear-load curve if the load range is sufficiently great. Similar results have been obtained in this investigation (see Figures 37 and 39).

This report uses the term seizing when a break occurs (rather than the term failure) to suggest what happens at the rubbing surfaces, because seizing, particularly with the Boerlage E.P. machine, is always associated with poor reproducibility. The intensity of these seizings is probably governed by the resistance of the oil film to rupture as well as by the ability of the liquid to recover from seizing. This property undoubtedly varies with each fluid so that comparison of wear curves is of little significance if seizing has occurred at some lesser load. The temperature undoubtedly determines the load at which seizing occurs. These regions may well be called regions of incipient seizing.

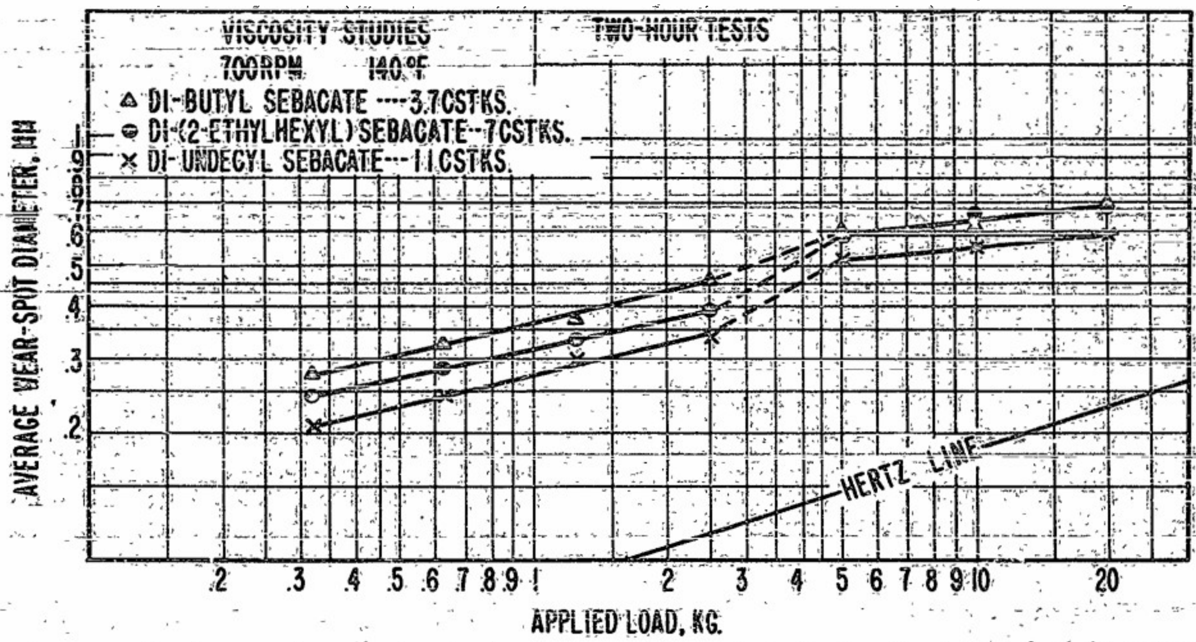


Figure 8

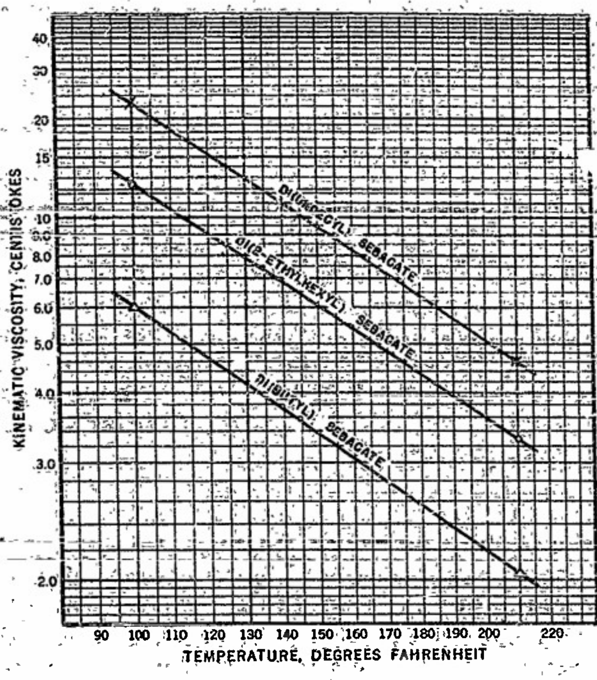


Figure 9 - Viscosity-temperature behavior

A wear-load curve for di-(2-ethylhexyl) sebacate was also determined at 188°F. At that temperature the viscosity of this diester is approximately the same as that of di-n-butyl sebacate at 140°F. Examination of their respective wear-load curves at these divergent temperatures (Figure 10) shows that the elevation of temperature caused the di-(2-ethylhexyl) sebacate to sieze at a lower load than was found at 140°F in Figure 8. The amount of wear was nearly the same for each fluid for loads of 5 to 20 kg. At intermediate loads (0.6 to 5 kg) analysis is unreliable because of the seizings which occur. At the lowest loads (0.3 and 0.6 kg) the amount of wear is the same for both fluids, and since that region is not complicated by seizings it is again concluded that viscosity does have an effect upon wear at these low loads.

Another example of the viscosity effect is shown in Figure 11. The wear-load curve of di-(2-ethylhexyl) sebacate at 109°F is shown in comparison with that of di-(undecyl) sebacate at 140°F. At these temperatures the viscosities of these fluids are identical (11 centistokes) as are the loads at which seizing occurred. These viscosity studies all lead to the conclusion that hydrodynamic lubrication does occur in the NRL four-ball wear machines at low loads.

Larsen and co-workers have reported remarkable differences in wear obtained with fluids that ranged in viscosity from approximately 5 centistokes to 6,500 centistokes (24). However, the character of the lubricant was altered radically. These fluids were compounded by the addition of polyisobutylene to an SAE grade motor oil. The interpretation of their results can be questioned on the basis of purity and the unknown relation of the viscosity-increasing effect of polymeric additives to the thin-film wear-preventive properties of an oil.

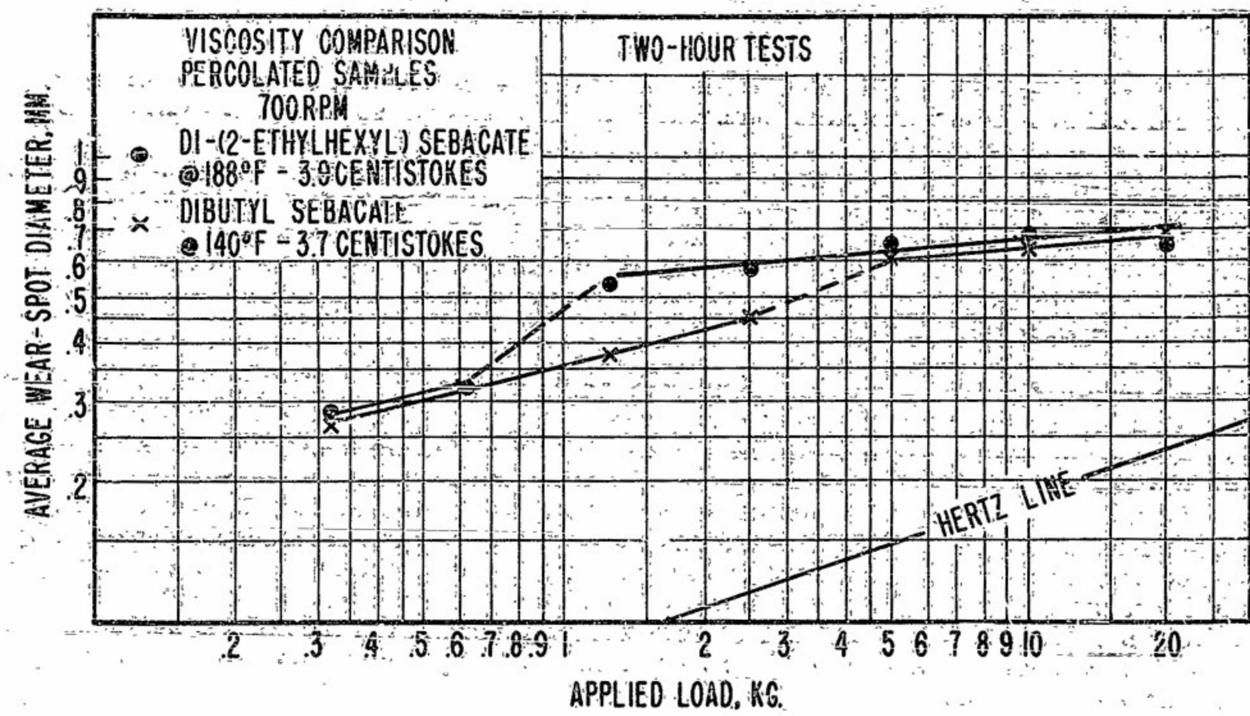


Figure 10

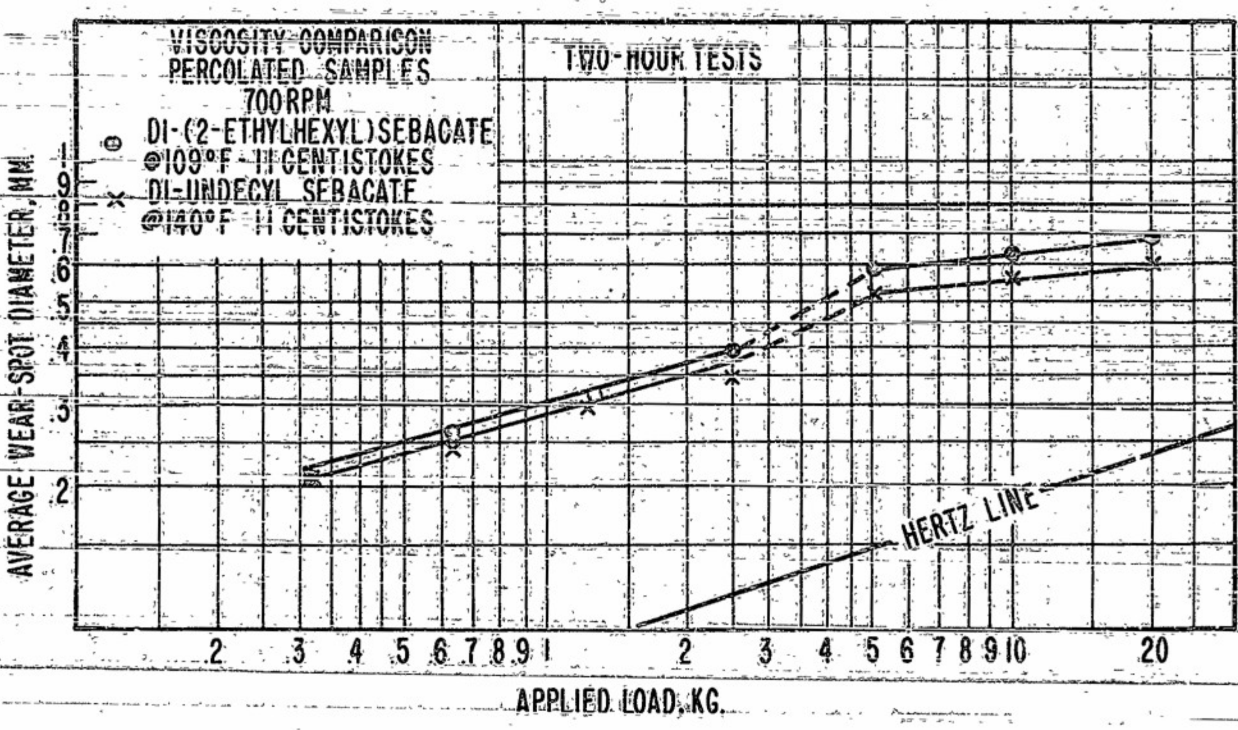


Figure 11

Effect of Speed

Larsen and co-workers (21, 22, 23, 24) concluded that in general speed in terms of rpm, is not critical over a wide range of temperature. They agreed, however, that temperature and pressure in the oil wedge near the area of contact will vary with speed. They assumed that an increase in temperature might either increase or decrease wear, but that an increase of the pressure in the oil wedge could only decrease wear. Fenske and co-workers later studied the relation between wear, vibration, and speed. They concluded that low speeds (600 to 700 rpm) were best suited for testing certain lubricants (54). They found wear results to vary with speed, but believed that wear would be independent of speed if all mechanical vibration were eliminated.

Data obtained at NRL from steel balls with white mineral oil C of Figure 7 in two-hour tests at 140°F show (Figure 12) that an increase in speed from 700 rpm to 4800 rpm resulted in a decrease in wear at loads of 0.6 kg to 5 kg. At intermediate loads (7 to 10 kg) there was little change in the wear. At 20-kg loads increasing the speed appeared to decrease the rate of wear. Larsen and his co-workers have suggested that higher speeds increase the oil-wedging effect near the contact area and that more of the load is carried hydrodynamically thus reducing wear. This would explain the decrease in wear with increase in speed at loads from 0.6 to approximately 7 kg. Presumably, at 10 kg-loads, the wedging effect becomes unimportant, and at 20-kg loads the high rate of heat generation at the contact surfaces caused both by high speeds and by loads results in the formation of oxidation products which act as wear preventives.

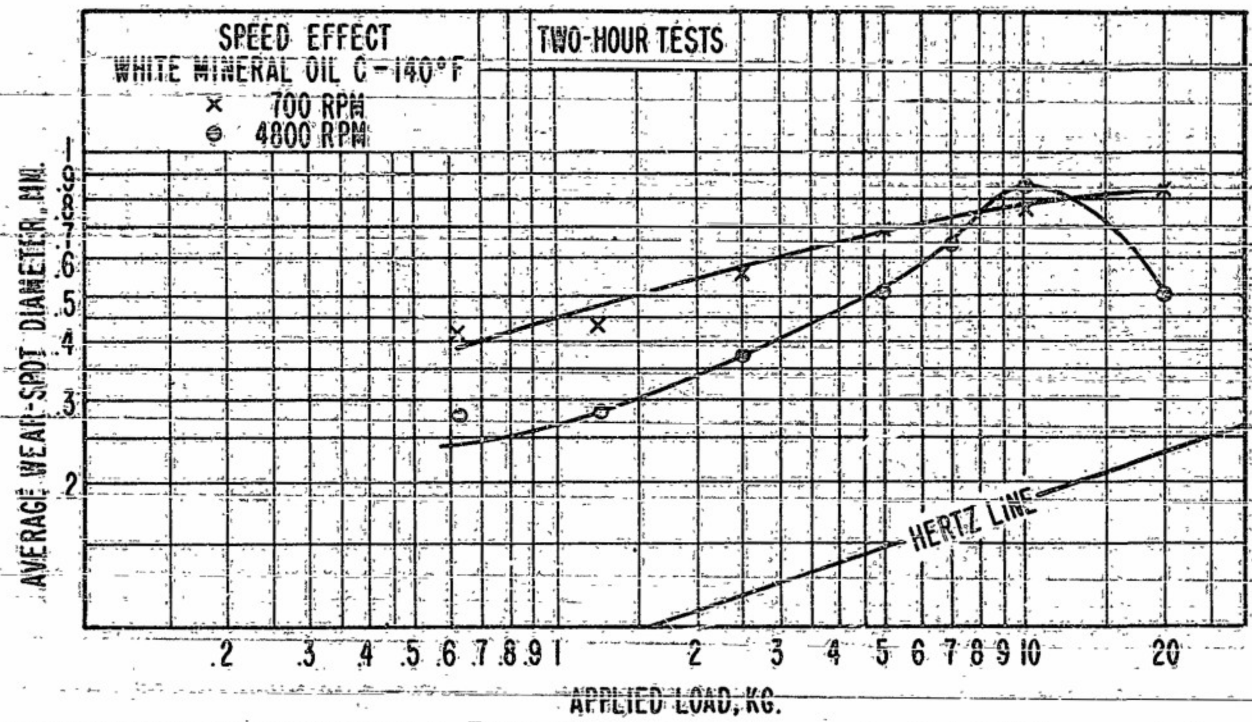


Figure 12

The temperature of the oil in the test cup affects the wear-speed relation. For example, the behavior of the test apparatus and the appearance of the wear scars at loads greater than 5 kg with white mineral oil C were normal at 140°F at 4800 rpm. At 266°F, however, the torque arm oscillated so violently that the test apparatus was damaged, and the appearance of the enormous wear scars was that usually associated with delayed seizing (42) of the Boerlage E.P. machine.

The test speed of 700 rpm was selected as a standard because the tests indicated that the wear-load curves were more complex at 4800 rpm, and that excessive vibration occurred. Less vibration occurred at 700 rpm and the results were more reproducible. Much of the reported work of other investigators was obtained at 700 rpm.

Effect of Time

The average wear-scar diameters obtained with two mineral oils were determined as functions of time. These were samples of an NS-2110 uninhibited petroleum oil and of a highly refined white mineral oil designated B. Their viscosity-temperature behaviors are shown in Figure 22 and in Figure 7, respectively. Each oil had been percolated through layers of activated fuller's earth and silica gel. Wear tests were made at 140°F with an applied load of 7 kg and a speed of 700 rpm. At selected time intervals the test was interrupted and the wear diameters measured. The test was then continued to the next time interval without removing the test balls. Generally, wear is somewhat higher for a given test interval if the test has been interrupted frequently, probably because it is difficult to exactly center the test cup to its original position. The volume of each lubricant was maintained at a constant level in the test cup by occasionally adding a few ml of fresh fluid. Approximately 15 ml of each sample was used for a complete test of 800 minutes. The results obtained are shown in Figure 13.

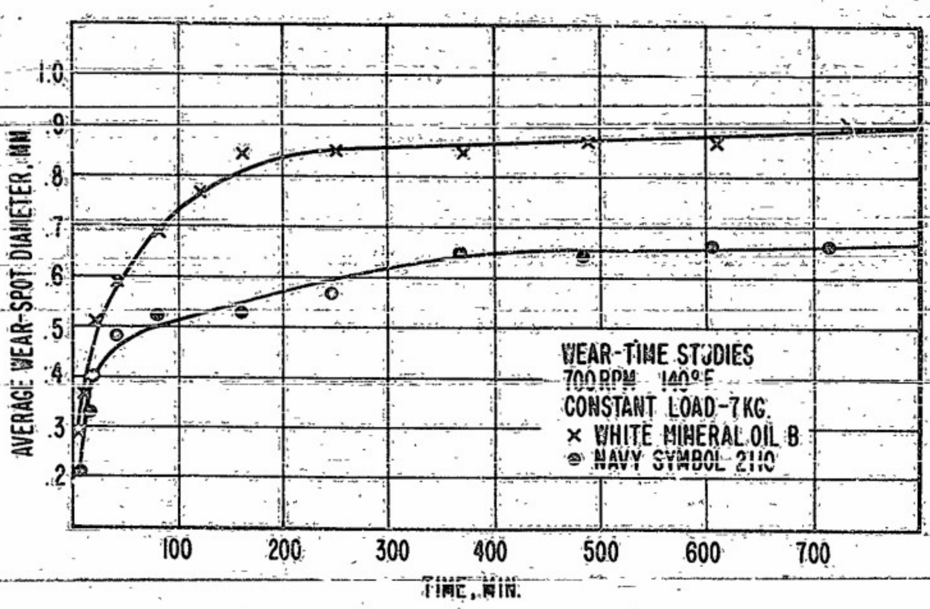


Figure 13

The curve for white mineral oil became nearly linear with respect to time in 160 minutes of operation, and that for NS-2110 became so between 100 and 200 minutes. The standard time of test per load adopted by Larsen et al. (24) was 120 minutes. They found that after approximately the first 15 minutes there was an increasing difference in wear between a group of uninhibited petroleum oils and a group containing an antiwear agent. This difference became increasingly greater with time. Therefore, they selected the time interval of 120 minutes per load largely upon the practical consideration that this interval made it possible to make two determinations per work day. It can be seen from the curves of Figure 13 that at this time interval it is possible to distinguish clearly between the wear rates of these lubricants. It is also possible to distinguish between them after a 60-minute time interval, and Fenske and co-workers employed this interval for some of their studies (55). However, 60 minutes seems much too short a time interval for studying many lubricants. It would be impossible to come to many of the conclusions made in this report if the time interval had been less than 120 minutes, since there would have been little difference in the wear rates of various lubricants at many loads. The viscosity studies of Figure 6 were based upon two-hour tests at each respective load and the results showed that wear increased when viscosity decreased. When, however, the time element was reduced to one hour, the wear-scar dimensions at each load were the same for both samples. Apparently wear is a cumulative process and small differences in wear rates require considerable time to be detected by the microscopic method of measuring wear-scar diameters.

The results obtained with some samples of an aqueous-base lubricant showed that even a 120-minute time interval does not reveal all aspects about the wear characteristics of some fluids. The wear-time curves at 140°F and a constant load of 7 kg for two of these fluids, Hydrolube U_3 and Hydrolube U_4 (56, 57) at 700 rpm are shown in Figure 14. The wear-time curve for Hydrolube U_4 shows that there are two levels of linearity present. Between the time intervals of 150 minutes and 900 minutes, wear has become linear with respect to time. After 800 minutes of operation, however, a rapid increase in wear occurs and linearity does not prevail again until after 1500 minutes of operation. The sudden increase in wear rate after 900 minutes of operation may indicate that actual mechanical failure occurred owing to a high temperature generated at the points of contact. This would seem unlikely at the low pressures existing after 800 minutes of operation. Since the same fluid was employed during the entire test, it may be that severe corrosion or wear became prevalent because of chemical deterioration of the aqueous fluid. Hydrolube U_3 did not show any evidence of breakdown after linearity was reached. It will be noted that it required 800 minutes of operation before linearity was reached with this sample.

From these results it is apparent that linearity depends upon the lubricant, and that, although a 120-minute time interval appears ample for most routine measurements of petroleum products, radically different fluids should be tested for longer periods of time at various loads and temperatures so that a better insight into the wear properties may be obtained. For instance, after 120 minutes of operation it could be concluded that Hydrolube U_3 is superior to Hydrolube U_4 at a 7-kg load and at a temperature of 140°F, but with time intervals of 600 to 800 minutes this conclusion would be rather doubtful. There would, however, be little doubt of the superiority of Hydrolube U_3 after 1500 minutes of operation. Another example is the wear-time curve of a polyglycol ether, Ucon-LB 100X, (See Table 1 for viscosity-temperature behavior) which is shown in Figure 14 at the same load and temperature as the hydrolubes. It required between 300 and 400 minutes before this wear rate reached linearity. After 120 minutes of operation this sample is comparable with Hydrolube U_4 but on the basis of a 400 minute time interval it is much inferior to Hydrolube U_4. On the basis of a 1200 minute or longer interval they again show comparable wear rates.

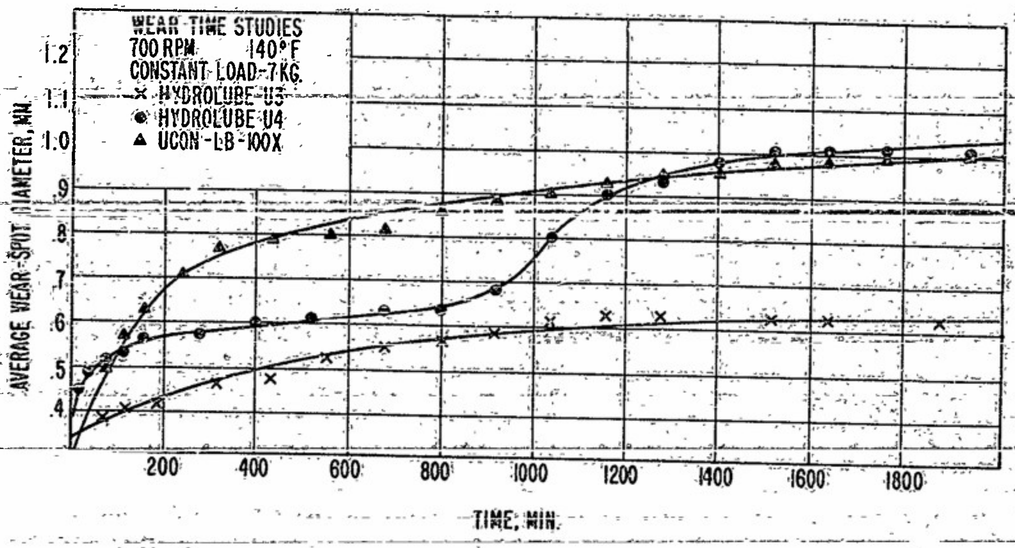


Figure 14

TABLE 1

Kinematic Viscosities of Fluids not Included in Temperature-Viscosity Charts of Figures 7, 9, and 22

Fluid	Viscosity (Centistokes)				
	100°F	140°F	212°F	256°F	350°F
Polymethylsiloxanes					
DC - 500	75	50	29	22	13
Polymethyl-phenyl Siloxanes					
DC - 550	95	49	20	13	6.9
DC - 710	122	55	21	14	6.8
Polypropylene Glycol Derivatives					
Ucon - LB 100	20	10	4.2	2.8	1.5
Ucon - LB 100X	21	11	4.3	2.8	1.5
Aqueous Fluids Hydrolubes					
U_3	16	8.5			
U_4	16	8.5			
Mineral Oils					
NS-2135	65	24	6.5	3.4	
Hydrocarbons					
Cetane	3.1	1.9	1.2		

Reproducibility

Among the factors influencing wear are the condition of the steel balls, the chemical nature of the lubricant, the applied load, and the alignment of the test apparatus. Tests have shown that reproducibility between machines is governed by alignment of the test apparatus and by vibration caused by defective spindle bearings.

Reproducibility For a Single Machine—In Figure 15 the average wear-scar diameters, plus and minus the standard deviation, is shown for white mineral oil C of Figure 7 for a group of three runs after 120 minutes of operation. The tests were made at 266°F and 4800 rpm with steel balls at selected load intervals. For comparative purposes the reproducibility in terms of the standard deviation of Hydrolube U_3 is shown in Figure 16 in the form of a band-chart. The wear scars are those formed after 120 minutes of operation at 140°F and 700 rpm. The results for both samples show that there is an intermediate load area where reproducibility is best, and that wear is poorer at the high and low loads tested.

It might appear from the results in Figures 15 and 16 that the reproducibility with a single machine is not appreciably influenced by the chemical nature of the lubricant, by the test temperature, or by the respective speeds employed, since the degree of reproducibility is approximately of the same order for both samples. However, these particular fluids are stable as regards seizing. Wear-load curves of chemically different lubricants reveal that good reproducibility is unattainable at some loads. Variation in temperature control may account, in part, for the lack of reproducibility at a particular load. In general, the more reproducible results were obtained with the more oxidation-stable fluids.

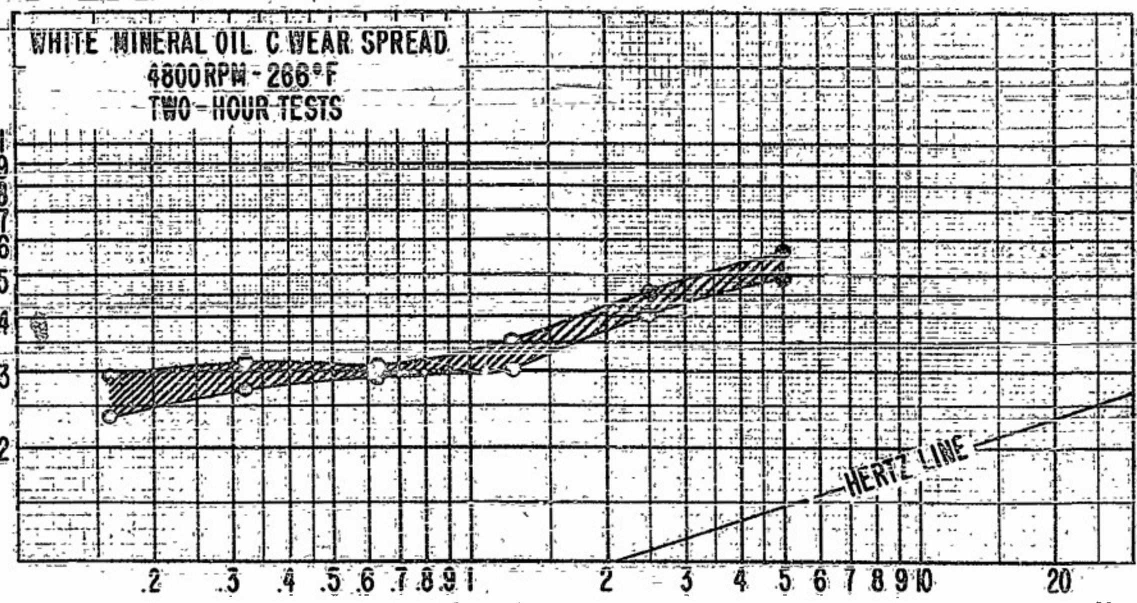


Figure 15

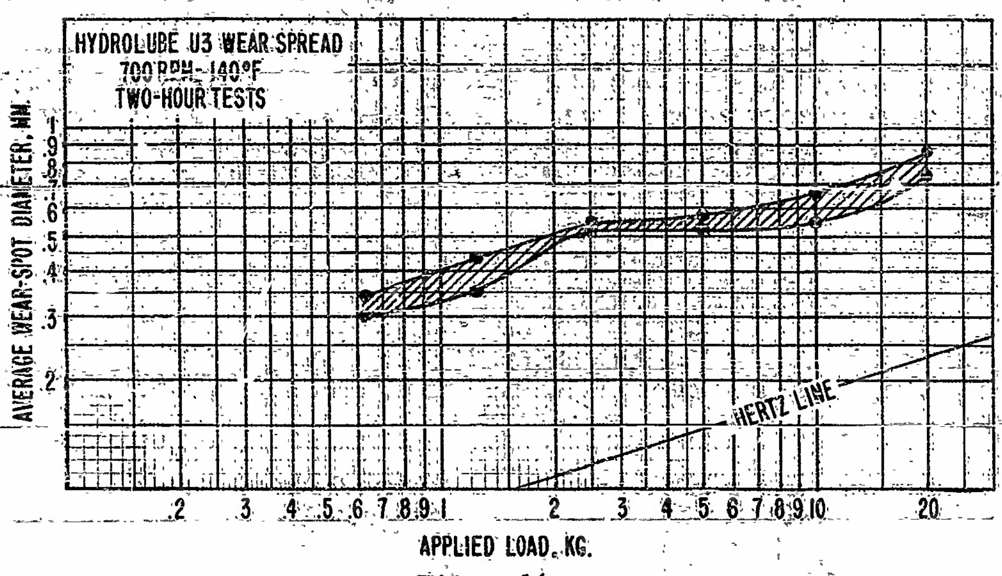


Figure 16

The effect of vibration caused by defective spindle bearings is shown in Figure 17. The spread of five wear-scar diameters formed after 120 minutes of operation with steel balls and an applied load of 7 kg is shown before and after replacing defective spindle bearings. The lubricant employed was white mineral oil C. The results show an improvement in reproducibility. Observations indicate that motor and belt vibration together with prolonged heating of the test cup and quill are the chief causes of deterioration of these bearings.

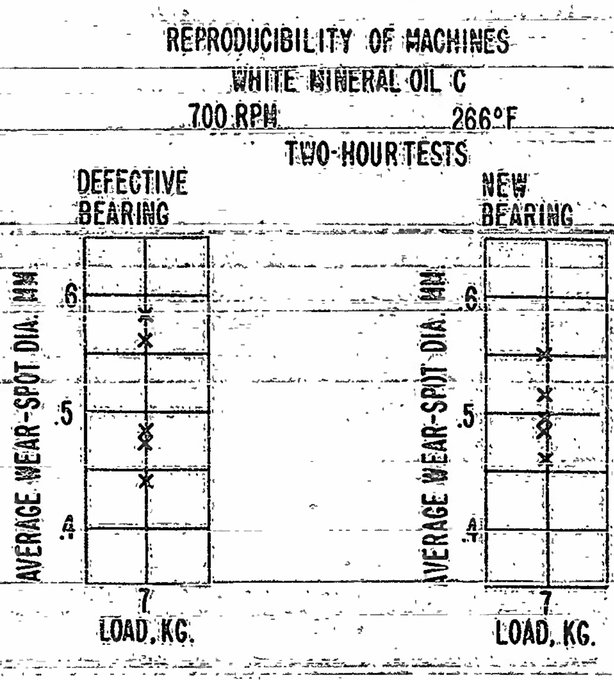


Figure 17

The effect of balls upon reproducibility is shown in Figure 18. The low-viscosity white mineral oil C, was used in five 120-minute test runs at 700 rpm. Four new steel balls were used for each run. The test temperature was 266°F and the applied load was 7 kg. Under identical test conditions five runs were also made with the same four balls for each run. This was accomplished by rotating the four balls to a new position. All the balls were from the same batch. The results showed a considerable improvement in reproducibility when the same balls were used. Undoubtedly, balls from different batches would have produced poorer results.

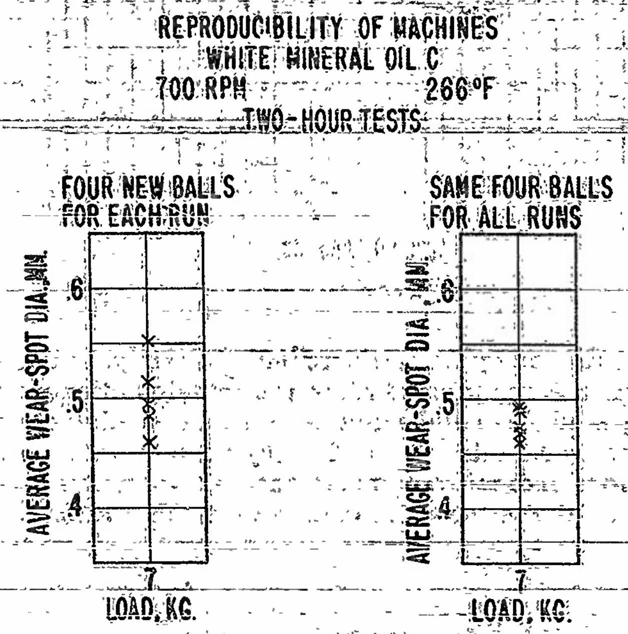


Figure 18

Reproducibility Between Machines—Shown in Figure 19 is the reproducibility between two machines before and after alignment of the chuck ball, ball adapter nut, operating head, and spindle assembly. A group of five runs were made with white mineral oil C and at an applied load of 7 kg and a speed of 700 rpm. The operating temperature was 266°F. Since tests had shown that greater reproducibility was obtained when the same balls were used, two groups of four balls, each from the same batch, were employed to obtain the results recorded. The results show that good alignment of mechanical parts is necessary for reproducing results between machines.

Additive Effect

That the four-ball wear machine is capable of distinguishing between the wear-preventive properties of lubricants is exemplified in Figure 20, which compares the results with NS-2135 mineral oil with and without 1 percent tricresyl phosphate, a widely used wear-prevention agent. At the same arbitrarily selected loads the samples were run for 120 minutes at 266°F and 700 rpm. Four new steel balls were used for each run. The results show an effective reduction of wear at low loads. As higher loads are applied, the effectiveness of the tricresyl phosphate becomes less until it is negligible at 20 kg. Clearly, although (as was showed earlier) there is a hydrodynamic component in the lubrication at 0.3-kg loads, there must be a boundary lubrication component; otherwise there would be no influence on the wear-scar diameter at such low loads by only 1 percent additive.

Friction Measurements

Torque measurements were usually recorded within the first 15 seconds of operation and at five minute intervals thereafter. Experience showed that the most reproducible measurements were those obtained in the first 15 seconds and at applied loads between 7 and 20 kg. Even at this time interval, however, the reproducibility was too poor to permit any but general conclusions. From the torque measurements the coefficient of friction was calculated by the mathematical tools outlined under the subtitle "Apparatus."

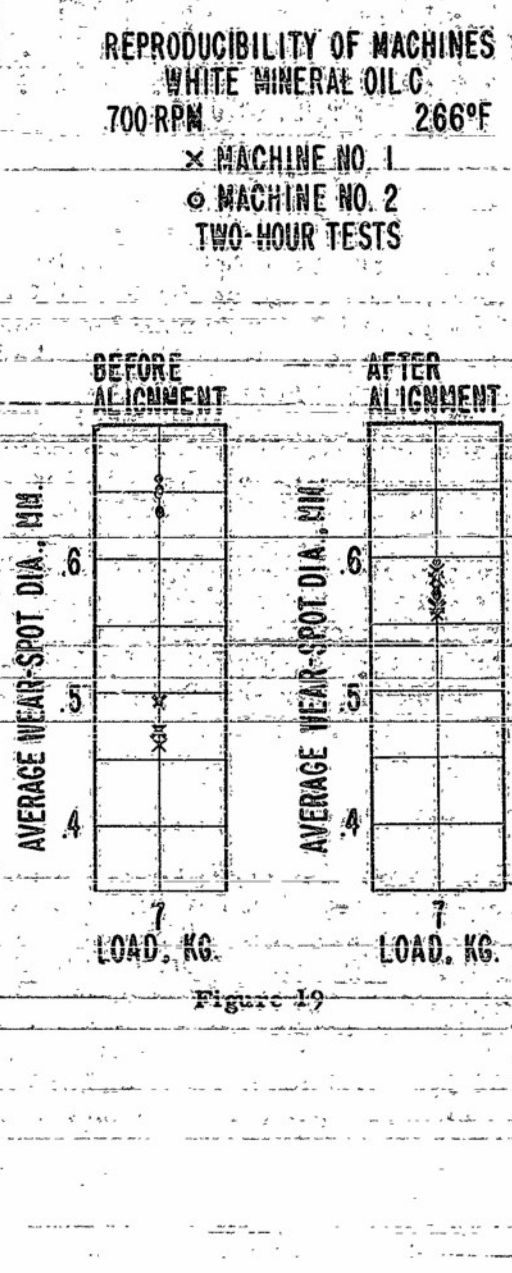


Figure 19

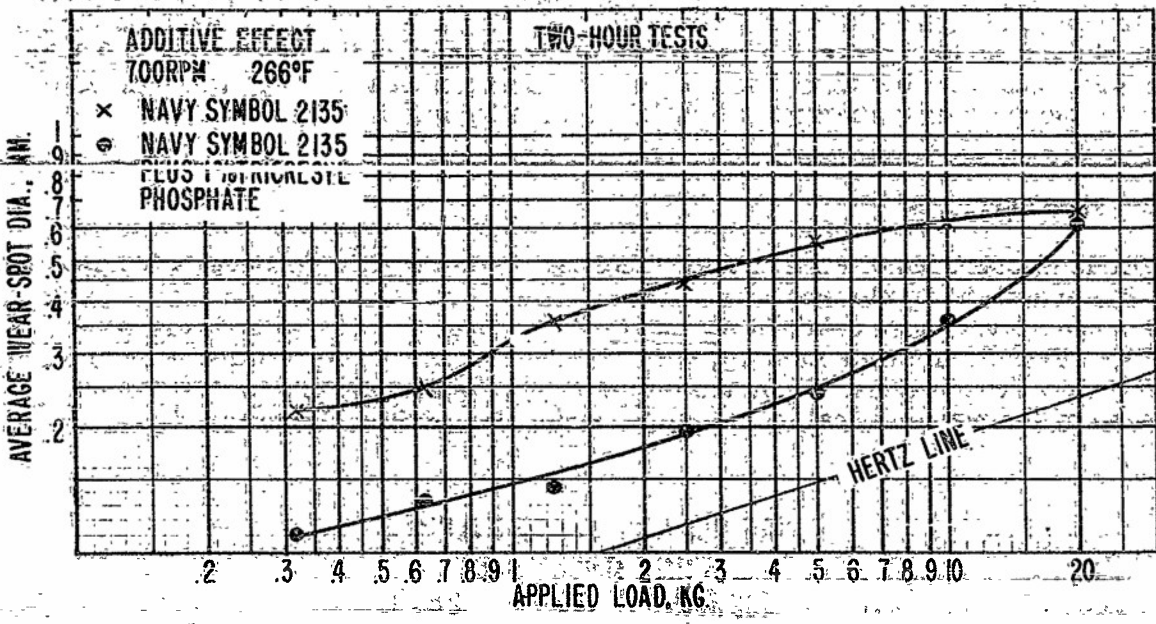


Figure 20

Where seizing did not occur, the initial coefficient of friction was the same for many diverse lubricants within the temperature range of 140° to 266°F and a load range of 10 to 20 kg. Undoubtedly small differences of friction do exist for these fluids, but the four-ball friction mechanism is too insensitive to detect them. None of the lubricants tested contained any of the known effective friction-reducing agents such as free fatty acids. After the test had been run for 120 minutes it was found that the final coefficient of friction was generally higher than the initial coefficient of friction, although the unit pressures were considerably less than at the start of the test. The data also disclosed that no simple relation existed between final wear-spot diameter and the initial or the final coefficients of friction.

It was found that the four-ball wear machines constructed at this Laboratory were too insensitive to measure accurately the coefficient of friction, although Perry (25) reported results that were of a fair order of reproducibility when similar machines were used. Fenske, and co-workers, however, using Precision Scientific Company machines also found the coefficient of friction very unreproducible when compared with the reproducibility of wear-spot measurements (55).

Miscellaneous Four-Ball Wear Phenomena

Wear-Scar Deposits—During a wear test, deposits were observed to form around wear scars when hard steel balls were employed. The quantity produced was generally dependent upon the size of the wear scar. An investigation of the relation of wear to the hardness of surfaces in the presence of the deposit has been reported by Webb (23). He used a petroleum motor oil in demonstrating that at 266°F, with a 7-kg load, and 700 rpm, wear was very high with hard steel rotating on hard steel even after 540 minutes of operation. At the same load and temperature, however, wear was very low when hard steel rotated on soft steel. The reduced wear with the soft balls was attributed to the reddish-brown deposits, identified as iron oxide. Microscopic observation revealed that the oxide became embedded in the soft balls at the points of contact, but not in the hard balls. He believed that the embedded oxide layer provided a protective film which prevented further oxidation of the sliding surfaces by the oxygen dissolved in the air-saturated lubricant.

In the NRL investigation consideration was given to the possibility of these deposits acting as abrasives which caused high wear when the material came between the sliding surfaces of the four hard-steel balls. Sketch A in Figure 21 shows the disposition of the deposits which formed around the wear scars. These deposits varied from a bright orange to a dark brown for most petroleum lubricants when either four hard-steel balls or four stainless-steel balls were used. Black, flocculent deposits were formed with monel balls and soft-steel balls. Water-base fluids produced reddish-brown deposits; those from the silicone lubricants varied from a white to a heavy-black gelatinous material which permeated the bulk fluid surrounding the four hard-steel balls. In general the amount of deposit varied directly as the wear-scar diameters.

Several attempts were made to remove the deposits as soon as formed and to prevent them from being carried back under the sliding surfaces. The most successful of these consisted of pumping fresh fluid continuously into the test cup and inserting a small felt-lined wiper, shown in sketch B of Figure 21, in the space between the rotating ball and the three lower balls. The wiper was very effective in removing much of the material carried by the rotating ball and the eddy currents of the fluid back under the contact surfaces, but some deposit was still found around the wear scars. Reducing the flow rate of the fluid to a point where the four balls were no longer immersed in a pool of lubricant but were merely covered by a flowing film did not reduce further the amount of deposit found around the wear scars.

When a felt wiper was used with white mineral C of Figure 7 the tests showed no reduction in wear after 120 minutes of operation with an applied load of 20 kg even though the amount of deposit accumulated on the surface around the contact areas was negligible. X-ray diffraction studies of the deposits formed with the white mineral oil did not reveal the presence of oxides of iron (although spectrochemical analysis showed the presence of much iron), nor did the nature of the deposits with a dimethyl silicone fluid, DC-500 (see Table 1 for viscosity-temperature characteristics) resemble the usual physical appearance of the oxides. The white deposit resembled the gel formed when this fluid was tested earlier in a unilaterally loaded journal-bearing machine (58). Brown and black particles were observed in the white gel. With a methyl-phenyl silicone, however, DC-710 (see Table 1 for viscosity-temperature characteristics) a considerable black deposit was found. Reference has been made to these deposits because of their possible relation to the extent of acceleration and reproducibility of wear in the four-ball wear machine. Later in this report reference will be made to the deposits formed by each lubricant studied.

Of possible interest in connection with wear-scar deposits on the three lower balls, is the appearance of the upper rotating ball after a wear test. The rotation of the upper ball forms an annular wear path parallel to the equator of rotation. This path consists of parallel striations around the ball which appear to form a mating surface with the striations visible on the surface of the wear scars. In general the path itself is free of debris, but debris is found on each spherical segment bordering the wear path. The deposit was always of the same nature as that around the wear scars and did not form any particular pattern.

Shape of Wear Scars—In general wear scars obtained with petroleum oils are round, the ellipticity seen through the microscope being due to the inclination of the axis of the scar. This is not true for all fluids since wear scars produced by some of the aqueous-base fluids and some silicones at certain applied loads produce elliptical wear scars like those illustrated at C in Figure 21. Elliptical wear scars are usually removed from the test cup and measured. The average of the major and minor axes is considered the measure of wear. The reason for these peculiar scars is not apparent. Under extreme pressure conditions such wear scars are commonplace particularly in the region of immediate seizing (e.g., the branch marked CD on the extreme-pressure curve in Figure 2). It has also been observed that some wear scars are rather irregular in shape or square-round (see Figure 21-C) so that the accuracy of measurement is rather poor. This was particularly true when monel balls were used.

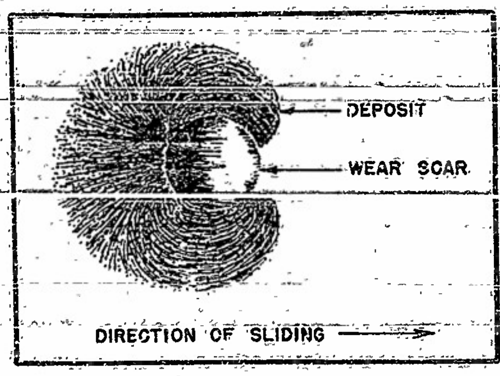
Theoretically it should be possible to obtain only round wear scars unless seizing occurs. Fenske and co-workers have reported that wear scars on steel balls became elliptical when the speed was increased from 670 rpm to 1725 rpm (55). Presumably their statement was based upon studies with a blended white oil. NRL studies with petroleum oils at 4800 rpm did not produce such wear scars, but it may very well be that there is a relation between the fluid, the sliding speed, and the degree of ellipticity. Most wear scars have been observed at 700 rpm with temperatures of either 140°F or 266°F. This report will mention any unusual wear scars formed with the lubricants studied.

These varied phenomena show the complexity of wear as observed in the four-ball machine. It is apparent that viscosity effects cannot be ignored. Any standard method of evaluation must be sufficiently broad to encompass a wide range of loads, temperatures, and speeds. If the range of variables is limited, only a partial and incomplete picture of the wear characteristics of a lubricant is obtained. For any particular application a narrow range of variables may be sufficient to characterize the wear properties of a fluid. For research purposes the entire load range must be included and the temperature variable needs to be investigated at several temperatures over the operating range of the lubricant. Unfortunately speeds in excess of 700 rpm are likely to introduce vibrational errors into the drill-press model of the four-ball machine.

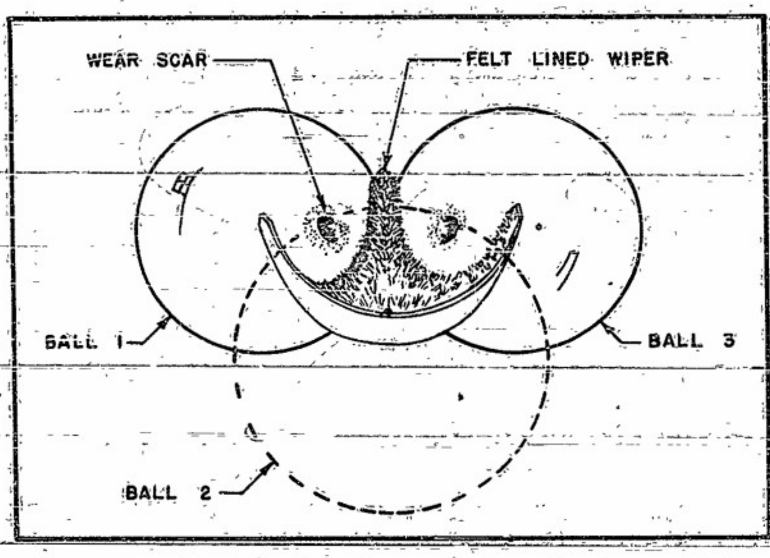
STUDIES OF SOME DIVERSE LUBRICANTS

The literature discloses that the four-ball machine is clearly capable of differentiating between petroleum oils with and without additives. Much of the published work pertains to mineral oils or to pure hydrocarbons. Adequate information is not available about the four-ball behavior of the aliphatic diesters (52, 53), the polyglycol ethers (59, 60, 61), and the silicones (62, 63, 64). It was one of the objectives of this investigation to show the nature of the wear-load curves of some of these new synthetic lubricants and to compare the results with comparable grades of some Navy Specification oils.

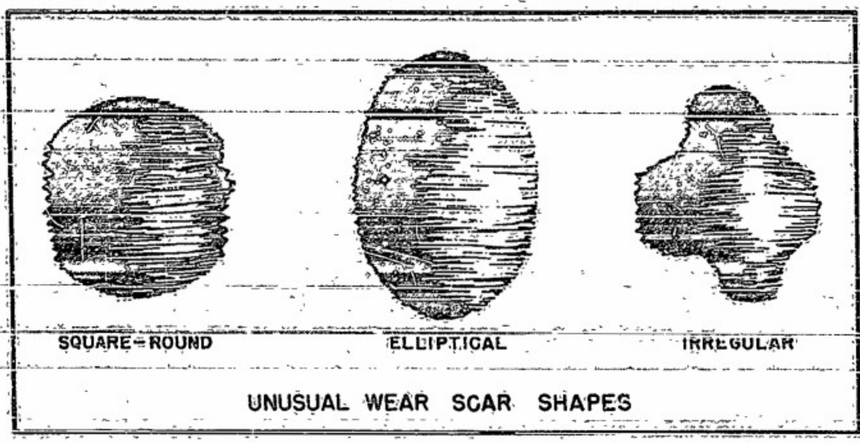
The two temperatures investigated were 140°F and 266°F. The coefficient of friction at 10-kg and 20-kg loads was measured for most of these samples at the beginning and at the conclusion of a test (Table 2). Also included in Table 2 are the median values of the initial and final coefficient of friction for all samples listed. The initial coefficient of friction appeared to be the most reproducible and was of the order of 0.10 for most of the lubricants except the silicones. The final coefficient of friction was generally nearly the same but was unreproducible for all samples listed, and often varied as much as 30 percent of the reported value. Only measurements made at 10 kg and 20 kg are included, since they seem to be the most reproducible. The effect of antioxidants and of the removal of adsorbable material were also studied; rarely did either cause significant changes in the coefficient of friction.



(a)



(b)



(c)
Figure 21

TABLE 2

Friction and Wear Data on Oils Studied

Lubricant Designation	Initial Coefficient of Friction				Final Coefficient of Friction				Final Wear-Scar Diameter, mm.			
	Applied Load 20kg		Applied Load 10kg		Applied Load 20kg		Applied Load 10kg		Applied Load 20kg		Applied Load 10kg	
	140°F	266°F	140°F	266°F	140°F	266°F	140°F	266°F	140°F	266°F	140°F	266°F
NS - 2110 UP	.09	.11	.10	.09	.13	.12	.10	.09	.731	.800	.561	.476
NS - 2110 P	.09	.09	.09	.10	.10	.14	.12	.12	.794	.709	.556	.556
NS - 9250 UP	.09	.09	.10	.10	.08	.09	.06		.459	.513	.284	
NS - 2190T UP	.09	.08	.10		.11	.12	.13		.680	.726	.514	
Di-(2-ethyl-hexyl) sebacate plus antioxidant	.10	.10	.09	.10	.12	.12	.12	.04	.663	.805	.624	.533
Di-(2-ethyl hexyl) sebacate P	.09	.10	.10	.12	.12	.12	.13	.14	.601	.926	.505	.629
NO-14-0-20 UP	.09	.10	.10	.10	.11	.07	.11	.09	.635	.437	.527	.329
Ucon-LB 100 P	.09	.08	.10	.08	.12	.13	.13	.14	.652	.505	.567	.561
Ucon-LB 100 UP	.10	.10	.11	.10		.12		.11		.703		.380
Ucon-LB 100X (inhibited)	.11	.09	.11	.09	.10		.13		.669	.754	.510	.448
Median value of coefficient of friction for all samples	.09	.10	.10	.10	.11	.12	.12	.11				

UP - Unpercolated
P - Percolated

Coefficients of friction for the silicones are not included in Table 2 because the violent seizures which occurred made it impossible to obtain accurate readings. Since the friction forces were less erratic at 10 kg, an approximate value of the initial coefficient could be made. In general this value was about 0.20 for all silicones at 140°F, but at 266°F it had dropped to approximately 0.13. The final frictional torque was too erratic to be recorded.

Petroleums and Hydrocarbons

A viscosity-temperature chart of the three Navy-symbol petroleum oils examined is shown in Figure 22. A conventionally refined nonadditive oil is exemplified by NS-2110, a heavy-duty detergent-type oil by NS-9250, and an oxidation- and rust-inhibited turbine oil by NS-2190T.

The results obtained with percolated NS-2110 oil at both 140°F and 266°F are shown in Figure 23, where the diameter of the wear scars after 120 minutes of operation at 700 rpm are plotted against the applied load. At the lowest load (0.16 kg) the wear scar is identical at both temperatures. The wear-scar diameters increase more rapidly with increasing loads at the higher temperature until loads of approximately 2.5 kg are applied. This increase may be due to the decrease in the viscosity of the oil. As the applied load is increased above 2.5 kg, the graphs tend to converge at approximately a 20-kg load. At the higher loads (above 2.5 kg) the antiwear action of the polar oxidation products formed tends to neutralize the viscosity effect, and the antiwear action becomes the predominant effect at 20 kg. The contact temperature and the oil temperature in the test cup diverge as the applied load increases. The temperature of the contact may be sufficiently above the stable oil temperature so that polar oxidation products are formed. When the oil in the test cup is 140°F the contact temperatures are not sufficiently high to form polar materials with antiwear properties and the wear increases normally with the applied load.

The wear-load curves of unpercolated NS-2110 are shown in Figure 24. The difference between Figure 24 and Figure 23 may be attributed to the polar impurities originally present. It is shown graphically in Figure 25 for runs at 140°F. At loads approaching 10 kg and 20 kg the presence or absence of polar materials is of little consequence. One may conclude that wear protection inherent in unpercolated oils is partially due to adsorbable materials, and that these adsorbable materials are most effective at low unit pressures.

At both temperatures, when either the percolated or unpercolated oils were used, the wear scars were round and smooth and the debris had a red-brown color. Squealing of the apparatus occurred with both oil samples at various loads but was not continuous. Initial periods of quiet frequently preceded high noise levels. Frictional forces were constant for percolated and unpercolated oils and were of the same order of magnitude as for other mineral oils.

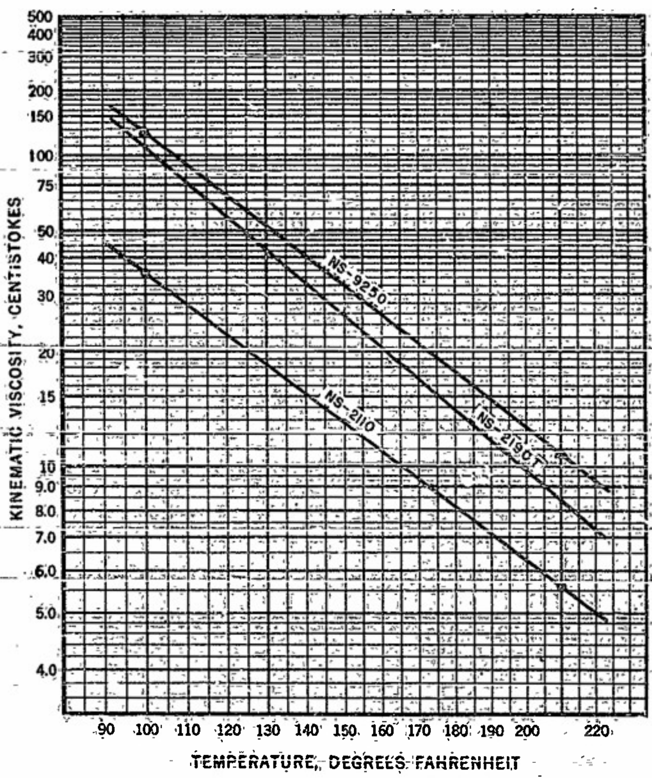


Figure 22 - Viscosity-temperature chart

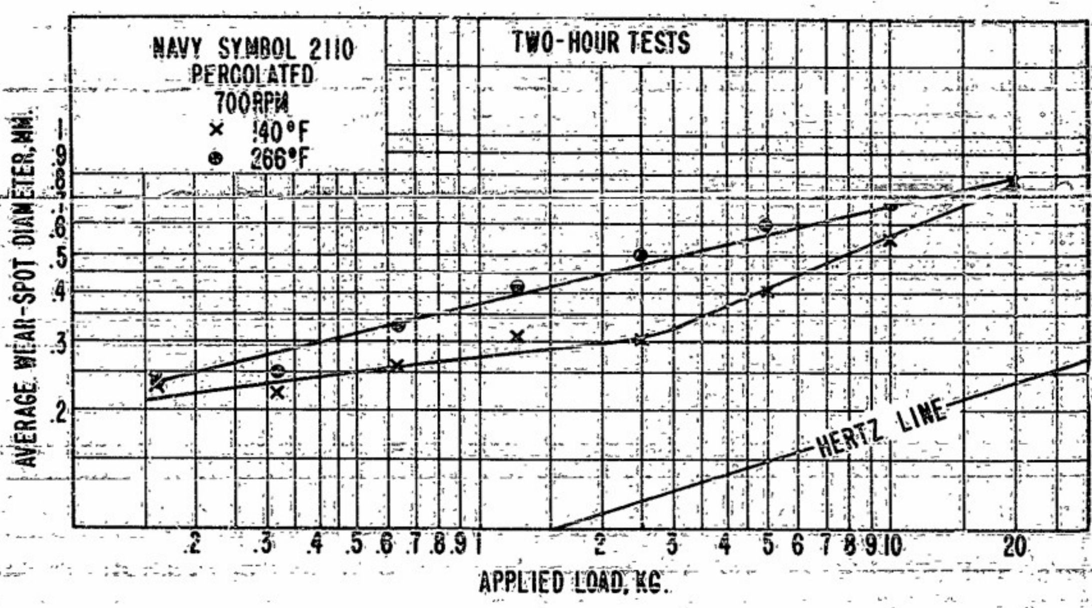


Figure 23

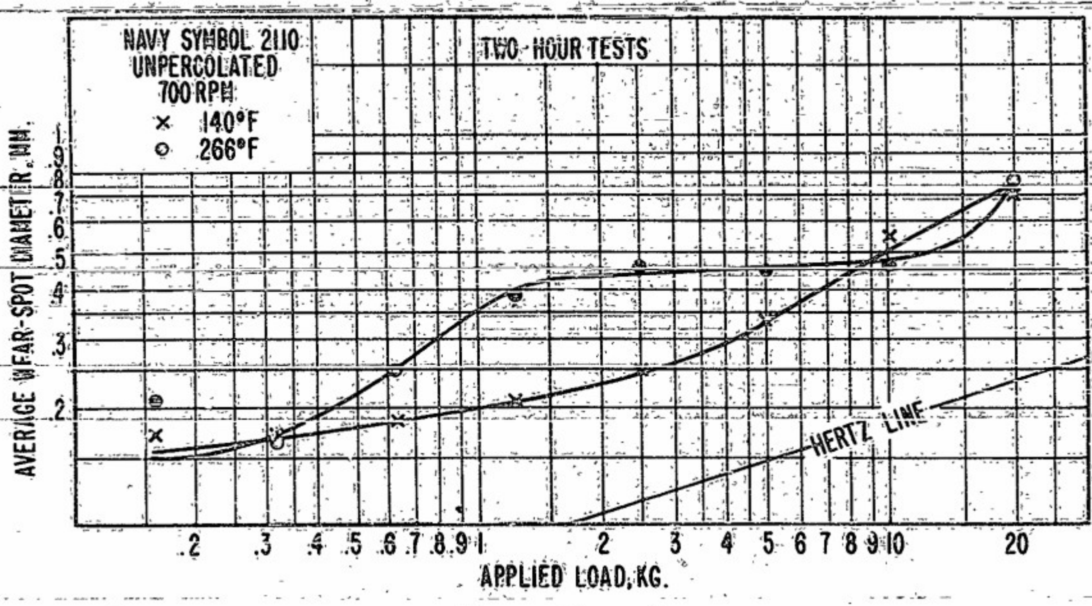


Figure 24

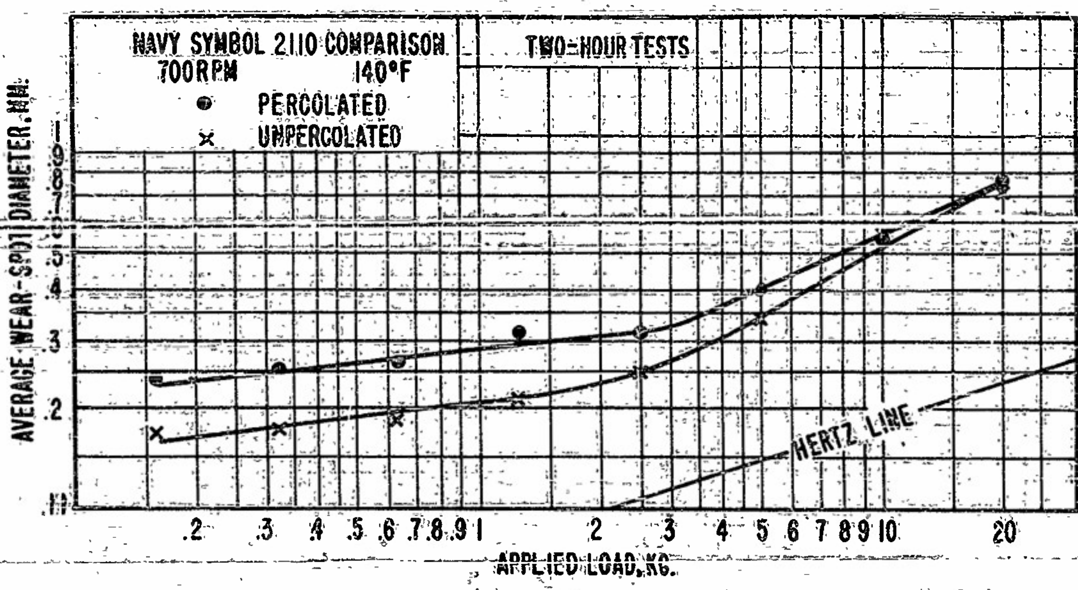


Figure 25

The wear-load diagram of NS-9250 oil (Figure 26) shows a reduction in wear at 266°F between the loads of 2 and 5 kg; this is attributed to the detergent additive. The points on these curves have been carefully checked. The wear debris formed at both temperatures was red-brown in color and the deposit was as shown in Figure 21A. No squealing was experienced with this sample. The initial coefficient of friction was of the same order as that of the other mineral oils.

The wear-load diagram for NS-2190T oil is shown in Figure 27. The occurrence of an unstable region of seizing at 140°F with approximately 1 to 2.5-kg loads would suggest that this turbine oil may be inadequate under certain service conditions. Under loads of less than 1 kg unusually low rates of wear were obtained; above loads of 2.5 kg excessive wear occurred. Elevation of the bulk-oil temperature to 266°F completely eliminated the seizing. At this temperature the sample showed considerable improvement in wear characteristics at nearly all loads. The reduction in wear which accompanied the increase in temperature is the reverse of that found with nonadditive oils. The effect of the additives completely overshadows that of viscosity at the low loads. This could be attributed to the increased activity of the additives at the higher temperature. The low wear observed suggests the presence of an antiwear agent as well as a rust inhibitor. The debris formed with this sample at both temperatures was the same red-brown material found for the majority of lubricants, the wear scars were round, and squealing occurred only occasionally. The initial coefficient of friction was of the same order as that of the other mineral oils.

The only pure hydrocarbon studied was cetane, manufactured by E. I. DuPont de Nemours and Company and designated as M.O. 62004. It is predominately n-hexadecane. A sample percolated through layers of fuller's earth and silica gel did not spread on the clean surfaces of either alkaline or acid water, and it gave higher wear at all loads (Figure 28) than did the sample as received. Another indication of the poor lubricating quality of the percolated sample was the excessive squealing obtained at almost all loads. Friction measurements on this sample are not included in Table 2 since wide variations in the torque were observed.

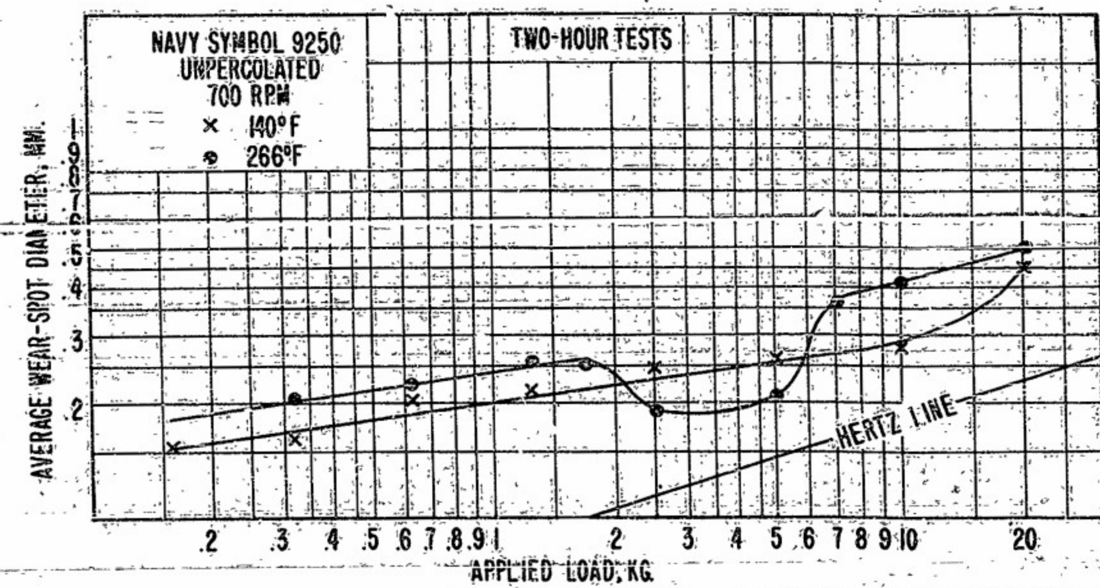


Figure 26

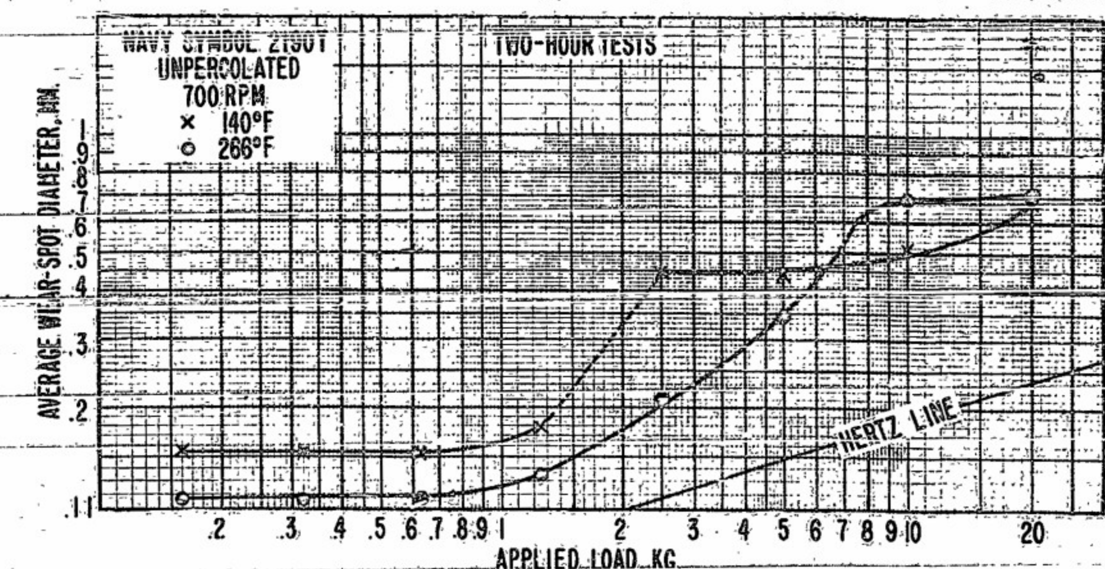


Figure 27

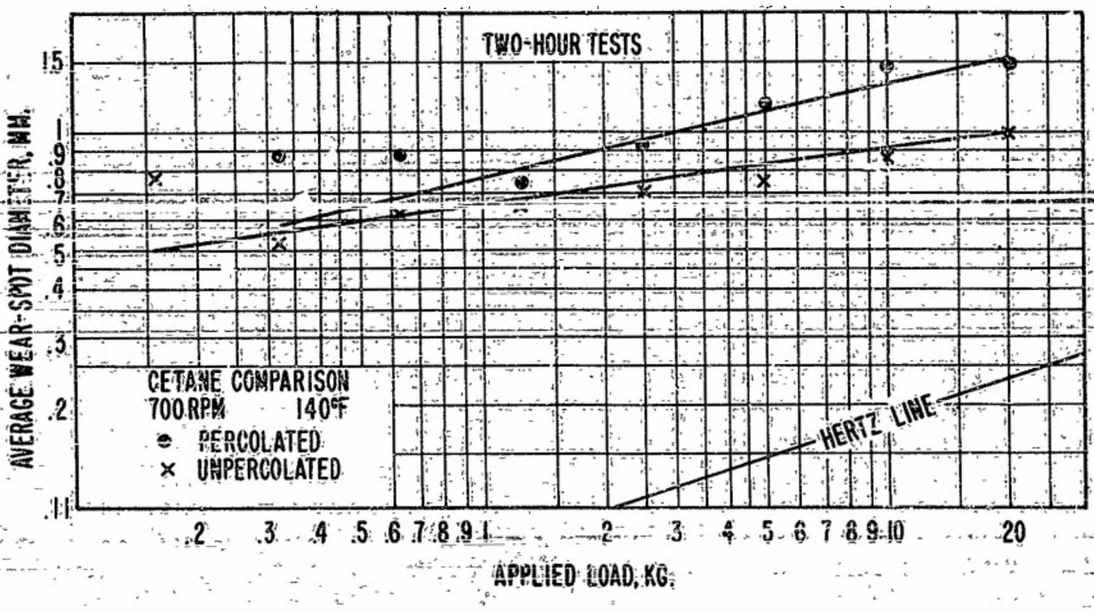


Figure 28

The effect of temperature upon the unpercolated sample of cetane at 140°F and 212°F is shown in Figure 29. The wear-load diagram shows a decrease in wear when the temperature was elevated. The unexpected decrease may be due to the oxidation products formed, which may have some antiwear action (65). With the percolated sample at 212°F such severe seizing occurred that efforts to obtain a wear-load curve were discontinued. The wear spots were round, and, with both percolated and unpercolated fluids, red-brown flocculent deposits were formed at both temperatures. Less squealing occurred with the unpercolated sample.

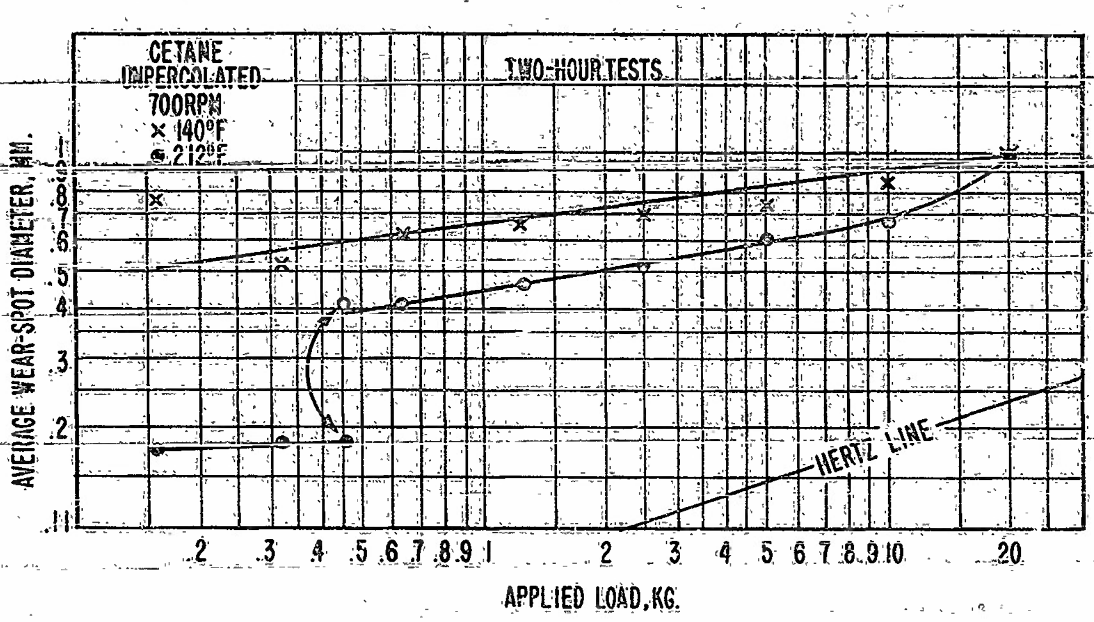


Figure 29

Silicones

Three silicone fluids manufactured by the Dow Corning Corporation were studied. Samples of these fluids were percolated through Florisil (66). Their viscosity-temperature properties are given in Table 2. No significant changes in the viscosity-temperature curves were caused by percolation. The results obtained with dimethyl silicone (DC-500 Serial No. 369-62-69), as received and after repeated percolation, are shown in Figures 30 and 31. There is little significant difference in the wear rates at 266°F between the percolated and unpercolated samples. Removal of adsorbable material had a detrimental influence upon the wear at 140°F. At this temperature the wear rate was low for the unpercolated sample and is comparable to that of a nonadditive mineral oil such as NS-2110 (Figure 23). The dotted lines in Figure 30 represent unstable regions of lubrication of the wear-load curve where seizing occurred. (Cf. Figures 8, 10, 11, 27.) Wear scars, formed at high loads and both temperatures for the percolated and unpercolated samples, were irregular in shape. At lower loads they were nearly circular and the squealing was not continuous as at high loads. A brownish-white gelatinous material was deposited around each wear scar.

The coefficient of friction was impossible to measure, because the torque arm oscillated violently at high loads and at each temperature with both the unpercolated and the percolated sample. Similar torque characteristics were found for all silicone fluids, therefore, the coefficient of friction for those fluids is not included in Table 2. In view of the fact that the torque arm oscillation was as severe with the dimethyl silicone as with other types of silicones, it was surprising that the wear scars were much smaller at nearly all loads and at each temperature.

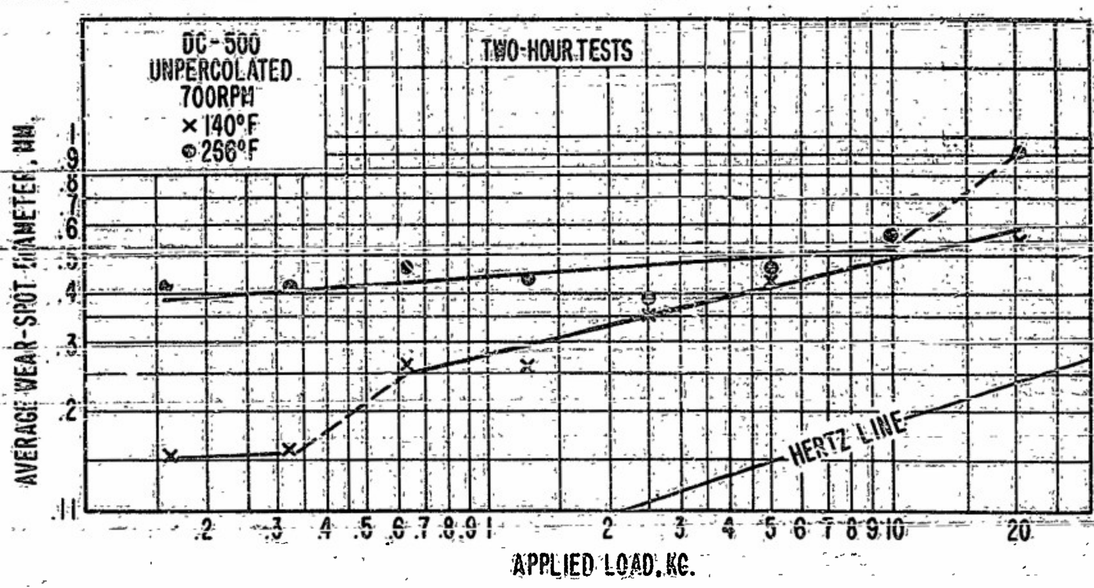


Figure 30

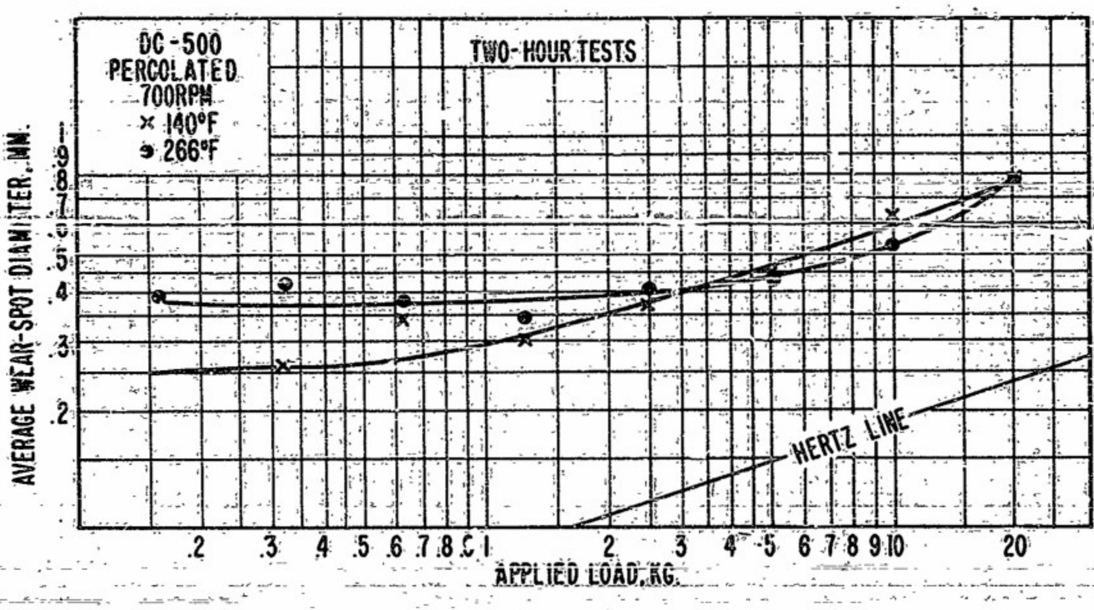


Figure 31

The wear-load curves of the methyl-phenyl silicone (DC-550 Serial No. BB-25) percolated and unpercolated are shown in Figures 32 and 33. The high rates of wear obtained at all loads is the result of severe seizings. These curves are typical of wear-load curves obtained with mineral oils under extreme-pressure conditions in the Boerlage four-ball machine. The results show the poor lubricating ability of this fluid with steel balls. Percolation of DC-550 caused seizing at lower loads (0.45 to 0.63 kg) than with the unpercolated sample at 140°F. At 266°F, percolation caused no significant change in the wear of DC-550 silicone. In general, increasing the temperature increased the wear. The wear scars formed at high loads were elliptical in shape, and the bulk fluid was permeated with a black gelatinous deposit. At low loads the fluid remained clear. Friction measurements were almost impossible to obtain because of seizing, but the approximate value was 0.20. Squealing occurred at nearly all loads, and seizing was so severe at 20 kg that it was impossible to lock the test cup sufficiently tight to prevent the three cup-balls from rotating. This difficulty was not experienced with DC-500.

The silicone with the higher phenyl-to-methyl ratio (DC-710, Serial No. 406-1-118) was as poor a lubricant as DC-550. The results for unpercolated DC-710 at both 140°F and 266°F are shown in Figure 34 and the results for the percolated sample in Figure 35. When the temperature was raised from 140°F to 266°F wear increased for both the percolated and unpercolated samples. Comparison of the percolated sample with the unpercolated sample revealed no change in wear at either 140°F or 266°F. With respect to friction, nature of deposit, and shape of wear scars, this sample behaved entirely like the sample of DC-550. Squealing was continuous, and at 20 kg seizing was of such magnitude as to rotate the three balls in the test cup.

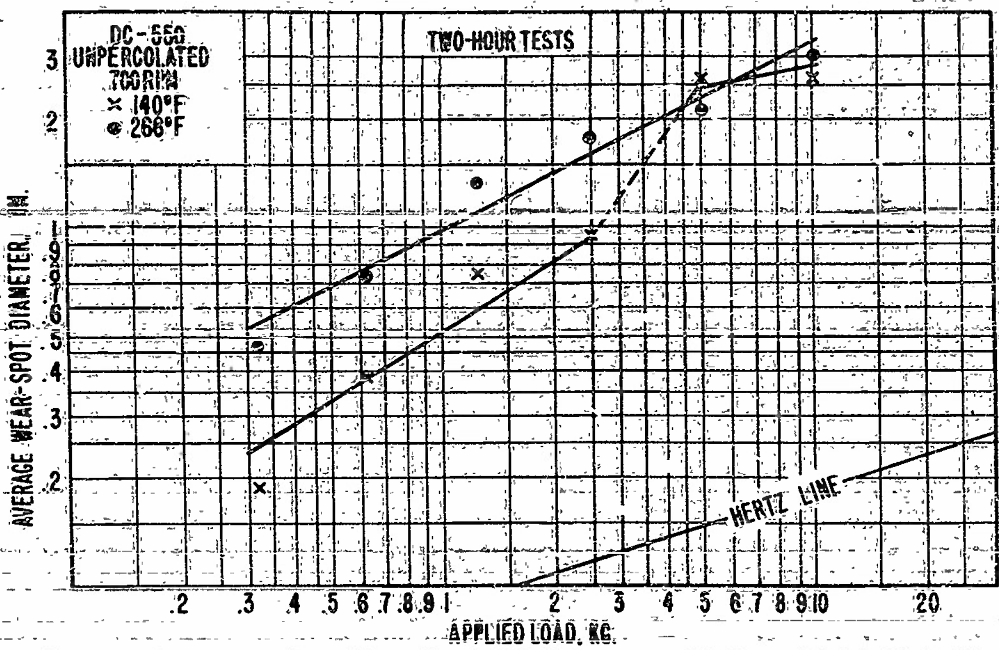


Figure 32

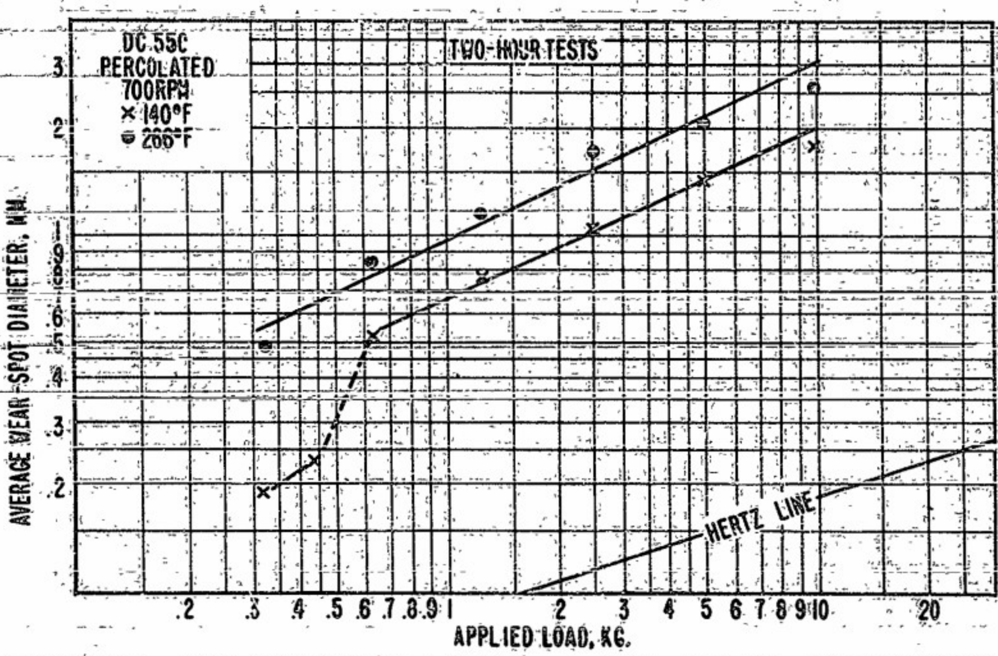


Figure 33

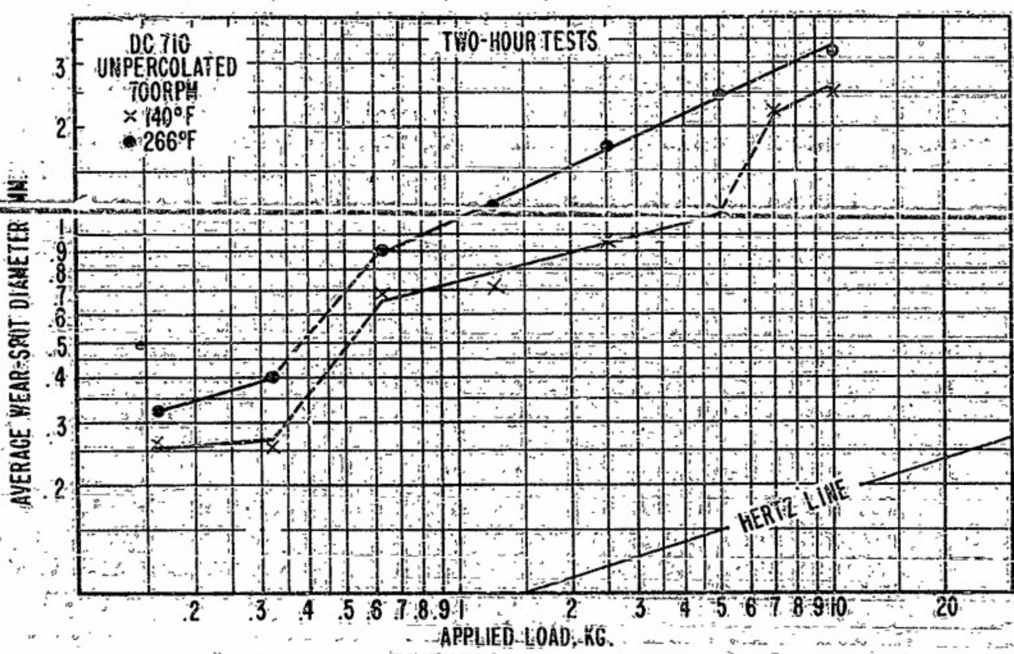


Figure 34

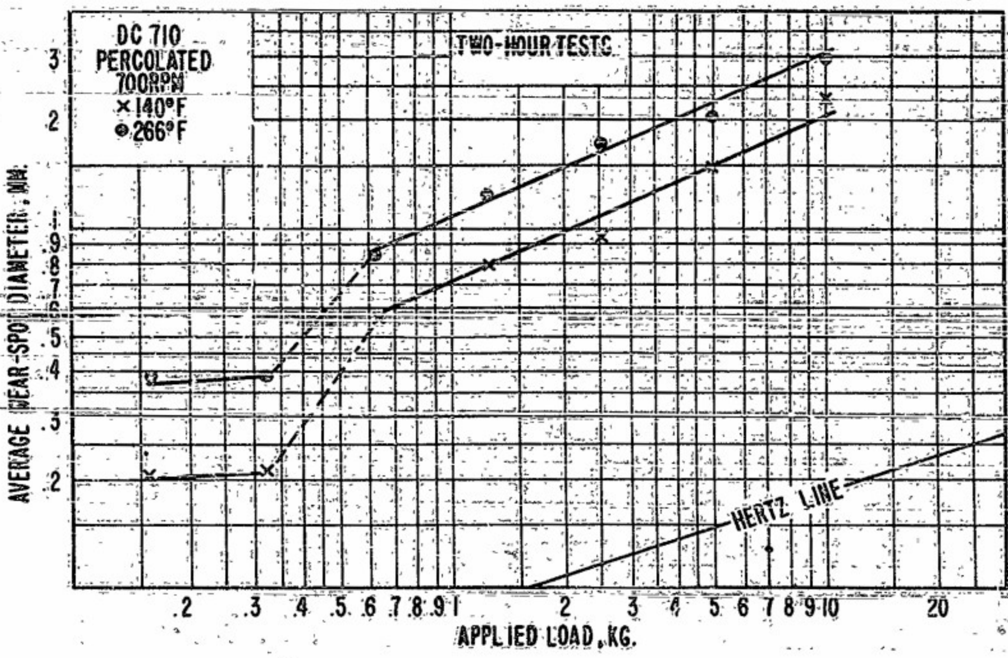


Figure 35

Comparison of the wear behavior of the silicones with that of cetane shows that DC-500 is a little better lubricant at high loads, but that cetane is a better lubricant than either DC-550 or DC-710. It is also concluded that, with respect to wear and the ability to resist seizure, the methyl-phenyl silicones are inferior to the dimethyl silicones as lubricants. However, at the lowest loads used the percolated DC-500 and the methyl-phenyl silicone, DC-710 cause approximately equal wear. This is clearly shown in Figure 36 which gives the curves for three percolated samples at 140°F. This conclusion is in accord with the earlier work at this Laboratory of Brophy, Larson, and Militz (58).

Diesters

Some results obtained with several diesters have been presented in conjunction with the viscosity studies. (The viscosity-temperature properties were given in Figure 9.) Among those studies was the wear curve of di-(2-ethylhexyl) sebacate at 140°F (Figure 8). This sample was percolated through fuller's earth and alumina, and the volatile impurities were removed by counter-current stripping (67). An increase in wear with an increase in temperature is shown in Figure 37. The dotted portion of the curves represents the regions of seizing. Seizing was observed at a lower load at 266°F than at 140°F. The initial and final coefficients of friction (0.10 - 0.12) are shown in Table 2 and are comparable to those for petroleum oils. The wear scars were round and surrounded by a brown deposit. Intermittent squealing was noted.

The effect of the antioxidant, 0.25 percent of 4-tertiary butyl, 2-phenylphenol (53), on the percolated di-(2-ethylhexyl) sebacate is shown in Figure 38. It is significant that the antioxidant had no effect upon the wear-load curve at 140°F other than to elevate the load at which seizing, indicated by the dotted portion of the curve, occurred. At 266°F the antioxidant eliminated the seizures between loads of 0.32 kg and 0.63 kg. The same percentage antioxidant in white mineral oil B had no effect upon the wear-load curve at either 140°F or 266°F. This would be expected if the general effect of the antioxidant is to eliminate seizing or reduce its intensity, or to elevate the load at which it occurs, since the uninhibited white mineral oil did not show seizure at either temperature.

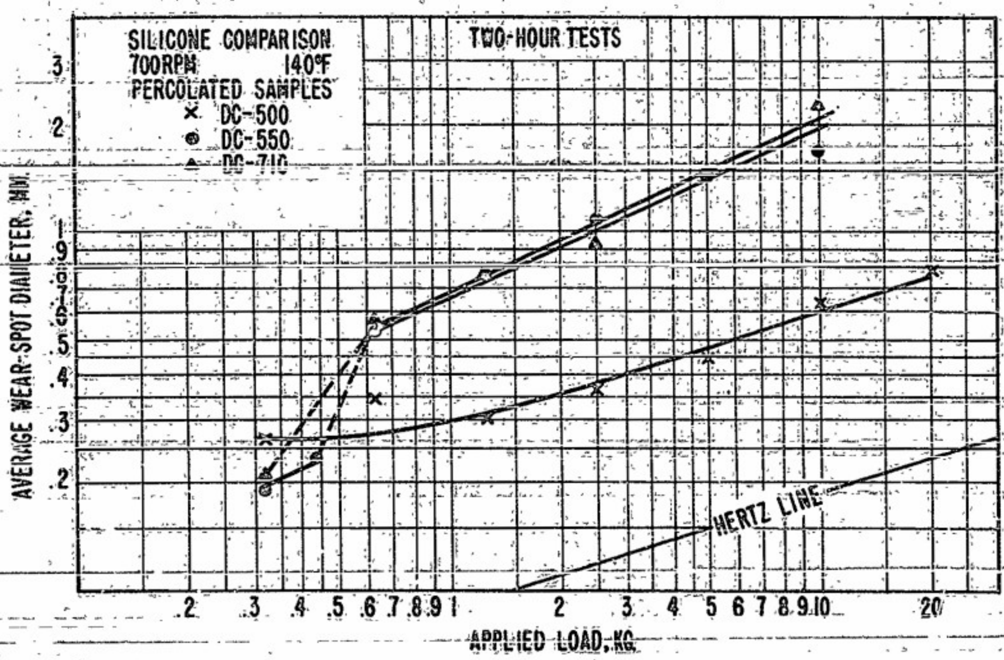


Figure 36

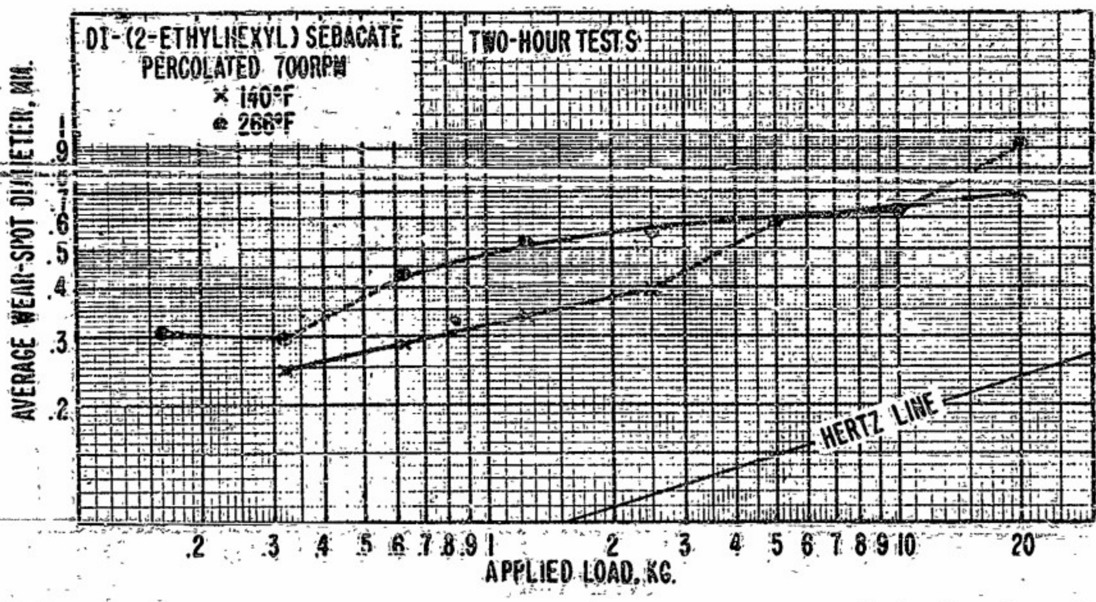


Figure 37

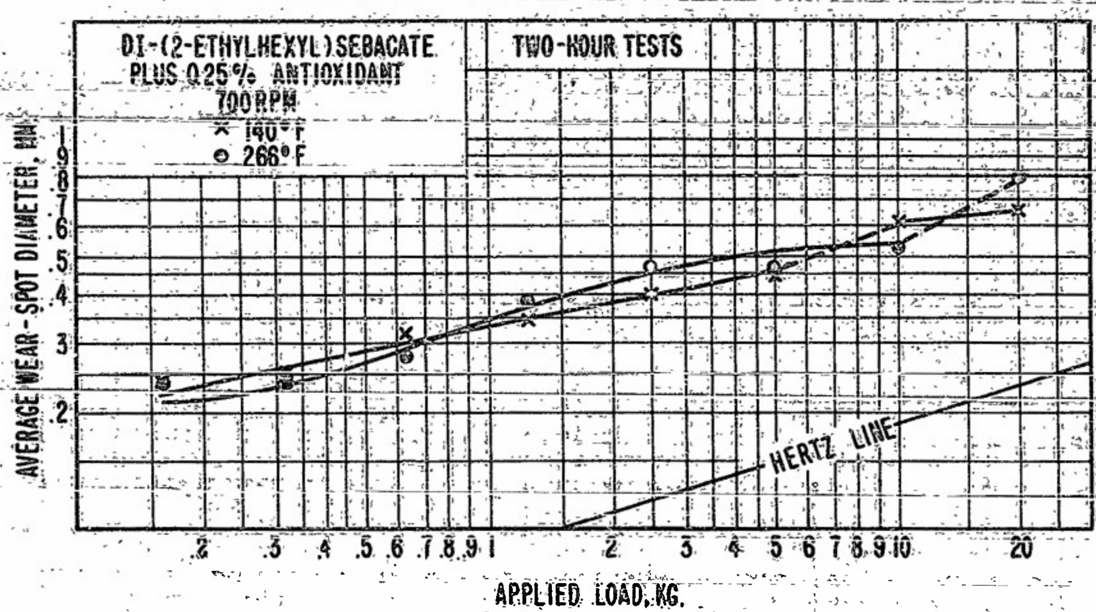


Figure 38

The wear-load curves at 266°F for the uninhibited di-(2-ethylhexyl) sebacate, the percolated white mineral oil B, and the percolated cetane at 140°F are shown in Figure 39. At these temperatures the samples have approximately the same viscosity (2.2 centistokes). Wear with cetane was higher at all loads than the wear with the sebacate or the white mineral oil.

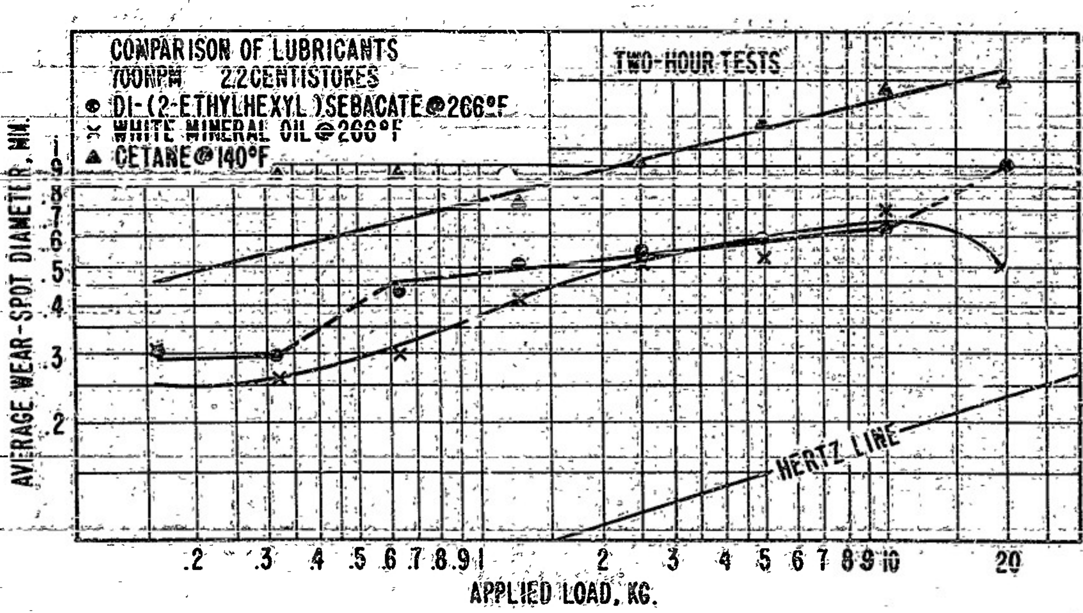


Figure 39

The results obtained with a di-(2-ethylhexyl) sebacate-base lubricant containing additives (Naval Ordnance Specification 14-0-20) are shown in Figure 40. The nature of the antioxidant was unknown, but the rust inhibitor was a high-molecular-weight barium petroleum sulphonate. A decrease in wear was obtained at 266°F at all loads. Presumably the antioxidant or the rust inhibitor is activated by the high temperature and gives considerable wear protection. This sample offered greater protection from wear than the laboratory-prepared sample containing only an antioxidant (Figure 38). The difference in wear at 140°F is not significant except in the load range 0.5 to 1.5 kg.

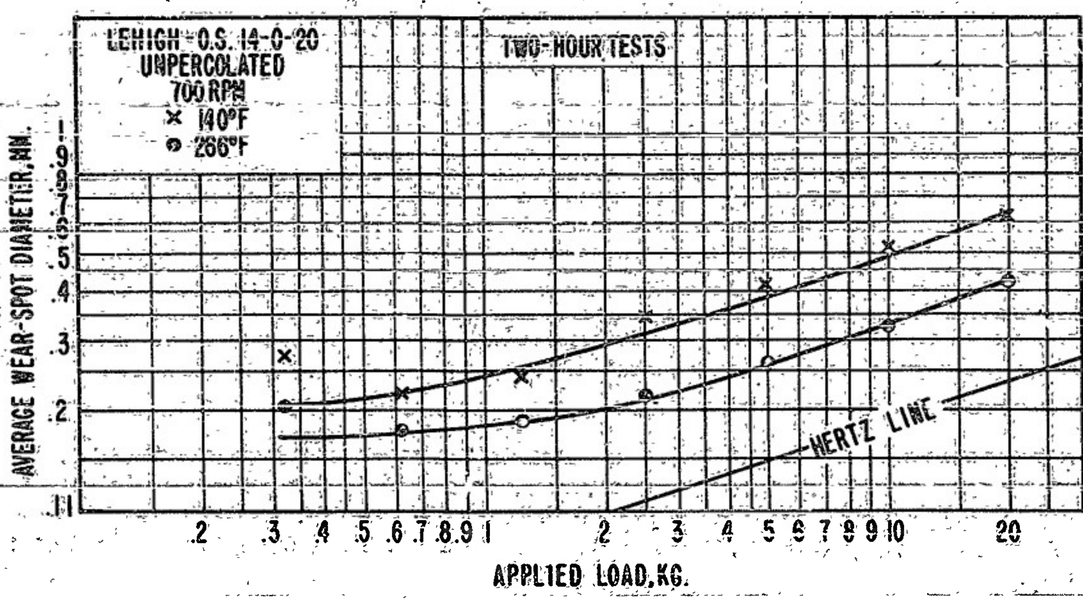


Figure 40

Polyglycol Ethers

The synthetic polyglycol ether LB-100 of the Carbide and Carbon Chemical Corporation was studied at 140°F and 266°F and the results are shown in Figure 41. The viscosity-temperature properties are given in Table 2. It will be seen that less wear occurs at the higher temperature with applied loads from 1 to 15 kg. This sample was stripped of volatiles but was not percolated. Aldehydes and acids may have been present and may have given wear protection at the intermediate loads when the temperature was 266°F. At loads less than 1.25 kg and 266°F, wear was slightly higher. The adsorbable material present probably acted as a mild wear preventive only when local contact temperatures are high. At low loads and unit pressures it would be expected that the viscosity effect would predominate resulting in higher wear.

The adsorbable material present in the sample of LB-100 was slight or was not an active wear-preventive at 140°F, since percolation through layers of fuller's earth and silica gel caused no change in the degree of wear (Figure 42); when, however, the temperature was raised to 266°F the difference between the unpercolated and the percolated sample was large (Figure 43). The wear debris was the same red-brown color for both the percolated and unpercolated samples. The wear scars were round and the initial coefficient of friction was a little higher for the unpercolated sample. A small amount of squealing occurred.

Figure 44 indicates that percolated LB-100 is unstable at 266°F since seizing occurred between 0.63 kg and 1.25 kg. The horizontal portion of the same wear curve between 1.25 kg and 20 kg may indicate that oxidation products effective in preventing further wear over a wide range of load were generated. Apparently these products are more effective in minimizing wear at high loads than the adsorbable material removed by percolation, because the wear curve for the unpercolated sample between 10 kg and 20 kg shows a trend toward much greater wear than that obtained for the percolated sample.

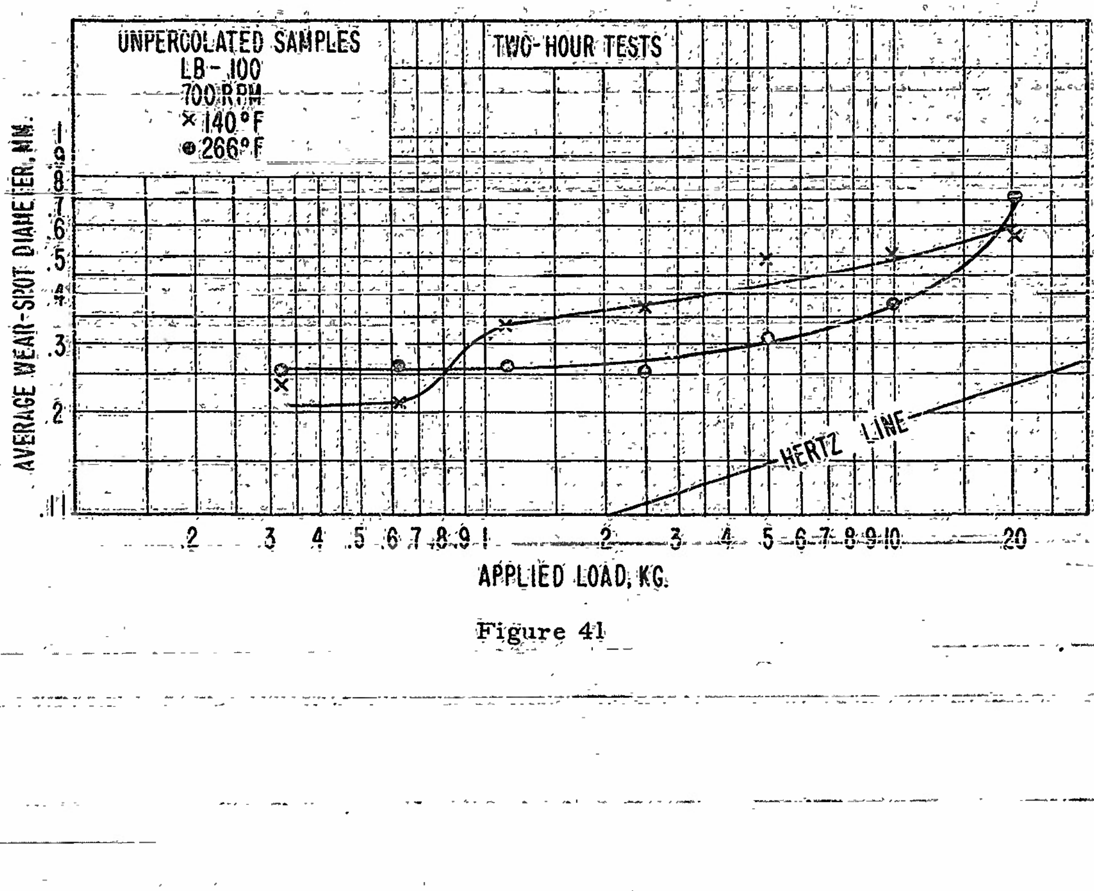
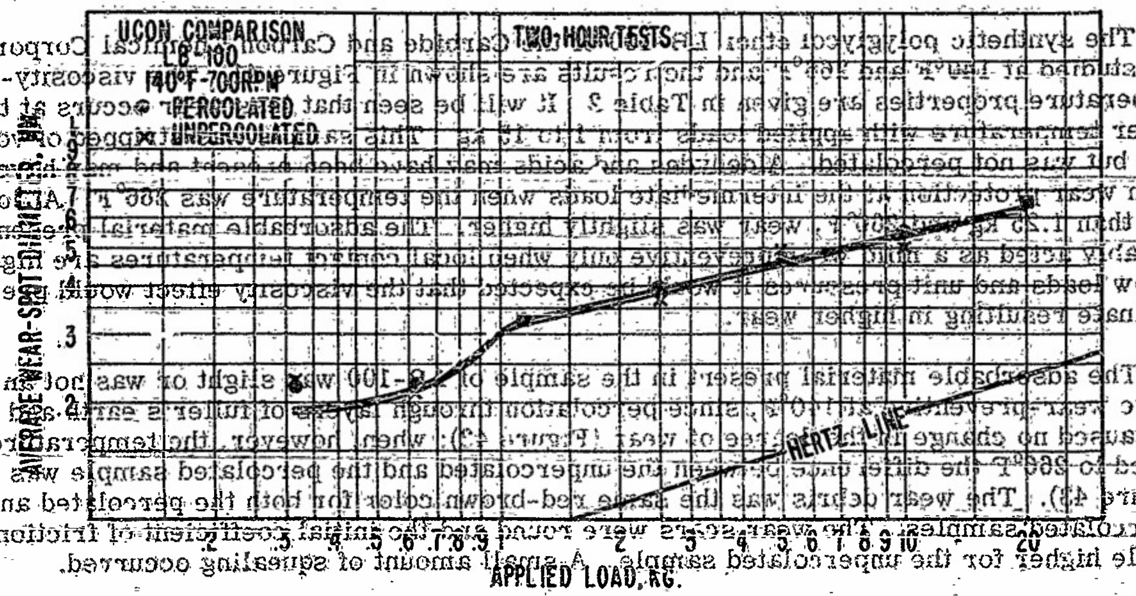


Figure 41


UCON COMPARISON
LB-100
140°F-700RPM
PERCOLATED
UNPERCOLATED
TWO-HOUR TESTS
AVERAGE WEAR-SPOT DIAMETER, MM.
HERTZ LINE
APPLIED LOAD, KG.

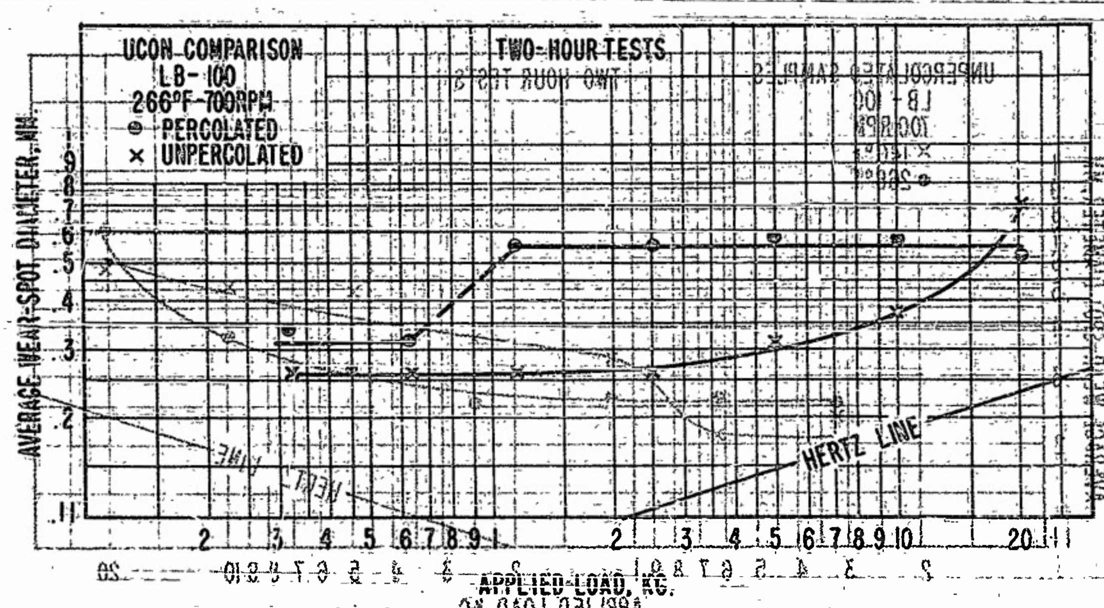

UCON COMPARISON
LB-100
266°F-700RPM
PERCOLATED
UNPERCOLATED
TWO-HOUR TESTS
AVERAGE WEAR-SPOT DIAMETER, MM.
HERTZ LINE
APPLIED LOAD, KG.

Figure 43

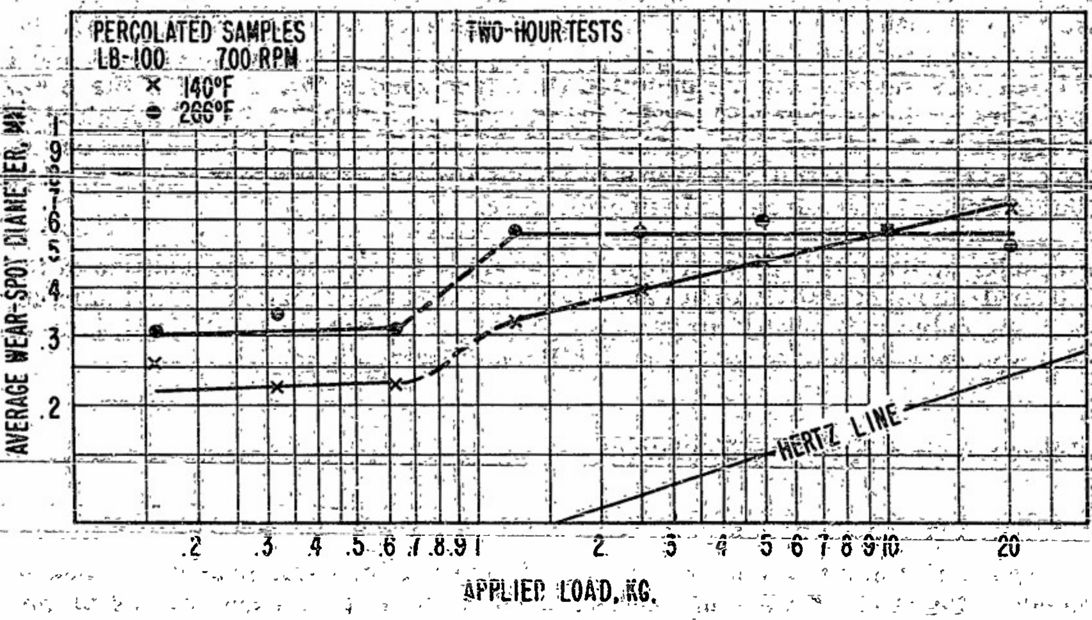


Figure 44

A sample of LB-100 containing approximately 2 percent of phenyl-alpha-naphthylamine as an antioxidant was evaluated at both 140°F and 266°F. This sample was designated LB-100X by the manufacturer. The wear-load curves obtained are shown in Figure 45. Apparently there is a stabilizing effect due to the presence of an antioxidant since there is no significant difference in the wear at the two test temperatures. However, the inhibited fluid showed much higher wear at 266°F than the unpercolated sample in Figure 41. There was also slightly more wear at 140°F.

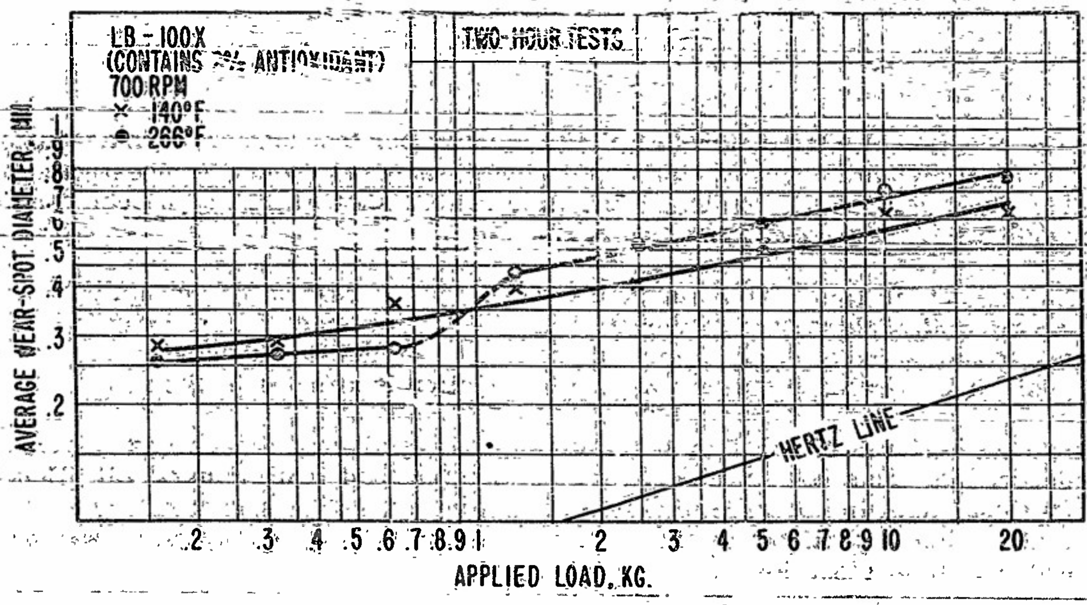


Figure 45

Comparison of Figure 45 with Figure 44 indicates that the presence of the antioxidant increased wear at loads higher than 10 kg when the temperature was 266°F. Also, the seizing which occurred between 0.63 kg and 1.25 kg for the percolated sample at 266°F in Figure 44 was less severe with the inhibited fluid (see Figure 45). At 140°F there was no apparent difference in wear at high loads, but at loads less than 2.5 kg the inhibited fluid produced higher wear. There was nothing unusual about the color of the debris or the shape of the wear scars. The initial coefficient of friction was a little higher than that of the uninhibited fluid. Squealing occurred only occasionally.

The results indicate that polyethylene glycol ether LB-100 with the addition of the antioxidant, phenyl-alpha-naphthylamine caused greater wear than an unpercolated sample of the fluid containing only its "natural" impurities. The general behavior with load, however, (Figure 45) was very much like that of a stabilized diester (Figure 38).

CONCLUSIONS AND RECOMMENDATIONS

General

The purpose of this study was twofold: To determine the usefulness of the wear-machine as an adjunct in the study of wear mechanisms and its value as a practical tool in the development of synthetic lubricants and antiwear agents for silicone, diester, petroleum and aqueous base lubricants.

(a) It is concluded that wear in the four-ball machine is tremendously complex and its value in wear mechanism studies is difficult to evaluate without further study of the various variables which affect wear as well as the types of wear which occur in the four-ball machine.

(b) The employment of the four-ball wear machine as a practical tool for forecasting a lubricant's resistance to wear prior to service tests, the ultimate criterion, appears very useful since this study showed detectable differences in wear for many lubricants irrespective of the variables which affect wear in the machine.

Specific

(a) The adoption of a time standard of 120 minutes per test load appears adequate for most petroleum lubricants, but new and unusual fluids should be investigated for very long periods of time since the time studies showed that some lubricants show evidence of breakdown after long periods of wear testing.

(b) Increasing the speed from 700 rpm to 4800 rpm decreased the amount of wear incurred with a petroleum lubricant at low loads. The decrease in wear is believed due to increased wedging of the lubricant between the rubbing surfaces at the higher rpm. It is concluded that the wear-load relation is affected by the rpm.

(c) At temperatures of 266°F or less, wear at nearly all loads increased as viscosity decreased. This was found to be true of diesters and white mineral oil. Hence the four-ball machine does not measure exclusively the effects of boundary friction and wear. This is particularly true at low loads since the viscosity effect was more pronounced at these loads.

(d) Reproducibility of measurements was adequate only after careful alignment, selection of spindle bearings, and the use of the same balls. Frequent checking of performance is necessary.

(e) In most instances there was less wear in the presence of polar adsorbable impurities. Their presence was less significant at high temperatures, presumably due to thermal desorption.

(f) Mineral oils and hydrocarbons are very poor lubricants in the absence of chemically active addition agents.

(g) The lubricating qualities of oxidation-stabilized and unstabilized diesters and polyglycol ethers are comparable with white mineral oil in the four-ball machine.

(h) Less wear occurs with the methyl silicones than with the methyl-phenyl silicones.

(i) Antioxidants added to diesters and polyglycol ethers have little effect on their wear-load curves.

(j) It is concluded that this machine offers many experimental conveniences for comparing the wear properties of lubricants and additives. Results are reasonably reproducible.

(k) Since a peculiar distribution of wear debris was noticed, its possible effect upon wear deserves further investigation.

(l) Further work is recommended on various aspects of wear prevention.

ACKNOWLEDGMENT

The excellent work of Mr. Charles Henderson, who built the wear machines, and of Mr. Paul Leach, who obtained a portion of the experimental data and aided in the preparation of tables and figures, is gratefully acknowledged. Indebtedness to Dr. William A. Zisman and Mr. Jere E. Brophy is likewise acknowledged for planning this study and for valuable suggestions during the course of its progress.

BIBLIOGRAPHY

1. Boerlage, G. D., Engineering, 135, 46-47 (1933)

2. Clayton, D., Inst. Mech. Eng., Proc., General Discussion on Lubricants and Lubrication, 2, 34-42 (1937)

3. Ibid., 274-284

4. Clayton, D., J. Inst. Petrol., 25, 709-728 (1939)

5. Clayton, D., J. Inst. Petrol., 26, 256-271 (1940)

6. Clayton, D., Engineering, 149, 131-135 (1940)

7. Dijck, W. J. D. van, and Blok, H., Proc. World Pet. Congress, Paris: 3, 445-451 (1937)

8. Davey, W., J. Inst. Petrol., 31, 73-88 (1945)

9. Ibid., 154-158

10. Davey, W., J. Inst. Petrol., 32, 575-581 (1946)

11. Davey, W., J. Inst. Petrol, 33, 574-577 (1947)

12. Ibid., 673-677

13. Kemmerer, H. R., and Garton, F. L., Nat. Petrol. News, 31, 551-555 (1939)

14. Van der Minne, J. L., Inst. Mech. Eng., Proc., General Discussion on Lubricants and Lubrication, 2, 429-441 (1937)

15. Krienke, C. F., Petrol. Refiner, 25, 467-470 (1946)

16. Blok, H., S.A.E. Journal, 44, 193-200 (1939)

17. Baxter, J. P., Snow, C. I., and Pierce, I. T., J. Inst. Petrol, 25, 761-770 (1939)

18. Boerlage, G. D., and Blok, H., Engineering, 144, 1-2 (1937)

19. Beeck, O., Givens, J. W., and Smith, A. E., Proc. Roy. Soc., A 177, 90-102 (1940)

20. Beeck, O., Givens, J. W., and Williams, E. C., Proc. Roy. Soc., A 177, 103-118 (1940)

21. Larsen, R. G., Lubrication Engineering, (August 1945)

22. Larsen, R. G., and Perry, G. L., Trans. Am. Soc. Mech. Engrs. 67, 45-50 (1945)

23. Webb, W. A., Science, 99, 369-371 (1944)

24. Larsen, R. G., Perry, G. L., and Webb, W. A., "Laboratory Studies of Corrosive and Abrasive Wear of Lubricated Surfaces," Shell Development Company (Unpublished), Jan. 27, 1942

25. Perry, G. L., "Lubrication Studies with API Hydrocarbons," Shell Development Co. (Unpublished) (1948)

26. Larsen, R. G., and Perry, G. L., "Chemical Aspects of Wear and Friction," MIT., Proc. of a Conference Mech. Wear, (1948)

27. Thorpe, R. E. and Larsen, R. G., Ind. Engineering Chem., 41, 938-943 (1949)

28. Almen, J. D., Automotive Inds., 73, 696-701 (1935)

29. Petit, H., Techn. Automobile et Aeriene, 29, 1-43 (1938)

30. Bargeboer, A., Polytechn. Weekblad, 34, 132-135, 214-218 (1940)

31. Schnurmann, R., Engineering, 149, 567-568 (1940)

32. Garton, F. L., Engineering, 150, 115 (1940)

33. Clayton, D., Engineering, 150, 216 (1940)

34. Mansion, H. D., Inst. of Automobile Engrs., Report 9196B (1940)

35. Beeck, O., J. Appl. Phys., 12, 512-518 (1941)

36. Mansion, H. D., Automobile Engrs., 32, 327-330 (1942)

37. Mansion, H. D., Engineering, 154, 138-139, 158-159 (1942)

38. Schuringa, A., Polytechn. Weekblad, 36, 214-215 (1942)

39. Beeck, O., Frontiers in Chem., 2, 235-291 (1943)

40. Thorpe, R. E., and Larsen, R. G., Ind. Eng. Chem. 41, 938 (1949)

41. Seemann, W., Oel and Kohle, 40, 15-19 (1944)

42. Adams, R. C., Collegeman, S. M., and Clinton, W. C., J. Am. Soc. Naval Engrs., 56, 213-224 (1944)

43. Davey, W., Ind. Eng. Chem., 42, 1837-1847 (Sept. 1950)

44. Howlett, J., J. Appl. Phys., 17, 137-149 (1946)

45. West, H. L., J. Inst. Petrol., 32, 206-229 (1946)

46. Hund, W. J., Larsen, R. G., Beeck, O., Vesper, H. G., Mech. Engr. 64, 525-530 (1942)

47. Tingle, E. D., "Fundamental Work on Friction Lubrication, and Wear in Germany," Brit. Intelligence, Obj., Sub-Comm. Final Rept. 1610 (Oct. 1947)

48. Timoshenko, S., Thoery of Elasticity, McGraw-Hill (1934)

49. Zisman, W. A., J. of Chem. Phys., 9, 534-551 (1941)

50. Ibid., 728-741

51. Ibid., 789-793

52. Bried, E. M., Kidder, H. F., Murphy, C. M., and Zisman, W. A., Ind. Eng. Chem., 39, 484-491 (1947)

53. Atkins, D. C. Jr., Baker, H. R., Murphy, C. M., and Zisman, W. A., Ind. Eng. Chem., 39, 491-499 (1947)

54. "The Evaluation of Various Compounds as Antiwear Additives for Petroleum Base Fluids." Penn. State College., Pet. Ref. Lab. PRL 3.37, Nov. 14, 1947 (Contract NOrd 7958, Task B)

55. "A Summary of the Wear and Lubrication Properties of Hydraulic Fluids as Determined in the Pesco Model 349 Gear Pump and the Four-Ball Wear Tester." Penn. State College Pet. Ref. Lab. PRL 3.35, May 2, 1947 (Contract NOrd 7958, Task B)

56. O'Rear, J. G., Militz, R. O., Spessard, D. R., and Zisman, W. A., "The Development of the Hydrolube Noninflammable Hydraulic Fluids," NRL Report P-3020, April 1947

57. Brophy, J. E. Fitzsimmons, V. G., O'Rear, J. G., Price, T. R., and Zisman, W. A., "Further Research on Hydrolube Fluids," NRL Report 3545, Sept. 1949

58. Brophy, J. E., Larson, J., and Militz, R. O., "Investigation of the Silicone Polymer Fluids Part VIII, High Temperature of Silicone Fluids in Journal Bearings," NRL Report C-3192, Oct. 1947

59. Kratzer, J. C., Green, D. H., and Williams, D. B., Pet. Ref., 25, 79-90 (1947)

60. Millett, W. H., The Institute Spokesman, 12, 4-7; No. 6 (1948)

61. "Ucon Brand" Fluids and Lubricants, 1947, Carbide and Carbon Chemical Corporation

62. Rochow, E. G., "An Introduction to the Chemistry of Silicones," 1946, Wiley

63. Bass, S. L., Hyde, J. F., McGregor, R. R., J. Am. Ceramic Soc., 29, 66-70 (1946)

64. Post, H. W., "Silicones and Other Organic Silicone Compounds," N. Y. (1949), Reinhold

65. Zisman, W. A., and Murphy, C. M., Jr., "A New Method for the Study of the Oxidation Stability and Corrosiveness of Lubricating Oils," NRL Report P-1849, March 1942

66 Fox, H. W., Taylor, P. W., and Zisman, W. A., Ind. Eng. Chem. 39, 1401-1409 (1947)

67. Murphy, C. M., Romans, J. B., and Zisman, W. A., Trans. ASME, 71, 561-574 (1949)

* * *

NAVY-DPPO PRNC, WASH., D.C.

Naval Research Laboratory. Report 3709.
A STUDY OF THE FOUR-BALL WEAR MACHINE, by W. C. Clinton, September 1950. 48 pp. & figs., UNCLASSIFIED.

Effects of load, temperature, time, speed, and viscosity upon wear in the four-ball wear machine have been studied. Individually and collectively these variables affect the rate of wear. Wear-load curves of a group of petroleum, diester, polyglycol ether, and silicone lubricants were determined at 140°F and at 266°F. Many of the characteristics of the wear-load curves could be explained in terms of viscosity, temperature, and the polar material present or generated at the sliding surfaces. There was usually less wear in the presence of adsorbable impurities. Pure hydrocarbons
(over)

1. Lubricants - Effectiveness
2. Wear testing
I. Clinton, W. C.

Naval Research Laboratory. Report 3709.
A STUDY OF THE FOUR-BALL WEAR MACHINE, by W. C. Clinton, September 1950. 48 pp. & figs., UNCLASSIFIED.

Effects of load, temperature, time, speed, and viscosity upon wear in the four-ball wear machine have been studied. Individually and collectively these variables affect the rate of wear. Wear-load curves of a group of petroleum, diester, polyglycol ether, and silicone lubricants were determined at 140°F and at 266°F. Many of the characteristics of the wear-load curves could be explained in terms of viscosity, temperature, and the polar material present or generated at the sliding surfaces. There was usually less wear in the presence of adsorbable impurities. Pure hydrocarbons
(over)

1. Lubricants - Effectiveness
2. Wear testing
I. Clinton, W. C.

Naval Research Laboratory. Report 3709.
A STUDY OF THE FOUR-BALL WEAR MACHINE, by W. C. Clinton, September 1950. 48 pp. & figs., UNCLASSIFIED.

Effects of load, temperature, time, speed, and viscosity upon wear in the four-ball wear machine have been studied. Individually and collectively these variables affect the rate of wear. Wear-load curves of a group of petroleum, diester, polyglycol ether, and silicone lubricants were determined at 140°F and at 266°F. Many of the characteristics of the wear-load curves could be explained in terms of viscosity, temperature, and the polar material present or generated at the sliding surfaces. There was usually less wear in the presence of adsorbable impurities. Pure hydrocarbons
(over)

1. Lubricants - Effectiveness
2. Wear testing
I. Clinton, W. C.

Naval Research Laboratory. Report 3709.
A STUDY OF THE FOUR-BALL WEAR MACHINE, by W. C. Clinton, September 1950. 48 pp. & figs., UNCLASSIFIED.

Effects of load, temperature, time, speed, and viscosity upon wear in the four-ball wear machine have been studied. Individually and collectively these variables affect the rate of wear. Wear-load curves of a group of petroleum, diester, polyglycol ether, and silicone lubricants were determined at 140°F and at 266°F. Many of the characteristics of the wear-load curves could be explained in terms of viscosity, temperature, and the polar material present or generated at the sliding surfaces. There was usually less wear in the presence of adsorbable impurities. Pure hydrocarbons
(over)

1. Lubricants - Effectiveness
2. Wear testing
I. Clinton, W. C.

and silicones were shown to be extremely poor lubricants in the absence of chemically active addition agents. Phenylation of the silicones increased wear at all loads and temperatures. Pure diesters and polyglycol ethers containing an antioxidant were comparable to white mineral oils.

and silicones were shown to be extremely poor lubricants in the absence of chemically active addition agents. Phenylation of the silicones increased wear at all loads and temperatures. Pure diesters and polyglycol ethers containing an antioxidant were comparable to white mineral oils.

and silicones were shown to be extremely poor lubricants in the absence of chemically active addition agents. Phenylation of the silicones increased wear at all loads and temperatures. Pure diesters and polyglycol ethers containing an antioxidant were comparable to white mineral oils.

and silicones were shown to be extremely poor lubricants in the absence of chemically active addition agents. Phenylation of the silicones increased wear at all loads and temperatures. Pure diesters and polyglycol ethers containing an antioxidant were comparable to white mineral oils