NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE 2846

EFFECTIVE LUBRICATION RANGE FOR STEEL SURFACES BOUNDARY LUBRICATED AT HIGH SLIDING VELOCITIES BY VARIOUS CLASSES OF SYNTHETIC FLUIDS

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SUMMARY

Synthetic lubricants are necessary to satisfy the physical property requirements for future lubricants of aircraft turbine engines. Boundary-lubrication data on the synthetic fluids are rather limited; consequently, the effects of a wide range of sliding velocities on boundary lubrication were studied.

Sliding-friction data and surface-failure properties show that a number of synthetics including diesters, polyethers, a silicate ester, and a phosphonate ester as well as a silicone-diester blend are more effective boundary lubricants at high sliding velocities than comparable petroleum oils. The blend of a diester in silicones, an alkyl silicate ester, and a compounded diester (containing lubrication additives) were more effective boundary lubricants at high sliding velocities than the comparable diesters from which the most widely accepted synthetic lubricants are made. A diester failed to lubricate nonreactive surfaces which indicates that the lubrication mechanism for diesters may involve chemical reaction with the lubricated surfaces.

INTRODUCTION

It is currently appreciated (references 1 to 6) that new types of lubricant must be found to replace current petroleum oils for the turbine-type aircraft engines of the immediate future. The present lubricants (specification MIL-O-6081A, grades 1010 and 1005), are not completely satisfactory because they are either too viscous for adequate pumpability (based on CRC studies in a simulated lubricants system) at low temperatures (-65° F) or because they have marginal lubricating ability and excessive volatility at present bearing operating temperatures (under 350° F). The lubricant requirements are further complicated by high "soak back" temperatures (approaching 500° F at present) of the bearings which cause thermal decomposition of the lubricant. New engines will have higher bearing operating temperature and lower starting temperature (-65° F or below) operational requirements. There is no evidence that a petroleum oil can satisfy these requirements; consequently, it has been necessary to consider other lubricants such as synthesized fluids for use in aircraft turbines. Military specification MIL-L-7808 is for such a synthetic lubricant. In order to be considered, synthetic lubricants must be thermally stable, be pumpable at low temperatures, and, in addition, must be capable of providing effective boundary lubrication under extreme conditions of temperature, load, and sliding velocity. A previous study of boundary lubrication of synthetic fluids and their decomposition films is reported in reference 7. Static friction coefficients of various esters in lubrication of steel on steel are reported in reference 8 (p. 856).

A number of synthetic fluids have either been considered or merit consideration as turbine lubricants on the basis of their viscometric and thermal stability properties. Unfortunately, boundary lubrication and friction data on these fluids are limited. In consequence, boundary lubricating effectiveness was studied at the NACA Lewis laboratory for a number of synthetic fluids. Only those fluids for which general chemical classification was available were included in these studies; this qualification precluded the study of several fluids for which only a proprietary designation was available.

Experiments were conducted with a kinetic-friction apparatus consisting of a steel ball sliding on a lubricated, flat, steel disk. Data were obtained with very thin films of synthetic fluids at sliding velocities from 75 to 18,000 feet per minute and with a load of 269 grams (initial Hertz surface stress, 126,000 lb/sq in.). The fluids studied included di(2-ethylhexyl) adipate, di(2-ethylhexyl) sebacate, diisooctyl adipate, diethylene glycol benzoate 2-ethylhexoate, tripropylene glycol n-butyl ether, water-soluble polyalkylene glycol, water-insoluble polyalkylene gylcol, dimethyl polysiloxane, chloromethylphenyl polysiloxane, a silicone diester blend, alkylsilicate ester, trifluorovinyl chloride polymer, dioctylbenzene phosphonate, and dioctylisooctene phosphonate.

EXPERIMENTAL FLUIDS

The properties of the synthetic fluids used as lubricants in these experiments are listed in table I. Commercial fluids were used without special treatment inasmuch as previous unpublished data obtained at the Lewis laboratory had indicated that percolation of diesters through silica, alumina, and Fuller's earth had no measurable effect on frictional properties under extreme boundary-lubrication conditions. No marked effect of percolation on friction was found in the research of reference 9 (p. 28) where data were obtained with synthetic lubricants such as diesters and polyglycol ethers.

The diesters are the class of synthetic fluids most widely accepted as aircraft lubricants and have been considered favorably for some time by the Naval Research Laboratory (reference 10) and by the Petroleum Refining Laboratory, Pennsylvania State College, (as noted in reference 5). Military specification MIL-L-7808 has a reference lubricant compounded using a diester as the base stock. Diesters have very good viscometric properties. Considerable research has been conducted on oxidation of diesters (reference 11), and some effective oxidation inhibitors have been developed for specific fluids (reference 12).

The polyethers were among the first commercially available synthetic lubricants. They have viscometric properties that are much superior to petroleum oils. Several polyether fluids have desirable thermal stability properties in that they do not generally form solid decomposition products. Theoretically, the fluids crack and the resulting fractions volatilize without leaving any residue (reference 13).

Silicones (reference 14) have the best viscometric properties of any known liquids. The silicones, however, have two limitations: inadequate oxidation resistance or thermal stability and poor lubricating effectiveness (particularly for steel surfaces). A private communication from a manufacturer of silicones indicates that the problem of increasing oxidation resistance and thermal stability is much less involved than that of improving lubrication. The manufacturer stated that it is possible to improve the oxidation stability of silicones at temperatures up to 500° F, so that the rate of formation of gelation products is very materially reduced.

Silicate esters also have very good viscometric properties and, when properly inhibited, can have good thermal stability as well as hydrolytic stability; these properties make the silicate esters a very promising class of fluids for use as lubricants. One of the products of decomposition of the silicate esters however is silica, an extremely abrasive material. This property may have an appreciable effect on wear under limiting conditions.

The phosphonate compounds have fairly good viscometric properties (table I). There has been speculation about probable toxicity and corrosiveness at elevated temperatures; these properties have not yet been adequately studied although some data are available on corrosion (reference 15). The phosphonate esters as well as certain phosphate esters may be useful in future lubrication problems.

Trifluorovinyl chloride polymers (reference 16) are high-density organic fluorine compounds that are most notable for chemical stability and nonflammability. Their viscosity-temperature characteristics are less desirable than those of other synthetic fluids.

APPARATUS AND PROCEDURE

Friction apparatus. - The friction apparatus used for these experiments was described previously in reference 7. A diagrammatic sketch of the basic parts of the apparatus is presented in figure 1. The apparatus consists primarily of two elements, an elastically restrained spherical rider (1/4-in. balls of SAE 1095 steel hardened to Rockwell C-60) and a rotating disk (normalized SAE 1020 steel; Rockwell hardness, A-50). 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 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 is the ratio of the measured friction force F to the applied normal load P.

The rider is forced to traverse a spiral path on the rotating disk so that portions of the wear track do not overlap. The disk and rider are enclosed, which permits the operating atmosphere of dried air to be slightly pressurized.

Preparation of friction specimens. - The disk specimens are prepared according to the detailed procedure reported in reference 17. The procedure includes surface grinding and nondirectional lapping to produce a surface having random finishing marks with a roughness of 4 to 8 microinches rms, as measured with a profilometer. The essentials of the cleaning process includes degreasing, scrubbing with moist levigated alumina powder, testing for cleanness by the ability of water to wet the surface, immediate rinsing with redistilled 95-percent ethyl alcohol, and drying in the friction apparatus with an atmosphere of dried, filtered air.

The ball specimens are cleaned by wiping with a cloth saturated with 95-percent ethyl alcohol and by rinsing with 95-percent ethyl alcohol. The rider is allowed to dry on the apparatus.

Experimental procedure. - During the experiments, the disk was rotated at a predetermined speed. 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 was observed and photographically recorded and the disk rotative speed was determined. A timer controlled the 3-second operation cycle. Change in the 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. Virgin surfaces on both the disk and rider were used in each run (shown as a data point on the figures).

The lubricating fluids were applied to the disk surface in drops from a clean platinum dipper and were allowed to wet the surface completely. In order to ensure that the films were thin enough to make hydrodynamic lubrication an impossibility, the disk was first rotated at approximately 2500 rpm for 5 minutes to throw off excess lubricant and then the lubricant film on the rotating disk was rubbed with lens tissue. Reference 18 indicates that a lubricant film of this type may approach a monomolecular film on the surfaces of the contacting asperities.

The friction data presented herein are complete for a representative experiment for each lubricant studied and were selected from several experiments with each fluid. In all but isolated cases, the maximum deviation in the coefficient-of-friction data for a given experimental condition was ±0.02 and, in general, was considerably less. For comparative purposes, a load of 269 grams was used for all the data 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 surfaces of lubricated aircraft-engine components.

RESULTS AND DISCUSSION

The most significant results to be discussed in regard to the data presented herein are those showing the effect of sliding velocity on surface failure and the friction coefficients that are obtained (during effective lubrication) with the various fluids. Failure points were determined by inspection of surface appearance for welding or metal transfer, wear rates, and friction trends. Three conditions were observed: no failure (that is, effective lubrication), incipient surface failure, and mass surface failure. When effective boundary lubrication was obtained, the coefficient of friction was essentially independent of load. Some preliminary results have indicated that, with increased loading, the sliding velocity necessary to cause lubrication failure was decreased.

Petroleum

The effect of sliding velocity on the lubrication of steel surfaces by conventional petroleum lubricants is discussed in reference 7. The data for petroleum oil presented in figure 2 are taken from reference 7 and are included herein for comparison with the synthetic fluids to be discussed. In the region of effective boundary lubrication, the data of reference 7 and of unpublished studies show that viscosity has no effect on friction and surface failure. It should be noted that this oil produced friction coefficients from 0.06 to 0.10 in the range of sliding velocities where it was an effective lubricant. The region of sliding velocities where surface failure progressed from the incipient-failure stage to a stage of mass failure was between 3000 and 3500 feet per minute. Failure is believed to be a function of the rate of heat energy released in sliding. At high sliding velocities, the increased amount of heat available causes physical desorption of, or lubricant decomposition in, the boundary film, allowing metallic contact. For lubricants within the same class (as shown in reference 7 for petroleums as an example) the sliding velocity at which failure takes place (critical velocity) is believed to be a function of the high-temperature stability of the particular lubricant.

Diesters

In the region of effective boundary lubrication, the friction coefficients obtained with the several diester-type fluids (fig. 3) are in the same range as those obtained for the petroleum lubricant. The presence of a lubrication additive (5 percent tricresyl phosphate) in the compounded diester (fig. 3(d)) has no beneficial effect on friction coefficient in the region of effective lubrication by the diester. All the diesters studied provided effective lubrication at sliding velocities at least twice as high as the petroleum oil (fig. 2) which has similar room-temperature viscosity. Reference 8 (p. 860) points out that ". . . there is no significant difference in the friction and wear reducing properties of these esters and the mineral oils described." While this result is true under the experimental condition of reference 8, it is obvious from the experimental results reported herein that there is a considerable difference in the ability of the diesters and of the petroleum oil to provide effective lubrication at high sliding velocities.

While viscosity is a convenient standard for comparing the "thick-film" lubricating effectiveness of various lubricants, no fundamental effect of viscosity in boundary lubrication should be anticipated. This lack of viscosity effect is confirmed by the data on diesters. Comparison of the data for three similar diesters (figs. 3(a) to 3(c)) and of their effect on surface failure indicates that the most viscous, di(2-ethylhexyl) sebacate, and the least viscous, di(2-ethylhexyl) adipate, showed evidence of incipient surface failure through the same range of sliding velocities (7000 to 8000 ft/min), while the diester of intermediate viscosity (diisooctyl adipate) showed evidence of incipient surface failure at somewhat higher sliding velocities (8000 to 10,000 ft/min).

The data of figure 3(c) are in agreement with that for the same diester as reported in reference 7. The studies of reference 7 did not, however, exceed a sliding velocity of 7900 feet per minute; therefore, no mass-failure point was noted.

Chemical structure may be a more significant basis for comparison than viscosity. The two diesters of figures 3(a) and 3(c), which showed incipient surface failure in identical sliding velocity ranges, had the same alcohol group in their structure. The diester of figure 3(b), which provided more effective lubrication, had the same acid group as the diester of figure 3(a) but was made with a different alcohol. The other diester lubricants included in figure 3 cannot be compared on this basis because of the presence of additives (fig. 3(d)) or because of a more complex and dissimilar structure (fig. 3(e)).

The tricresyl phosphate used in the diester lubricant of figure 3(d) is a lubrication additive that functions by chemical reaction. It is not a highly active material and is generally considered an antiwear agent. In accordance with the rate-of-reaction hypothesis (which states that rate of chemical reaction between additives and surfaces may be a limiting factor) advanced and substantiated in references 19 and 20, tricresyl phosphate would not likely be an effective additive at high sliding velocities because it is not a highly active material. However, the presence of the heavy acrylic polymer as a viscosity index improver may have caused the compounded diester to provide effective boundary lubrication at higher sliding velocities (range of incipient failure, 9000 to 10,000 ft/min) than the commercially pure plasticizer di(2-ethylhexyl) sebacate (failure, 7000 to 8000 ft/min) which is the principal constituent of the compounded diester.

The diethylene glycol benzoate 2-ethylhexoate of figure 3(e) cannot be compared directly with the other diesters because it is derived from a dialcohol rather than a diacid. Despite poor viscometric properties (table I), this diester was selected in order to determine whether or not diesters in general are good lubricants. Under conditions of effective lubrication, the friction coefficients of all diesters were approximately the same; the limiting usefulness, however, may be a function of the structural characteristics of the molecule.

With all diesters, in the range of velocities where effective lubrication was obtained, the wear areas of the rider (ball) specimens showed both the absence of welding (figs. 4(a) and 4(b)) and the presence of a tan surface film. When incipient failure of the lubricated surfaces occurred, the tan film became mottled with small areas of uncoated and slightly disturbed metal (fig. 4(c)). The observed surface stain or film may be a reaction product of the diester and the steel surface as suggested in reference 21. This possibility will be discussed in the section Practical Considerations.

Figures 4(d) and 4(e) show progressive failure at higher sliding velocities. Since all photomicrographs are shown at the same magnification, figure 4(e) shows the marked increase in size of the wear spot as mass failure occurs. These surfaces are typical of those observed with other lubricants in the various stages of lubrication effectiveness and can serve to illustrate what is meant when effective lubrication, incipient failure, or mass failure are described.

Polyethers

Although they are effective lubricants, the polyalkylene glycols do not produce quite as low values of coefficient of friction (figs. 5(a) and 5(b)) as were obtained with either the petroleum lubricant (fig. 2) or the diesters (fig. 3). The polyalkylene glycol fluids provided effective boundary lubrication at sliding velocities substantially higher than those at which the petroleum oil was effective but they were not effective at sliding velocities as high as were the diesters. The region of sliding velocities where surface failure progressed from the incipient stage to a stage of mass failure was between 5000 and 7000 feet per minute for the water-insoluble polyalkylene glycol and from 6000 to 7000 for the water-soluble polyalkylene glycol.

The tripropylene glycol n-butyl ether is marketed as a heat-transfer fluid and is not commercially represented as a lubricant. This material was studied in order to ascertain whether or not the lubricating properties observed for the fluids of figures 5(a) and 5(b) were common to other ethers having similar temperature ranges of fluidity. With the fluid of figure 5(c), friction values were substantially higher than those for the other polyethers; incipient surface failure was encountered at the minimum sliding velocity (75 ft/min) and mass failure commenced at 2000 feet per minute. This result would indicate that good lubricating ability is not common to all polyether fluids.

During the course of experiments with the polyalkylene glycol lubricants, the water-soluble type was observed, in particular, to show improved lubricating ability after the bulk lubricant had been exposed at room atmosphere for several days. Such behavior may be the result of moisture absorbed by the fluid from the room atmosphere. The presence of moisture might influence the formation of protective oxide films on metallic surfaces. This will be discussed more fully in the section Practical Considerations.

Silicones

The effect of sliding velocity on friction for silicone lubricants is shown in figure 6. With the 50 centistoke (at 25° C) poly-dimethyl siloxane (fig. 6(a)), mass surface failure occurred at all conditions of the experiment. The use of a less viscous (10 cs at 25° C) silicone did not influence either the friction data or the surface-failure properties. When the rider was allowed to traverse repeatedly the same circumferential path, progressive surface failure caused friction coefficients to be up to 50 percent greater than those given in figure 6(a).

The chloromethylphenyl polysiloxane of figure 6(b) is a manufacturer's experimental fluid intended to have improved lubricating ability. The friction data in figure 6(b) do not indicate that the lubricating properties of the silicones have been appreciably improved. It should be noted, however, that the degree of surface failure observed in this experiment was not as severe as that obtained with the fluid of figure 6(a) although some surface failure was observed in all cases. Mild incipient failure occurred at sliding velocities up to 3000 feet per minute; the severity of incipient surface failure increased with higher sliding velocities.

Silicone Diester Blend

The lubricating properties of silicones can be markedly improved by blending them with 30 to 50 percent (by volume) of solvent (reference 22). A solution of one-third diester in silicones was suggested therein as a probable practical lubricant having both good lubrication properties and good viscometric properties (approaching those of the pure silicones). The data of reference 22 were at low sliding velocities (120 ft/min), and data at high sliding velocities are not available. The data of figure 6(c) were therefore obtained at high sliding velocities with a blend of one-third di(2-ethylhexyl) sebacate in a dimethyl polysiloxane fluid (one-half 50 cs fluid and one-half 10 cs fluid). Because a less viscous silicone was used, the viscosity of the lubricant of figure 6(c), as shown in table I, was appreciably less than the viscosity of the fluids of figure 6(a) or 6(b). This fluid was a very effective lubricant (fig. 6(c)). Friction coefficients were in a range (approaching 0.10) that are common to effective boundary lubrication and there was no excessive wear or evidence of surface failure until the sliding velocity exceeded 10,000 feet per minute. Incipient surface failure was experienced at sliding velocities of 11,000 and 12,000 feet per minute but extreme mass failure was not observed.

Silicate Ester

The alkyl silicate ester (fig. 7) is an effective boundary lubricant at sliding velocities up to 9500 feet per minute. Incipient surface failure occurred at 9500 feet per minute and mass surface failure occurred at 10,000 feet per minute. The friction coefficients obtained with the silicate ester under conditions of effective boundary lubrication were as low as those experienced with any of the fluids studied. Since one of the decomposition products of the silicate ester is silica, the sharp break in the friction curve might be a result of the formation of that harmful material as surface failure occurred.

Phosphonate Esters

Some boundary-lubrication data for two phosphonate esters are given in figure 8. The dioctyl benzene phosphonate (fig. 8(a)) provided effective boundary lubrication at sliding velocities up to 5000 feet per minute at which incipient surface failure was observed. Mass failure of the sliding surfaces occurred at sliding velocities of 6000 feet per minute and higher. The dioctylisooctene phosphonate (fig. 8(b)) was a slightly better boundary lubricant than the other phosphonate ester. Friction coefficients were slightly lower and the fluid was an effective boundary lubricant at higher sliding velocities. With dioctylisooctene phosphonate, incipient surface failure began at a sliding velocity of 6000 feet per minute and mass failure was first observed at a sliding velocity of 6500 feet per minute. It might have been expected that these phosphonate compounds would serve as chemically active antiwear additives in the same manner as tricresyl phosphate, however, the results obtained in these experiments indicated that the phosphonate esters did not have any unusual lubrication properties.

Halocarbon

The data of figure 9 for the trifluorovinyl chloride polymer show friction increasing as sliding velocities were increased. Visual study of the surfaces did not show any indication of incipient surface failure until a sliding velocity of 3000 feet per minute was obtained. Mass failure apparently occurred to the surface at 7000 feet per minute although failure was not as drastic as that experienced with other types of lubricant. The unusual behavior of this fluid might be accounted for on the basis of decomposition of the fluid lubricant to form compounds having "extreme pressure" characteristics. It is speculated that the trifluorovinyl chloride polymer may have decomposed under sliding conditions to produce a chlorine compound which acted as an extreme pressure agent.

Practical Considerations

The requirements of future aircraft turbine engines with respect to viscometric and thermal stability properties appear rather severe at the present time. Some relaxation in requirements based on design changes and a better understanding of the lubrication phenomenon in aircraft turbine engines possibly could be made. An example of a design change would be the use of a pumping system to handle more viscous fluids at low temperatures. Also, high-temperature minimum viscosity requirements might be relaxed for specific types of engine. In particular, for present turbojet engines having rolling contact bearings, all lubricated parts subject to failure operate in the region of boundary lubrication;

since viscosity is not an important variable in boundary lubrication, relaxation of the high-temperature minimum viscosity requirements might be possible. In boundary lubrication, viscosity may be important only because, with higher viscosity, greater thermal stability in petroleum fractions (or possibly in any one type of synthetic fluid) is usually obtained. This probably is not true as different types of synthetic fluid are compared.

Reduction gearing of turbine-propellor engines, where high loading is encountered, represents a different problem. In this case, high viscosity is desirable at operating temperature because gear lubrication has an important hydrodynamic component (reference 23). The good viscometric properties of silicone diester blends might be employed to satisfy the very stringent high-temperature-viscosity requirement necessary to enable the hydrodynamic component to be fully utilized in obtained increased load capacity of gearing. The physical properties and lubricating abilities of the silicone diester blends have not been fully evaluated; however, these blends show considerable promise.

The silicate ester, as well as the silicone diester blend, is a very good lubricant for high sliding velocities and has exceptionally good viscometric properties (table I). Because of these good viscometric properties, more viscous (at 100° F) silicate esters could probably be used for gear lubrication. Hydrolitic instability of silicate esters is a very important problem that could be a limiting factor in their widespread use.

The majority of synthetic lubricants being considered for use in aircraft turbines are esters of various types. In the data presented herein all the ester-type fluids (diesters, silicate ester, and phosphonate ester) had good lubrication properties. In the course of future development of the use of these fluids, it is important to have some basic understanding as to why esters lubricate. One reasonable concept of the mechanism of lubrication for esters, as described in references 8 and 21, indicates that hydrolysis of esters would lead to the formation of a very small amount of fatty acid which when absorbed could attack the metal to form the corresponding soap film. Thus, lubrication would be provided by a chemisorbed soap film resulting from lubricant decomposition.

In order to check the validity of the suggested mechanism, an experiment was conducted with nonreactive friction specimens lubricated with a typical diester. A synthetic sapphire (Al_2O_3) ball was used sliding on a Vycor glass disk lubricated with a rubbed film of di(2-ethylhexyl) sebacate. The results of this run (fig. 10) indicate that chemical reaction may be important in lubrication by ester-type fluids. With the nonreactive specimens, the diester did not provide effective lubrication except at the minimum sliding velocity (75 ft/min) and the type of surface failure progressed rapidly to a severe scoring. Failure of the glass surface was observed to occur as a copious removal of fine glass particles from the disk surface rather than mass welding as occurs with steel specimens.

If the mechanism of lubrication is one of hydrolysis and subsequent metal attack to form the soap film, the type of metal to be lubricated must be considered. Esters may not lubricate the noble-type metals that are not attacked by fatty acids; also, completely effective hydrolysis inhibitors may deprive esters of their lubricating ability by preventing the formation of fatty acids. Much research has been directed at the problem of providing additives to inhibit hydrolysis of esters, however, these inhibitors probably will not become so effective that they would adversely affect the lubricating ability of esters. Other forms of chemical instability such as oxidation and pyrolysis, which are normally considered detrimental, could have a similar beneficial effect on the lubricating ability of esters (reference 8, p. 860).

Qualitative observation of the performance of polyether lubricants indicates that available oxygen (from moisture or possibly from decomposition of the lubricant) and the formation of oxide films on surfaces have considerable effect on lubrication. With several polyether fluids, erratic performance was observed during screening tests with a SAE lubricant tester modified to have the specimens operating in pure sliding, with no hydrodynamic lubrication possible. When particularly good results were obtained, the specimens had formed surface films that were believed to be oxides. Also, better results were obtained with the water-soluble series than the water-insoluble series having, otherwise, essentially the same properties. Those results may have been influenced by the presence of more water in the water-soluble polyethers.

SUMMARY OF RESULTS

Studies were made of the lubricating effectiveness of various classes of synthetic fluid in boundary lubrication of steel surfaces at high sliding velocities. The following observations were made:

1. Sliding-friction data and surface-failure properties show that a number of synthetics including diesters, polyethers, a silicate ester, and phosphonate esters as well as a silicone diester blend are more effective boundary lubricants at high sliding velocities than petroleum oils of comparable viscosity. The breakdown of effective lubrication with these synthetics takes place at much higher sliding velocities than with the petroleum oil.

2. A blend of silicones and a diester, an alkyl silicate ester, and a compounded diester (containing lubrication additives) were more effective boundary lubricants at high sliding velocities than were comparable diesters from which the most widely accepted synthetic lubricants are made.

3. A diester failed to lubricate nonreactive surfaces which indicates that the lubrication mechanism for diesters may involve chemical reaction with the lubricated surfaces.

Lewis Flight Propulsion Laboratory
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TABLE I - PROPERTIES OF EXPERIMENTAL FLUIDS

Fluid	Viscosity at °F (cs)				A.S.T.M. pour point (°F)	C.O.C. flash point (°F)	C.O.C. fire point (°F)
	-65	-40	100	210			
Diesters							
Di(2-ethylhexyl) adipate[a]	6000	877	8.12	2.34	-94	395	418
Diisooctyl adipate[a]	6962	-----	10.13	2.83	-103	408	418
Di(2-ethylhexyl) sebacate[a]	8297	-----	12.78	3.32	<-70	440	472
Compounded diester (Di(2-ethylhexyl) sebacate plus additives)[b,c]	16,000	2700	20.8	5.3	<-75	450	475
Diethylene glycol benzoate 2-ethylhexoate[b]	[g]	-----	10.9	2.5	-70	415	425
Polyethers							
Tripropylene glycol n-butyl ether[a]	4657	-----	5.07	1.42	-105	288	395
Polyalkylene glycol (water soluble)[a]	12,503	-----	9.28	2.43	-83	220	230
Polyalkylene glycol (water insoluble)[a]	4587	-----	7.87	2.35	<-103	280	300
Silicones							
Dimethyl polysiloxane[a]	668	-----	39.75	15.3	<-103	520	585
Chloromethylphenyl polysiloxane[b]	1500	-----	41.0	13.5	-94	540	----
Silicone diester blend							
Dimethyl polysiloxane plus one-third di(2-ethylhexyl) sebacate	------	205	15.5	5.75	<-75	375	415
Silicate ester							
Tetrakis(2-ethylhexyl) silicate[b,f]	1400	260	6.8	2.4	<-100	395	450
Phosphonate esters							
Dioctylbenzene phosphonate[a]	------	[d]8359	11.38	2.64	-87	----	----
Dioctylisooctene phosphonate[a]	------	[d]9003	12.22	2.77	-90	----	----
Halocarbon							
Trifluorovinyl chloride polymer[a]	6524	-----	4.13	1.13	-105	none	none
Petroleum[e]							
MIL-O-6081(grade 1010)[a]	40,000	-----	9.95	2.47	<-70	300	----

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[a] Measured values.

[b] Manufacturer's data.

[c] Additives consist of 0.5 percent phenothiazine, approximately 4 percent viscosity index improver, and 5 percent tricresyl phosphate.

[d] At -50° F.

[e] For comparison only.

[f] Includes oxidation inhibitor.

[g] Above pumpability limit.

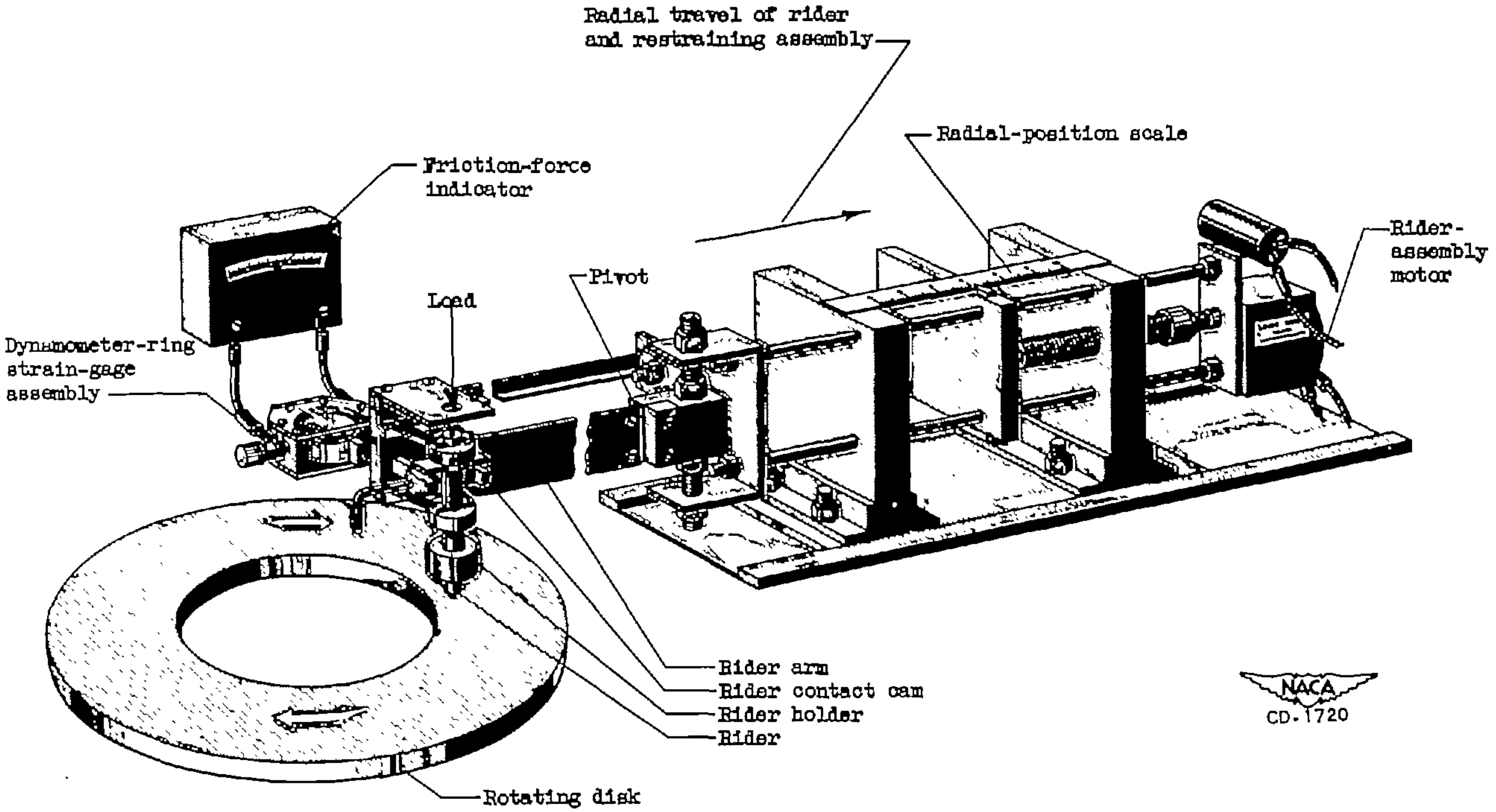


Figure 1. - Schematic diagram of sliding-friction apparatus.

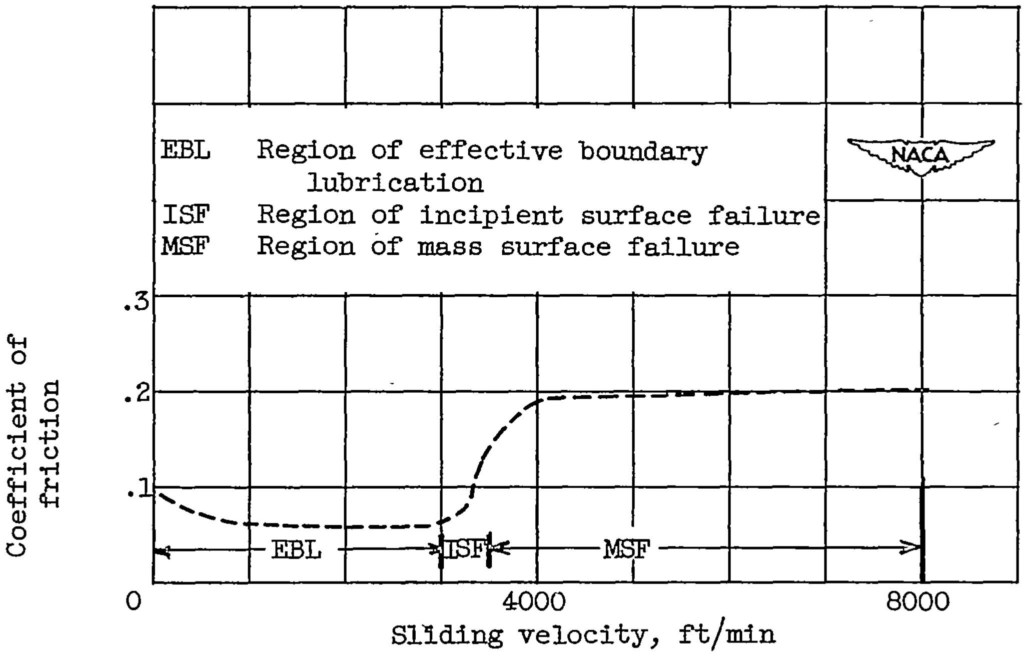
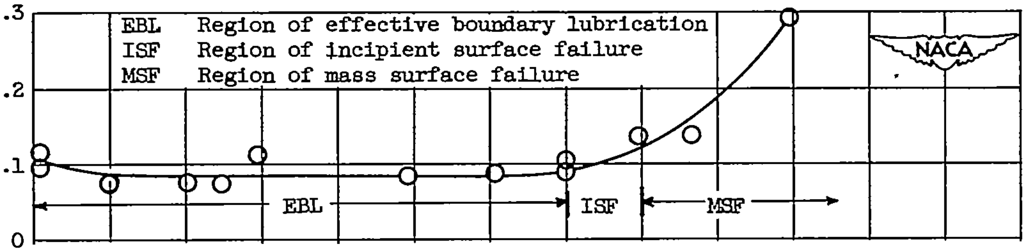
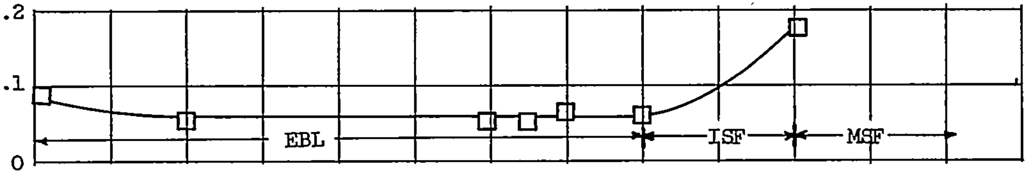


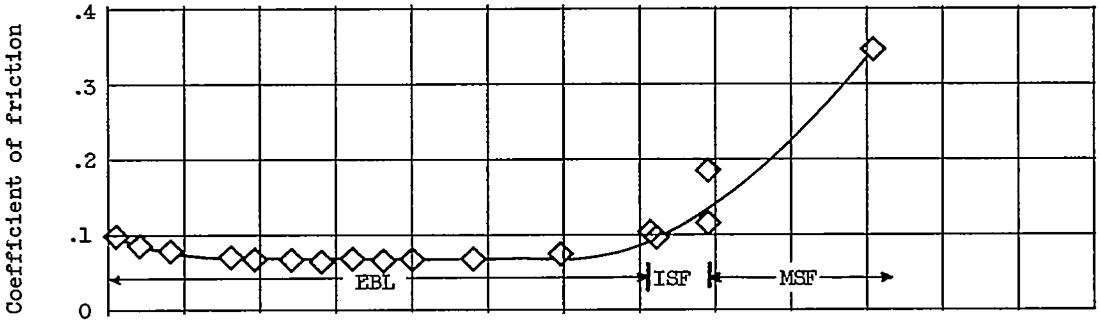
Figure 2. - Effect of sliding velocity on coefficient of friction of steel surfaces boundary lubricated with petroleum oil (MIL-O-6081A,grade 1010). Load, 269 grams. (Data from reference 7.)



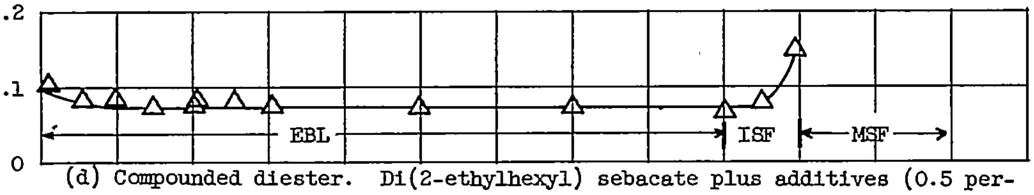
(a) Di(2-ethylhexyl) adipate.



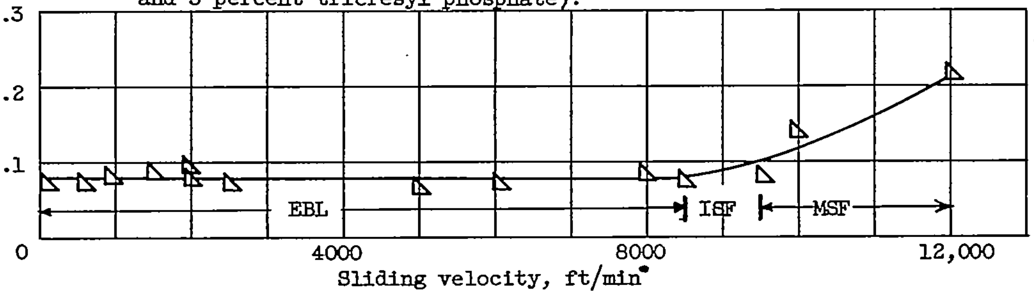
(b) Diisooctyl adipate.



(c) Di(2-ethylhexyl) sebacate.

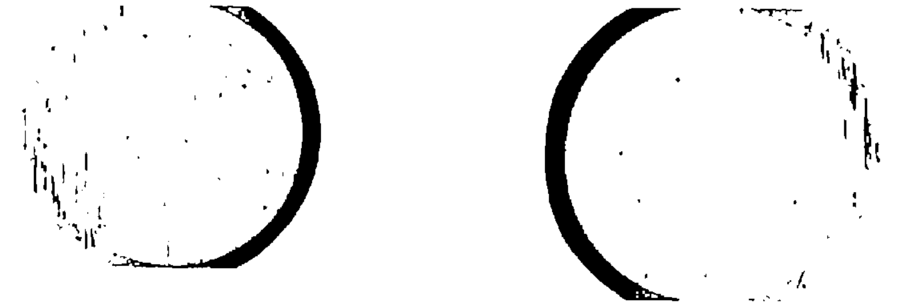


(d) Compounded diester. Di(2-ethylhexyl) sebacate plus additives (0.5 percent phenothiazine, approximately 4 percent viscosity index improver and 5 percent tricresyl phosphate).



(e) Diethylene glycol benzoate 2-ethylhexoate.

Figure 3. - Effect of sliding velocity on friction of steel surfaces boundary lubricated with various diesters. Load, 269 grams.



(a) Effective lubrication. Sliding velocity, 5000 feet per minute.

(b) Effective lubrication. Sliding velocity, 7000 feet per minute.

(c) First evidence of incipient failure. Sliding velocity, 9000 feet per minute.

(d) Incipient failure. Sliding velocity, 9500 feet per minute.

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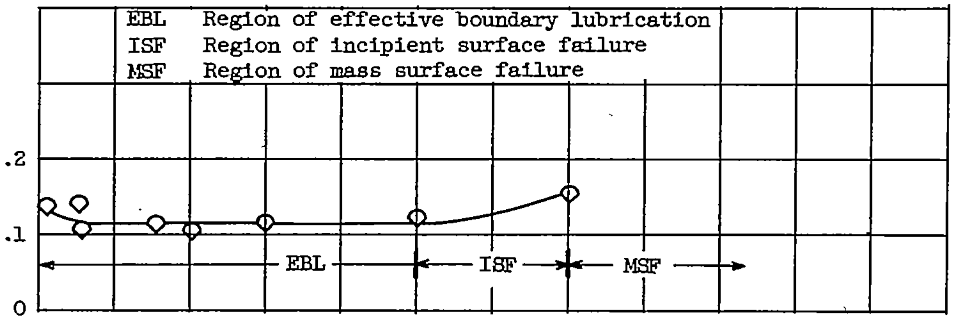
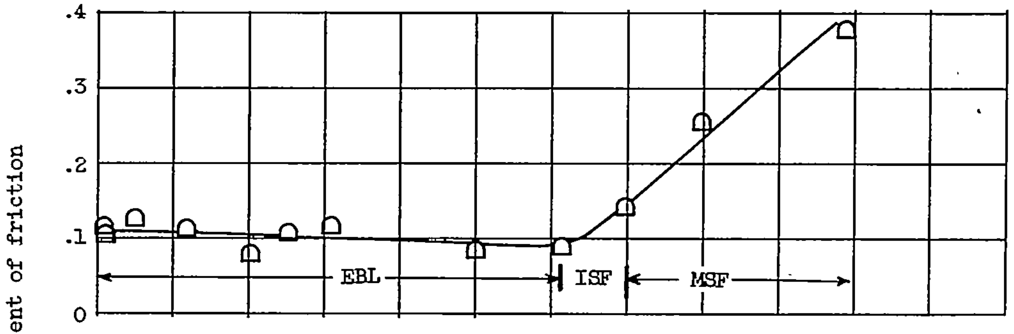
(e) Mass failure. Sliding velocity, 10,000 feet per minute.

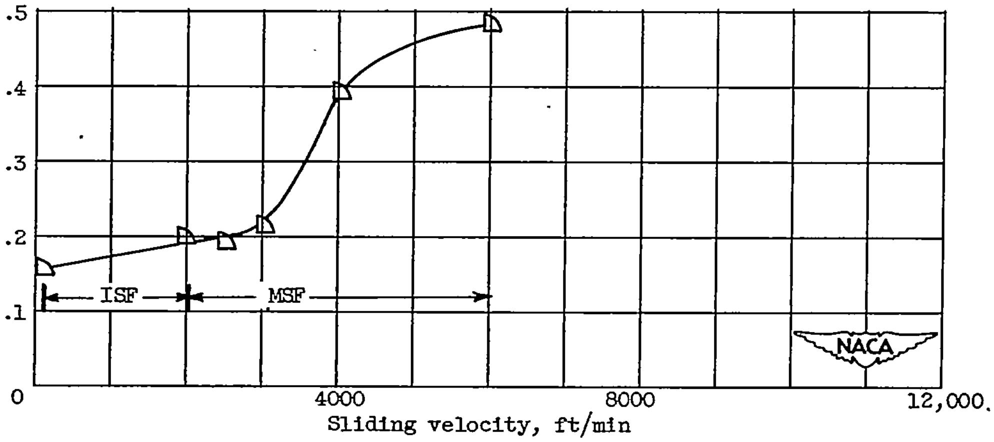
Figure 4. - Photomicrographs showing typical progression of surface failure on different wear areas of ball specimens after 3-second runs at various sliding velocities. Load, 269 grams (initial Hertz stress, 126,000 psi). Boundary lubricated by the compounded diester-type fluid (containing lubrication additives) of figure 3(d). X100.



(a) Water-insoluble polyalkylene glycol.

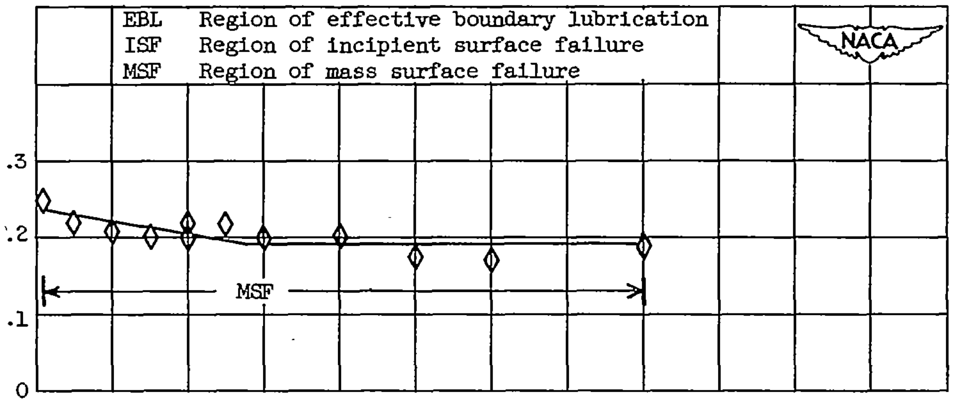


(b) Water-soluble polyalkylene glycol.

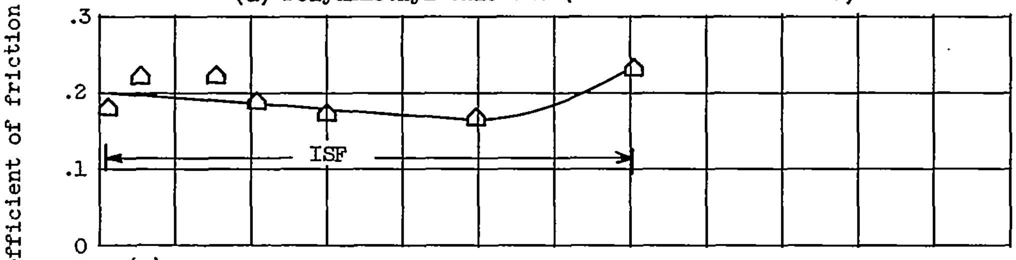


(c) Tripropylene glycol n-butyl ether.

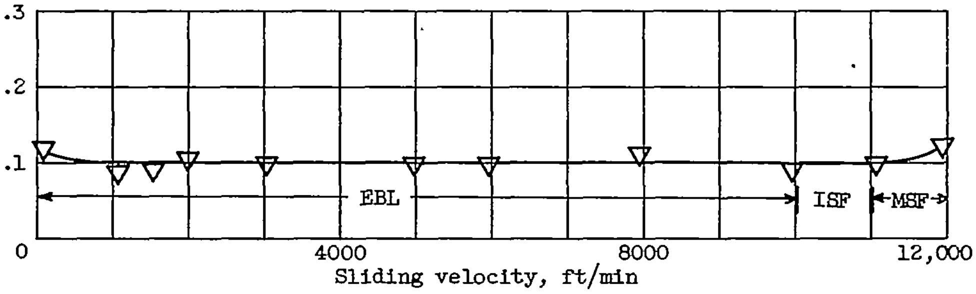
Figure 5. - Effect of sliding velocity on friction of steel surfaces boundary lubricated with various polyethers. Load, 269 grams.



(a) Polydimethyl siloxane (data from reference 7)



(b) Chloromethylphenyl polysiloxane. No mass surface failure throughout speed range covered.



(c) Blend of two-thirds silicone and one-third di(2-ethylhexyl) sebacate. No extreme surface failure in region of mass surface failure.

Figure 6. - Effect of sliding velocity on friction of steel surfaces boundary lubricated with various silicone lubricants. Load, 269 grams.

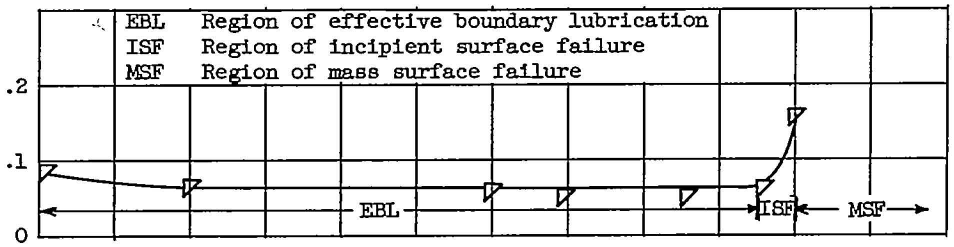
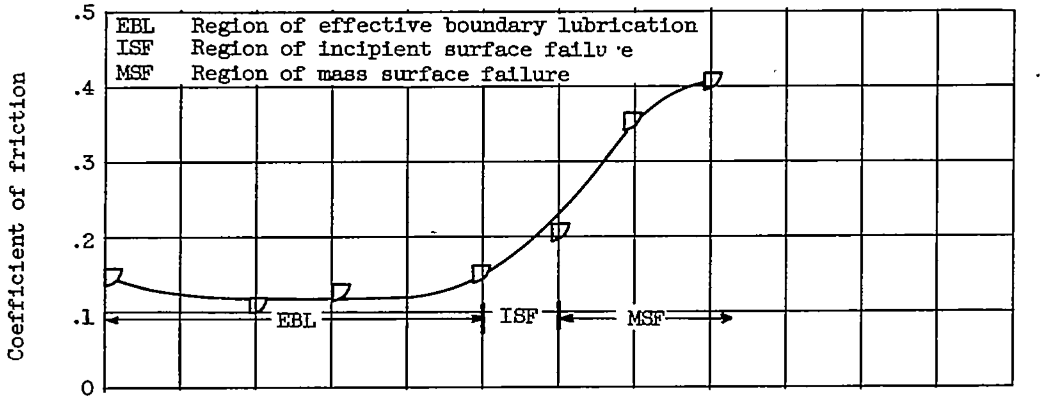
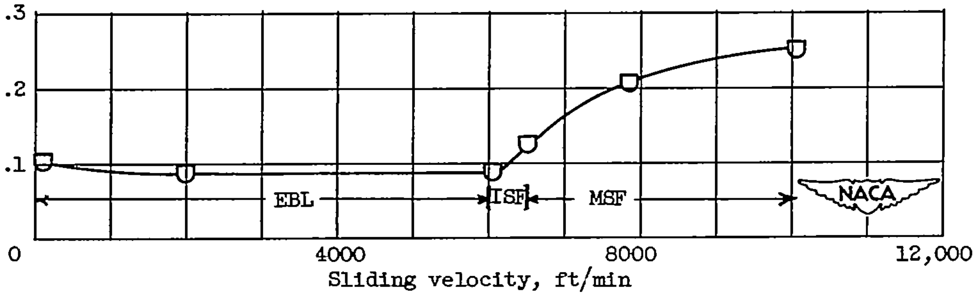


Figure 7. - Effect of sliding velocity on friction of steel surfaces boundary lubricated with alkyl silicate ester. Load, 269 grams.



(a) Dioctyl benzene phosphonate.



(b) Dioctyl isooctene phosphonate.

Figure 8. - Effect of sliding velocity on friction of steel surfaces boundary lubricated with phosphonate esters. Load, 269 grams.

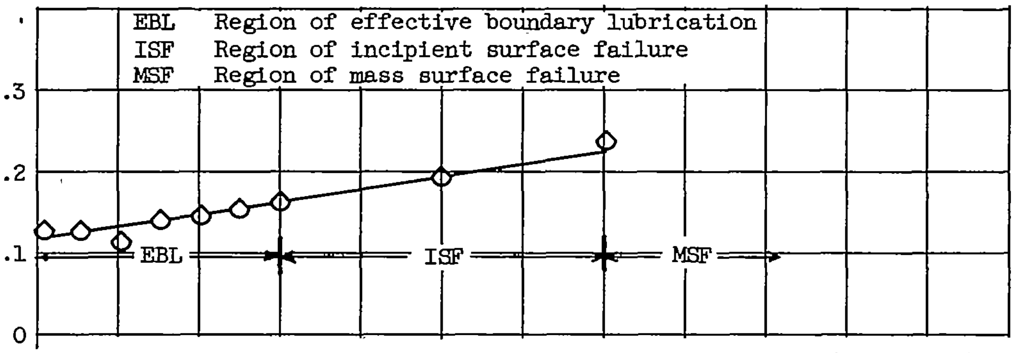


Figure 9. - Effect of sliding velocity on friction of steel surfaces boundary lubricated with trifluorovinyl chloride polymer. Load, 269 grams.

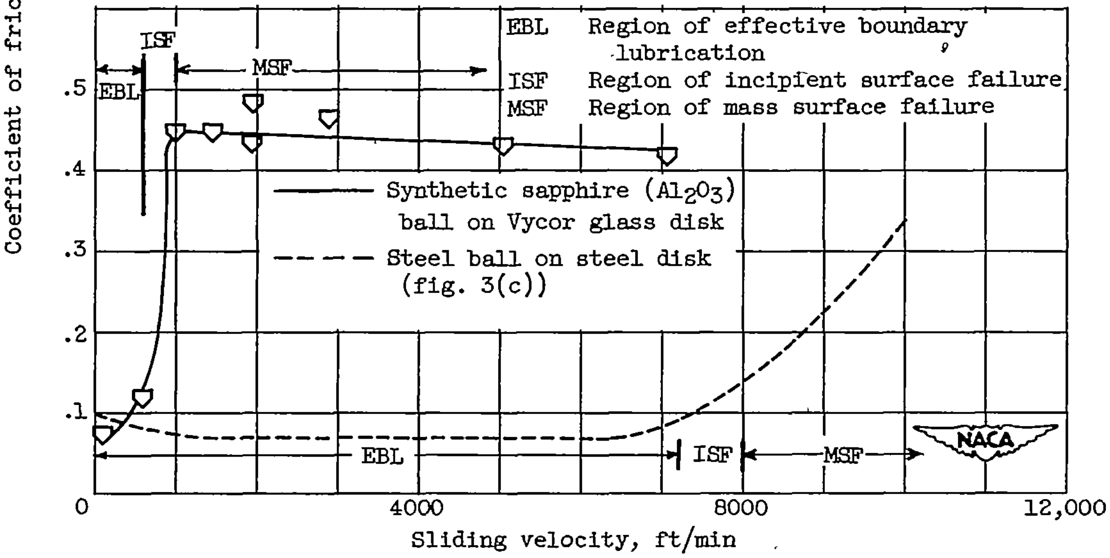


Figure 10. - Effect of slider materials on lubrication by a typical diester lubricant, di(2-ethylhexyl) sebacate. Load, 269 grams.

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