25p

NASA TN D-1708

N63-15769
Code-1

NASA TN D-1708

TECHNICAL NOTE

D-1708

INFLUENCE OF MICROSTRUCTURAL INCLUSIONS ON FRICTION AND WEAR OF NICKEL AND IRON IN VACUUM TO 10^{-9} MILLIMETER OF MERCURY

By Donald H. Buckley and Robert L. Johnson

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON May 1963

534485
28p

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

TECHNICAL NOTE D-1708

INFLUENCE OF MICROSTRUCTURAL INCLUSIONS ON FRICTION AND WEAR OF NICKEL AND IRON IN VACUUM TO 10^{-9} MILLIMETER OF MERCURY

By Donald H. Buckley and Robert L. Johnson

15769

SUMMARY

Friction, wear, and welding characteristics of three binary alloy systems were studied at ambient pressures from 760 to 10^{-9} millimeter of mercury. Studies were conducted with nickel-oxygen, nickel-tin, and iron-sulfur alloys.

Friction and wear studies were made with a hemispherical (3/16-in. rad.) rider, which slides in a circumferential path on the flat surface of a rotating metal disk of the same material. The specimens were tested at various ambient pressures with a load of 1000 grams (2.2 lb), a sliding velocity of 28 to 1800 feet per minute, and a temperature of 75° F.

The incorporation of nickel oxide (1.35 to 7.50 percent) in electrolytic nickel resulted in friction and wear properties in vacuum for nickel, which were characteristic of that experienced for nickel-base alloys in air at atmospheric pressure. The addition of tin (optimum 20-percent tin) to electrolytic nickel reduced friction and wear of nickel in vacuum by a factor of 10. The fundamental lubrication mechanism, however, is not the same for the two alloy systems. The addition of various percentages of sulfur (present as ferrous sulfide) to electrolytic iron (0.01- to 0.45-percent sulfur) reduced friction, wear, and welding of electrolytic iron in vacuum (10^{-9} mm Hg).

INTRODUCTION

The operation of mechanical devices in the vacuum environment of space presents some special problems in the field of lubrication. The usefulness of conventional oil and grease lubricants or lubrication systems in space is limited because of the high evaporation rates of some of these materials in vacuum (refs. 1 to 4). In some areas, solid-film lubricants may be successfully used in place of oils and greases. Although solid-film lubricants do not exhibit the high evaporation rates of conventional oils and greases, they have limited endurance lives that often cannot be reliably predicted. Potential problems in lubrication exist, and therefore lubrication failure of operating mechanisms may occur.

Lubrication failure, either by evaporation or by wearing away of the lubricant film in space, may result in intimate contact of mating surfaces. When such

contact of conventional bearing, gear, or seal materials occurs in an environment such as the vacuum of space (10^{-9} to 10^{-13} mm Hg), high friction, adhesive wear, and mass welding of contacting surfaces will probably result (refs. 1 to 3). These factors will be much greater in vacuum than those normally encountered in air where metal surface oxides and adsorbed contaminant films reduce the possibility of such intimate contact.

Since these surface contaminants are not present in space and adequate external lubrication for long-term applications may be a problem, it would be desirable to have self-lubricated components (bearings, gears, and seals). Such components could have lubricants within the microstructure (ref. 5), which would, therefore, give low friction and wear and be capable of supplying a surface film that would prevent the occurrence of mass welding in the absence of a lubricant or in the event of lubrication failure.

The reduction of friction and wear of materials in oxygen-free environments has been achieved by the addition of inclusions or contaminants to the structure of these materials; these inclusions have been particularly successful in the grain boundary regions (ref. 1, pp. 8 to 23, and ref. 6, pp. 93 to 100). The addition of materials such as silicon to nickel (ref. 6) has produced two-phase structures, one phase of which furnishes a protective surface film that acts to reduce friction and wear. As these exposed films are worn away, new films are supplied continuously from the alloy structure.

In general, the manufacturers of bearing materials have attempted to obtain alloys that were free of inclusions and contaminants because of reduced fatigue life with such alloys (refs. 7 and 8). In space applications, fatigue failure may be of secondary importance (compared to lubrication failure), and some types of inclusions may be desirable to help provide lubrication.

The objectives of this investigation were: (1) to determine whether alloy systems could be developed that would incorporate inclusions capable of the reduction of the welding tendency of metals in the absence of surface oxides and adsorbed films and (2) to determine the friction and wear characteristics of some of these alloys in vacuum to 10^{-9} millimeter of mercury. Simple binary alloy systems were used in order that the influence of a single alloying constituent could be closely studied.

Friction and wear experiments were conducted with a 3/16-inch-radius rider, which slides on a $2\frac{1}{2}$-inch-diameter disk specimen. The rider was loaded against the disk with a 1000-gram load, and surface speeds were varied from 28 to 1800 feet per minute. The duration of each experiment was 1 hour.

APPARATUS

The apparatus used in this investigation is described in detail in reference 1 and is shown in figure 1. The basic elements of the apparatus were the specimens (a $2\frac{1}{2}$-in.-diam. flat disk and a 3/16-in.-rad. rider) mounted in a

vacuum chamber. The disk specimen was driven through a magnetic drive coupling. The coupling had two 20-pole magnets 0.150 inch apart with a 0.030-inch diaphragm between magnet faces. The driver magnet that was outside the vacuum system was coupled to a hydraulic motor. The second magnet was completely covered with a nickel-alloy housing (cutaway in fig. 1) and was mounted on one end of the shaft within the chamber. The end of the shaft that was opposite the magnet contained the disk specimen.

The rider specimen was supported in the specimen chamber by an arm that was mounted by gimbals and bellows to the chamber. A linkage at the end of the retaining arm, away from the rider specimen, was connected to a strain-gage assembly. The assembly was used to measure frictional force. Load was applied through a dead-weight loading system.

Attached to the lower end of the specimen chamber was a 400-liter-per-second ionization pump and a mechanical forepump with liquid-nitrogen cold traps. The pressure in the chamber was measured adjacent to the specimen with a nude hot-cathode ionization gage. In the same plane as the specimens and ionization gage was a diatron-type mass spectrometer (not shown in fig. 1) for determination of gases present in the vacuum system. A 20-foot, 3/16-inch-diameter stainless-steel coil was used for liquid-nitrogen and liquid-helium cryopumping of the vacuum system.

It has been established in reference 9 that the ambient pressure of outer space (beyond 1200 km) is between 10^{-9} and 10^{-13} millimeter of mercury, and the principal gaseous species present at these pressures are hydrogen and helium.

The data of figure 2 indicate the oxygen partial pressures that are required for the dissociation of metal oxides at various temperatures. At all oxygen pressures above the curve, oxidation of metal will occur, while at all pressures below the curve, dissociation of the oxide occurs in accordance with the equation that accompanies the curve. As the temperature is increased, the reaction kinetics (rate) for the formation of surface oxides is increased. If the oxygen pressure is held constant, however, the tendency for the oxygen to bond to the metal will decrease, and at some point (curve) the energy is great enough to inhibit oxide formation. Examination of the data of figure 2 indicates that, at room temperature, in order to dissociate surface oxides and to prevent further oxide formation on iron, oxygen partial pressures of the order of 10^{-30} millimeter of mercury are required. Figure 2 only indicates a concentration effect and not the kinetics of surface reactions at pressures above those that are necessary to achieve dissociation. Since oxygen is absent in outer space, it would be desirable to reduce oxygen partial pressures in space simulation chambers to a level where surface oxides could not form within the period of experimentation.

Pressures of the order of magnitude necessary to prevent oxidation of metals are difficult to achieve with present vacuum technology. It is, therefore, desirable to know the gaseous species present in vacuum systems and to develop methods for the removal of those materials that are not present in a space environment. Mass spectrometer data were, therefore, obtained in the vacuum friction and wear apparatus with various pumping techniques; the data obtained are presented in figure 3. Examination of the data indicates that considerable hydro-

gen (2), nitrogen (14), oxygen (16), hydroxyl (17), water (18), carbon monoxide (28), nitrogen N_2 (28), and carbon dioxide (44) are present in the vacuum system. (Numbers in parentheses are molecular weights divided by charge.) With a simple bakeout at 200° F, the ambient pressure decreased, and a considerable decrease in the quantities of the gases present was obtained. When liquid nitrogen was used to cryopump the system, a further reduction in gas concentration was observed. When liquid helium was used as the cryopumping fluid, all gas partial pressures were reduced below the detectable range (sensitivity of mass spectrometer indicated by the manufacturer to be 5.0×10^{-13} mm Hg) except water and hydrogen. By purging the vacuum system with dry nitrogen, prior to pumpdown, all detectable gases were removed except hydrogen. The hydrogen concentration increased slightly, however, when all other gases were removed. This increase was believed to be caused by an increased diffusion and desorption of hydrogen from the metal chamber walls or reduction of the partial pressure of the other gases in the system.

SPECIMEN PREPARATION

Casting Procedure

The three binary alloy series used for this investigation included the systems of nickel-oxygen, nickel-tin, and iron-sulfur. All specimen preparation was done at the Lewis Research Center. The nickel-oxygen system was prepared by the addition of nickel oxide to pure electrolytic nickel. The nickel oxide (under 200 mesh) was cold compressed into slugs that were packed into the center of a zirconium oxide crucible and electrolytic nickel packed around the nickel oxide compacts. The furnace was then evacuated to 10^{-4} millimeter of mercury. The chamber was filled with dry argon, and the temperature was then raised to 2750° F to melt the charge. After the material melted, it was poured into a cold copper mold and was allowed to cool to room temperature.

The nickel-tin alloys were prepared in a manner similar to that used for the nickel-oxygen samples. Compensation for vaporization of tin in the melting process was made, and the necessary adjustment in addition of tin was included in each charge.

The iron-sulfur alloys were prepared by the addition of iron sulfide slugs to electrolytic iron. The casting procedure was similar to that used in the preparation of the other two alloy series.

The castings from the melts were machined into specimens, and samples were taken for chemical analysis and metallographic examination. The chemical analyses for the principal alloying elements were made, and the compositions are presented in table I.

Specimen Finish and Cleaning Procedure

The disk and rider specimens were of the same material in friction and wear experiments and were finish ground to a roughness of 4 to 8 microinches. Before

each experiment, the disk and rider were given the same preparatory treatment: (1) a thorough rinsing with acetone to remove oil and grease, (2) a polishing with moist levigated alumina on a soft polishing cloth, and (3) a thorough rinsing with tap water followed by distilled water. For each experiment, a new set of specimens was used.

RESULTS AND DISCUSSION

The tendency for clean metals or alloys to weld in vacuum is demonstrated by the data of figure 4 obtained from reference 1. The conventional bearing steel 52100 welded readily in vacuum once residual surface oxides and contaminating films were worn away. As was observed in reference 1, mass welding or seizure of metal surfaces did not occur in the presence of surface oxides and other films; based on these results, an approach that can be taken to avoid such welding would be the addition of oxides to the metal structure. Thus, a continuous supply of metal oxide would be available from the structure to replace surface films that are worn away.

In order to facilitate the study of individual alloying constituents on the friction, wear, and welding tendency of alloys in vacuum, simple binary systems were used. Electrolytic iron was first selected as a base metal, and iron oxide (Fe_2O_3) was added to a melt of iron. The iron-oxygen system was selected because the lower oxide of iron (FeO) is known (from the iron-oxygen phase diagram) to form. This oxide has been shown to have desirable friction properties. The iron oxide, however, was reactive, and chemical attack of the crucible material occurred. Limited experimentation with different crucible materials and alteration of the casting procedures did not eliminate the problem.

Nickel-Oxygen System

Electrolytic nickel was then substituted for iron as a base metal, and nickel oxide (NiO) was incorporated in the structure. With nickel oxide, no evidence of crucible attack was observed. Various percentages of the oxide were incorporated in the structure of electrolytic nickel. The nickel oxide percentages (±0.08 percent), together with the microstructure of each alloy, is presented in figure 5.

A hardness survey of the surface of the nickel - nickel oxide alloys indicated an average Rockwell hardness of B61 in the nickel matrix. In the areas of finely dispersed nickel oxide, there was a slight hardness increase. In those areas where large nickel oxide particles segregated, the hardness approximated Rockwell B85. The individual oxide particles were too small for hardness checking.

The friction, wear, and welding characteristics of these alloys were next determined in vacuum, and the results obtained are presented in figure 6. All the experiments of figure 6 were started at an ambient pressure of 10^{-9} millimeter of mercury; however, considerable outgassing in some of the experiments occasionally raised the pressure to 10^{-8} millimeter of mercury.

The coefficient of friction obtained with electrolytic nickel was erratic. The maximum was 2.42; however, this was measured at short periods when friction data could be read. During the principal portion of the experiment, considerable welding and weld breaking occurred and resulted in rapid changes in friction readings. Wear measurements to the rider specimen after the experiment indicated a wear of 5.28×10^{-3} cubic inch. A true measure of wear under operating conditions as described in this experiment is extremely difficult to achieve, because metal is being transferred back and forth from one specimen to another continuously. Examination of both disk and rider surfaces after the experiment revealed macroscopic pieces of transferred material on both specimen surfaces.

The addition of various percentages of nickel oxide to electrolytic nickel reduced both friction and wear of nickel in vacuum (fig. 6). The coefficient of friction for the nickel - nickel oxide alloys ranged from 0.5 to 0.8. This friction is in the range of that which might be experienced with nickel-base alloys in air at atmospheric pressure (ref. 6). The rider wear decreased to less than half that experienced with electrolytic nickel. The transfer of large quantities of metal from one surface to another decreased with increase in nickel oxide content. From the results with these alloys, the addition of nickel oxide to nickel seemed to decrease the welding tendency in vacuum and to reduce friction and wear to a limit that would be experienced for nickel-base alloys in air at atmospheric pressure. The addition of nickel oxide to the structure functions in a manner similar to that of the surface oxides formed in air. The presence of the nickel oxide reduces welding, friction, and wear in vacuum (where surface oxides are present). It essentially substitutes for the normal oxides.

Nickel-Tin System

Although the addition of nickel oxide to electrolytic nickel improved performance in vacuum, friction and wear were still high. Consideration was therefore given to the production of a structure that would be self lubricating. Examination of the physical properties of various soft metals indicated that tin might be a desirable metal for vacuum lubrication applications. Tin has a low evaporation rate in vacuum, has good lubricating characteristics as a thin film, and, when alloyed with a base metal like nickel, will produce a duplex structure (ref. 10). This duplex structure consists of a hard matrix with a dispersed soft phase. Various percentages of pure tin were therefore alloyed with electrolytic nickel. The microstructure of the nickel-tin alloys, together with compositions (±0.35 percent), are presented in figure 7. A nickel-tin compound (Ni_3Sn) appears in the grain-boundary region with the addition of 5-percent tin to nickel; the nickel-tin was identified by X-ray diffraction. As the percentage of tin in the alloy is increased, a continuous increase in concentration of the nickel-tin compound occurs along the grain boundaries. Hardness testing of the alloy surface revealed a general increase in alloy hardness with increasing tin content as shown in the following table. In all structures, the nickel-tin phase had an

Tin in nickel-tin alloy composition, percent	5	10	15	20	25
Rockwell hardness	B67	B77	B80	B85	B106(C30)

average Rockwell hardness of C50. The relative hardness of matrix and addition phases will be discussed later.

The friction and wear characteristics of the nickel-tin alloys were next determined in vacuum (10^{-9} mm Hg), and the results are presented in figure 8. The addition of 5-percent tin to nickel was sufficient to decrease the coefficient of friction from 2.42 to 0.22 (approximately, a factor of 11). The wear decreased to one-fifth of that obtained with pure nickel. These results demonstrate that a duplex structure, when one phase is capable of surface flow, is extremely effective to reduce friction and wear. The coefficient of friction was approximately the same at 5-, 10-, 15-, and 20-percent tin. At 25-percent tin, an increase in friction was observed that indicated that there may be optimums in phase concentrations necessary to achieve the minimum in friction coefficient. There was, however, a continuous decrease in wear with increased tin content. (The wear decreased from 5.28×10^{-3} cu in. for electrolytic nickel to 0.01×10^{-3} cu in. for 25-percent tin-nickel alloy or a decrease in wear by a factor of 528.)

Since the nickel-tin alloy hardness increased with increasing amounts of tin, the rider wear might be related to hardness effects. In order to determine the influence of hardness on a reference material, some friction and wear experiments were conducted with 52100 bearing steel in vacuum (10^{-7} mm Hg). The 52100 bearing steel had been hardened to various Rockwell-hardness levels. The results obtained in these experiments are presented in figure 9. In general, a change in hardness from Rockwell B92 (C12) to C62 had little influence on the friction and wear of 52100 bearing steel in vacuum. The friction observations agree with comments made in reference 11, where it is stated that, for all clean metal surfaces, the friction shall vary by a factor of less than 2. The wear results obtained in figure 9 cannot be considered to show a significant hardness effect.

With the nickel - nickel oxide system, the particles of nickel oxide were harder than nickel; it is postulated that the nickel oxide, when moved out over the surface, served to maintain an interface between the nickel surfaces. With increasing oxide content, however, the wear mechanism becomes one of abrasion with less adhesive wear occurring. In the case of nickel-tin alloys, the nickel-tin compound (Ni_3Sn) is the harder phase, but unlike the classic copper-lead bearing alloy of a duplex nature, the harder phase has the lower melting point. The basic surface-film requirement is a low shear strength. Usually shear strength and hardness vary together. Shear strength has been related in a more fundamental manner, however, to melting point and to heat of fusion. Since the harder phase sustains greater contact pressures and has the lower melting point, this phase is readily softened and smeared over the initially softer nickel-rich phase. As more nickel-tin alloy of the lower melting phase is added, a more continuous film is interposed at the interface, and wear decreases. The addition, however, of large amounts of this phase (25-percent tin in nickel) results in a loss of the thin-film concept of soft metal over hard matrix, and the friction coefficient represents that of the basic compound (Ni_3Sn).

Iron-Sulfur System

Sulfur has been used for some time as an additive to stainless steels to im-

prove ease of machining these alloys (hence, the term free machining). It has also been used in various compounds as extreme pressure additive to oils and in sulfur hexafluoride as a reactive gas lubricant. It was, therefore, decided to incorporate sulfur in the structure of pure electrolytic iron, to determine the influence of sulfur on the friction and wear characteristics of iron in vacuum. Since very small quantities of sulfur are soluble within the iron structure, any sizeable additions of sulfur to iron should result in segregation of the sulfur, as iron sulfide, along the grain boundaries.

Various amounts of sulfur were added, as iron sulfide, to electrolytic iron, and the microstructure of each, together with the composition (to the nearest hundredth of a percent) are presented in figure 10. Our examination of figure 10 indicates that sulfur is present as iron sulfide within the iron structure as well as along the grain boundaries for all sulfur containing melts. The considerable amount of sulfur in the 0.45-percent iron-sulfur alloy resulted in a structure described in reference 12 as a "cell membrane" or enveloping structure because of the pattern shown by iron sulfide in the vicinity of the grain boundaries.

Some vacuum friction and wear experiments were next conducted with these iron-sulfur alloys, as well as electrolytic iron, and the results obtained are presented in figure 11. With electrolytic iron, considerable welding and mass transfer occurred; an accurate measure of friction and wear was difficult. The type of wear and welding of pure electrolytic iron in vacuum is demonstrated by the photomicrograph and surface profile tracings of figure 12(a). The addition of as little as 0.01 percent sulfur to iron resulted in a decrease in the welding tendency and a coefficient of friction of 0.38 was obtained for the alloy at 10^{-9} millimeter of mercury. Further additions of sulfur to iron reduced the coefficient of friction to less than 0.3. The welding tendency of the iron-sulfur alloys was observed visually to decrease with increasing sulfur content; this result is partially illustrated by the surface profile tracings and photomicrographs of figure 12.

In figure 12, for electrolytic iron, a considerable amount of rider material welded to the disk, as evidenced by the large spikes or peaks in the surface-profile tracing and surface photomicrographs. When 0.45 percent sulfur was added to iron, however, these spikes or peaks of transferred material are not observed. These results indicate that sulfur effectively reduces the welding tendency of iron in vacuum.

Since the mechanism of lubrication by sulfur in iron is one of surface flow of the iron sulfide over the iron, alteration of parameters, such as sliding velocity, temperature, load, etc., could influence the results obtained. For example, increase in these parameters tends to increase surface temperatures that may result in: (1) increased surface flow of iron sulfide, (2) melting of iron sulfide at the interface, and (3) dissociation of iron sulfide in vacuum. The coefficient of friction for 0.45-percent sulfur-iron alloy was therefore determined while one of these parameters, namely, sliding velocity, was varied from 28 to 1800 feet per minute at an ambient pressure of 10^{-9} millimeter of mercury. The results of this experiment are presented in figure 13. A change in sliding velocity did not appreciably influence the coefficient of friction. The friction data obtained between 300 and 400 feet per minute did not agree with the values

obtained in figure 11. The data of figure 11 were obtained with separate sets of specimens, while those obtained in figure 13 were obtained with a single set of specimens for a range of sliding velocities for short intervals.

The addition of sulfur to metals, in general, tended to accelerate oxidation (refs. 13 and 14). In order to determine the influence of various ambient pressures (oxygen concentrations) on the friction characteristics of the 0.45-percent iron-sulfur alloy, an experiment was conducted at ambient pressures from 760 to 10^{-9} millimeter of mercury, and the results are presented in figure 14. The coefficient of friction did not markedly change at pressures where rapid oxidation of the base metal occurred. At 760 millimeters of mercury, where the oxide film was copious, the coefficient of friction, however, remained less than 0.3.

SUMMARY OF RESULTS

From the data obtained in this investigation with various alloys during sliding contact in vacuum to 10^{-9} millimeter of mercury, the following summary remarks can be made:

1. Small concentrations of inclusions of stable constituents that were capable of surface flow provided interface films that were effective in the reduction of friction, wear, and surface welding.

2. The presence of relatively small quantities of sulfur (0.01 to 0.45 percent) as iron sulfide (mostly concentrated in the grain boundary region of iron) served to prevent the occurrence of mass welding of contacting sliding surfaces in vacuum. It also appreciably reduced both friction and wear of iron.

3. A change in sliding velocity and ambient pressure did not appreciably affect the coefficient of friction obtained with 0.45-percent sulfur in iron. The surface film could be maintained over a range of sliding velocities (28 to 1800 ft/min) at 10^{-9} millimeter of mercury, and the friction did not change at ambient pressures where oxidation occurred.

4. The presence of tin in electrolytic nickel reduced both friction and wear. The friction decreased by a factor greater than 10 and the wear decreased by a factor greater than 500. In some problem areas, this alloy may be utilized without the addition of other alloying agents.

5. The presence of oxygen as nickel oxide in electrolytic nickel improved friction and wear properties.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, February 5, 1963

REFERENCES

1. Buckley, D. H., Swikert, M., and Johnson, R. L.: Friction, Wear, and Evaporation Rates of Various Materials in Vacuum to 10^{-7} mm Hg. ASLE Trans., vol. 5, no. 1, Apr. 1962, pp. 8-22; discussion, pp. 22-23.

2. Riehl, W. A., Looney, W. C., and Caruso, S. U.: Compatibility of Engineering Materials with Space Environment. Item 1, Pt. II of ARPA Order 92-59, Army Ord. Missile Command, Oct. 25, 1960.

3. Freundlich, M. M., and Hannan, C. H.: Problems of Lubrication in Space. Lubrication Eng., vol. 17, no. 2, Feb. 1961, pp. 72-77.

4. Freundlich, Martin M., and Jagodowski, Stanley S.: Lubricant for High-Vacuum Environment. TR 60-728, pt. 1, WADD, Mar. 1961.

5. Johnson, Robert L., Swikert, Max A., and Bisson, Edmond E.: Friction and Wear of Hot-Pressed Bearing Materials Containing Molybdenum Disulfide. NACA TN 2027, 1950.

6. Buckley, D. H., and Johnson, R. L.: The Influence of Silicon Additions on Friction and Wear of Nickel Alloys at Temperatures to 1000° F. ASLE Trans., vol. 3, no. 1, Apr. 1960, pp. 93-100.

7. Morrison, T. W., Wolfe, H. O., and Remorenko, R. P.: Materials in Rolling-Element Bearings for Normal and Elevated (450° F) Temperatures. ASLE Trans., vol. 2, no. 1, Apr. 1959, pp. 129-146.

8. Jackson, E. G.: Rolling Contact Fatigue Evaluation of Bearing Materials and Lubricants. ASLE Trans., vol. 2, no. 1, Apr. 1959, pp. 121-128.

9. Jastrow, Robert: Lunar and Terrestial Atmospheres. Advances in Aero. Sci. Vol. 5. Plenum Press, Inc., 1960, pp. 338-345.

10. Anon.: Metals Handbook. ASM, Cleveland (Ohio), 1948.

11. Moore, A. J. W., and McG. Tegart, W. J.: Relation Between Friction and Hardness. Proc. Roy. Soc. (London), ser. A, vol. 212, no. 1111, May 22, 1952, pp. 452-458.

12. Wohrman, C. R.: Inclusions in Iron. Am. Soc. Steel Treating, Cleveland (Ohio), 1928.

13. Uhlig, Herbert H.: The Corrosion Handbook. John Wiley & Sons, Inc., 1948.

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

TABLE I. - COMPOSITION OF ALLOY CASTINGS FORMED

IN ZIRCONIUM OXIDE CRUCIBLE

System	Alloying agent	Amount of alloying agent added, percent	Concentration of agent in finished specimens, percent
Nickel - nickel oxide	Nickel oxide	1.50 2.00 2.50 3.00 5.00 6.50	1.35 1.77 1.99 2.52 4.73 6.08
Nickel-tin	Tin	5.40 10.80 16.25 21.0 26.50	5.03 9.65 15.35 19.65 25.21
Iron - iron sulfide	Sulfur added as iron sulfide	0.020 .040 .100 .250 .750	0.011 .028 .054 .145 .450

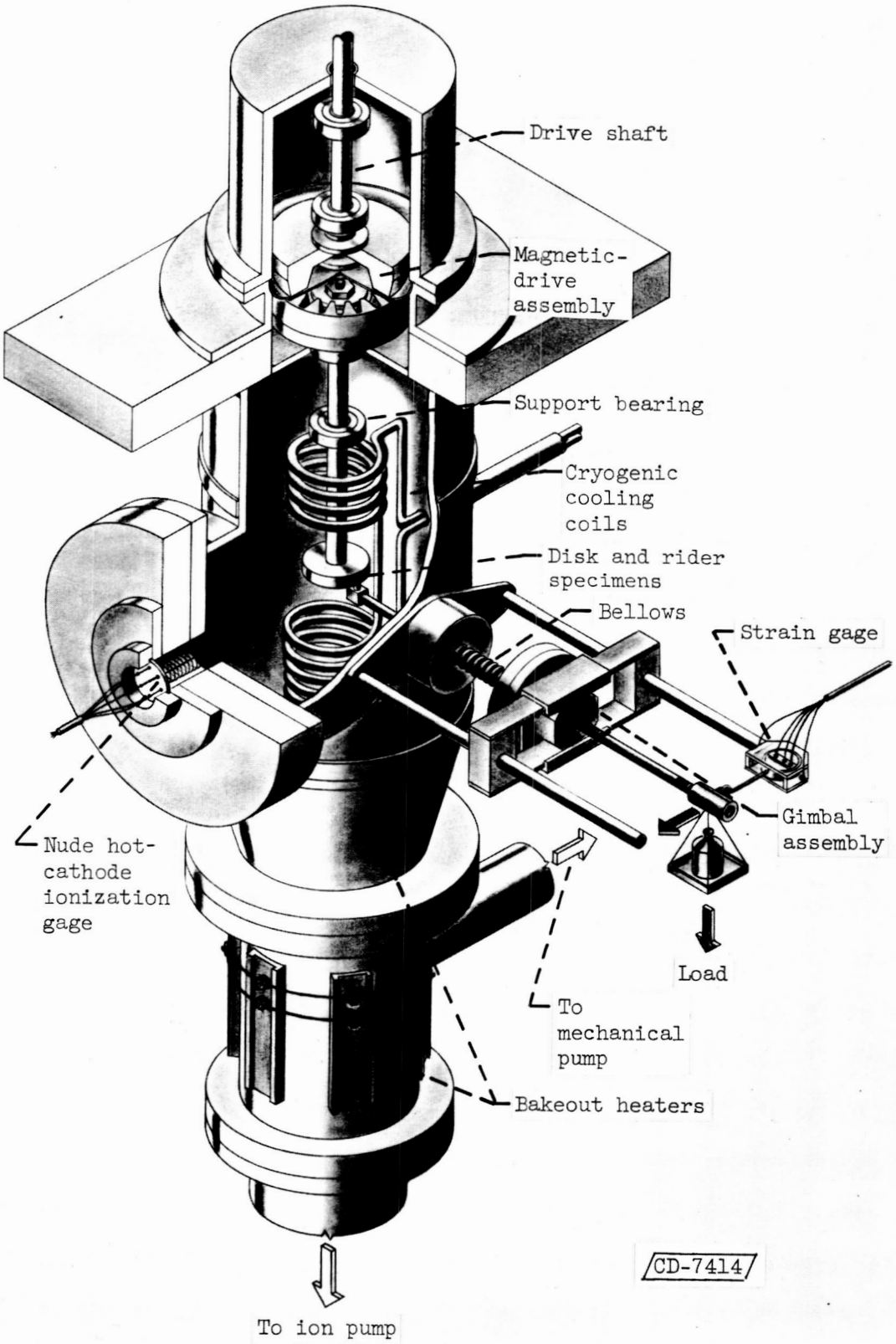


Figure 1. - Vacuum friction and wear apparatus.

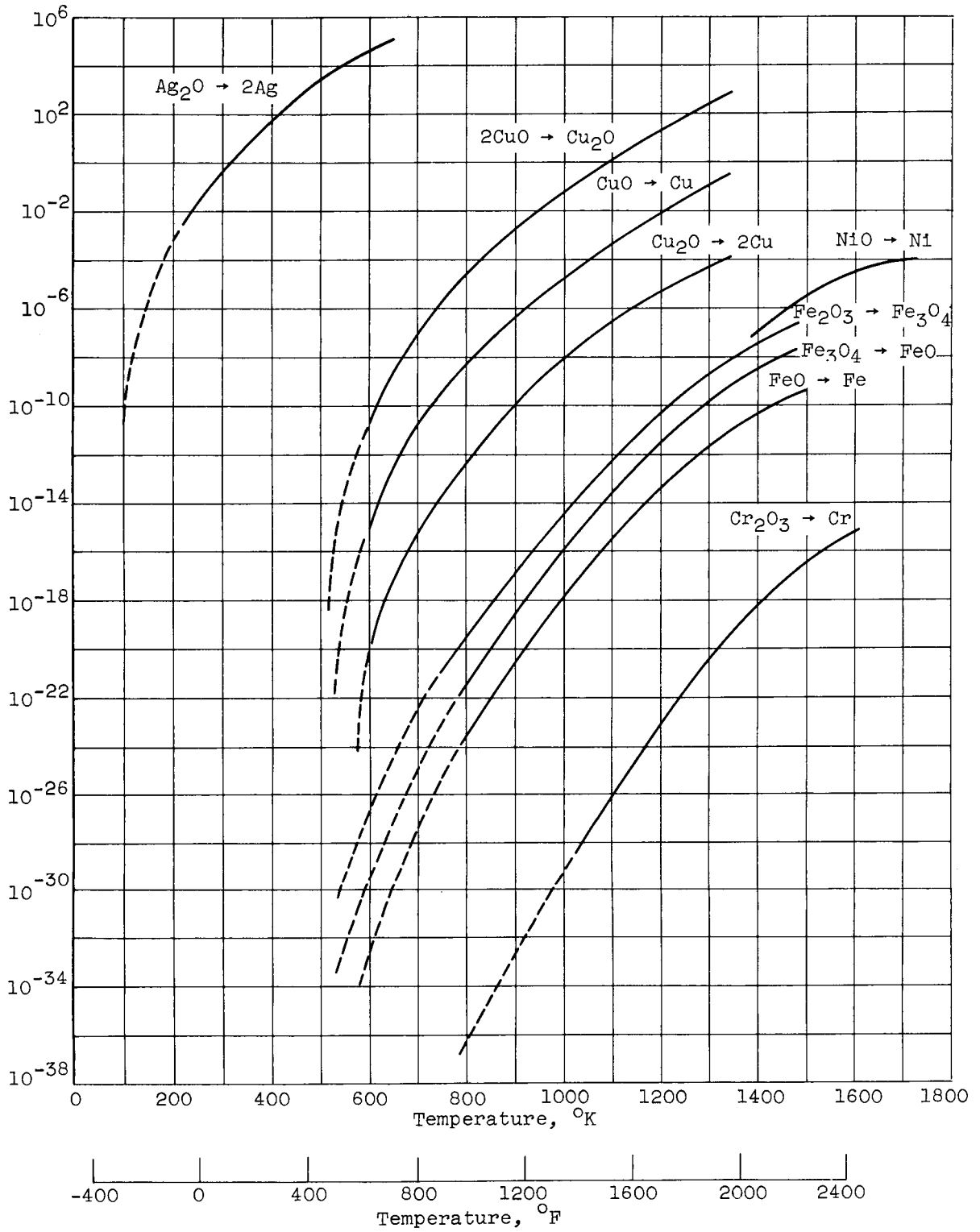


Figure 2. - Oxygen partial pressure necessary for the dissociation of metal oxides at various temperatures.

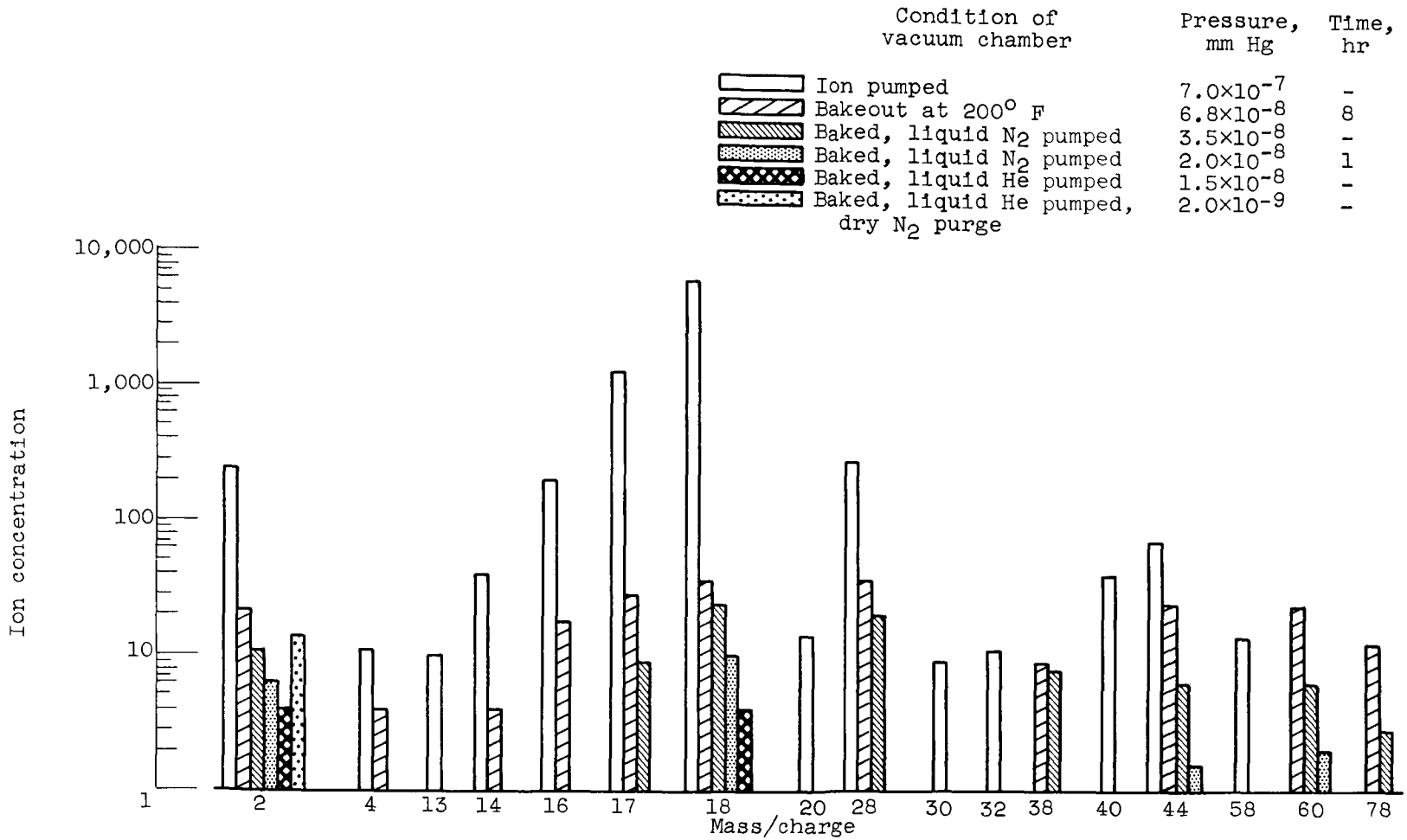


Figure 3. - Mass spectrometer data obtained in vacuum friction and wear apparatus.

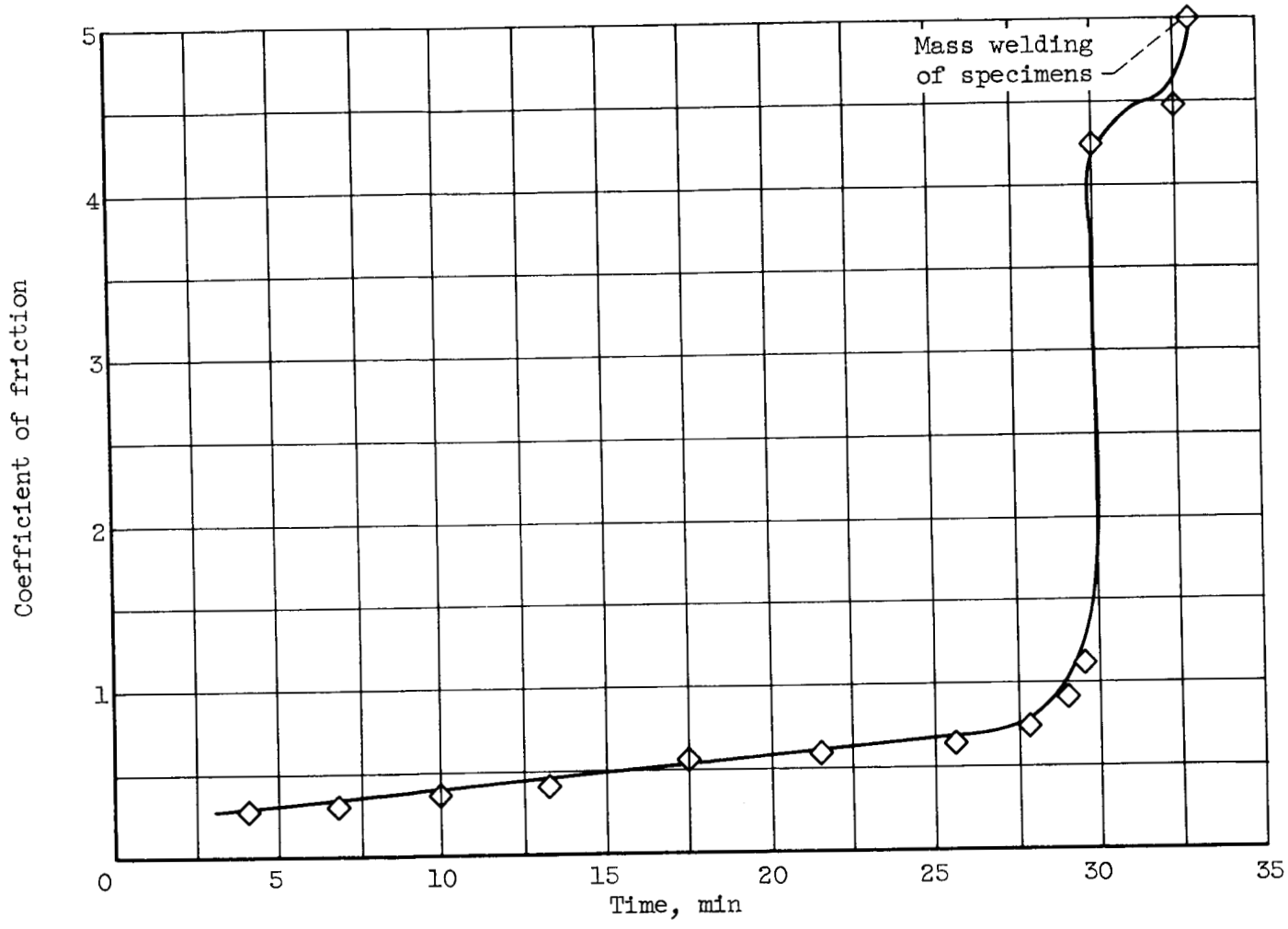
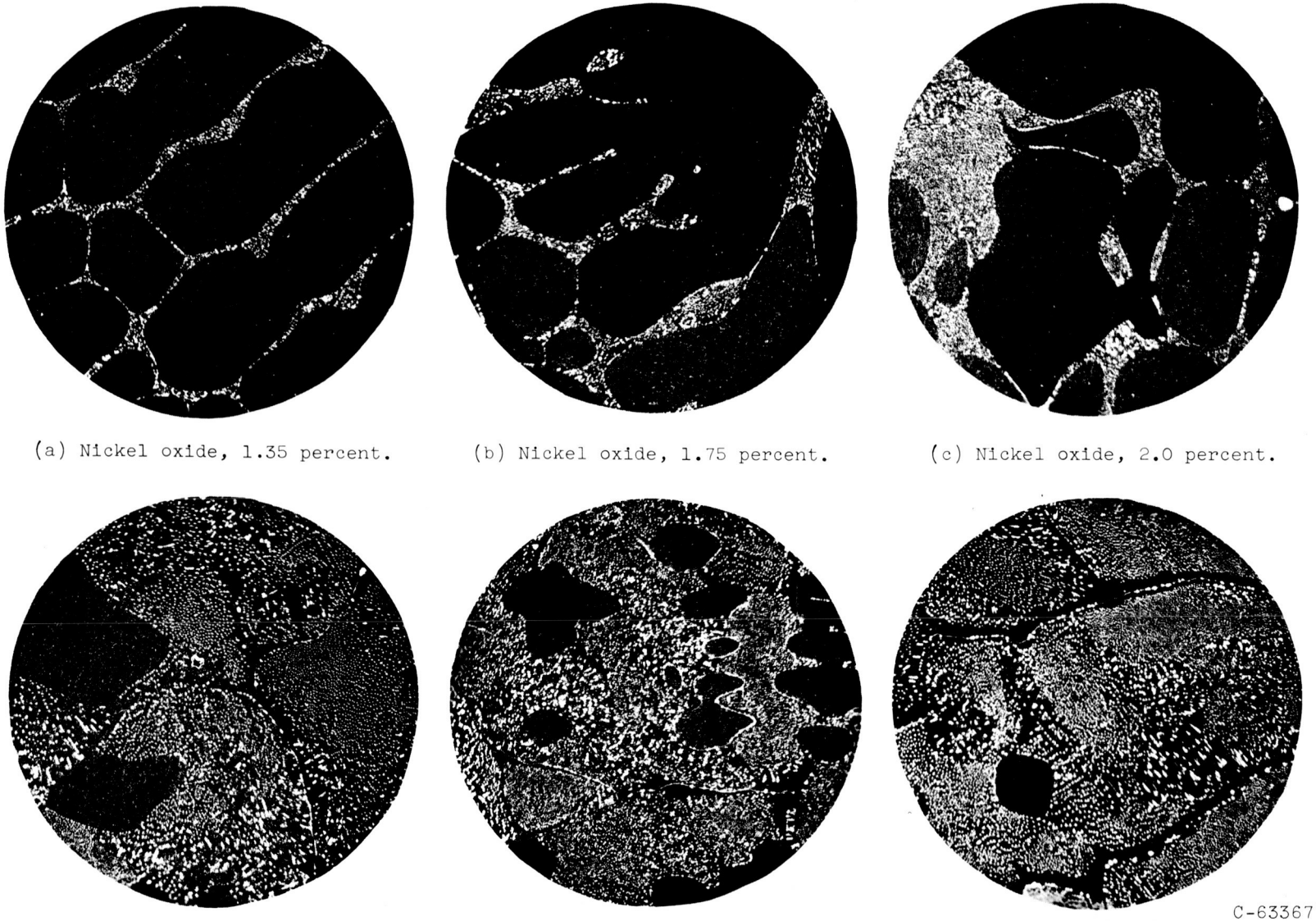


Figure 4. - Coefficient of friction for 52100 bearing steel sliding on 52100 bearing steel in vacuum with liquid helium cryopumping at 2.0×10^{-7} millimeter of mercury; sliding velocity, 390 feet per minute; load, 1000 grams.



(a) Nickel oxide, 1.35 percent.

(b) Nickel oxide, 1.75 percent.

(c) Nickel oxide, 2.0 percent.

(d) Nickel oxide, 2.50 percent.

(e) Nickel oxide, 4.75 percent.

(f) Nickel oxide, 6.0 percent.

C-63367

Figure 5. - Microstructures of various nickel - nickel oxide alloys; ×250.

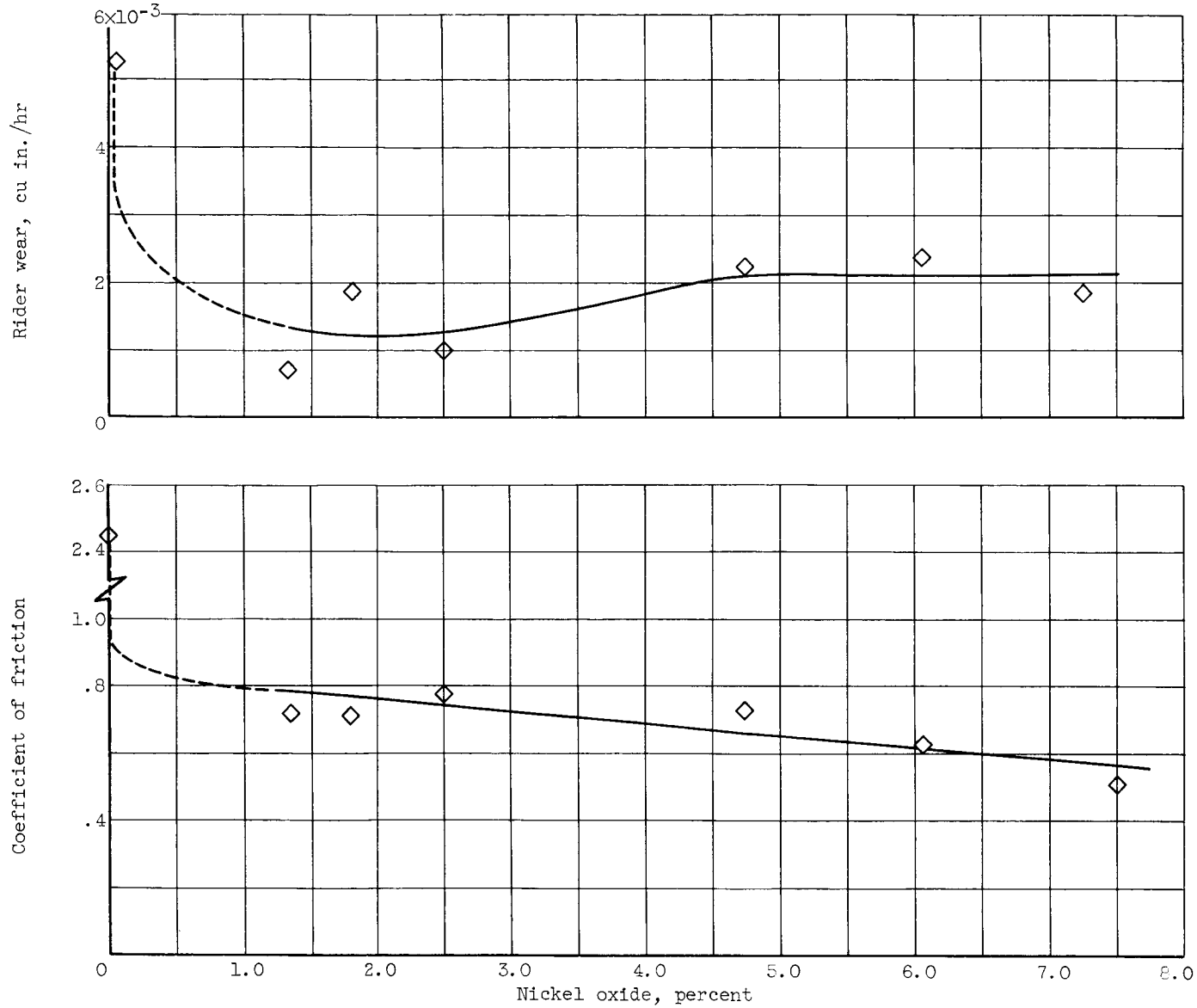
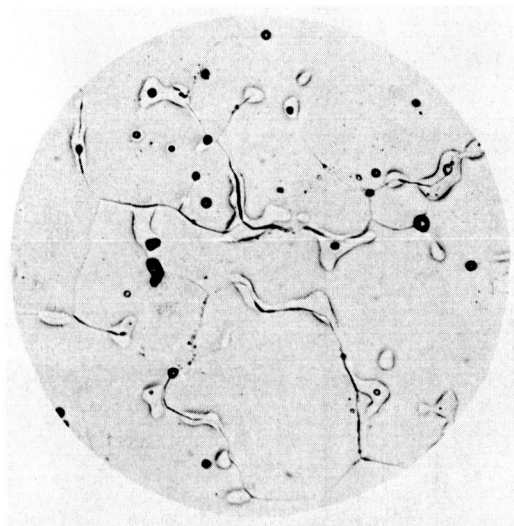
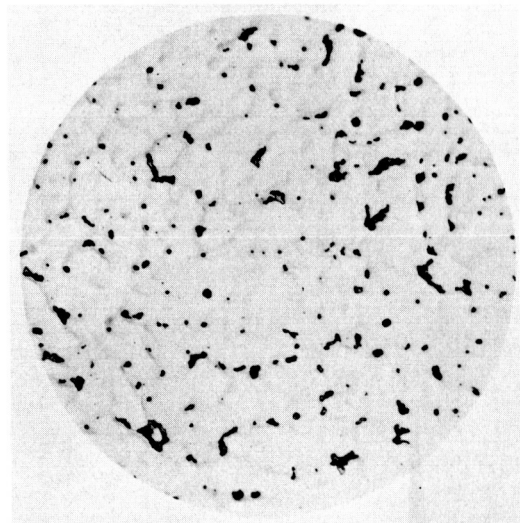


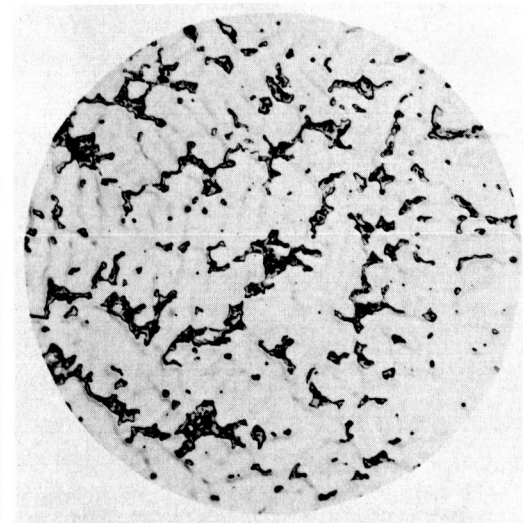
Figure 6. - Coefficient of friction and rider wear for various nickel oxide - nickel alloys at 10^{-8} to 10^{-9} millimeter mercury; sliding velocity, 390 feet per minute; load, 1000 grams; duration of run, 1 hour; and ambient temperature, 75° F.



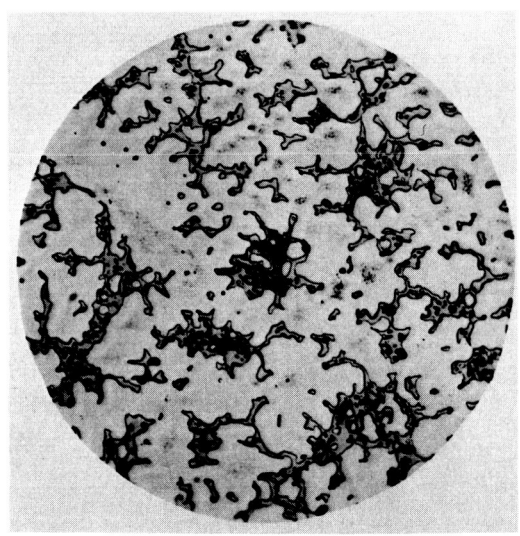
(a) Tin, 5 percent.



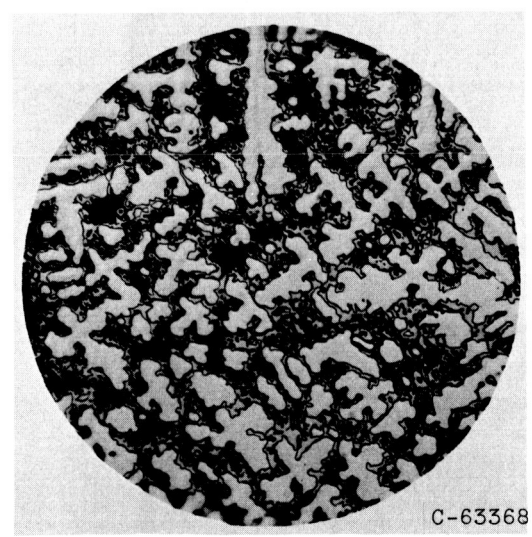
(b) Tin, 10 percent.



(c) Tin, 15 percent.



(d) Tin, 20 percent.



(e) Tin, 25 percent.

Figure 7. - Microstructures of various nickel-tin alloys (electropolished and nital etched); ×250.

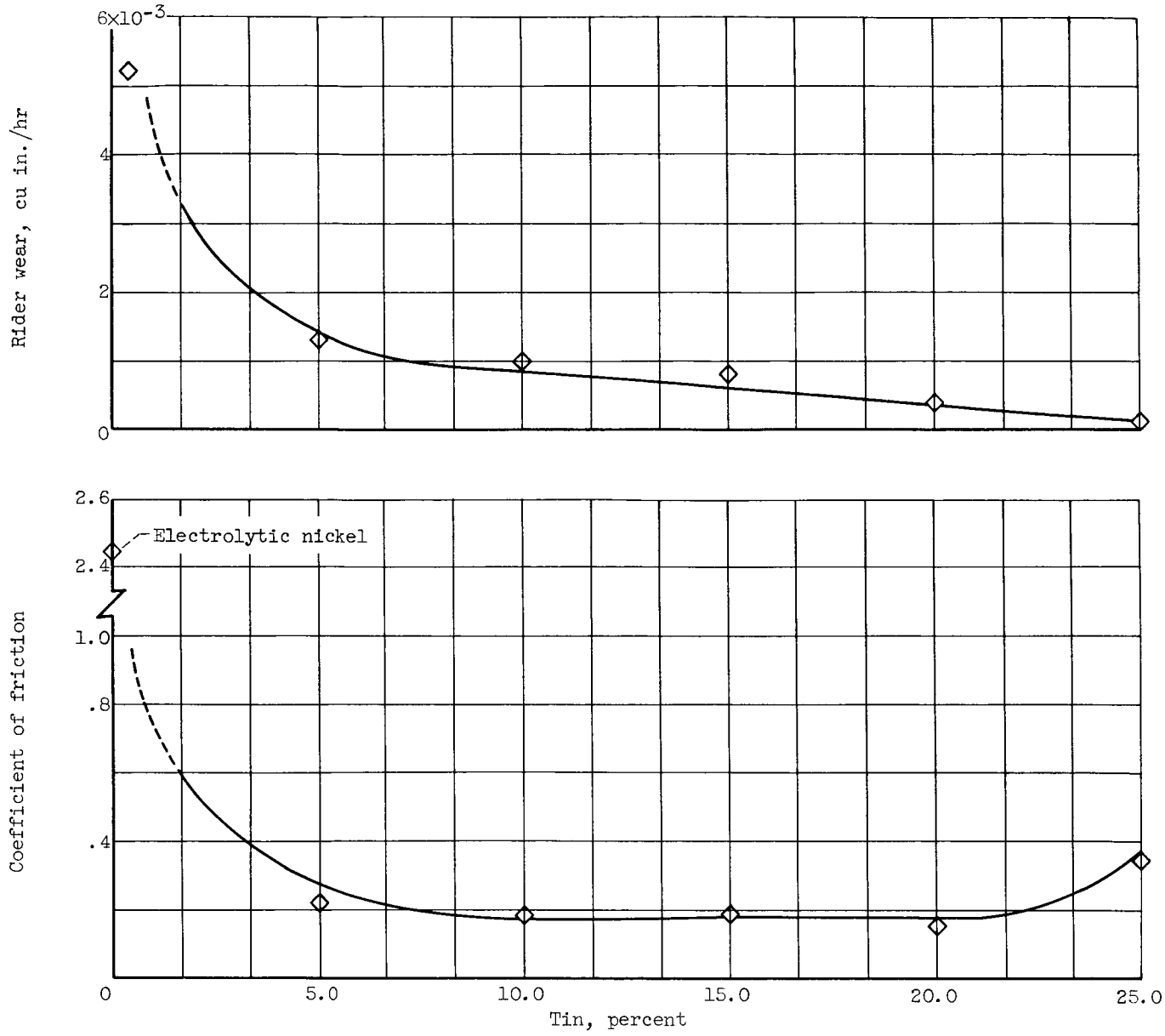


Figure 8. - Coefficient of friction and rider wear for nickel-tin alloys at 10^{-9} millimeter mercury; sliding velocity, 390 feet per minute; load, 1000 grams; duration of run, 1 hour.

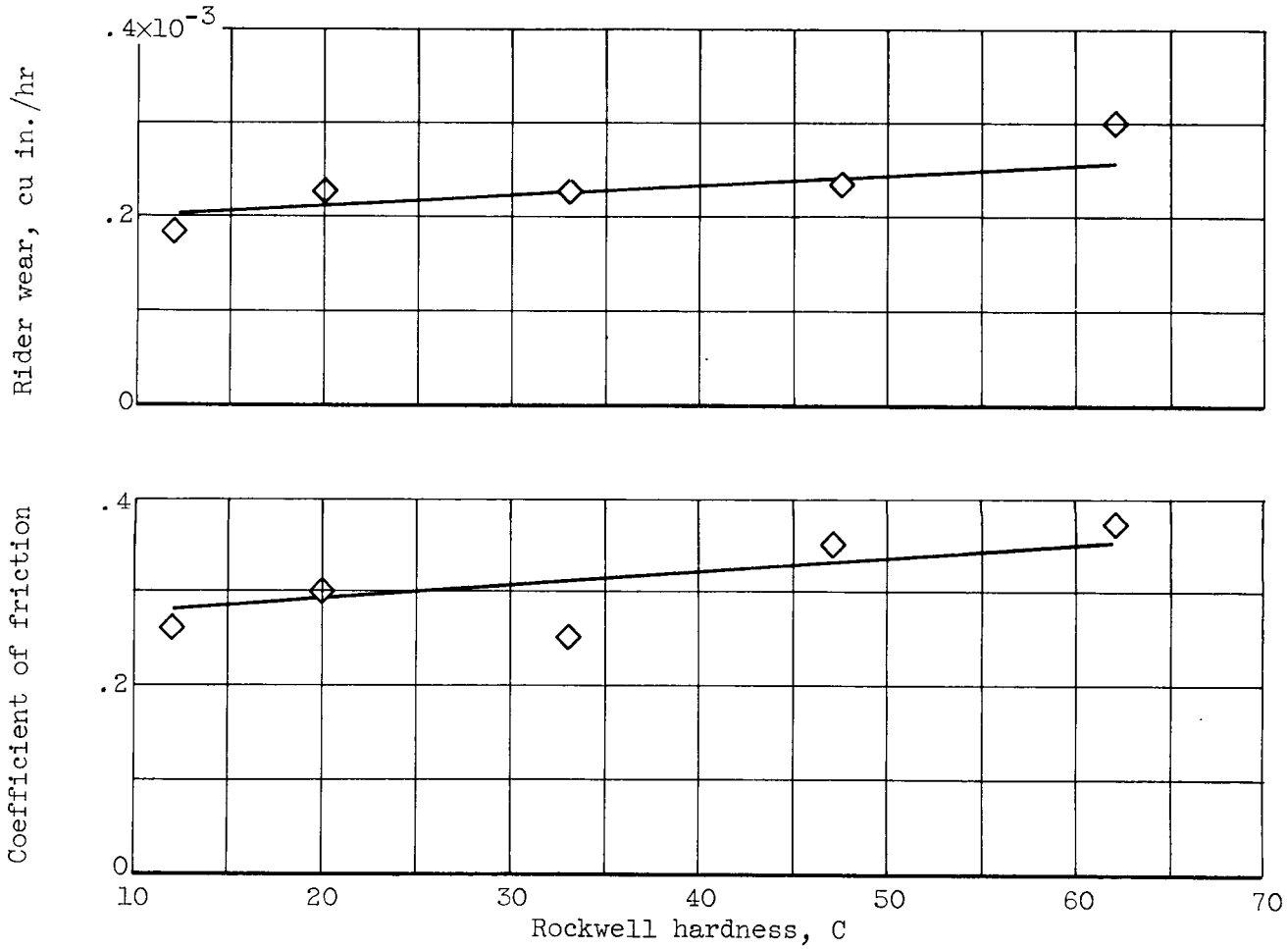
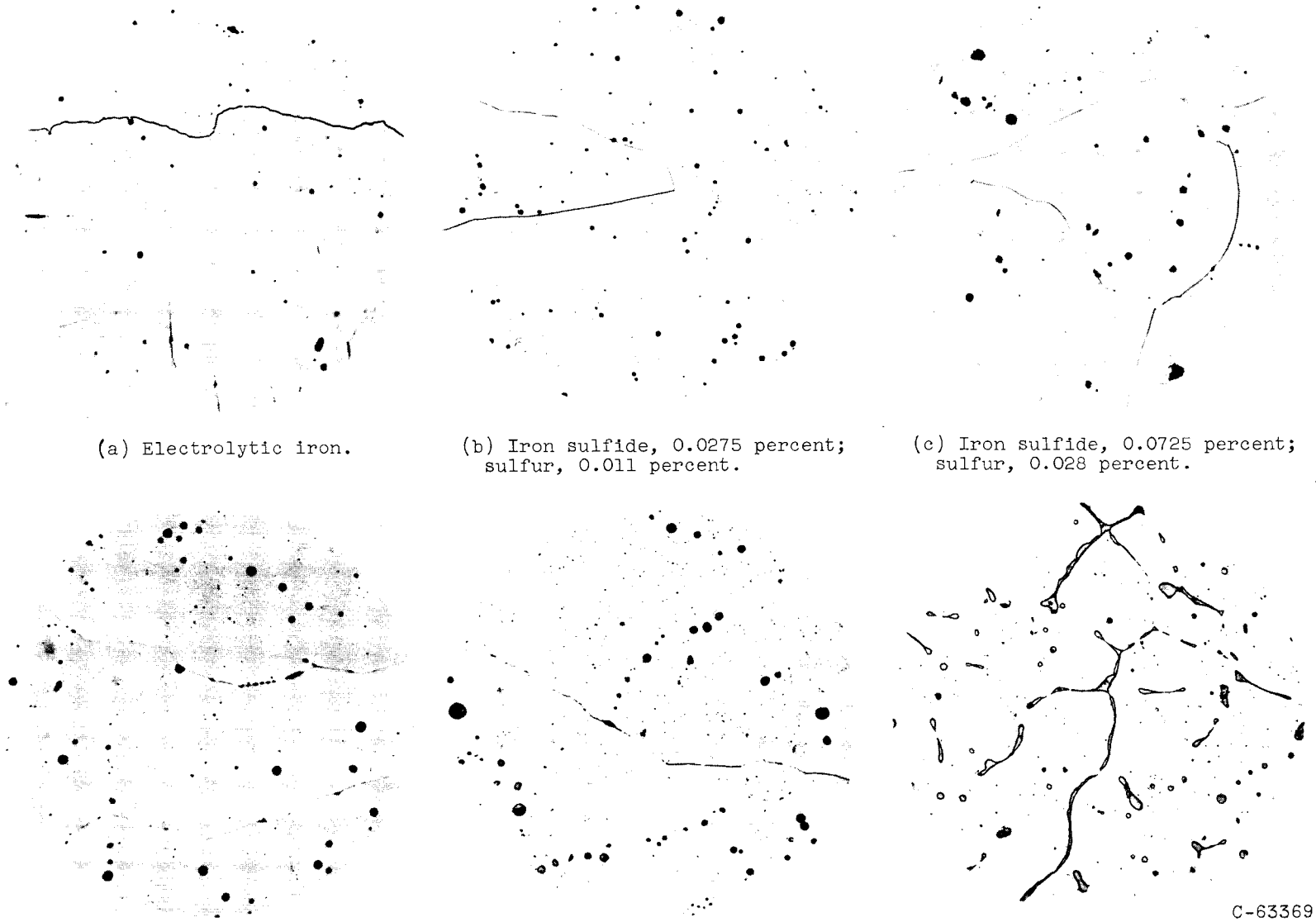


Figure 9. - Friction and wear of 52100 bearing steel sliding on 52100 bearing steel at 10^{-7} millimeter mercury; sliding velocity, 390 feet per minute; load, 1000 grams; duration of run, 1 hour; temperature, 75° F.



(a) Electrolytic iron.

(b) Iron sulfide, 0.0275 percent; sulfur, 0.011 percent.

(c) Iron sulfide, 0.0725 percent; sulfur, 0.028 percent.

(d) Iron sulfide, 0.1375 percent; sulfur, 0.054 percent.

(e) Iron sulfide, 0.275 percent; sulfur, 0.145 percent.

(f) Iron sulfide, 1.238 percent; sulfur, 0.45 percent.

Figure 10. - Microstructures of electrolytic iron and electrolytic iron containing various percentages of sulfur (nital etched), ×250.

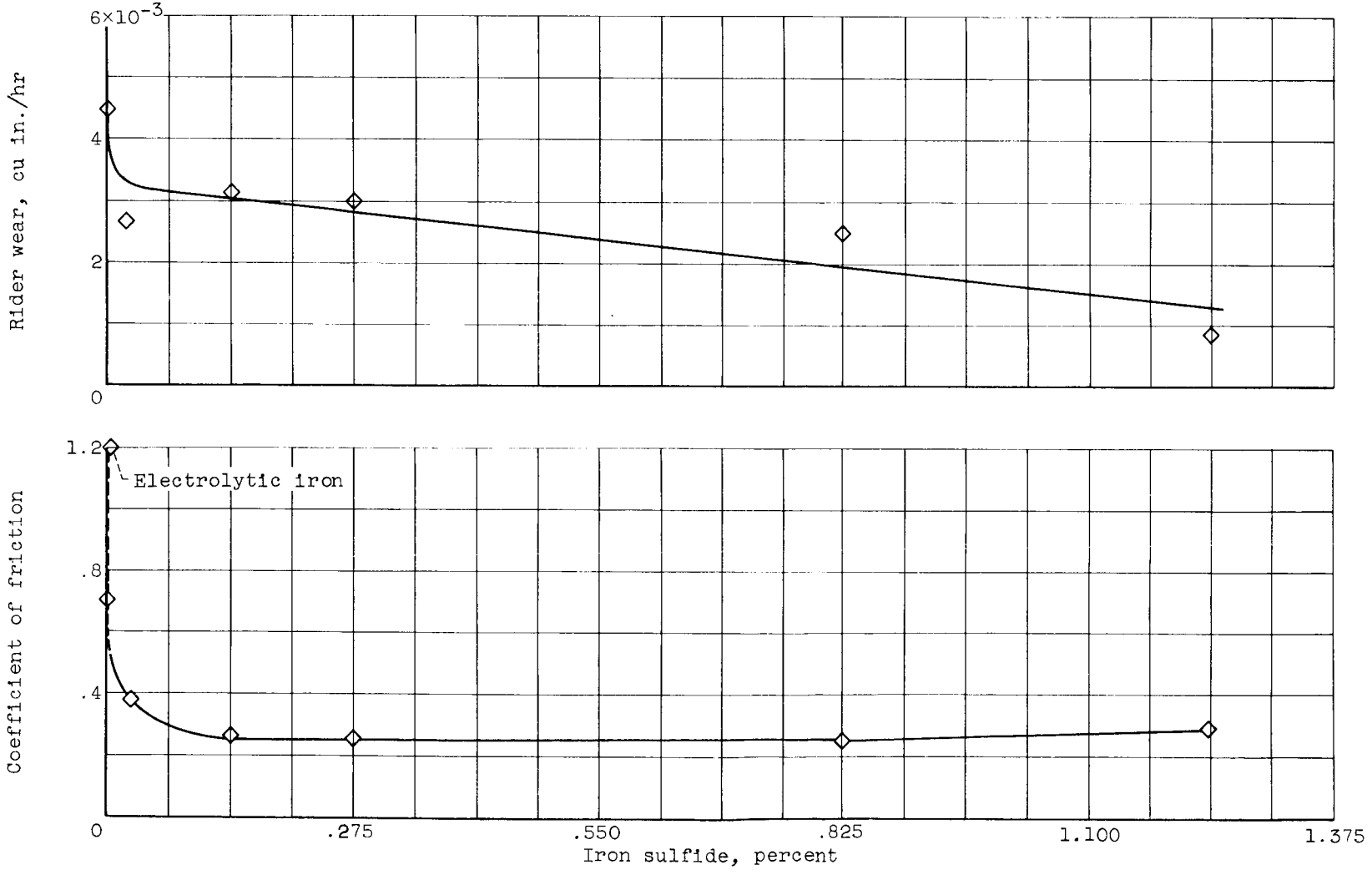
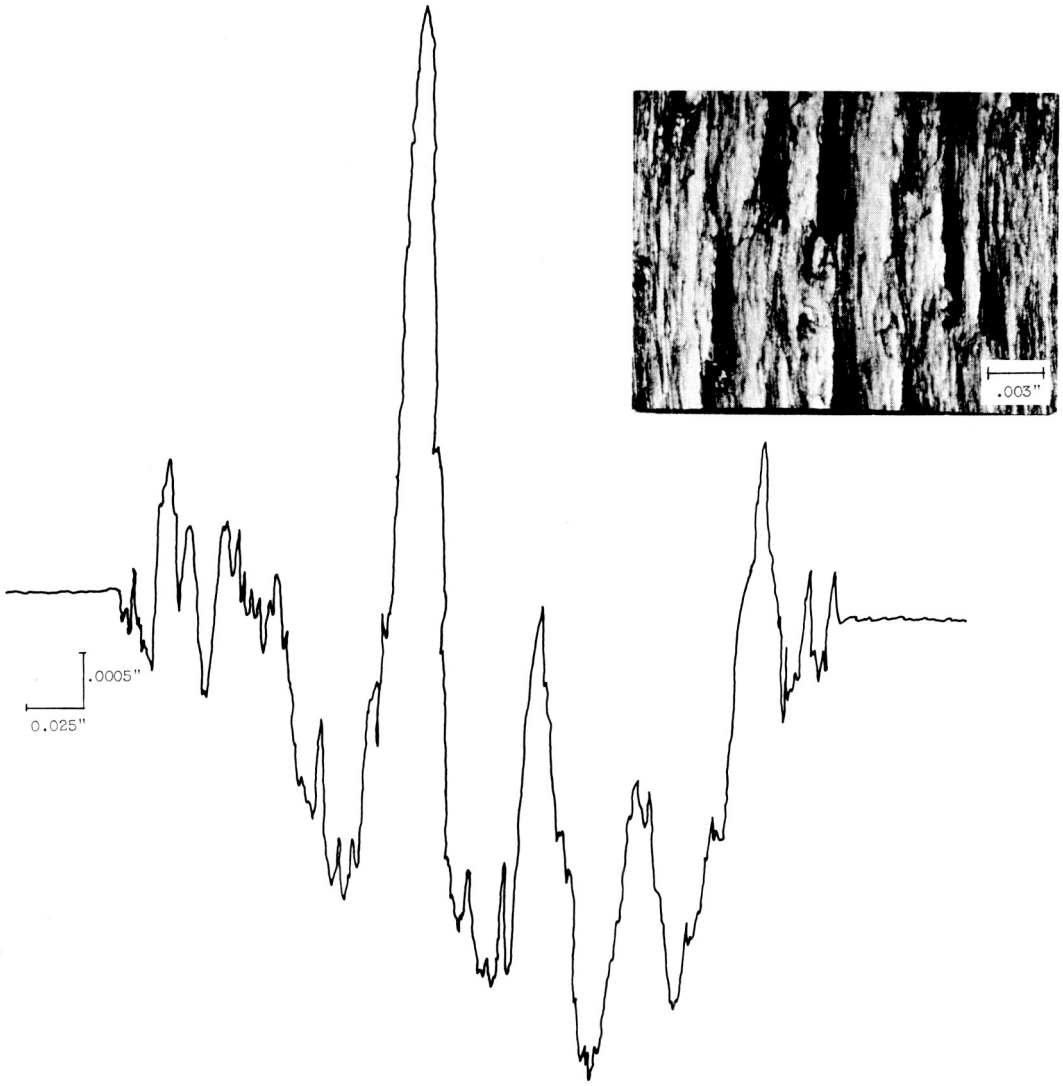
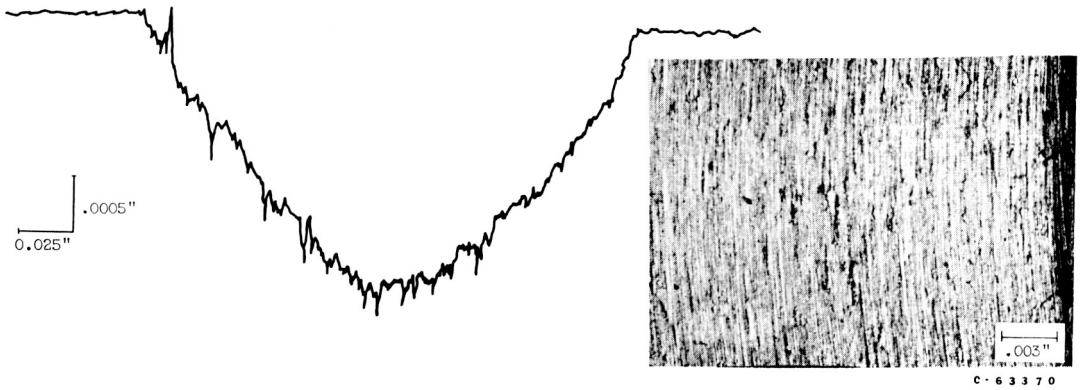


Figure 11. - Coefficient of friction and rider wear for various sulfur-iron alloys at 10^{-9} millimeter mercury; sliding velocity, 390 feet per minute; load, 1000 grams; duration of run, 1 hour; ambient temperature, 75° F.



(a) Electrolytic iron.



(b) 0.447-Percent sulfur-iron alloy.

Figure 12. - Surface profile tracings and photomicrographs. Sliding velocity, 390 feet per minute; load, 1000 grams; temperature, 75° F; in vacuum at 10^{-9} mm Hg.

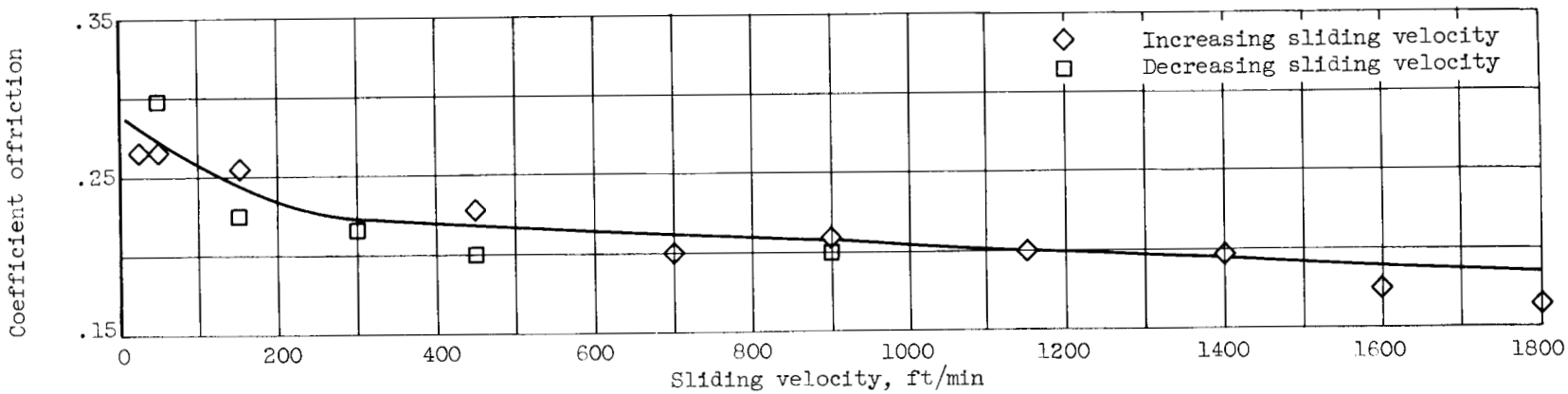


Figure 13. - Coefficient of friction at various sliding velocities for a 0.45-percent sulfur in iron-sulfur alloy; ambient pressure, 10^{-9} millimeter mercury; load, 1000 grams; ambient temperature, 75° F.

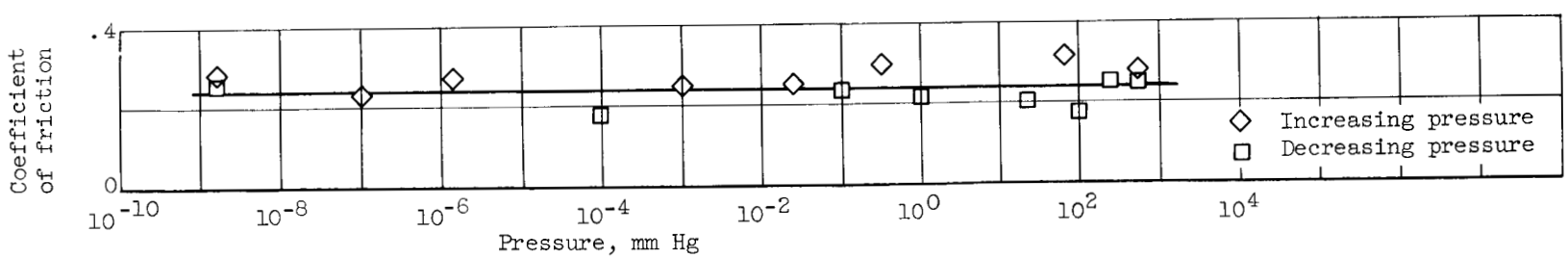


Figure 14. - Coefficient of friction for 0.45-percent sulfur in sulfur-iron alloy at various ambient pressures; sliding velocity, 390 feet per minute; load, 1000 grams; ambient temperature, 75° F.

NASA-Langley, 1963 E-1937