NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2076

FRICTION OF SURFACE FILMS FORMED BY DECOMPOSITION OF COMMON LUBRICANTS OF SEVERAL TYPES

By Robert L. Johnson, Douglas Godfrey
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SUMMARY

An experimental investigation was conducted to determine the effect on friction of films formed on steel surfaces by decomposition of common lubricants of several types. The films were formed by heating, in air, surfaces to which a thin film of fluid lubricant had been applied. The investigation was carried out with a kinetic-friction apparatus employing an elastically restrained spherical rider (1/4-in. diam) that radially traversed a spiral path on a rotating steel-disk specimen. Experiments were conducted over a range of sliding velocities between 75 and 8000 feet per minute with loads from 269 to 1017 grams (initial Hertz surface stress of 126,000 to 194,000 lb/sq in.). Surface studies were made using standard metallurgical and physical-measurement equipment and techniques.

The data obtained indicated that the prepared decomposition films were, in general, beneficial to sliding surfaces with regard to friction and wear. Measured values of friction between the spherical riders and the steel disks covered with the decomposition films were in the same general range as those obtained under boundary lubrication conditions for the original fluid lubricants. The mechanism by which these films decrease friction may be the same as that of lubrication by thin metallic films. Discontinuities and cracks indicated that the film materials do not serve as highly viscous fluid lubricants.

Although film strength of neither a silicone-polymer fluid nor its decomposition product was individually sufficient to satisfactorily support the minimum load used, a combination of the two materials permitted the load to be effectively supported. Very low friction and acceptable film strength were obtained by using this combination at surface stresses that approximate the maximum

commonly used in the design of lubricated surfaces for aircraft power plants. Such a combination should be especially satisfactory in high-temperature lubrication because the decomposition film would be regenerated.

INTRODUCTION

A number of recently developed types of aircraft engine are characterized by high operating temperatures. These temperatures introduce critical cooling problems in lubrication systems because the lubricants are required to contact hot surfaces; the heat from these surfaces causes thermal cracking of the lubricant and also accelerates the processes of oxidation, polymerization, or other forms of decomposition (reference 1), resulting in lacquer deposits on the surfaces. A typical example of this action is reported in reference 2, in which Gurney states that after shutdown of a turbojet engine, the turbine-bearing temperatures may be high enough to cause decomposition of the lubricant. Recent research on roller bearings has indicated that a cage material that had a catalytic effect on the decomposition of lubricants was very effective as long as the lacquer deposit was not removed. Studies by Blok on gear-tooth surfaces (reference 3) and research by Bowden and Ridler on surfaces operating in pure sliding (reference 4) have shown by direct measurement that high surface temperatures are momentarily attained under conditions of boundary lubrication. These temperatures are sufficiently high to cause continued local decomposition of the lubricants. These considerations indicate that a fundamental evaluation of the role of such films would be worthwhile. In the specific case of turbine roller bearings, the presence of a lacquer film on surfaces in pure sliding, as between the retainer and its locating surface, may be the factor that will allow satisfactory operation during starting when there is a lack of effective fluid lubrication.

A study was made at the NACA Lewis laboratory to determine the friction characteristics of films formed on steel surfaces by decomposition of common lubricants of several types. The possibility that such a film may serve as a highly viscous fluid lubricant was considered, as well as the probable relation of such films to the run-in of sliding surfaces. This study was conducted with a kinetic-friction apparatus consisting of an elastically restrained steel ball (1/4 in. in diameter) sliding in a spiral path on a rotating steel disk. Experiments were conducted with various lubricating films on steel disks at sliding velocities from 50 to 8000 feet per minute with loads from 269 to 1017 grams (initial Hertz surface stress of 126,000 to 194,000 lb/sq in.). Studies were made of decomposition films formed from a number of common petroleum and synthetic lubricants including the current specification AN-0-9 turbojet engine oil, white oil, an aliphatic diester (di-2-ethylhexyl sebacate), a polyglycol ether (polyalkylene glycol derivative), and a dimethyl silicone polymer. Friction experiments were conducted to aid in resolving the roles of the films on steel specimens using surfaces having boundary-lubricating films of the various fluid lubricants, surfaces having decomposition films formed from the various fluid lubricants, and surfaces having thin films of fluid silicone polymer on decomposition films formed from the silicone polymer.

APPARATUS AND PROCEDURE

Friction apparatus. - The friction apparatus used for these experiments is the same as the equipment described in reference 5, except that a hydraulic motor was substituted for the previously used electric-drive motor. A diagrammatic sketch of the basic parts of the apparatus is presented in figure 1. The principal elements of the apparatus are the specimens, which are an elastically restrained spherical rider and a rotating disk. The disk specimens had an outer diameter of 13 inches and were made of normalized SAE 1020 steel, Rockwell number A-50. The rider specimens used were commercial balls, 1/4 inch in diameter, and were made of SAE 1095 steel hardened to Rockwell number C-60. The rider load P is applied along the vertical axis of the rider holder. Friction force between the rider and the disk is measured by four strain gages mounted on a copper-beryllium dynamometer ring. The friction-force readings F are obtained from an indicating-type calibrated potentiometer and are recorded using a motion picture camera (64 frames/sec), timed to operate for the 3 seconds covering the duration of each friction run. The coefficient of kinetic friction μ_k was computed from the equation

$$\mu_k = \frac{F}{P}$$

where F is the measured friction force and P is the applied normal load.

A motor-driven radial-feed mechanism, calibrated to indicate radial position of the rider, caused the rider to traverse a spiral path on the rotating disk so that portions of the wear track did not overlap. The disk is mounted on a flywheel that is supported and located by radial and thrust bearings. The rotating specimen is driven through a flexible coupling by a hydraulic motor operating under constant fluid pressure with speed adjusted by varying the flow of the hydraulic fluid; this arrangement allows good speed control over a range of sliding velocities between 50 and 18,000 feet per minute. The disk and rider are enclosed, permitting the operating atmosphere of dried air to be slightly pressurized. 1229

Specimen preparation. - The physical properties of the lubricants used for both the experiments involving the fluid lubricants and the experiments involving the decomposition films formed from the lubricants are listed in table I. The lubricants were so selected that their viscosities generally fell in the range of 10 to 70 centistokes at 100° F as an attempt was made (particularly in the synthetic lubricants) to obtain lubricants with high flash points as long as the pour points were within the general range of -40° to -70° F. Data of reference 5 and unpublished results indicate that there was relatively no effect of viscosity on the coefficient of kinetic friction with lubricants that covered the viscosity range from 20 to 110 centistokes at 100° F.

The surface films were formed by heating the disk specimens in air. Before heating, a thin film of the fluid lubricant was uniformly deposited on the disk surface; in most cases, the quantity of the fluid was approximately 1 cubic centimeter and the fluid was uniformly applied as a fine mist. Decomposition of the fluid lubricant was accomplished by heating the disks to temperatures slightly higher than those at which the first visible vaporization of the lubricants occurred. The temperatures were maintained as long as 14 hours until it was apparent that no fluid remained on the surfaces. Special precautions were taken to assure uniform heating of all parts of the disk.

Prior to the deposition of lacquer films, the disks were finished and cleaned according to the procedure described in reference 5. The disks were finished by surface grinding and nondirectional lapping to produce a surface having random finishing marks with a roughness of 6 to 8 microinches rms, as measured with a profilometer. The cleaning process included in sequence: soaking and wiping in a low-aromatic cleaning naphtha, wiping with clean cloths saturated with a solution containing equal parts of acetone and benzene, scrubbing with moist levigated alumina powder, rinsing under tap water to remove the alumina, testing for cleanness by the ability of water to wet the surface, immersing in redistilled 190-proof ethyl alcohol to remove the water, rinsing with redistilled 190-proof ethyl alcohol, and drying on the friction apparatus in an atmosphere of dried, filtered air.

After the films were formed on the disk, the surfaces were cleaned by repeated light contact of a clean cloth saturated with benzene and then with a cloth saturated with redistilled ethyl alcohol. This process did not appear to dissolve any of the film materials present. As mentioned in reference 6, the generally accepted distinction between engine varnish and lacquer is that varnish is soluble in acetone.

The rider specimens were cleaned by wiping with a cloth saturated with ethyl alcohol and by rinsing with redistilled 190-proof ethyl alcohol. The rider was allowed to dry on the apparatus.

Experimental procedure. - During the experiments, the disk was rotated at a predetermined speed and, by means of a cam arrangement, the loaded rider was lowered onto the disk as the radial feed was started. As the rider traversed the disk, friction force, as indicated by the potentiometer, was observed and photographically recorded and disk rotative speed was determined with an electric revolution counter and synchronized timer. The timer controlled the operation cycle of the camera, the radial-traverse mechanism, and the revolution counter. The runs were terminated by lifting the rider from the disk surface. Mean sliding velocity for the runs was computed from the recorded rotative-disk speed and the mean diameter of the rider path. Change in diameter of the rider path on the disk during radial travel of the rider caused a maximum deviation in sliding velocity of approximately 3 percent from the mean value. An unworn area of a rider was used in each run.

In experiments with the fluid lubricants, both on clean steel disks and on the film materials, the lubricants were applied in drops with a clean platinum dipper and allowed to wet the surface completely. The disks were then rotated at the maximum speed of the experiment (approximately 2500 rpm) for 5 minutes, causing excess lubricant to be thrown off and leaving only a very thin film.

The films and the surfaces of the disk specimen were studied using common physical-measurement and metallographic equipment before and after the experiments. Hardness and surface-roughness measurements were used as control factors in evaluation of the disk specimens prior to the experiments. Photographic studies of the film materials were made using transmitted light through films formed on glass microscope slides.

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The friction data presented are complete for a representative experiment of each surface condition studied and were selected from a mass of data from several experiments on each variable. The limits of experimental error in the friction values presented were not constant in all the experiments because of difficulties in maintaining absolute control of film thickness. In all but isolated cases, the maximum experimental error in friction coefficient was ±0.03 and, in general, was considerably less. For comparative purposes, a load of 269 grams was used for the majority of the curves presented because this load produces an initial Hertz surface stress (126,000 lb/sq in.) that is in the range of stresses commonly attained in aircraft-engine components that require lubrication. According to reference 7, this stress is also within the range of normal stresses (69,000 to 282,000 lb/sq in.) for turbine-engine rolling-contact bearings. At the same time, surfaces in contact under relatively light load and having a large apparent area of contact can have high stresses at localized contact areas. Even with lightly loaded surfaces, local pressure at the small points of contact may exceed the flow pressure of the materials (reference 8) and cause plastic flow at these points. The actual area of contact is experimentally shown in reference 8 to be a function of load and to be unaffected by the apparent area of contact; from these considerations the minute points of contact are assumed to flow plastically until their contact cross section is sufficient to enable them to support the applied load. The flow pressures (yield strengths) of the materials used in this investigation varied from 65,000 to over 200,000 pounds per square inch.

RESULTS AND DISCUSSION

Fluid lubricants. - Friction data obtained using various fluid lubricants on clean steel surfaces are presented in figure 2. These lubricants were the same as those used to form the lubricant decomposition films of this investigation. The data of figure 2 are presented for subsequent comparison with the data from the decomposition films. These data show the effect of sliding velocity on kinetic friction for a number of the petroleum and synthetic types of lubricant that might be considered for use as aircraft-engine lubricants. The three petroleum lubricants (percolated white oil and specification AN-0-9 aircraft-turbine oils, grades 1010 and 1005) showed similar trends (fig. 2(a)) that include characteristic break points in the curves after which higher friction was observed, possibly indicating partial film failure. The differences in the break points for the petroleum lubricants might be attributed to the relative decomposition temperatures of the lubricants; the lubricant with the lowest decomposition temperature showed a break point at lowest velocity and the lubricant with the highest decomposition temperature showed a break point at highest velocity.

Comparison of these data for the petroleum lubricants on steel with those for the petroleum lubricant on steel reported in reference 5 shows that the most important difference is in the presence of the break point in the curves presented herein. A possible explanation for this difference lies in the variation in procedure for applying the lubricant film. The film described in reference 5 was applied by rubbing and the excess was not spun off; as a result, the film would be much thicker than in the current investigation, which would tend to delay film breakdown.

Friction values for the commercial aliphatic diester and the polyglycol ether (fig. 2(b)) were similar at the lower sliding velocities, in spite of the relatively large differences in viscosities, and remained low at the higher velocities. The polyglycol ether showed a slight break point at a sliding velocity of 1500 feet per minute, which would normally indicate a breakdown of the film. In most cases, such break points indicate a partial failure of the lubricating film causing stick-slip sliding to occur. Because there was no evidence that stick-slip sliding had occurred with the polyglycol ether, consideration of the data-curve break point as a film failure is unwarranted. The data obtained with the silicone polymer (fig. 2(b)) were completely in the range of stick-slip sliding, which is the reason this curve was faired as a smooth curve. The film strength of the silicone-polymer lubricant was insufficient to provide adequate boundary lubrication with the minimum load used in these experiments (269 grams, initial Hertz surface stress of 126,000 lb/sq in.) at even the minimum sliding velocity of 75 feet per minute.

In figure 2(c), a comparison of the friction data for all fluid lubricants is shown over a range of sliding velocities.

Decomposition films. - The decomposition films formed for these experiments appear to be similar to those that form in an aircraft engine. The exact composition of the lacquers occurring in engines is unknown although the decomposition of lubricants is unquestionably a combination of chemical changes that have been variously termed: "oxidation," "polymerization," and "thermal coking" (reference 1). Among others, the following factors influence these chemical changes: high temperature, catalysts, oxygen concentration, and lubricant contaminants. The films used in the friction experiments reported herein were not formed under the combined effects of all the variables present in engines; however, the simple fact that the films thus formed were similar to those found on engine parts indicates that high temperature and oxygen concentration may be important factors in the decomposition of engine lubricants in service. The formation and lubrication characteristics of decomposition films formed from a silicone polymer in journal bearings are discussed in reference 9. In general, these data show that the decomposition film was instrumental in causing a marked increase in load capacity in a bearing nominally operating under hydrodynamic conditions.

Data obtained with thin films of lubricant-decomposition products on steel friction specimens are shown in figure 3. Evaluation of these data should include consideration of the fact that the film surfaces were repeatedly cleaned with benzene and with alcohol so that the surfaces were cleaned of all residual fluid lubricant that may have been initially present on the film. The data obtained with the decomposition films of the three petroleum lubricants (white oil and specification AN-O-9 aircraft-turbine oils, grades 1010 and 1005) exhibit (fig. 3(a)) the same characteristic break point shown for the fluid lubricants in figure 2(a), although the critical velocities at which these breaks occur are different. For the films formed from the synthetic lubricants (fig. 3(b)), no similar characteristic is observed. In the case of the films formed from the aliphatic diester and the polyglycol ether, the data fell on a single curve showing a downward trend but flattening out at the higher sliding velocities. In several of the curves of figure 3, the friction of the decomposition films approaches that obtained in boundary lubrication with the fluid lubricants (fig. 2). The fact that over most of the range of sliding velocities the decomposition film formed from the silicone polymer caused lower friction than did the fluid lubricant is considered significant.

In figure 3(c), a comparison of the friction data for the decomposition films formed from all the lubricants is shown. Also, included for comparative purposes is the friction curve for dry, clean steel from reference 5. In general, the data indicate that the presence of the decomposition films appreciably reduced the friction when compared to the clean steel.

The surfaces produced by decomposition of the fluid lubricants were unsuitable for photomicroscopy. The films formed from the synthetic lubricants were essentially transparent and films formed from the petroleum lubricants had insufficient reflectivity to allow satisfactory photomicrographs to be obtained from the disk specimen. A series of films was therefore prepared on glass microscope slides and photographed with transmitted light. In figure 4, representative samples of these photomicrographs showing a single wear track made by a friction specimen (1/4-in.-diam steel ball) slowly drawn across the surface with a load of 269 grams are presented. A track and the surface of a film obtained with polyglycol ether are shown in figure 4(a). This surface is also representative of that obtained with the aliphatic diester. The track observed in the film formed from the silicone polymer (fig. 4(b)) shows discontinuity and non-homogeneity of the surface subjected to sliding. The area adjacent to the track shows cracking similar to that which occurs with brittle materials. Light interference lines are observed adjacent to each crack, indicating that the film has pulled away from the underlying surface. The high contrast of figure 4(c) obliterates the fact that some film material remains in the track plowed through the film formed from specification AN-O-9, grade 1010 lubricant. This surface is also representative of the surface obtained with white oil. In this case, the plowing did rupture the film or at least break the film loose from the glass base, as indicated by light interference lines adjacent to the plowed surface, which were observed with reflected light. The conditions evident on the glass slides may not be entirely representative of those occurring on metal surfaces because steel is believed to influence the process of decomposition. For instance, the film formed from the silicone polymer on steel appeared to have a blue color, whereas the decomposition of the same fluid on glass was essentially without color. The apparent coloration of the film formed on steel is probably caused by underlying oxides of iron but may be the result of some other chemical change in the film material that was influenced by the constituents in the steel. The films formed on steel, however, showed the same general appearance after sliding as was observed on the glass slides. These data indicated that the films were serving as thin solid lubricants.

Surface loading. - Most of the lubricants and decomposition films showed no well-defined effect of loading on friction at the velocities investigated except where surface failure was involved. That is, Amonton's Law that friction coefficient is independent of applied load held true in the general case. In those cases in which surface failures were involved, however, the sliding velocity at which surface failure occurred was decreased with increased surface loading. As in the case of other variables discussed, the silicone-polymer fluid and its decomposition film proved the exception to the general case. The performance characteristics of the silicone fluid are of primary importance in this investigation because the material is being considered for many high-temperature lubrication applications; consequently, the lubricating characteristics of the silicone fluid will be more fully presented than is the case for the other lubricants studied.

The effect of sliding velocity on kinetic friction with load as a parameter for a thin lubricating film of the silicone-polymer fluid is shown in figure 5(a). These data show in general that at all sliding velocities, the coefficient of friction is not independent of load, that is, Amonton's law does not hold. Evaluation of these data should include consideration of the fact that the lowest load used in these experiments, which resulted in an initial Hertz surface stress of 126,000 pounds per square inch, is in the stress range common to sliding surfaces. The film breakdown observed in these studies, as evidenced by some increase in friction coefficient with increase in load, would not preclude the use of the silicone-polymer fluids in low-load applications or where hydrodynamic lubrication is obtained. With the three loads investigated, friction becomes essentially independent of sliding velocity at 5000 to 7000 feet per minute. The friction observed in this velocity range for the 1017-gram load is approximately the same as that obtained for dry steel in reference 5, which, with the occurrence of stick-slip sliding, might indicate that the film has been completely broken down.

In general, as shown in figure 5(b), the coefficient of friction increases with an increase in load for a surface having a decomposition film formed by heating the silicone-polymer fluid. These data do not indicate any simple relation in the effects of load and no explanation can be offered at this time for the characteristic shape of these curves. Lubrication by the decomposition film has been considered to result from essentially hydrodynamic action of a very viscous film. Although the minimum points in a curve such as that for the 269-gram load in figure 5(b) might possibly be construed as the knee point in the ZN/P curve, which is common to hydrodynamic lubrication, surface studies of these films after sliding do not support such a possibility. As was shown in figure 4(b), the silicone film subjected to sliding is displaced and ruptured and the adjacent areas show a crack network throughout the entire thickness of the film, which indicates that it was acting as a solid brittle material.

Probably the best explanation for the mechanism of lubrication by the decomposition film is offered in the theory of metallic thin-film lubrication presented in reference 10. This theory states that a low-shear-strength solid film over a hard base serves to decrease friction through the low shear strength of the film, whereas the area of contact remains low because of the hard base. According to this theory, the optimum film would be of the minimum thickness required to support the loads involved; by limiting the thickness, the plowing factor in friction is reduced. The decomposition film material probably adheres to the base metal by a simple physical bond.

Fluid lubricant on decomposition film. - The effect on lubrication of decomposition films used in conjunction with the fluid silicone-polymer lubricant is discussed in reference 9 for the low-load application of journal bearings. Under such conditions, reference 9 indicates that the decomposition film provides a margin of safety that compensates for the low film strength of the silicone-polymer fluid. The cumulative effect of the combination of the fluid lubricant and its decomposition film for various loads is shown in figure 6. At a load of 269 grams, no complete failure of the lubricating film occurred and friction between the sliding surfaces was very low over the entire range of sliding velocities. Even at the higher loads, the cumulative effect is still apparent (fig. 6) although at the highest load (1017 grams) partial film failures occurred intermittently. The displacement of the load curves from one another, as shown in figure 6, is also characteristic of both the fluid lubricant and the decomposition film (figs. 5(a) and 5(b)). No deviation from Amonton's Law has been introduced by the cumulative effects of the two lubrication variables.

In figure 7, the effect of sliding velocity on kinetic friction at a load of 269 grams is presented for three different conditions of lubrication with the silicone-polymer, namely: fluid film, decomposition film, and a fluid-film overlay on a decomposition film.

Practical significance. - High-temperature lubrication is complicated by the decomposition of the lubricants. The silicone-polymer fluids are among the most temperature-stable of the lubricants that are currently available; however, they have the deficiency of poor lubricating ability caused by low film strength. The use of a decomposition film as a pretreatment on lubricated surfaces may provide supplementary lubrication over a range of loads exceeding the present design limit for most lubricated surfaces and over a considerable range of sliding velocities. A significant point in the use of such films is that if the operating temperatures of the lubricating surfaces are high enough and a supply of the fluid continues to be present, the decomposition film will be regenerated. Although very thin, such a film could be effective in reducing friction according to the theory for metallic thin-film lubrication. Formation of decomposition films from all types of lubricants may be a significant factor in the run-in of lubricated surfaces.

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SUMMARY OF RESULTS

Decomposition films formed by heating surfaces to which several common synthetic and petroleum lubricants had been applied were studied to determine the effects of such films on friction and load capacity of surfaces. At sliding velocities between 75 and 8000 feet per minute with loads of 269, 519, and 1017 grams, the following results were observed:

1. In general, decomposition products formed from several synthetic and petroleum lubricants were beneficial to slider surfaces with regard to friction and load capacity when compared to the dry, clean steel surfaces. Friction values with the film materials were in the same general range of values as those obtained in boundary lubrication with the original fluid lubricants.

2. The combination of a silicone-polymer fluid and a decomposition film formed from that lubricant produced desirable cumulative effects on both friction and load capacity over the complete range of sliding velocities and at extreme surface loads.

3. The effectiveness of a decomposition film in friction was not caused by hydrodynamic action of the film as a highly viscous fluid. The film was plowed and partly displaced from the surface during sliding and may act as a low-shear-strength solid film.

Lewis Flight Propulsion Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, August 31, 1949.

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TABLE I - MEASURED PHYSICAL PROPERTIES OF LUBRICANTS INVESTIGATED

Lubricants	Viscosity (centistokes)		Viscosity index	A.S.T.M. pour point (°F)	C.O.C. flash point (°F)	Color	Specific gravity (60°/60° F)	Neutralization number
	100° F	210° F						
Petroleum								
White oil	77.80	8.19	76	23	450	Colorless	0.883	0.025
AN-O-9, grade 1010	9.95	2.47	72	-76	300	Straw	.871	.050
AN-O-9, grade 1005	5.03	1.64	83	below -76	220	Straw	.860	.025
Synthetic								
Aliphatic diester	12.50	3.31	155	below -76	450	Very light straw	.916	.050
Polyglycol ether	66.80	11.20	142	-38	535	Deep red	.994	[a].250
Silicone polymer	38.50	15.60	174	below -76	520	Very light straw	.967	.025

[a]Red color of original material made accurate determination of end point impossible.

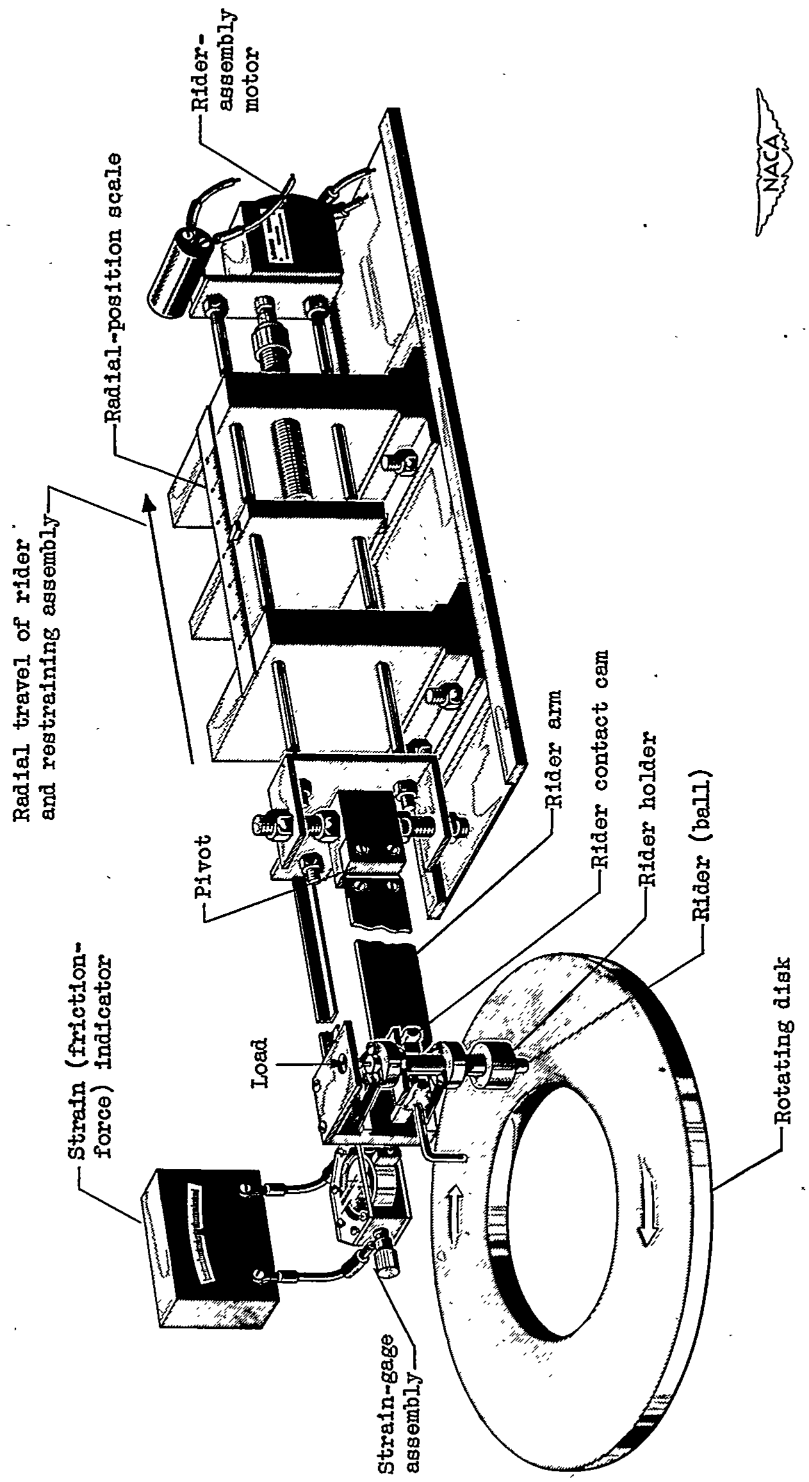
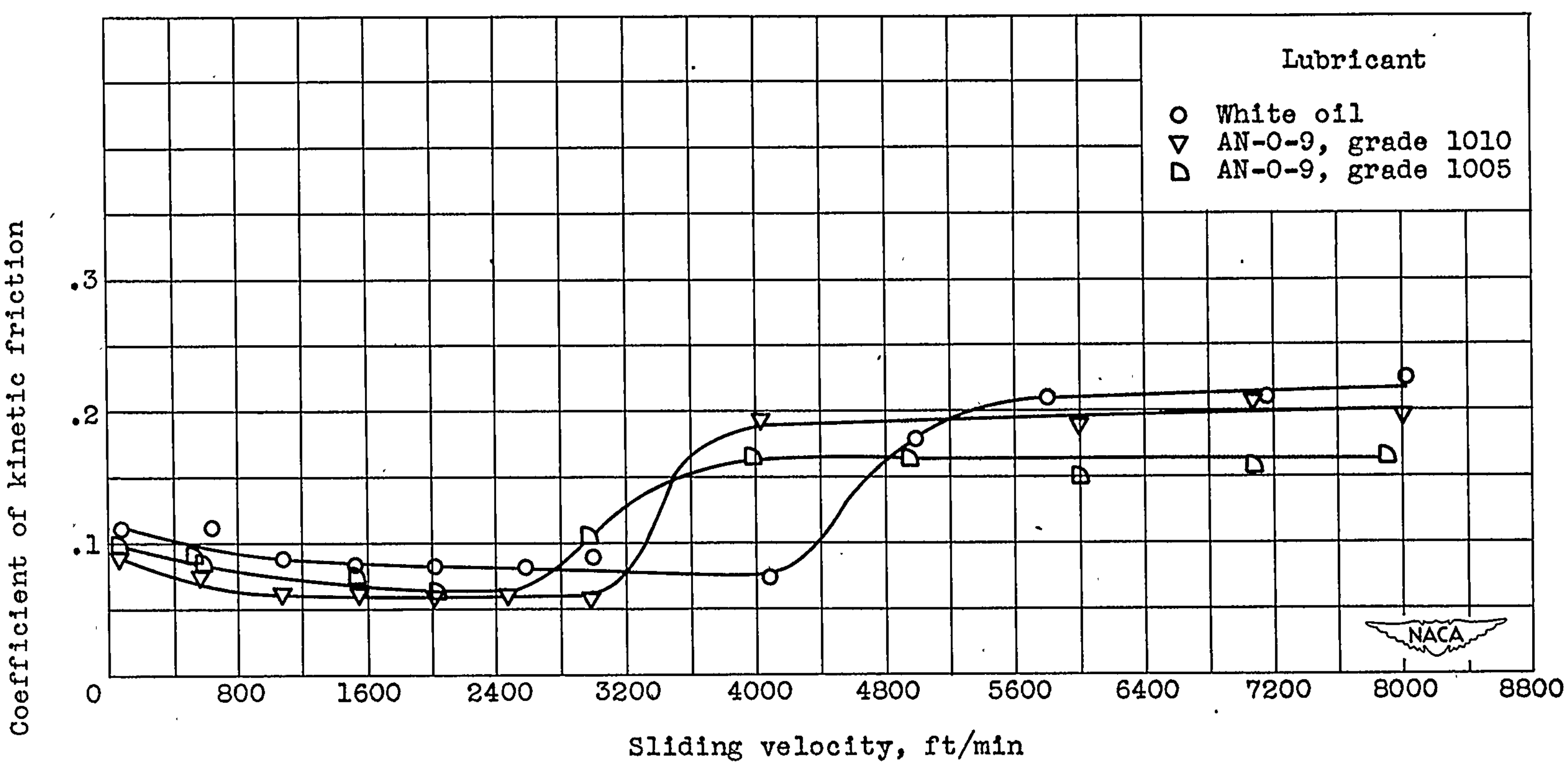
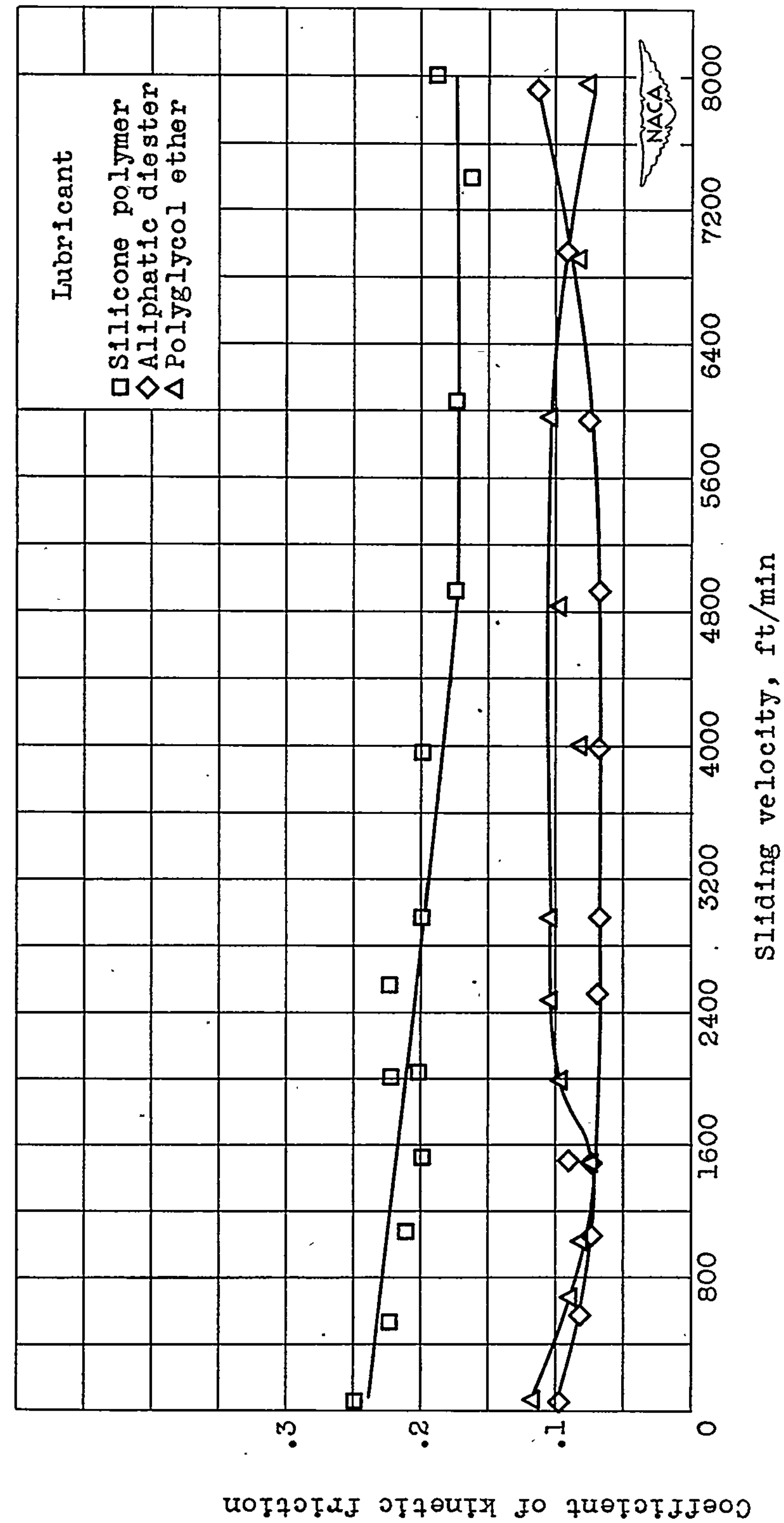


Figure 1. - Schematic diagram of sliding-friction apparatus.



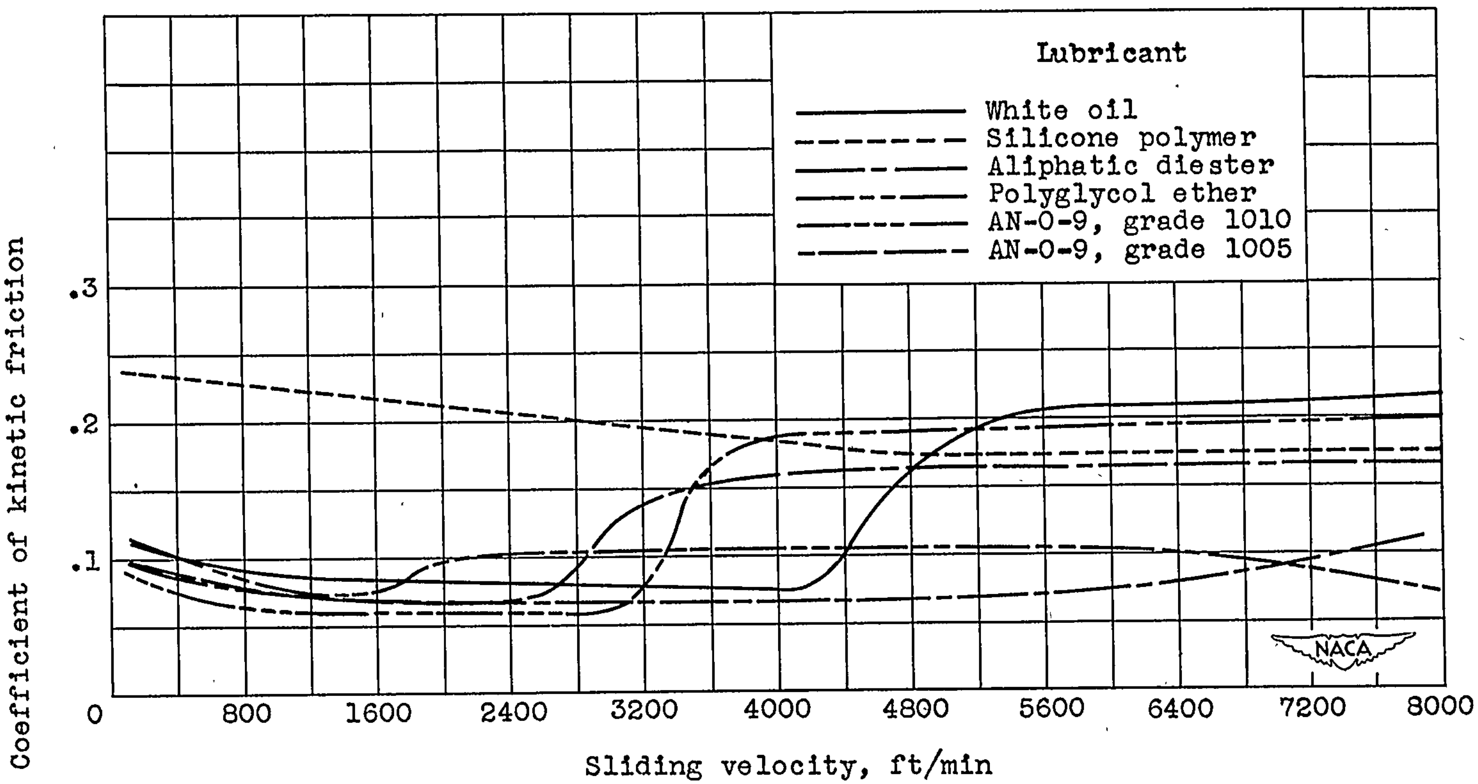
(a) Petroleum lubricants.

Figure 2. - Effect of various fluids in boundary lubrication on sliding friction with 269-gram load (initial Hertz surface stress, 126,000 lb/sq in.).



(b) Synthetic lubricants.

Figure 2. - Continued. Effect of various fluids in boundary lubrication on sliding friction with 269-gram load (initial Hertz surface stress, 126,000 lb/sq in.).



(c) Comparison of petroleum and synthetic lubricants.

Figure 2. - Concluded. Effect of various fluids in boundary lubrication on sliding friction with 269-gram load (initial Hertz surface stress, 126,000 lb/sq in.).

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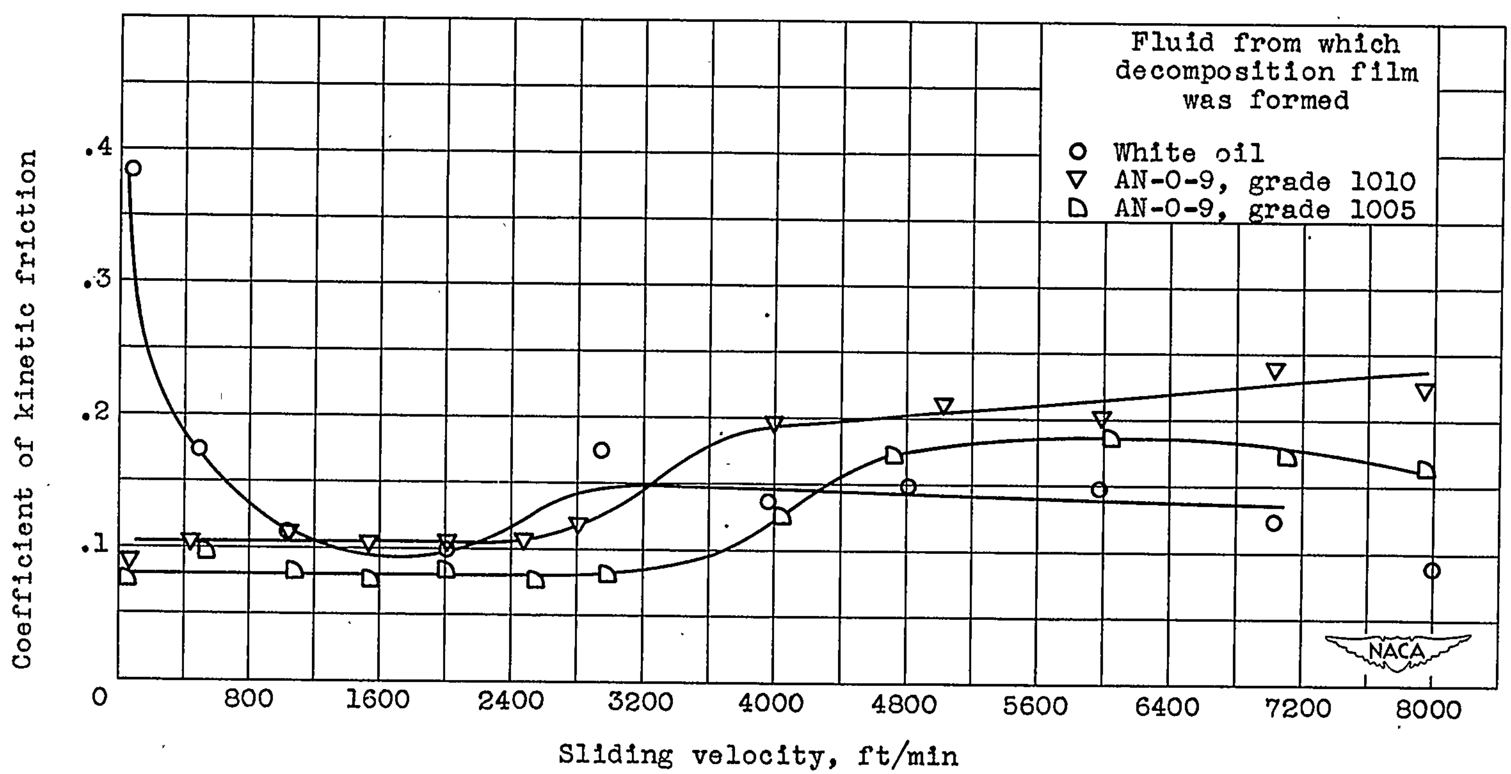
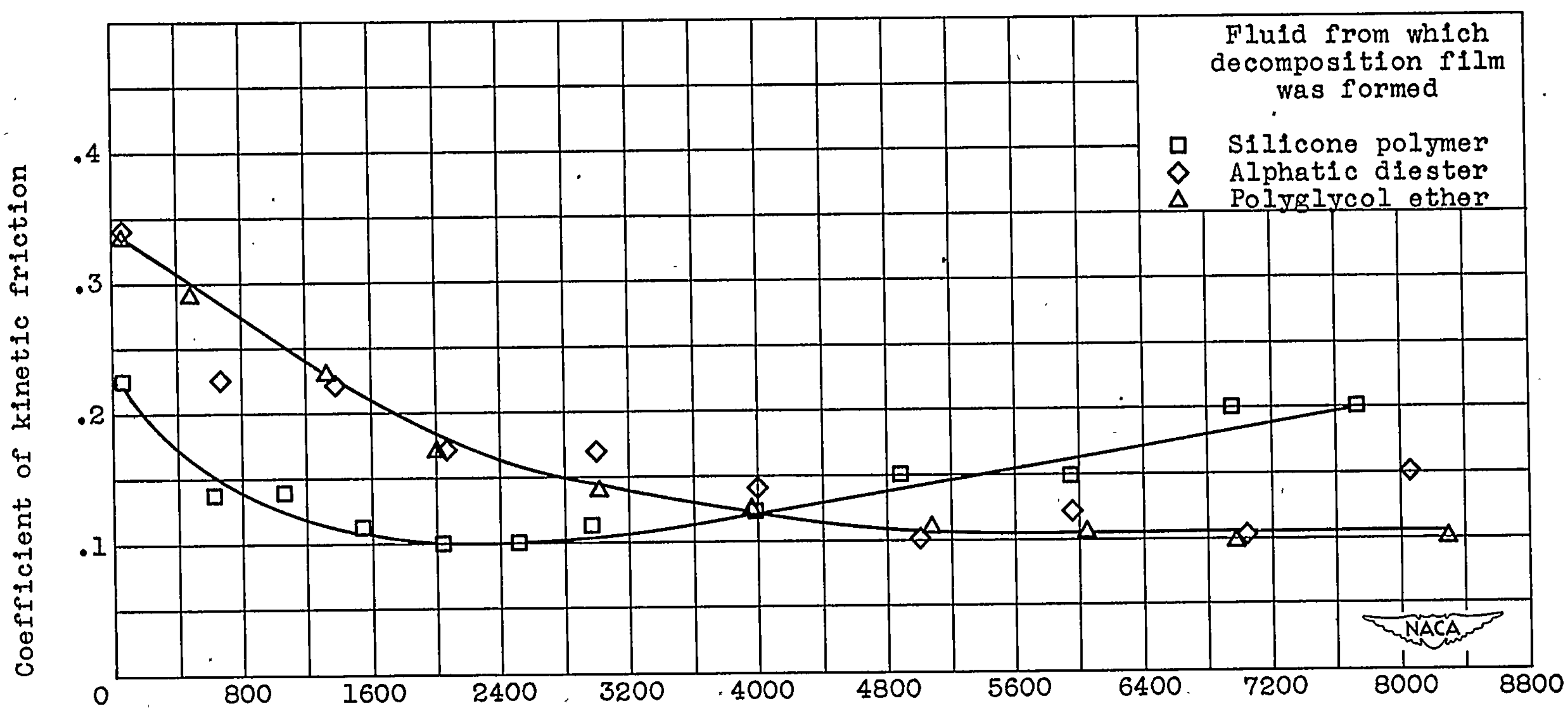


(a) Petroleum lubricants.

Figure 3. - Effect of lubricant decomposition films on sliding friction with 269-gram load (initial Hertz surface stress, 126,000 lb/sq in.).



(b) Synthetic lubricants.

Figure 3. - Continued. Effect of lubricant decomposition films on sliding friction with 269-gram load (initial Hertz surface stress 126,000 lb/sq in.).

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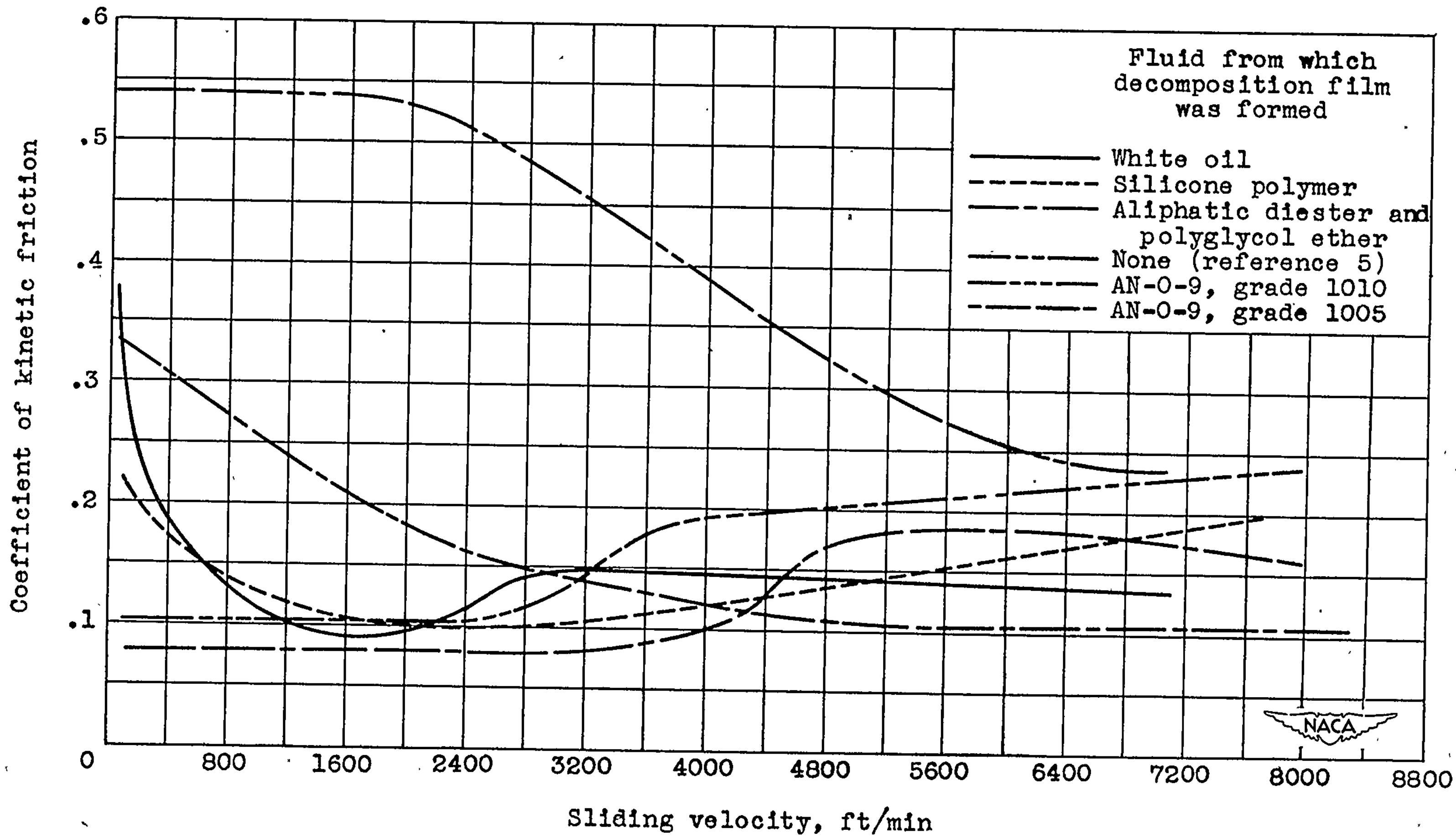
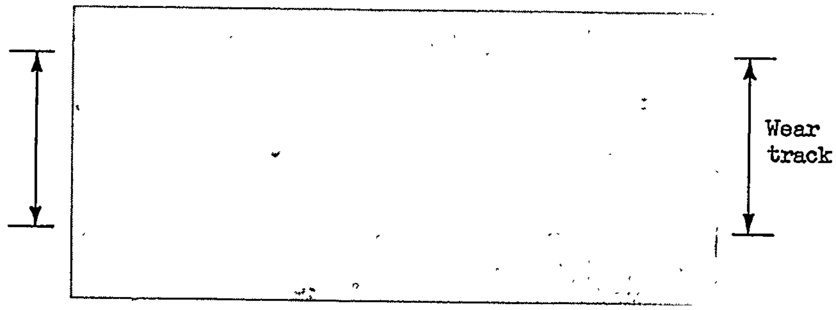
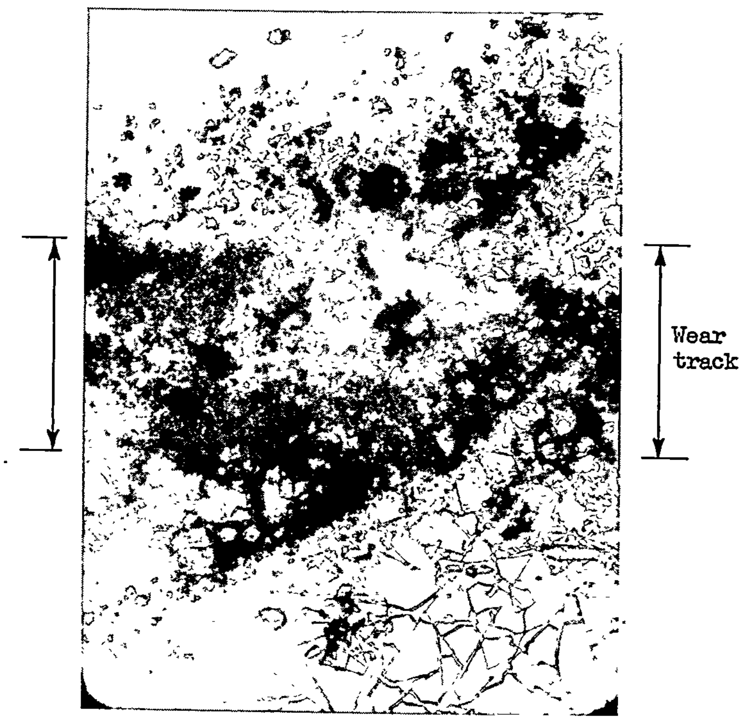


(c) Comparison of petroleum and synthetic lubricants.

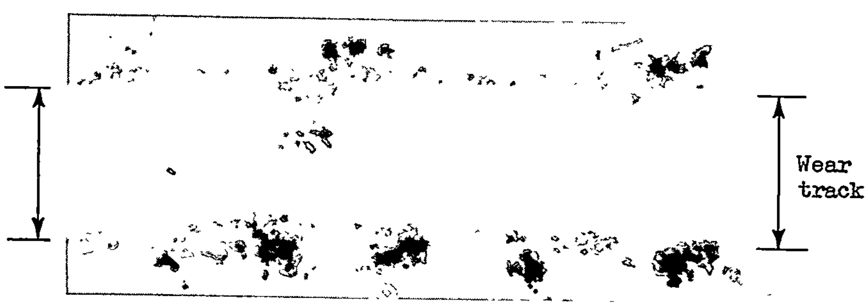
Figure 3. - Concluded. Effect of lubricant decomposition films on sliding friction with 269-gram load (initial Hertz surface stress, 126,000 lb/sq in.).



(a) Film formed from polyglycol-ether lubricant.



(b) Film formed from silicone-polymer lubricant.



(c) Film formed from petroleum lubricant (AN-O-9, grade 1010).

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Figure 4. - Photomicrographs by transmitted light of lubricant decomposition films formed on glass microscope slides after being subjected to sliding of a 1/4-inch-diameter steel ball with a 269-gram load. X250.

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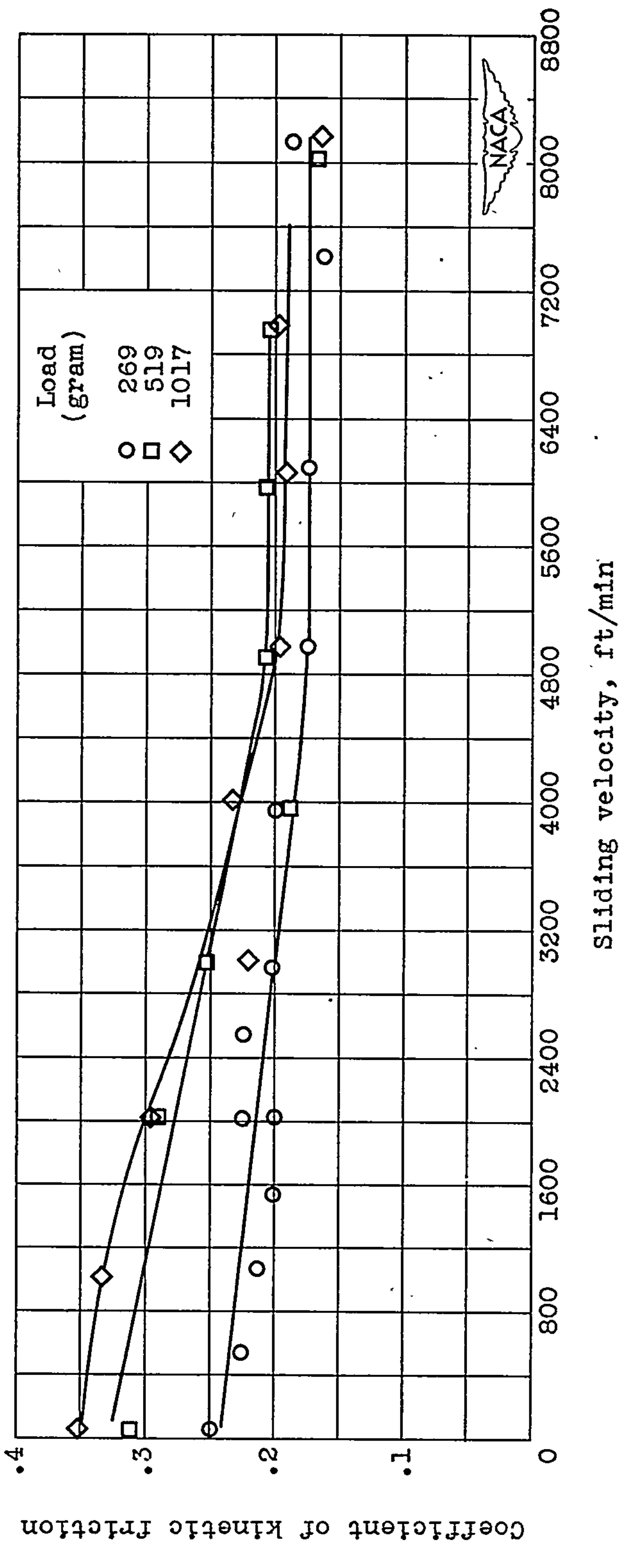
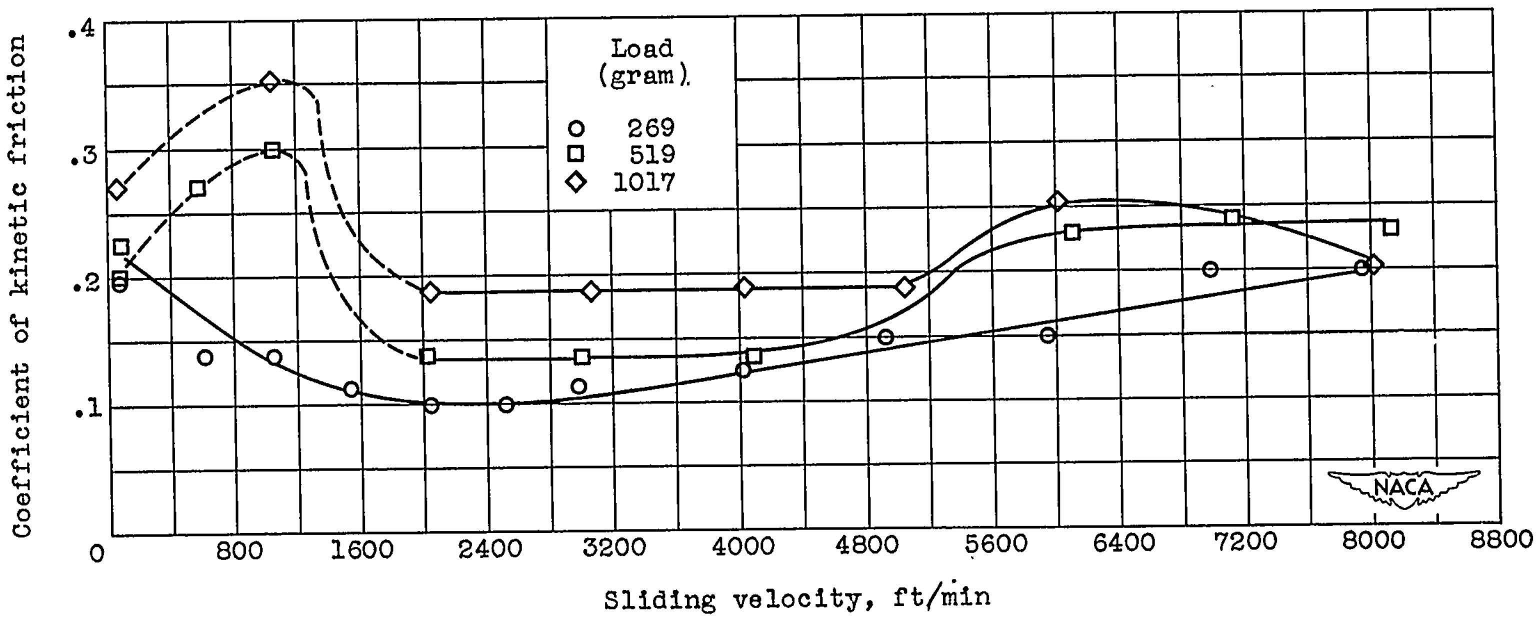


(a) Steel surface lubricated with a silicone-polymer fluid.

Figure 5. - Effect of sliding velocity on kinetic friction with load as a parameter.



(b) Steel surface coated with a thin film formed by decomposition of a silicone-polymer fluid.

Figure 5. - Concluded. Effect of sliding velocity on kinetic friction with load as a parameter.

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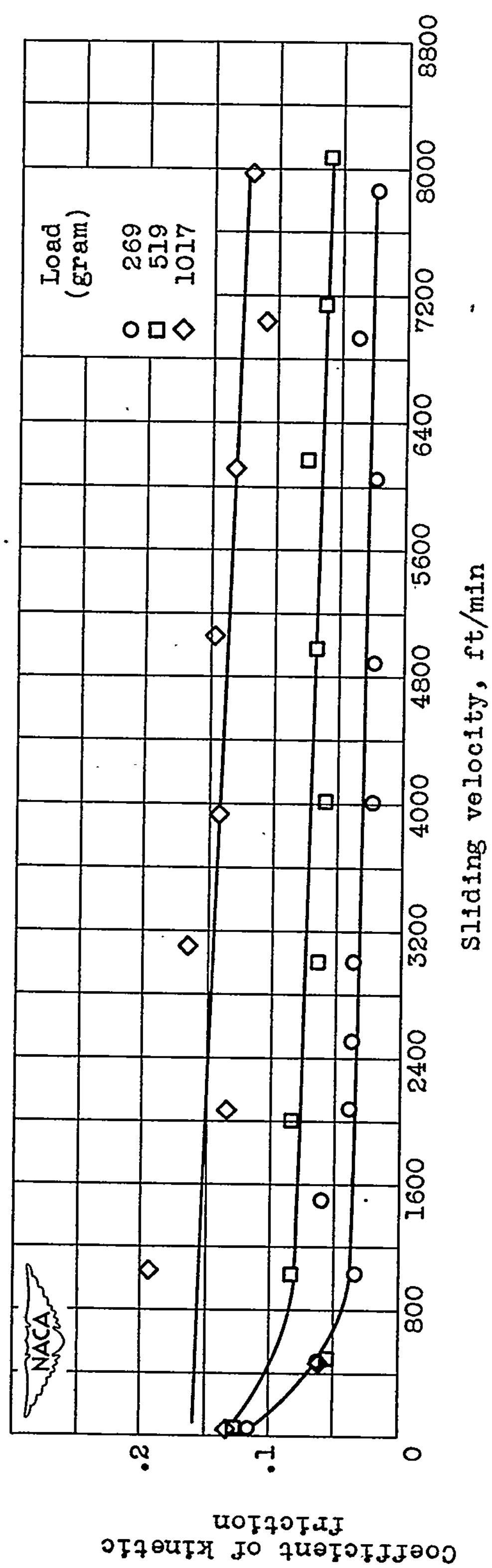

Figure 6. - Effect of sliding velocity on kinetic friction with load as a parameter. Silicone-polymer fluid on a decomposition film formed from silicone-polymer fluid on a steel surface.

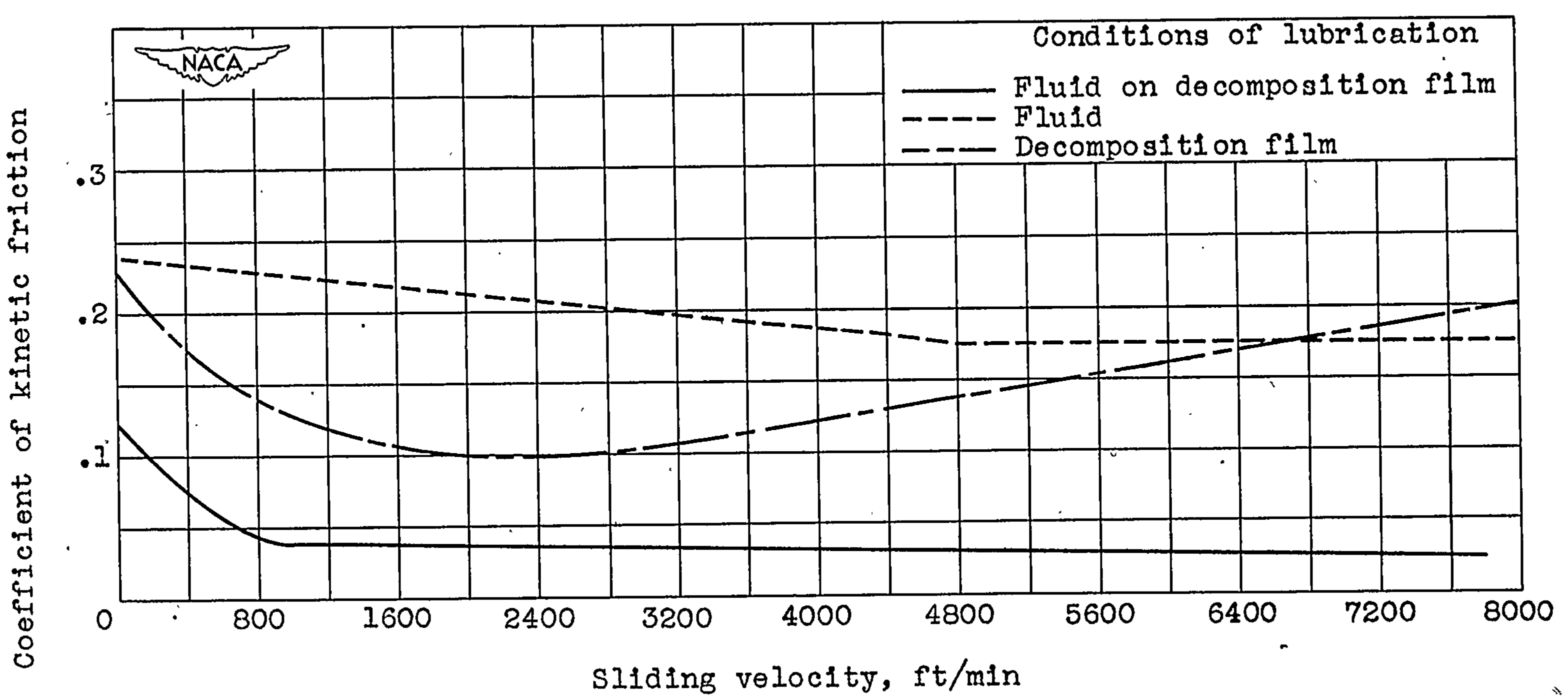

Figure 7. - Effect of sliding velocity on kinetic friction for conditions of lubrication including a silicone-polymer fluid and decomposition films formed from silicone-polymer fluid with 269-gram load (initial Hertz surface stress 126,000 lb/sq in.).

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