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MEMORANDUM

LUBRICATING PROPERTIES OF LEAD-MONOXIDE-BASE COATINGS OF VARIOUS COMPOSITIONS AT TEMPERATURES TO 1250° F

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LUBRICATING PROPERTIES OF LEAD-MONOXIDE-BASE COATINGS OF VARIOUS COMPOSITIONS AT TEMPERATURES TO 1250° F

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SUMMARY

A number of ceramic coatings of different compositions containing lead monoxide (PbO) were studied to determine their relative merits as dry-film lubricants. Lead monoxide is known to be an effective solid lubricant at elevated temperatures, and this oxide was the main component in all compositions studied. Friction and wear properties were determined at temperatures from 75° to 1250° F, at a sliding velocity of 430 feet per minute, and at a normal load of 1 kilogram.

In all of the coatings, PbO was the component primarily responsible for the lubricating properties. Oxides other than PbO had an indirect effect on lubrication by influencing such properties as adhesion, hardness, vitrifying or glaze-forming tendency, melting or softening point, and chemical stability of the coatings. Notable among these oxides were magnetite (Fe_3O_4), which had generally a beneficial influence on ceramic-to-metal adhesion, and silica (SiO_2), which inhibited the oxidation of PbO and enhanced the tendency for glaze formation on the sliding surfaces.

Several of the compositions studied provided protection against metal-to-metal adhesive wear, galling, or seizure at test temperatures from 75° to 1250° F. Coating friction coefficients ranged from 0.20 to 0.37 at 75° F but were around 0.08 to 0.20 at temperatures of 1250° F.

INTRODUCTION

The need for high-temperature lubricants becomes increasingly critical as greater emphasis is placed on rocket propulsion and supersonic aircraft. The lubricants must be capable of reducing the friction torque required in the operation of components exposed to temperatures of 1000° F and higher and also of preventing galling of the sliding surfaces. The use of a bonded solid lubricant appeared to be a promising approach to this problem.

The results of previous NACA research (ref. 1) indicate that powdered lead monoxide (PbO) is a good lubricant at 1000° F and possibly higher temperatures. References 2 and 3 describe NACA research on PbO-base films containing small percentages of silica (SiO_2) and bonded to metal surfaces as ceramic coatings. The results of these investigations indicate that the lubricating properties of the coatings improve with decreasing coating thickness down to the minimum thickness studied (0.0005 in.). A satisfactory coating thickness on martensitic stainless steel (consistent with good endurance life) is 0.001 inch. The results further indicate that the friction coefficients decrease under conditions (such as high environmental temperature and/or high sliding velocity) that result in localized high temperatures at the ceramic surface.

The low friction obtained at high surface temperatures can probably be related to lubrication by the viscous flow of a soft lead oxide glass or glaze rather than to lubrication by shear along crystal cleavage planes as is the usual case with solid lubricants.

The first objective of the subject investigation was to study the effects of various oxide additions on the lubricating properties of PbO-base coatings. The favorable results reported in references 2 and 3, which were obtained by the addition of a glass-forming oxide, SiO_2, stimulated interest in determining the effects of other vitrifying oxides. Vanadium pentoxide (V_2O_5) and boric oxide (B_2O_3), which are representative of commonly used vitrifying oxides (ref. 4), were selected for this investigation. Other additions were also studied for other purposes. For example, bentonite clay was of interest because it is a good suspending agent for PbO in an aqueous medium; further, the silicate content of bentonite would tend to impart some vitrifying tendency. Additions of Fe_3O_4 were studied as a means of increasing adhesion and hardness of coatings applied to austenitic stainless steel.

The second objective was to study the effects of base-metal composition on the lubricating properties of PbO-base coatings. The base metals studied (AISI types 440-C and 304 stainless steels and Inconel X) were chosen because they differed widely in the type and amount of oxide formed on their surfaces at the firing temperatures. The effect of base-metal oxides on the bonding and lubricating properties of the coatings could thereby be deduced by a comparative study of coatings applied to these alloys. Base-metal oxides were expected to have an effect on the properties of the coating because it is known that, at high temperatures, oxides of the substrate metal can diffuse into existent oxide films and alter their physical properties (ref. 5).

The scope of the investigation included formulations, application, composition, and structure analyses, as well as friction and wear studies of these coatings. Friction and wear were measured at temperatures from 75° to 1250° F and at a sliding velocity of 430 feet per minute.

MATERIALS AND PROCEDURE

Materials

The rider specimens for all tests run at temperatures up to 1000° F were M-1 tool steel hardened to Rockwell C-60. Cast Inconel riders with initial room-temperature hardnesses of Rockwell B-75 to B-80 were used at 1250° F. Each rider was cylindrical (3/8-in. diam. and 3/4-in. length) with a hemispherical tip (3/16-in. rad.) ground on one end. The disk specimens (2.5-in. diam. and 0.5-in. thickness) to which the coatings were fused were type 440-C martensitic stainless steel, type 304 austenitic stainless steel, or Inconel X. Before the coatings were applied, the plane surfaces of each disk were ground flat and parallel to within 0.0005 inch.

The coatings were prepared from reagent-grade oxide powders of about 200-mesh particle size. The bentonite clay was a technically pure grade of about 300-mesh particle size.

Procedure

Application of coatings. - Most of the coatings were applied as follows: A thin layer (about 1/16 in. thick) of dry mixed oxide powder was dusted onto the flat, clean surface of a friction disk. The specimen was then placed in a furnace at a sufficiently high temperature to melt the oxides and form a uniform, molten film. The disk was then removed from the furnace, placed on a water-cooled steel block, and allowed to cool in room air. Instead of being applied as dry powders, the mixtures containing bentonite were brushed onto the metal surfaces as an aqueous suspension. The specimens were then baked at 200° F to drive off the water before firing. The coatings were finish-ground to a thickness of 0.001 inch.

The times and temperatures in the furnace that resulted in satisfactory coatings varied with the powder compositions. Optimum times and temperatures will also vary with the size of the object being coated and with the geometry of the furnace. The furnace used in this work was an electric resistance furnace with a cylindrical hot zone of 12-inch diameter and 8-inch height. Twelve uniformly spaced Globars were arranged around the circumference of the hot zone. With this furnace, satisfactory coatings were obtained with the various powder compositions and alloys when the following firing conditions were employed:

(a) PbO Powder on 440-C; 10 minutes at 1900° F.

(b) PbO Powder on Inconel X; 7 minutes at 1800° F.

(c) 95 Percent PbO plus 5 percent SiO_2 on 440-C; 8 minutes at 1650° F.

(d) 95 Percent PbO plus 5 percent V_2O_5 on 440-C; 7 minutes at 1900° F.

(e) 95 Percent PbO plus 5 percent B_2O_3 on 440-C; 8 minutes at 1600° F.

(f) 85 Percent PbO plus 10 percent Fe_3O_4 plus 5 percent SiO_2 on 304; 6 minutes at 1800° F.

(g) 86.4 Percent PbO plus 9.1 percent bentonite plus 4.5 percent SiO_2 on 440-C; 4 minutes at 1800° F, cool, then 5 minutes at 1900° F. (Double firing appeared to be quite helpful in obtaining a uniform coating.)

Cleaning. - Before each test, both the rider and the disk specimens were subjected to the following cleaning procedure:

(1) Wash with acetone.

(2) Scrub with levigated alumina. (This step omitted in cleaning coated disks to avoid embedding alumina particles in the comparatively soft coatings.)

(3) Wash in tap water.

(4) Wash in distilled water.

(5) Scrub with acetone.

(6) Scrub with 95 percent ethyl alcohol.

(7) Dry in room air.

Testing. - The apparatus used in performing the friction and wear studies is shown in figure 1. A complete description of this apparatus is given in reference 3. All tests were run in air with the specimens under a normal load of 1 kilogram and at a sliding velocity of 430 feet per minute. The temperature was held constant and the friction recorded continuously during each test. Test duration was usually 1 hour. The specimens were held at test temperature for about 1/2 hour before each run.

RESULTS AND DISCUSSION

The results in general indicate that the compositions of PbO-base films can be varied considerably as to the type and amount of other oxides present without altering the basic friction and wear properties of the coatings. The added oxides function in specific ways, such as influencing the adhesion, hardness, vitrifying tendency, softening or melting point (ref. 6), and chemical stability of the coatings. Some of the coatings provided low friction coefficients from 250° to 1250° F. Others either lubricated well above 500° F but not at the lower temperatures or lubricated well below 800° F but not at higher temperatures. Therefore, the temperature ranges of effective lubrication for the various coatings were different; but where they overlapped, the friction and wear properties were quite similar. Photographs of friction specimens coated with the various PbO-base films under discussion are given in figure 2.

Figure 3 gives the friction coefficients and the rider wear at various temperatures for M-1 tool steel sliding against unlubricated 440-C. The same type of data for these metals lubricated by a coating containing PbO and SiO_2 and described in reference 2 is also presented. The data in this figure will be a basis for comparison in evaluating the other coating compositions. For convenience, the data for the unlubricated metals are repeated as a reference curve in figures 4 to 6.

The specific effects of the various oxide additions on the friction, wear, and other properties of the coatings are given in the following sections.

Pure PbO Fused to Type 440-C Stainless Steel

As shown in figures 4 and 7, at all temperatures from 75° to 1250° F, the friction coefficients and rider wear obtained with pure PbO fused to type 440-C stainless steel were much lower than those obtained with the unlubricated metals. Friction coefficients at 500° F and higher temperatures were within the range of effective boundary lubrication (friction coeff. less than 0.20). Microscopic examination showed that no galling or metal transfer occurred at any temperature studied.

X-ray diffraction patterns of these coatings indicated that they contained iron oxide (table I). The results of chemical quantitative analyses given in table II show that the iron oxide content calculated as Fe_3O_4 was over 10 percent. The high percentage of iron oxide was probably caused by oxidation of the base metal during the firing process and diffusion of base-metal oxides throughout the molten ceramic. This is quite plausible, because rapid increases in diffusion rates occur when a liquid phase appears in an oxide layer, and these rates may be many orders of magnitude higher than at temperatures below the melting point (ref. 5).

It was observed in this investigation that iron oxide imparts hardness to the coatings and may stabilize the PbO form of lead oxide. No pattern for any oxide of lead other than PbO was obtained in the X-ray diffraction studies of this coating. The diffraction pattern was sharp and well defined, indicating a high degree of crystallinity. However, the coating material in the wear tracks became glazed during sliding. The formation of a glazed track on a coating composed of only PbO and iron oxide may be due to the fact that PbO itself has glass-forming properties (ref. 7). (See specimen 1, fig. 2(a).) Minute spalled regions along the edges of the wear track indicated that the bond may not have been as good as that obtained with the reference coating (specimen 3, fig. 2(c)).

Pure PbO Fused to Inconel X

The lubricating properties of pure PbO fused to Inconel X are given in figures 4 and 7. Low friction coefficients and very low rider wear were obtained from 75° to 800° F, but high rider wear was obtained at higher temperatures.

The coatings contained comparatively small percentages of base-metal oxide (table II). This is to be expected, because Inconel X has better high-temperature oxidation resistance than type 440-C.

The coatings were very soft and quite crystalline. The high degree of crystallinity was indicated by the X-ray diffraction pattern obtained, but it was even more obvious from the over-all appearance of the coatings. Large crystals can be seen on specimen 2 of figure 2(b). The crystals were plate-like in structure and were easily flaked off with a sharp instrument.

95 Percent PbO + 5 Percent V_2O_5 Fused to Type 440-C Stainless Steel

The lubricating properties of 95 percent PbO plus 5 percent V_2O_5 fused to 440-C are given in figures 5 and 7. Low friction and rider wear were obtained over the entire temperature range studied. However, the bond strength of these coatings was not consistent. A disk for which no serious bond failures occurred is shown in figure 2(d) (specimen 4). Specimen 5, however, has a large spalled area where gross bond failure occurred when the coating was being ground to the desired thickness. This coating may be of considerable interest if the metal-to-ceramic bond can be improved.

X-ray analyses indicated the presence of Pb_3O_4 in this coating (table I). The V_2O_5 is apparently not an effective oxidation inhibitor for PbO. X-ray analyses further indicated the presence of Fe_3O_4. Chemical quantitative analyses (table II) showed that the iron oxide content was over 12 percent. This high percentage of iron oxide is evidence in agreement with studies reported in reference 5, which show that the oxidation rates of stainless steels in contact with V_2O_5 are higher than those of the same metals heated in contact with air alone. However, the poor adherence demonstrates that Fe_3O_4 does not improve bond strength unless it is present in a tight, adherent transition layer. In the presence of V_2O_5, a consistently adherent transition layer did not form.

95 Percent PbO + 5 Percent B_2O_3 Fused to Type 440-C Stainless Steel

The lubricating properties of the B_2O_3-containing coatings are shown in figures 5 and 7. A friction coefficient of about 0.14 was obtained at temperatures from 75° to 1000° F. Rider wear was low at 75° and at 500° F but quite high at 1000° F. Both friction and wear were high at 1250° F. These coatings are apparently too soft and easily squeezed out of the zone of sliding at 1000° and 1250° F.

The coatings were completely amorphous to X-rays, indicating a high degree of vitrification. A disk coated with this material is shown in figure 2(e) (specimen 6). As in the case of the PbO-SiO_2 reference coating, less iron oxide was present in the final composition than in coatings prepared from pure PbO on stainless steel (table II). B_2O_3 and SiO_2 appear to have some inhibiting effect on the oxidation of type 440-C during the firing process.

85 Percent PbO + 10 Percent Fe_3O_4 + 5 Percent SiO_2 Fused to Type 304 Stainless Steel

During preliminary attempts to coat type 304, the importance of base-metal composition became evident. In these attempts, a powder mixture containing 95 percent PbO and 5 percent SiO_2 was used. After firing, the coatings exhibited a mottled appearance and poor bond to the metal surface. No problems of poor adhesion or of mottling were encountered when the same powders were bonded to type 440-C (ref. 2).

One of the important differences between the austenitic alloy (type 304) and the martensitic alloy (type 440-C) is that the latter oxidizes more rapidly at elevated temperatures and therefore supplies more iron oxide to the molten PbO during a given firing period. It was observed that iron oxide increases the fluidity of molten PbO. A melt of high fluidity becomes homogeneous more readily than a highly viscous one, and this is reflected in improved uniformity after solidification. Further, reference 8 indicates that the presence of an adherent, iron-oxide-rich transition layer at the ceramic-metal interface is probably required to obtain good bond to the steel surface. As a result of these considerations, it appeared plausible that the beneficial effects of iron oxide might be obtained in coatings applied to oxidation-resistant steels by addition of iron oxide to the mixed oxide powders prior to firing. Fe_3O_4 was added rather than Fe_2O_3 because, as indicated in reference 9, the presence of Fe_2O_3 between sliding metal surfaces causes excessive surface damage, whereas Fe_3O_4 actually reduces friction and helps prevent welding and metal transfer. Mixed oxide powders containing 85 percent PbO, 10 percent Fe_3O_4, and 5 percent SiO_2 were therefore fired onto type 304 stainless steel; and adherent, uniform coatings were obtained (fig. 2(f), specimen 7). The coefficients of friction and the rider wear obtained with this coating were approximately the same as those obtained with the reference coating of PbO-SiO_2. The data are given in figures 6 and 7.

86.4 Percent PbO + 9.1 Percent Bentonite + 4.5 Percent SiO_2

Fused to Type 440-C Stainless Steel

It is often impractical to apply dry powders to metal surfaces before firing. A suspending agent (bentonite) was added to a 95 percent PbO plus 5 percent SiO_2 mixture to give the following powder composition: 86.4 percent PbO, 4.5 percent SiO_2, 9.1 percent bentonite. This composition was made into a water suspension that could be brushed or sprayed.

The friction and wear data are given in figures 6 and 7. A photograph of this coating is shown in figure 2(g), specimen 8. Friction coefficients were about the same as those obtained with the reference coating (fig. 3). Rider wear was about the same at 500°, 1000°, and 1250° F, but was considerably higher than obtained with the reference coating at lower temperatures. No wear data are given in figure 6 for 75° and 250° F because the coatings failed by brittle fracture at these temperatures early in the tests. However, typical friction coefficients before and after failure are given for these temperatures. The brittleness at low temperatures was caused by aluminum silicate introduced by the bentonite. The brittleness can probably be decreased by adding bentonite to PbO powders containing little or no free silica or by using an organic suspending agent such as gum arabic or gum tragacanth that will burn off during the firing process.

Thermal Expansion Coefficients

An important consideration in coating metals with ceramics is the proper matching of thermal expansion coefficients. The mean thermal expansion coefficient for the 300-series stainless steels from 68° to 1600° F is about 11.0×10^{-6} inch per inch per $^\circ$F; for the 400-series alloys, it is about 6.2×10^{-6} inch per inch per $^\circ$F (ref. 10). The calculated expansion coefficients for all the coatings were about 7×10^{-6} inch per inch per $^\circ$F. The values for the coatings were based on the factors given in reference 11 for calculating the expansion coefficients of enamels from their compositions. The compositions used in the calculations were the compositions after firing, which are given in table II. Although the values for the coatings were intermediate between those of the two alloy types, no problems of spalling occurred during thermal cycling involved in the application and testing of the coatings. This is probably largely due to the softness of PbO (moh hardness is 2.2). The requirements for close matching of the thermal expansion coefficients of the base metal and the ceramic to obtain good thermal shock resistance in an enamel apparently can be relaxed considerably for coatings containing a large percentage of PbO.

SUMMARY OF RESULTS

Friction and wear studies of PbO-base ceramic coatings were conducted at temperatures from 75° to 1250° F and at a sliding velocity of 430 feet per minute. X-ray diffraction patterns and chemical analyses were obtained for all the coatings. The major results were as follows:

1. In all coating compositions studied, PbO was the component primarily responsible for the lubricating properties observed. Other components influenced such properties as vitrifying tendency, softening temperature, and adhesion.

2. Low rider wear and friction coefficients of 0.20 or less were obtained in air at 1250° F with ceramic-coated bearing surfaces prepared from the following mixed powders fused to the designated alloys: pure PbO fused to type 440-C stainless steel, 95 percent PbO plus 5 percent SiO_2 on type 440-C, 95 percent PbO plus 5 percent V_2O_5 on type 440-C, 85 percent PbO plus 10 percent Fe_3O_4 plus 5 percent SiO_2 on type 304, and 86.4 percent PbO plus 9.1 percent bentonite plus 4.5 percent SiO_2 on type 440-C.

3. Some of the specific effects obtained with various oxide additions to the powder compositions were as follows: Generally, iron oxide (Fe_3O_4) improved the adherence and uniformity of coatings applied to

ferrous metals. Boric oxide and silicon dioxide increased the vitrifying tendency of the coatings. The addition of a suspending agent (bentonite) made it possible to hold PbO in suspension in water and thus facilitated application to metal surfaces by brushing prior to firing.

4. Close matching of the thermal expansion coefficients of the ceramics and the base metal did not appear to be critical. This probably can be attributed to the softness of PbO and the tenacity of the bond between properly formulated PbO coatings and metal surfaces.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, December 4, 1958

REFERENCES

1. Peterson, M. B., and Johnson, R. L.: Solid Lubricants for Temperatures to 1000° F. Lubrication Eng., vol. 13, no. 4, Apr. 1957, pp. 203-207.

2. Sliney, Harold E., and Johnson, Robert L.: Bonded Lead Monoxide Films as Solid Lubricants for Temperatures up to 1250° F. NACA RM E57B15, 1957.

3. Sliney, Harold E.: Effect of Sliding Velocity on Friction Properties and Endurance Life of Bonded Lead Monoxide Coatings at Temperatures up to 1250° F. NACA RM E58B11, 1958.

4. Morey, George W.: The Properties of Glass. Reinhold Pub. Corp., 1938, p. 75.

5. Kubaschewski, O., and Hopkins, B. E.: Oxidation of Metals and Alloys. Butterworths Sci. Pub. (London), 1953.

6. Levin, Ernest M., McMurdie, Howard F., and Hall, F. P.: Phase Diagrams for Ceramists. The Am. Ceramic Soc., Inc., 1956.

7. Anon.: Lead in the Ceramics Industries, sec. 1. Lead Industries Assoc., 1956, p. 1.

8. Dietzel, A., and Meures, K.: Reactions Important for Adherence When Firing Ground Coats Containing No Adherence-Promoting Oxide. Jour. Am. Ceramic Soc., vol. 18, no. 2, Feb. 1935, pp. 35-36.

9. Bisson, Edmond E., Johnson, Robert L., Swikert, Max A., and Godfrey, Douglas: Friction, Wear, and Surface Damage of Metals as Affected by Solid Surface Films. NACA Rep. 1254, 1956. (Supersedes NACA TN 3444.)

10. Anon.: Stainless Steel Handbook. Allegheny Ludlum Steel Corp., 1956, pp. 1-3.

11. Andrews, A. I.: Enamels. The Twin City Printing Co., Champaign (Ill.), 1935, p. 134.

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TABLE I. - RESULTS OF X-RAY DIFFRACTION STUDIES OF PbO-BASE COATINGS

Powder composition prior to firing, weight percent, and base metal	Over-all pattern intensity	Crystalline phases identified in fired coating (a)		Comments
		Positive	Probable (b)	
100 PbO on 440-C stainless steel	Strong	αPbO βPbO	Fe_3O_4 Fe_2O_3	Strong pattern indicates high degree of crystallinity. Little or no glass in coating
100 PbO on Inconel X	Strong	αPbO Cr_2O_3	NiO	Strong pattern indicates high degree of crystallinity
95 PbO + 5 SiO_2 on 440-C	Fair	αPbO	Fe_3O_4 Fe_2O_3	Decreased pattern intensity probably indicates the presence of some glass. Pattern for 4 PbO·SiO_2 almost identical with PbO pattern. Either or both are indicated.
95 PbO + 5 V_2O_5 on 440-C	Strong	αPbO βPbO Fe_3O_4	Pb_3O_4 V_2O_5	Strong pattern indicates high degree of crystallinity. Relatively clear Fe_3O_4 pattern may indicate increased base-metal corrosion in presence of V_2O_5; V_2O_5 pattern indicates incomplete reaction of V_2O_5 with PbO to form the lead vanadate
95 PbO + 5 B_2O_3 on 440-C	None	None	None	Inability to diffract X-rays indicates coating was almost entirely glass
85 PbO + 10 Fe_3O_4 + 5 SiO_2 on 304 stainless steel	Strong	αPbO Fe_3O_4 SiO_2 (Quartz)	None	Strong pattern and the identification of SiO_2 indicates a very high degree of crystallinity
86.4 PbO + 9.1 bentonite + 4.5 SiO_2 on 440-C	Fair to none in duplicate runs	αPbO, Fe_3O_4 } when pattern obtained		Weak pattern or absence of pattern indicates very strong glass-forming tendencies.

[a]αPbO taken as yellow, orthorhombic allotrope; βPbO taken as red, tetragonal allotrope.

[b]Probable (pattern incomplete, but sufficient line matching to indicate strong possibility).

TABLE II. - CHEMICAL COMPOSITION OF LEAD-OXIDE-BASE CERAMIC COATINGS

Base metal and powder composition prior to firing, weight percent	Results of chemical quantitative analyses of coating after firing, weight percent	Calculated molecular composition from data in column 2, weight percent[a]
100 PbO on 440-C	79.5 Pb 7.51 Fe	86.0 PbO 10.4 Fe_3O_4 3.6 unaccounted
100 PbO on Inconel X	83.0 Pb .51 Cr .86 Ni	89.5 PbO .75 Cr_2O_3 1.09 NiO 8.66 unaccounted
95 PbO + 5 SiO_2 on 440-C	79.5 Pb 4.90 SiO_2 4.24 Fe	86.0 PbO 4.9 SiO_2 5.9 Fe_3O_4 3.2 unaccounted
95 PbO + 5 V_2O_5 on 440-C	74.3 Pb 9.09 Fe 2.01 V	80.0 PbO 3.6 V_2O_5 12.6 Fe_3O_4 3.8 unaccounted
95 PbO + 5 B_2O_3 on 440-C	79.10 Pb 4.40 Fe 3.30 B	85.5 PbO 10.6 B_2O_3 6.1 Fe_3O_4 2.2 excess
85 PbO + 10 Fe_3O_4 + 5 SiO_2 on 304	72.3 Pb 11.8 Fe 5.14 SiO_2	78.2 PbO 5.14 SiO_2 16.4 Fe_3O_4 0.3 unaccounted
86.4 PbO + 9.1 bentonite + 4.5 SiO_2 on 440-C	68.50 Pb 9.72 Fe 1.14 Al 6.57 SiO_2	74.0 PbO 13.5 Fe_3O_4 2.16 Al_2O_3 6.6 SiO_2 3.7 unaccounted

[a]Compounds present were identified by X-ray diffraction with the exception of the boron-containing coating, which was too glassy to give a diffraction pattern; B_2O_3 was assumed; Fe_3O_4 was also assumed for this coating based on analogy with the other coatings. All compounds are listed as simple oxides only to illustrate the metal to oxygen ratios. Many of these oxides may actually be present in combination as double oxides.

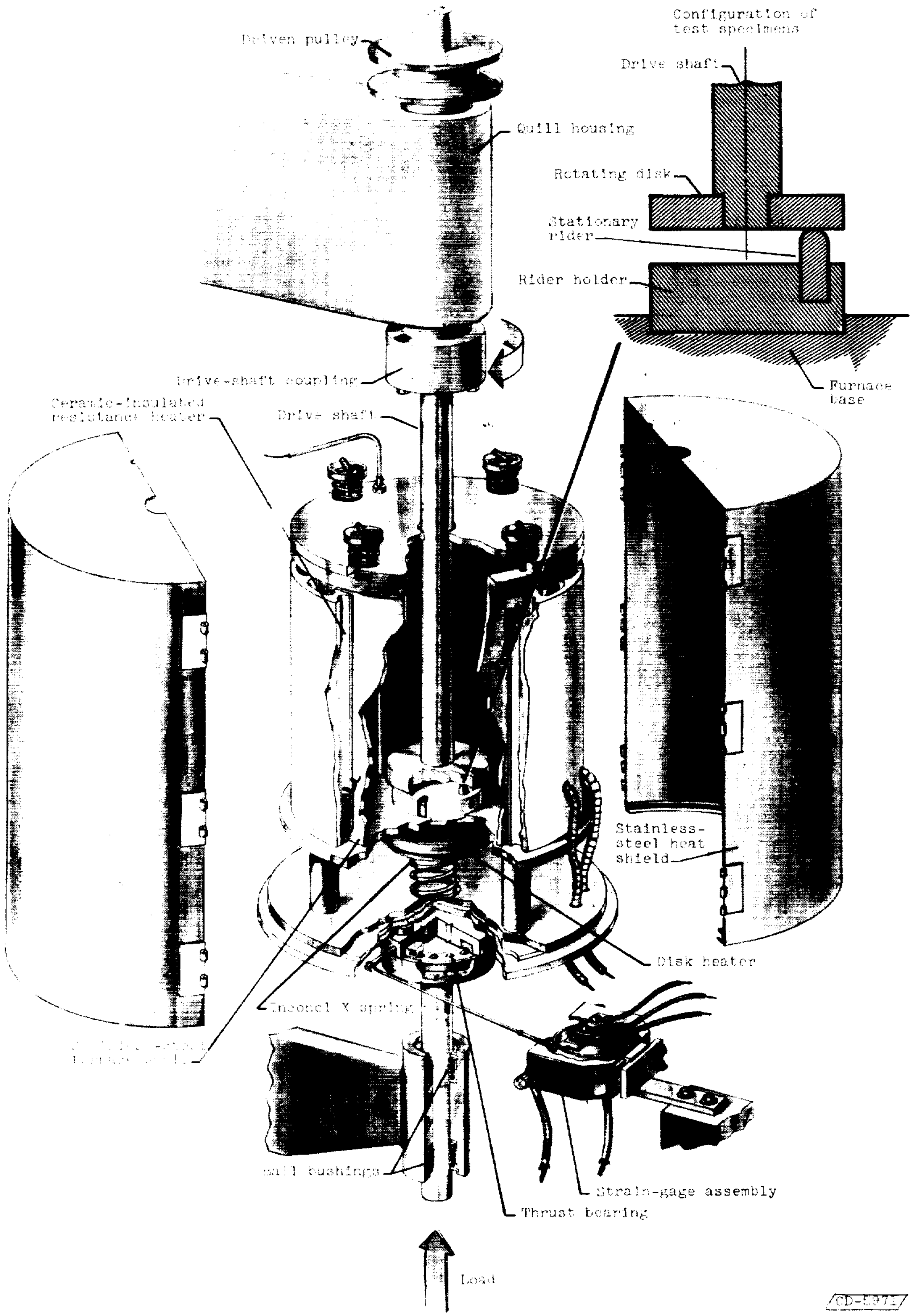
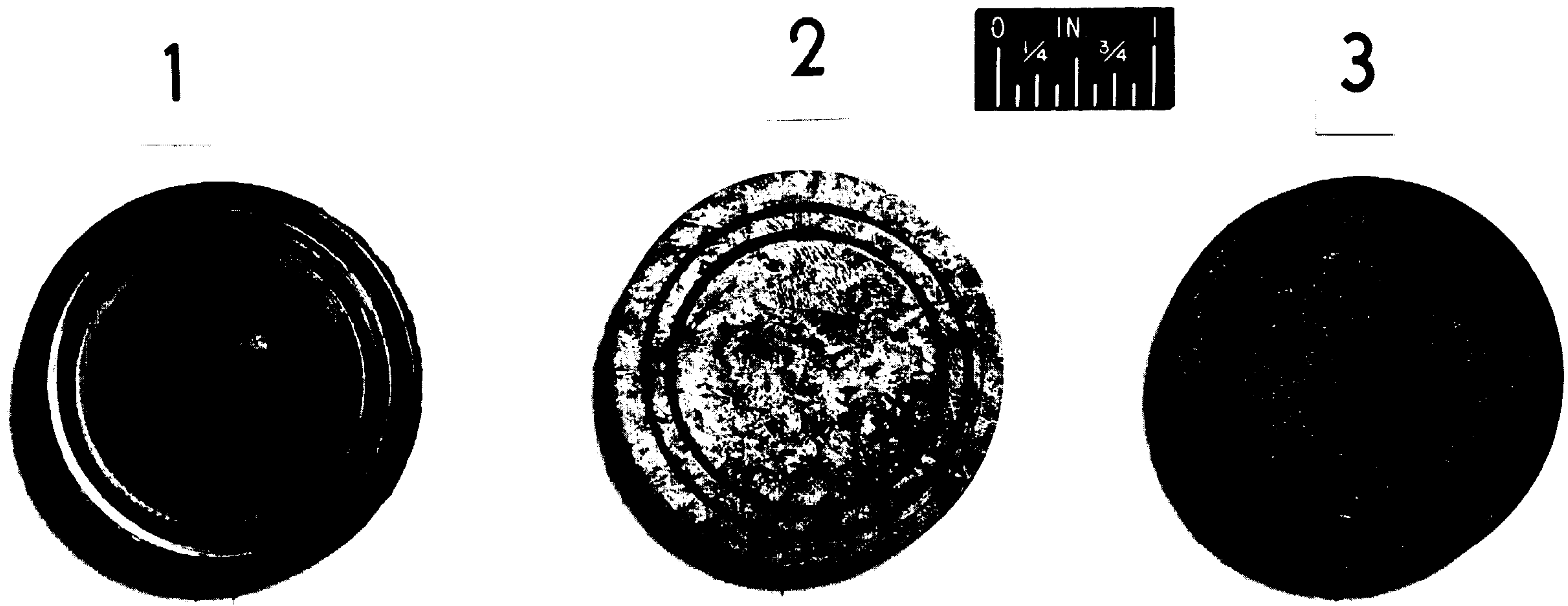


Figure 1. - Apparatus.



(a) 100 Percent PbO on 440-C.

(b) 100 Percent PbO on Inconel X.

(c) 95 Percent PbO plus 5 percent SiO_2 on 440-C.

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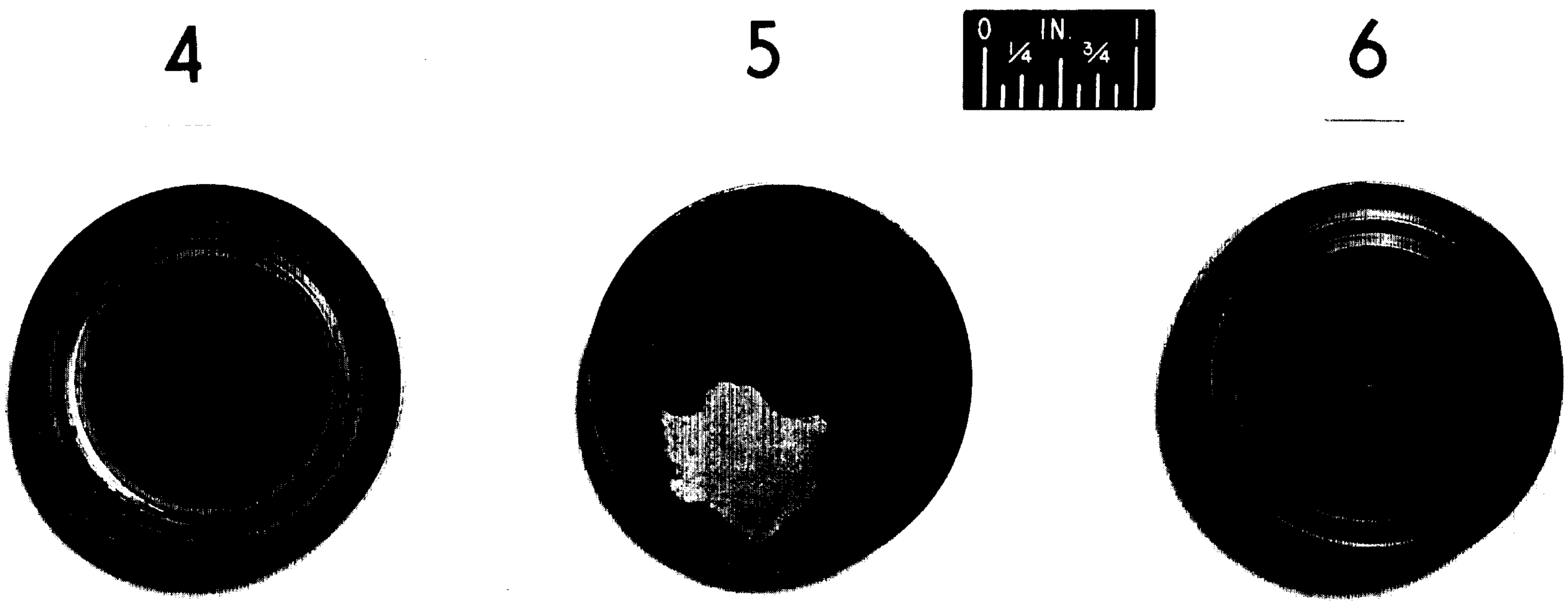
Figure 2. - Appearance of coated surfaces after friction and wear tests.



(d) 95 Percent PbO plus 5 percent V_2O_5 on 440-C. (Coating failure on specimen 5 occurred during grinding to desired thickness.)

(e) 95 Percent PbO plus 5 percent B_2O_3 on 440-C.

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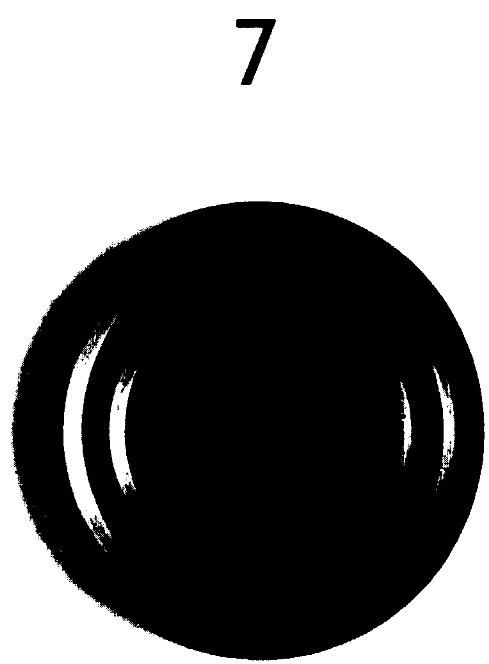
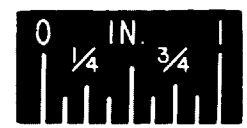
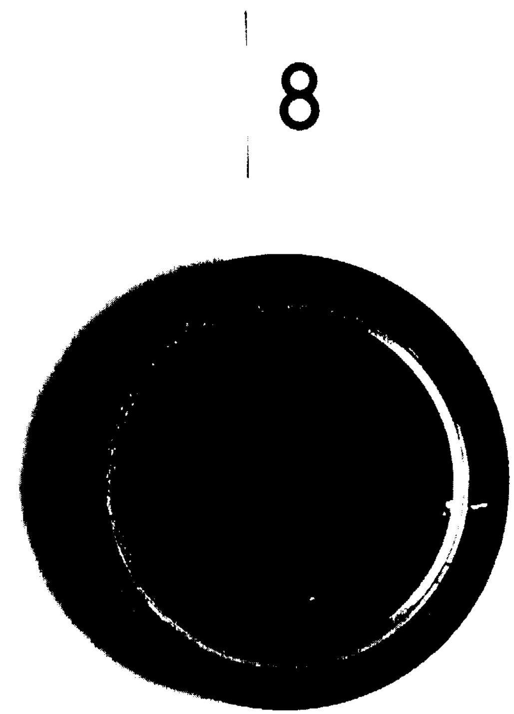
Figure 2. - Continued. Appearance of coated surfaces after friction and wear tests.







(f) 85 Percent PbO plus 10 percent Fe_3O_4 plus 5 percent SiO_2 on 304.

(g) 86.4 Percent PbO plus 9.1 percent bentonite plus 4.5 percent SiO_2 on 440-C.

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Figure 2. - Concluded. Appearance of coated surfaces after friction and wear tests.

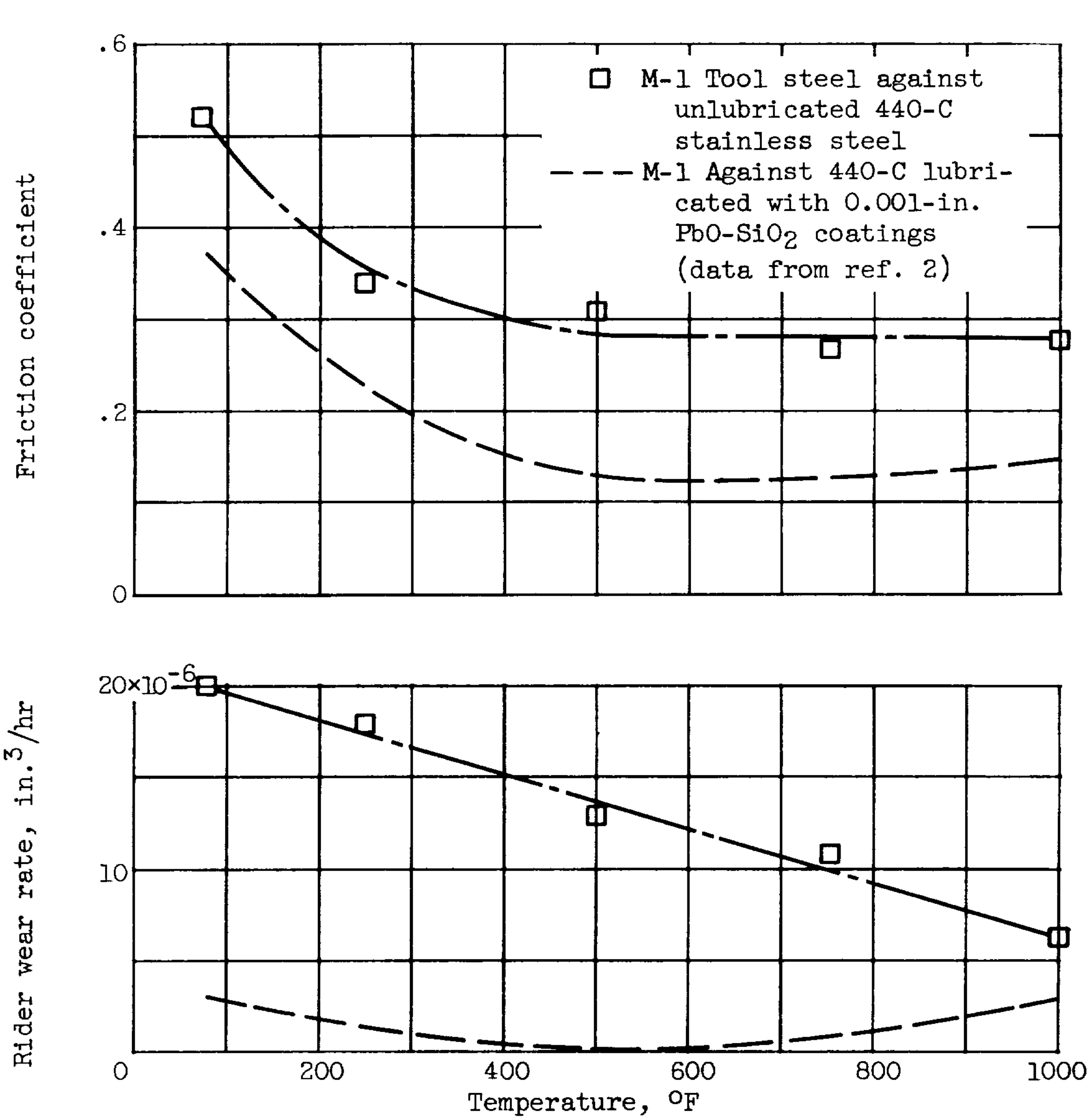

Figure 3. - Friction coefficient and rider wear at various temperatures with unlubricated metals and with same metals lubricated with reference $PbO\text{-}SiO_2$ coating. Sliding velocity, 430 feet per minute; load, 1 kilogram; radius of rider specimen, 3/16 inch.

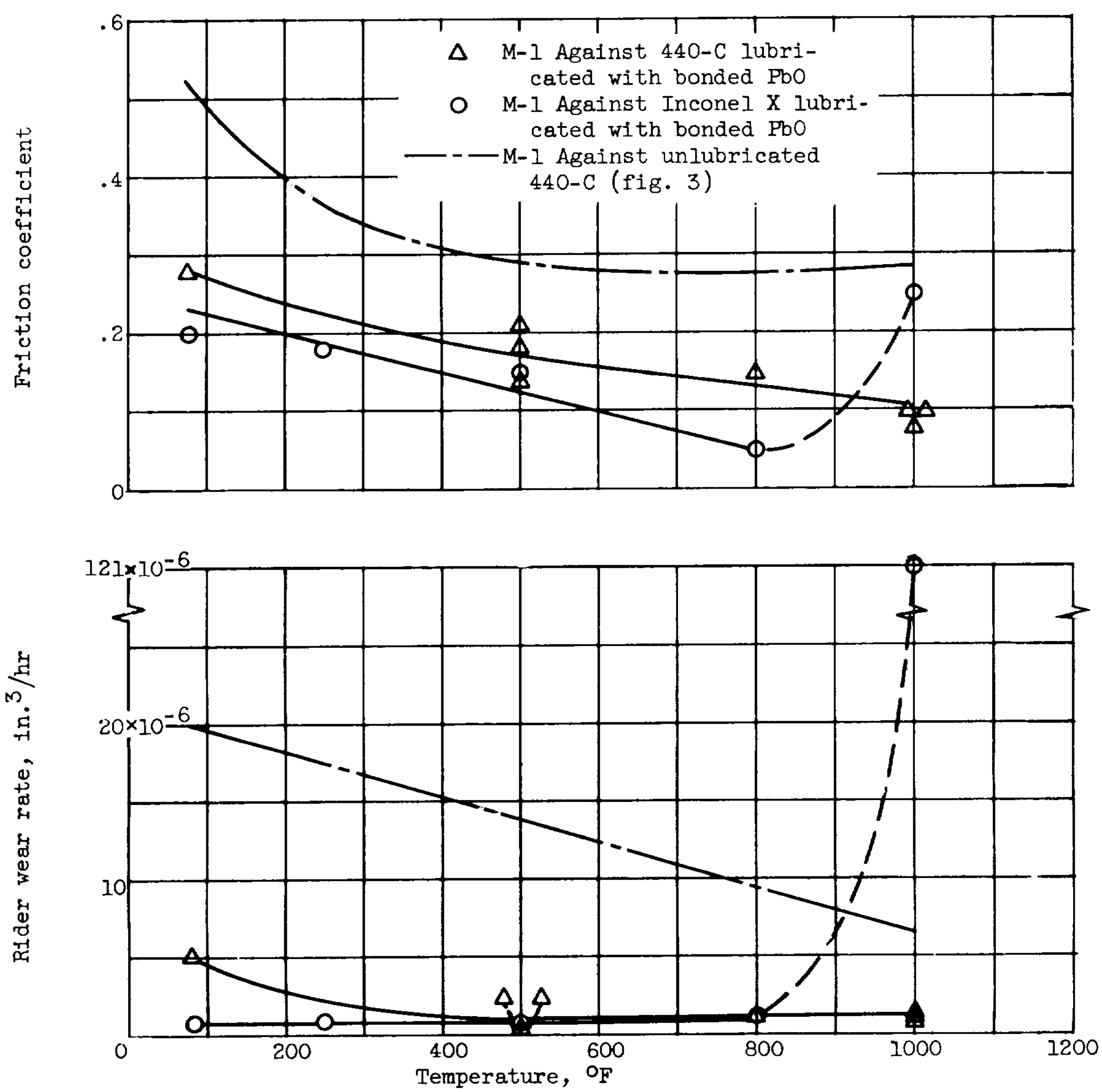

Figure 4. - Friction coefficient and rider wear at various temperatures with metals lubricated by 0.001-inch-thick bonded coatings prepared from pure lead monoxide compared with unlubricated metals. Sliding velocity, 430 feet per minute; load, 1 kilogram; radius of rider specimen, 3/16 inch.

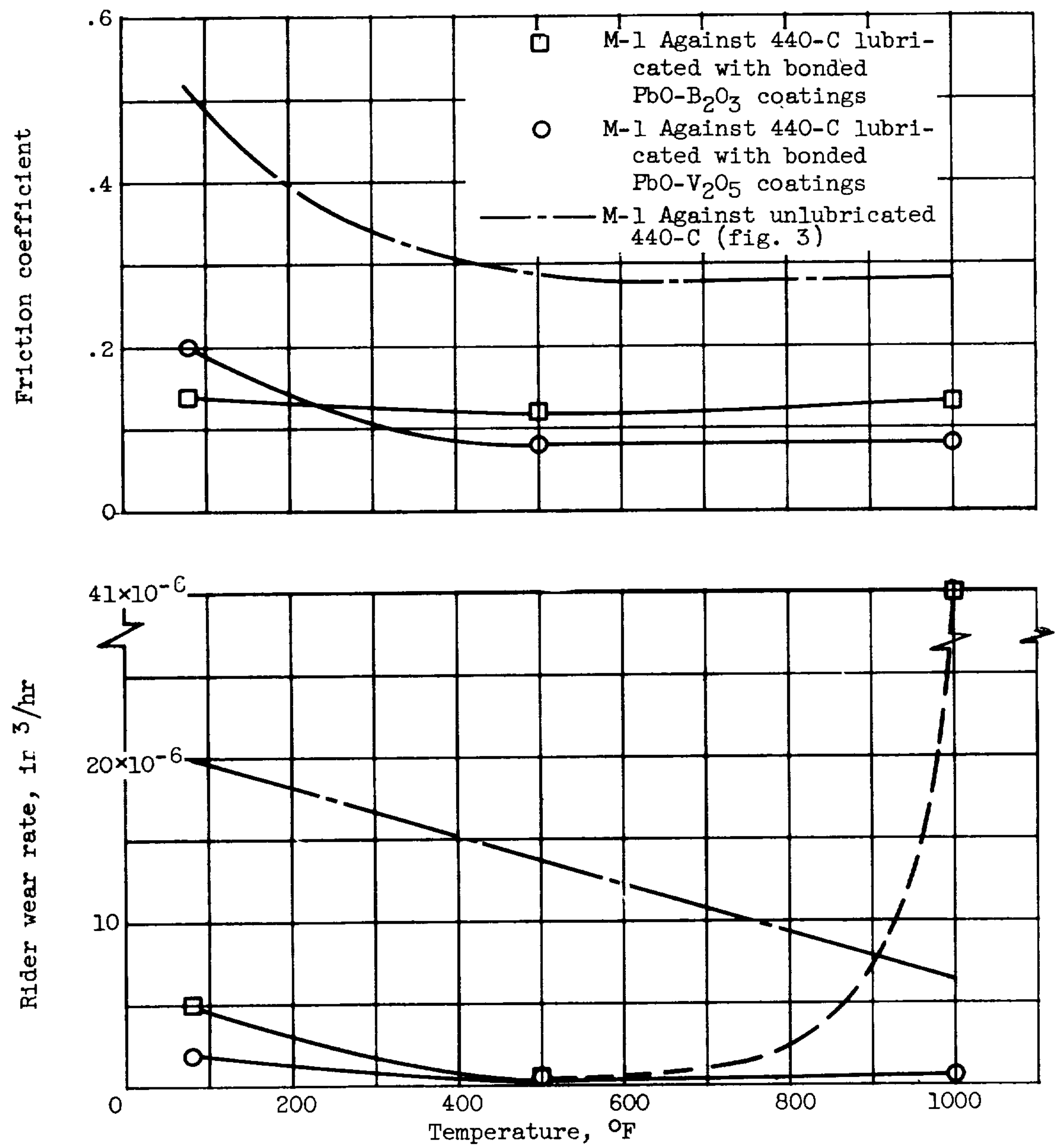

Figure 5. - Friction coefficient and rider wear at various temperatures with metals lubricated by 0.001-inch-thick bonded coatings prepared from mixture of oxides containing PbO plus 5 weight percent of another oxide compared with unlubricated metals. Sliding velocity, 430 feet per minute; load, 1 kilogram; radius of rider specimen, 3/16 inch.

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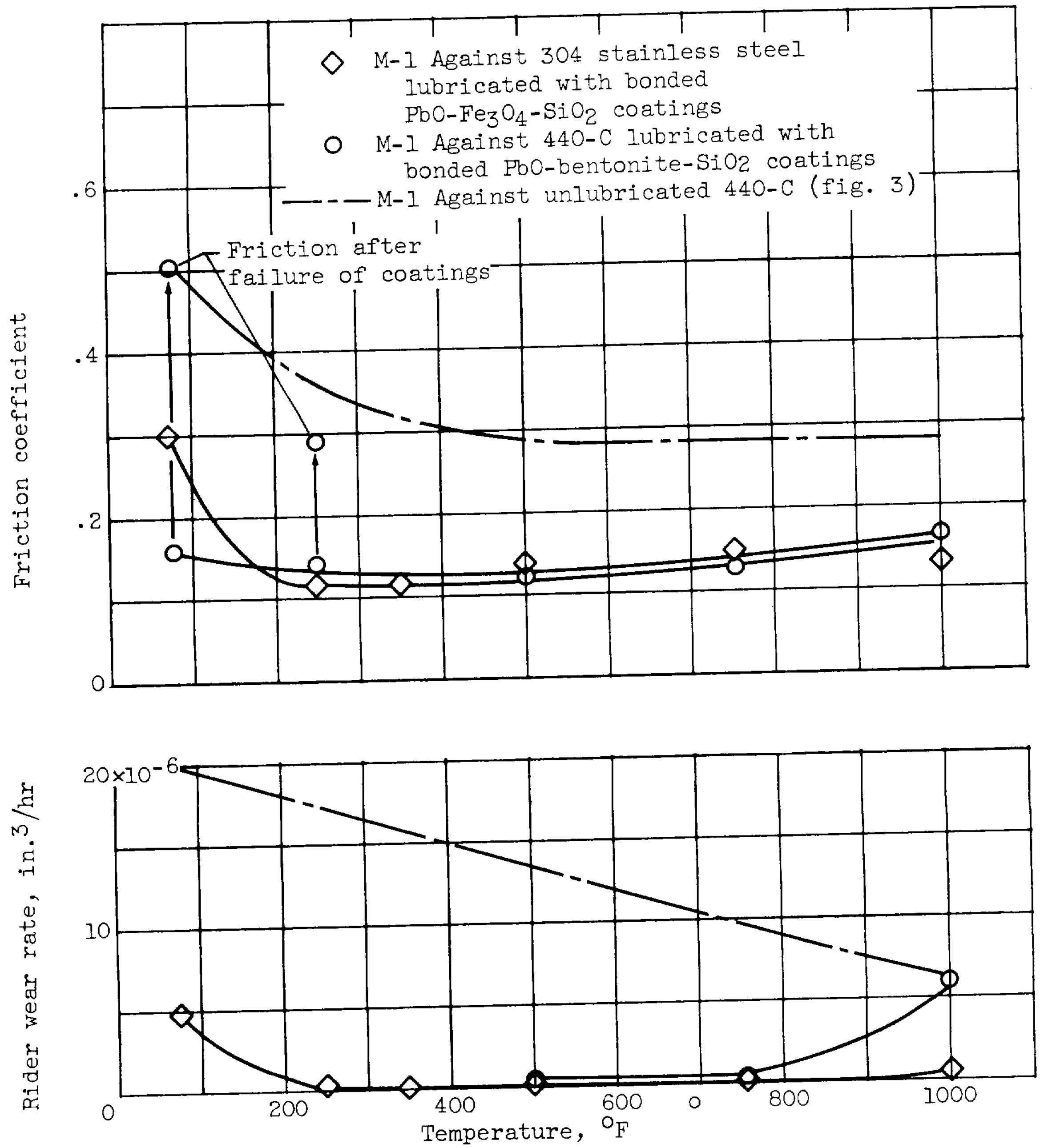

Figure 6. - Friction coefficient and rider wear at various temperatures with metals lubricated by 0.001-inch-thick bonded coatings prepared from mixture of oxides consisting of PbO plus two other oxides (see table II for compositions) compared with unlubricated metals. Sliding velocity, 430 feet per minute; load, 1 kilogram; radius of rider specimen, 3/16 inch.

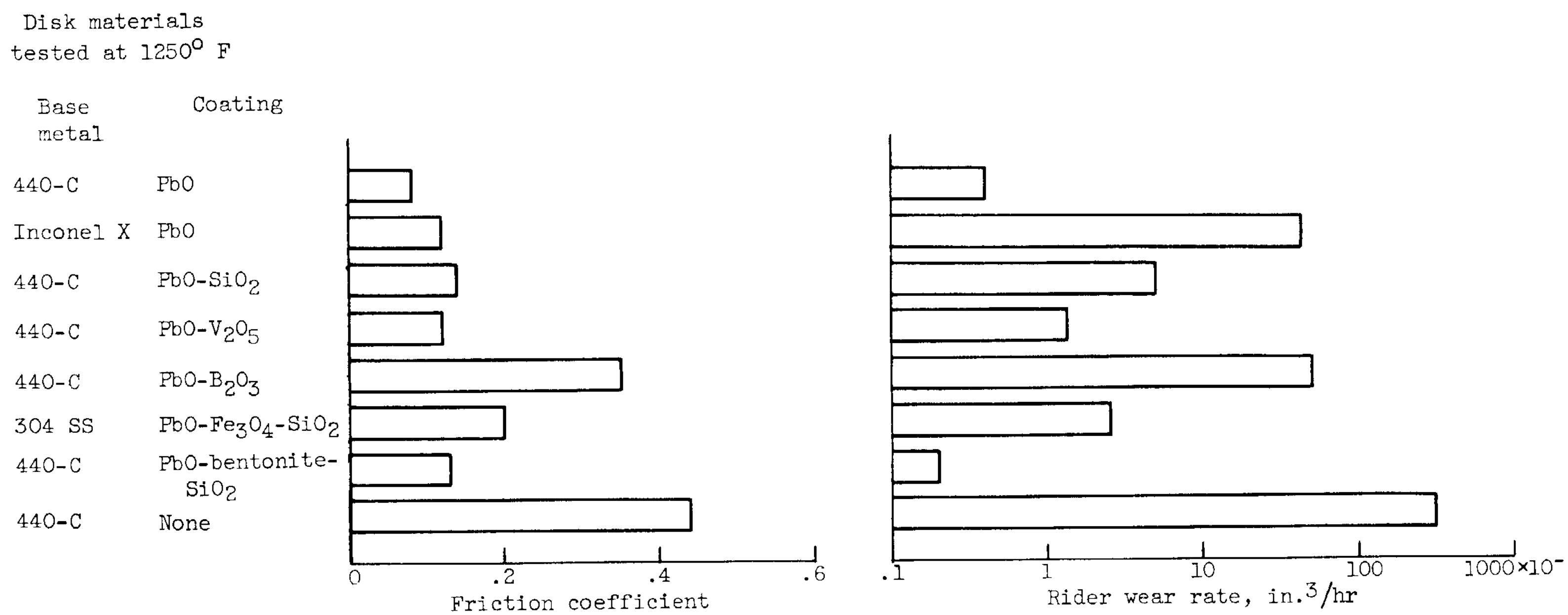

Figure 7. - Friction coefficient and rider wear at 1250° F for cast Inconel riders against several metals lubricated with 0.001-inch-thick bonded PbO coatings. Sliding velocity, 430 feet per minute; load, 1 kilogram; radius of rider specimens, 3/16 inch.

NASA MEMO 3-2-59E
National Aeronautics and Space Administration.
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Lead monoxide was the component that was primarily responsible for lubricating properties of various ceramic coatings studied. Other oxides in the formulations influenced such properties as softening points, adherence to metals, hardness, vitrifying tendencies, or chemical stability. Oxidation of the base metal during coating at elevated temperatures had important and often beneficial effects. Several of the coatings protected metals against adhesive wear at test temperatures from 75° to 1250° F. Friction coefficients ranged from 0.20 to 0.37 at 75° F and from 0.08 to 0.20 at 1250° F. The sliding velocity in all experiments was 430 ft/min.

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2. Lubricants (3.8.5)
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