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FRICTION, WEAR, AND DECOMPOSITION MECHANISMS FOR VARIOUS POLYMER COMPOSITIONS IN VACUUM TO 10^{-9} MILLIMETER OF MERCURY

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

Experiments were conducted with various polymer compositions in vacuum (10^{-9} mm Hg) to determine the friction, the wear, the decomposition mechanisms, and the evaporation rates of one of these materials. The materials included the basic polymers polytetrafluoroethylene (Teflon, PTFE), polychlorotrifluoroethylene (PCFE), and polyimide. In addition, experiments were conducted on these polymers with various fillers incorporated into their structures.

Friction and wear experiments were conducted with hemispherical rider specimens (usually a polymer) under a 1000-gram load sliding on flat disk surfaces (various materials). These experiments were conducted at sliding velocities from 30 to 1480 feet per minute. With the aid of a mass spectrometer, the decomposition of polymers was monitored in the friction and wear studies. Evaporation rate was determined in vacuum to 10^{-8} millimeter of mercury with polyimide at temperatures to 875° F.

Experimental results for PTFE indicate that certain fillers (glass fiber and copper powder) markedly improve the friction and wear characteristics of some polymers (PTFE) in vacuum, while others (molybdenum disulfide, MoS_2) offer essentially no improvement. The apparent nature of wear and the decomposition mechanism for polymer compositions, during the sliding process in vacuum, are considered related to the frictional heat generated at the sliding interface and the means for its dissipation. The polyimide polymer compositions were found to have relatively good friction and wear properties in a vacuum (10^{-9} mm Hg) and are stable in vacuum at ambient temperatures to 500° F.

INTRODUCTION

In many space mechanisms where lubrication systems are involved, it is often highly desirable to utilize self-lubricating components. These components, including bearings, seals, and gears, can be especially useful in those areas where conventional lubricating techniques cannot be employed. Self-lubricating materials in such systems prevent high-friction adhesive wear and metal welding that might normally be encountered with conventional all-metal systems. Some solid polymeric materials, such as Teflon, have merit in these components because of

their self-lubricating properties. Experimental lubrication studies are being conducted in vacuum environments as well as in actual flight experiments to determine the effects of a space environment on the lubricating characteristics of such polymers (refs. 1 to 4).

Although some polymers appear attractive for use in space applications, these materials have a number of serious limitations; these limitations are imposed by such properties of polymers as poor mechanical characteristics, poor thermal conductivity, and temperature limitations. Mechanical properties, such as compressive creep of materials like Teflon, require special design considerations. The poor thermal conductivity of polymers can create another problem in vacuum or space environment. Since dissipation of heat in a vacuum is primarily by conduction and radiation, operating components of lubrication systems will experience temperatures greatly in excess of those normally encountered at atmospheric pressure (760 mm Hg). The lack of good heat dissipation by conduction with polymers and the relatively low decomposition temperatures for most polymers (less than 800° F) might therefore further limit the use of polymers in vacuum, despite the good lubricating characteristics of some of these materials.

In an attempt to improve these properties of polymers, numerous fillers have been used in the polymers by others to enhance not only their mechanical and thermal properties but also their lubricating characteristics. These fillers have included metals, glass fibers, inorganic compounds, and solid film lubricants. Some of these fillers have improved the friction and wear properties of polymers (refs. 5 to 9).

The objectives of this investigation of polymers, with and without fillers, were to determine in vacuum (10^{-9} mm Hg): (1) the friction characteristics and the wear mechanism of polymers, (2) the mechanism of decomposition of polymers sliding on metal and ceramic surfaces with the aid of a mass spectrometer, (3) the behavior of polymers in the process of sliding where the mode of heat dissipation changes, and (4) the evaporation rates of basic polymers (10^{-8} mm Hg). The materials examined in this study were commercially available products and included polytetrafluoroethylene (Teflon, PTFE), polychlorotrifluoroethylene (KEL-F, PCFE), a polyimide, and the basic polymers containing various fillers (glass fibers, metals, and solid lubricants).

The evaporation experiments of this investigation were made at ambient pressures to 10^{-8} millimeter of mercury and temperatures to 875° F. The friction and wear experiments were conducted with a 3/16-inch-radius rider hemisphere (usually a polymer) sliding on a $2\frac{1}{2}$-inch-diameter disk (various materials) at surface speeds of 30 to 1480 feet per minute and a load of 1000 grams at ambient pressures to 10^{-9} millimeter of mercury. These conditions are representative of those experienced in bearings, gears, and seals in space.

APPARATUS

The apparatus used in this investigation for friction and wear studies is shown in figure 1. The basic elements of the experiment were the specimens (a

$2\frac{1}{2}$-in.-diam. flat disk and a $\frac{3}{16}$-in.-rad. rider specimen) mounted in a vacuum chamber. The apparatus is described in detail in reference 2. A modification in the apparatus described in reference 2 has been made. This modification consisted of replacing a 5-horsepower canned induction motor as the drive mechanism with a hydraulic motor and a magnetic drive coupling. The coupling is composed of two 20-pole magnets separated by a distance of 0.150 inch with a 0.030-inch diaphragm between magnet faces. One magnet was the driver magnet and was outside the vacuum system. It was coupled to a hydraulic motor. The second magnet was completely canned with a nickel-alloy housing (cut away in fig. 1) and was mounted on one end of the shaft within the chamber. The disk specimen was mounted at the end of the shaft opposite the magnet. The internal drive support utilized size 204-R angular contact ball bearings having the cages coated with a commercial type, bonded molybdenum disulfide film.

The rider specimen was supported in the specimen chamber by a retaining arm that consisted of a gimbal and a bellows mounted 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 deadweight loading system.

Attached to the lower end of the specimen chamber was a 400-liter-per-second ionization pump and a mechanical forepump using liquid-nitrogen cold traps. The pressure in the chamber was measured adjacent to the specimen with a nude hot-cathode ionization gage.

The mass spectrometer used in these studies was mounted with the tube mouth $1\frac{1}{2}$ inches from the specimens, in the same plane with the specimens and the nude ionization gage. The mass spectrometer was a diatron type, 180° focusing, with a permanent magnet and capable of reading masses of 2 to 80.

The evaporation rate apparatus used in this study is described in reference 2. The apparatus used a 5/16-inch-diameter by 1/8-inch-thick specimen of the basic polyimide polymer suspended from an electronic balance (sensitivity 0.01 mg) in the mouth of a wire-wound tungsten-element cylindrical furnace. About 1 inch above the furnace was a copper condensing plate, which was liquid nitrogen cooled. The entire apparatus was enclosed in a glass bell-jar system, and pressure within the system was measured with a nude hot-cathode ionization gage adjacent to the evaporating specimens.

EXPERIMENTAL PROCEDURE

The metal disk and rider specimens used in friction and wear experiments were finish ground to 4 to 8 microinches. Before each experiment, the disk and the rider were given the same preparatory treatment. This treatment consisted of: (1) a thorough rinsing with acetone to remove oil and grease, (2) polishing with moist levigated alumina on a soft cloth, and (3) a thorough rinsing with tap water followed by distilled water. For each experiment, a new set of specimens was used. The polymer compositions were scrubbed with acetone followed by an alcohol rinse.

RESULTS AND DISCUSSION

Polytetrafluoroethylene and Polychlorotrifluoroethylene

In order to determine the ability of the polymers polytetrafluoroethylene and polychlorotrifluoroethylene to lubricate in a vacuum environment, such as might be encountered in space, some friction and wear studies were conducted at 10^{-9} millimeter of mercury with rider specimens of the two polymers sliding on 440-C stainless-steel disks. The results obtained are presented in figure 2. Both friction and wear for unfilled PTFE and PCFE were high in vacuum. The friction and wear for both were very nearly the same, which indicates that very little difference in friction and wear characteristics resulted from the presence of chlorine in the polymer. The wear to both materials was high, and the type of wear debris obtained can be seen in figure 3. In general, the wear mechanism of the two polymers sliding on metal surfaces was one of an abrasion process. Despite the low surface roughness of the 440-C disk (4 to 8 μin.), extreme abrasion of the polymer occurred, and large wear particles were obtained that adhered to the disk surface.

An interesting observation was that the large particles with a sawdust-like appearance struck and adhered to the disk surface. Although the disk was rotating in a horizontal position with the interface surface down (see fig. 1), the major portion of the wear particles adhered to it, particularly adjacent to the inner and outer edges of the wear track. Later examination showed the particles were sticky to the touch. This sticky nature of the particles indicates that heat generated at the sliding interface was transferred to the polymer particles, which thus increased particle surface temperatures and caused surface degradation of the particles. The polymer particles are thus absorbing some of the frictional heat generated in the sliding process.

Glass-Fiber-Filled Polymers

In order to determine the influence of a filler on the friction and wear characteristics of the two polymer compositions, experiments were conducted with 25 percent glass-filled (glass filled refers to glass fibers in all cases) PTFE and PCFE polymers in vacuum. The results obtained are presented in figure 2. With 25 percent glass-filled PTFE the friction was slightly higher than that which was obtained with unfilled PTFE. The wear, however, decreased by two orders of magnitude with the addition of 25 percent glass to the polymer. With the PCFE glass-filled composition, the wear could not be measured because the specimen swelled and completely lost its shape (see photo inserts of fig. 2). The softening point for this material is about 400° F (ref. 10). The specimen must have reached this temperature because the swelling and gas pockets could be seen within the specimen. This result was not noted (see photo insert of fig. 2) with 25 percent glass-filled PTFE, which has a softening point at about 550° F.

The fact that the unfilled PCFE did not swell and the glass-filled composition did may have resulted from the ability of the virgin PCFE to dissipate a large quantity of heat in the wear particles. With the glass-filled composition much less wear is observed, and the heat generated at the sliding interface must be dissipated to a large extent by conduction from the polymer body to the rider

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holder assembly of the apparatus. The presence of glass fillers may increase the ability of the heat generated to be carried to within the polymer body.

The marked improvement in wear observed for glass-filled PTFE in figure 2 over the results obtained with unfilled PTFE under the same conditions suggested further study with glass-filled compositions. The results obtained in additional friction and wear studies with glass-filled PTFE compositions are presented in figure 4. The addition of 15 percent glass to PTFE improves both the friction and the wear obtained with PTFE. With 25 percent glass fiber in the polymer no improvement in wear over the 15 percent glass composition is observed. An increase in friction is observed for the 25 percent glass composition over that obtained with the unfilled PTFE and 15 percent glass-filled PTFE. It appears that an optimum in the quantity of glass filler in PTFE for vacuum applications may be something less than 25 percent. An interesting observation is the photomicrograph of the wear area of the 25 percent glass-filled composition in vacuum (see photo insert of fig. 4). The wear debris about the rider specimen was black in color. Chemical tests indicated the presence of iron in the debris, but about 70 percent of the film was carbon. This film will be discussed in greater detail in the discussion of figures 7 and 8.

Solid Lubricant Fillers

Molybdenum disulfide has been added to PTFE in an attempt to improve its lubricating characteristics. Friction and wear results obtained with 10 percent MoS_2 in PTFE are presented in figure 4. In general, addition of 10 percent MoS_2 did not improve the friction and wear characteristics of PTFE as can be determined by a comparison with unfilled PTFE. Another composition examined in vacuum was 5 percent molybdenum disulfide – 15 percent glass PTFE composition. This composition has been reported to have improved wear characteristics over the 15 percent glass PTFE composition (ref. 4). Friction and wear results obtained in vacuum are presented in figure 4. Again, it can generally be said that MoS_2 did not improve friction and wear.

Metal Powder Fillers

Since metals are good heat conductors, some friction and wear experiments were next conducted with copper- and silver-filled PTFE riders sliding on 440-C stainless steel in vacuum. The friction and wear data obtained in these experiments together with reference data for copper, silver, and PTFE are presented in figure 5. The friction coefficient obtained for metal-filled (copper and silver) PTFE was lower than that obtained with the unfilled PTFE or the metals themselves sliding on 440-C stainless steel. The wear for silver-filled PTFE was about the same as that obtained with silver metal sliding on 440-C stainless steel. The wear for copper-filled PTFE, however, was approximately one-twentieth that obtained with copper metal and approximately one-hundredth that obtained with unfilled PTFE. The appearance of the specimen is shown in figure 6. With metallic copper, the rider specimen had a trailing edge that appeared to have been molten metal. With the PTFE composition containing 25 percent copper, the wear was not characterized by abraded particles as with the unfilled polymer or as observed with copper metal. The wear mechanism will be discussed in more detail in refer-

ence to figures 7 and 8. It must be pointed out that some of the heat generated at the sliding interface is carried to within the polymer rider specimen and is transferred from the rider specimen to the specimen holder. Thus, the temperature of the polymer rider specimen is lower than it would be if all of the heat generated remained within the body.

Since surface conditions (such as temperature) can change the behavior of materials, some friction experiments were conducted in vacuum with PTFE and glass- and copper-filled PTFE compositions sliding on 440-C stainless steel over a range of sliding velocities. The results obtained in these experiments are presented in figure 7. Changing sliding velocity will change surface temperatures and could influence the friction results obtained. Examination of figure 7, however, indicates that changing sliding velocity did not influence the friction coefficient for the three compositions examined.

Decomposition Mechanisms

In conjunction with the friction experiments at various sliding velocities, mass spectrometer data were obtained for the three PTFE compositions, and the results obtained are presented in figure 8. In this figure is plotted ion concentration for mass to charge ratios M/e of $19(F^+)$, $31(CF^+)$, and $50(CF_2^+)$. It is interesting to note that with unfilled PTFE (fig. 8(a)) a relatively insignificant amount of M/e $19(F^+)$ was obtained and therefore was not plotted. The concentration of both M/e 31 and M/e 50 decreased with increasing sliding velocity. Since with increasing sliding velocity the surface temperature increases, it might be expected that an increase in these concentrations with sliding velocity would occur as a normal result of increased degradation with temperature. As was indicated in the discussion of figures 2 and 3, the wear process with unfilled PTFE consisted of abrading particles. These particles were sticky, which indicated that frictional heat had caused degradation. As the sliding velocity was increased, wear increased from 5.0×10^{-8} cubic inch per foot of sliding at 390 feet per minute to 6.5×10^{-8} cubic inch per foot of sliding at 980 feet per minute (see wear values of fig. 8(a) at 390 and 980 ft/min), and the amount of heat carried away with the wear particles would probably increase. Furthermore, the contact time of the particles in the contacting interface decreased with greater sliding velocity, and the time at degradation temperature available for thermal decomposition to occur decreased. The concentration of decomposition products therefore decreased with increased sliding velocity.

With the 25 percent glass-filled PTFE composition (fig. 8(b)), the ion concentrations for M/e $19(F^+)$, M/e $31(CF^+)$, and M/e $50(CF_2^+)$ are found to increase with increasing sliding velocity. This result is not like that obtained with unfilled PTFE where very little M/e $19(F^+)$ was observed. With the 25 percent glass-filled PTFE, M/e $19(F^+)$ was the principal decomposition product detected by the mass spectrometer. This indicates that carbon to fluorine bond cleavage must be occurring at the sliding interface. Wear of the glass-filled PTFE is much less than for the unfilled PTFE (fig. 2); therefore, less heat is carried away with wear particles and the temperature at the interface will be higher. A thin film of PTFE may be interposed between the metal surface and the glass fibers. As a result of a thin film present, it is hypothesized that localized decomposition of the PTFE film occurred and increased with an increase in sliding

velocity or surface temperature. The presence of carbon on the glass-filled PTFE rider surface in figure 4 and only a small concentration of carbon observed in the mass spectrometer tracing (not shown in fig. 8(b)) indicated that decomposition was occurring at the sliding interface and not in the mass spectrometer. If decomposition were occurring in the mass spectrometer, the ion concentration for carbon should increase with the increase in fluoride ion concentration. This, however, was not observed. If decomposition was occurring in the mass spectrometer by carbon to fluorine bond cleavage, an increase in fluoride ion concentration would be accompanied by a carbon ion concentration increase. This was not observed. It must be pointed out, however, that some cleavage of the carbon to fluorine bond must be expected to occur in the mass spectrometer.

In the sliding velocity experiments conducted with copper-filled PTFE, very small concentrations were observed for M/e ratios of 19 and 31 over the range of sliding velocities investigated (see fig. 8(c)). These results indicate that decomposition of the PTFE was slight. This effect cannot be related to wear because the wear was the same for both glass- and copper-filled compositions (figs. 2, 3, 5, and 6). With copper it is believed a mechanism similar to that observed with glass prevails that is a thin film of PTFE, which is interposed between the copper particles, and the metal disk surface functions as a lubricant. Unlike the glass fillers, however, copper is a good heat conductor. The copper dissipates the heat generated and reduces the decomposition of PTFE. Although there is nominally only 25 percent copper present in the PTFE composition at the sliding interface, the discrete particles flow out, and the exposed area of interface copper increases on the interface (see bright areas of photo insert of fig. 8(c)).

Heat rejection appears to play an important role in the decomposition of PTFE. Some experiments were therefore conducted with a 15 percent glass-filled PTFE composition sliding on (1) aluminum oxide (a poor heat conductor), (2) silver, and (3) copper (both good heat conductors) to determine the influence of thermal conductivity of the disk material on the wear characteristics. These data are presented in figure 9. The mass spectrometer data obtained in the experiments are presented in figure 10. The friction and wear results are comparable for aluminum oxide and copper disk materials. A comparison of the mass spectrometer data of figure 10 indicates that, as might be anticipated, the concentration of the polymer degradation products is much less with the copper disk than that with aluminum oxide.

The silver disk specimen has the highest thermal conductivity, but the results are not in agreement with those obtained for the other two disk materials. With silver it might be expected that the least amount of PTFE decomposition would occur. The friction and wear were higher, and a higher concentration of decomposition products was observed with the silver disk than that obtained with copper. The friction coefficient obtained appeared to more closely approach the friction for metal-metal combinations. Examination of the rider surface after the experiment indicated transfer of silver to the rider surface (see photo insert of fig. 9). These results indicate that silver was sliding on silver rather than PTFE sliding on silver. With metal on metal, greater frictional heating occurs, and a higher concentration of PTFE decomposition products is obtained than with PTFE sliding on metal. Silver, at the pressures of this investigation, does not have an oxide present on its surface. This would suggest a physical

transfer of silver to the PTFE surface. Reaction of the disk surfaces with hydrogen sulfide gas did not reveal the presence of PTFE film on the disk surface.

Graphite and Carbon Fillers

Although graphite is not expected to lubricate in a vacuum, its addition to PTFE might improve the heat-dissipating characteristics of PTFE. Therefore, some friction and wear experiments were conducted in vacuum with PTFE containing 25 percent graphite or 25 percent coke flour. The friction and wear results obtained in these experiments are presented in figure 11. The greatest reduction in friction and wear was obtained with the 25 percent coke flour. This may again be a result of heat dissipation from the sliding interface. The graphite platelets tend to orient themselves in the process of molding the polymer composition in such a way as to result in a separation of the individual platelets. The platelets are consequently separated by PTFE. Furthermore, orientation by both molding and sliding processes provided for the poorest thermal conductivity that could be obtained because of the normal anisotropy of graphite. With the coke flour the carbon is in particle form, which does not tend to orient, and a greater degree of particle-to-particle (carbon) contact can occur within the polymer matrix, serving as a better heat-conduction path from the metal-polymer interface than is the case with graphite.

Polyimides

A relatively new development in the field of plastics has been the polyimide compositions. In order to gain some insight into the possible usefulness of this material as a space lubricant and some concept of its relative stability in a vacuum, some evaporation studies were conducted with the material in vacuum to 10^{-8} millimeter of mercury and at ambient temperatures to 875° F. The results obtained in these experiments are presented in figure 12. The evaporation rate for the polyimide was less than 10^{-10} $(g)(cm^{-2})(sec^{-1})$ at ambient temperatures to 500° F. The evaporation rate was so low that no weight change was noted within the sensitivity of the electronic balance (0.01 mg). At temperatures above 500° F the polyimide began to lose weight at an appreciable rate, and at 875° F the rate was so high that it could not be followed with the recorder.

Because of the encouraging results obtained in evaporation studies with the polyimide composition, some friction and wear studies were conducted in vacuum (10^{-9} mm Hg) with polyimides sliding on both metals and itself. The results obtained in these experiments are presented in figures 13 to 15. In figure 13, the friction and the wear are compared for polyimide riders on 440-C stainless-steel disks, with the polyimide cut in two directions from the parent material block. Although the friction for polyimides on 440-C stainless steel was relatively low, the wear to the polyimide rider was somewhat high. If these results are compared with those obtained in figure 2, with unfilled PTFE, however, the wear for the polyimide is only one-fifteenth that obtained with PTFE, and the friction is also lower.

Friction and wear experiments were next conducted with the polyimide sliding

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on polyimide, and the results obtained are presented in figure 13. The friction coefficient obtained with polyimide sliding on polyimide was much higher than that obtained with polyimide on 440-C stainless steel. The wear to the rider specimen with polyimide on polyimide, however, was one five-hundredth that of polyimide on metal. Surface profile traces and photomicrographs are presented in figure 14 for the wear area to the metal and polyimide disk specimens. With the metal disk, a thin nearly transparent polyimide film was transferred to the disk surface. The film was not thick enough to be detected in the surface profile traces (magnification of 1000 in the vertical direction). The polyimide disk specimen did, however, show evidence of wear.

A 15 percent graphite-filled polyimide composition was also examined in friction and wear studies, and the results obtained are presented in figure 13. The presence of graphite in the polyimide did not improve its lubricating characteristics; relatively high friction and wear were obtained.

In figure 15 are plotted friction curves as functions of time for the polyimides. With the filled and unfilled polyimide on 440-C, the friction was very low at 1 minute of operation. The friction coefficient began to increase with time and after 5 minutes was relatively constant for both materials. These results suggest that with time the transfer of a thin film of polyimide to the disk surface occurs. In the first 5 minutes it is polyimide sliding on metal, and then after 5 minutes polyimide is sliding on a thin film of polyimide. With polyimide sliding on itself, the friction was between 0.7 and 0.8 initially, and gradually decreased to 0.56 after 2 minutes of the experiment. These results suggest possible surface orientation effects of the polymer. Once an oriented film is obtained on the surface, the friction decreases to a lower but relatively constant value.

SUMMARY OF RESULTS

Based on the data obtained in this investigation with polymer compositions in friction and wear studies in vacuum, the following summary remarks can be made:

1. Relatively high friction and abrasive type of wear were obtained with unfilled polytetrafluoroethylene (PTFE) polymer in vacuum. The addition of some fillers (glass fibers and copper powder) markedly improved the friction and wear characteristics observed for PTFE, while the addition of another filler, 10 percent molybdenum disulfide, offered essentially no improvement in its friction and wear characteristics.

2. The wear and decomposition mechanisms for polymer compositions in a vacuum (10^{-9} mm Hg) appear related to the frictional heat generated at the sliding interface and the means for its dissipation. Fillers can markedly influence the nature of wear and the decomposition products formed at the sliding interface.

The polymer decomposition products formed at the sliding interface with PTFE sliding on metal surfaces varied with composition. With unfilled PTFE heat appeared to be dissipated to wear particles in such a way that the principal prod-

ucts of decomposition were the heavier molecular weight fragments of the polymer unit; in contrast, with glass-filled compositions, the principal decomposition product was fluorine. In PTFE structures containing copper (good thermal conductivity), very small concentrations of decomposition products were observed.

3. The polyimide polymer compositions had relatively good friction and wear properties at room temperature in a vacuum (10^{-9} mm Hg) and were relatively stable at ambient temperatures to 500° F. Lower friction was encountered with polyimide sliding on metal than with polyimide sliding on itself. A comparison of the friction and wear characteristics of the polyimide with unfilled PTFE indicates the polyimide to be superior in vacuum.

Lewis Research Center
    National Aeronautics and Space Administration
        Cleveland, Ohio, July 26, 1963

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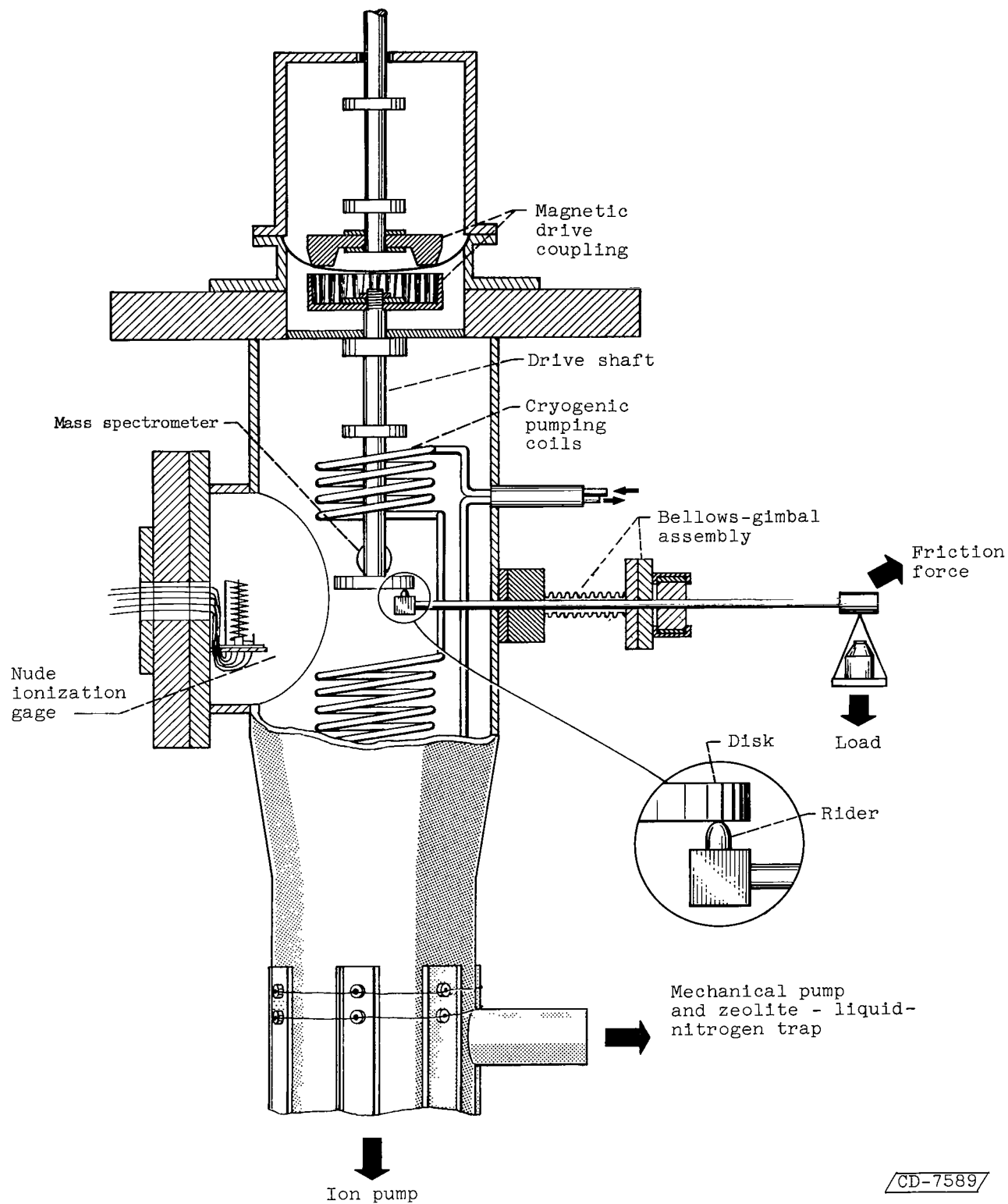
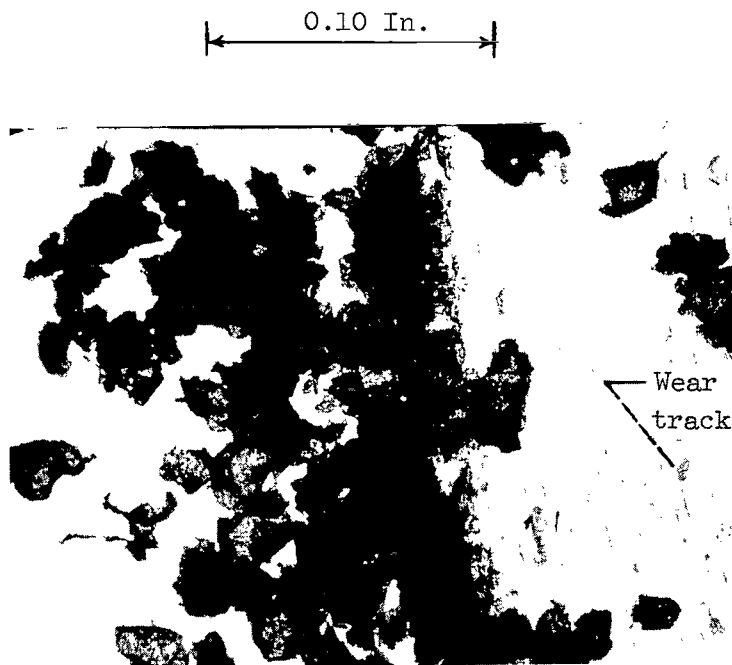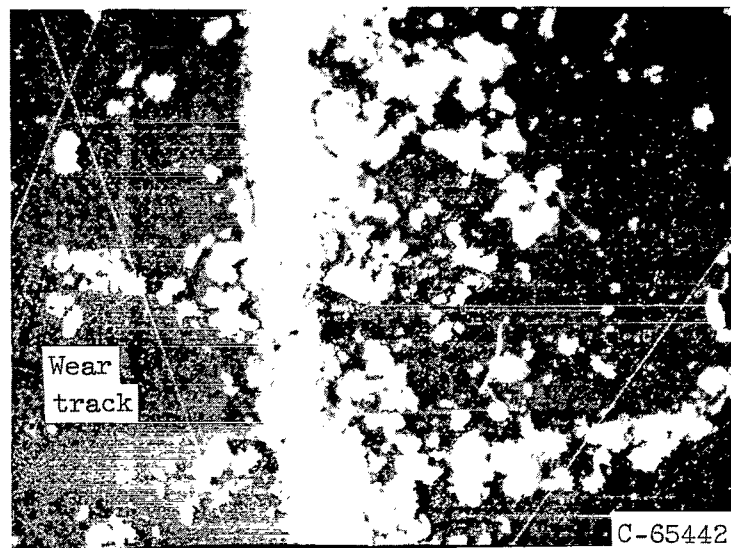Figure 1. - High vacuum friction and wear apparatus.
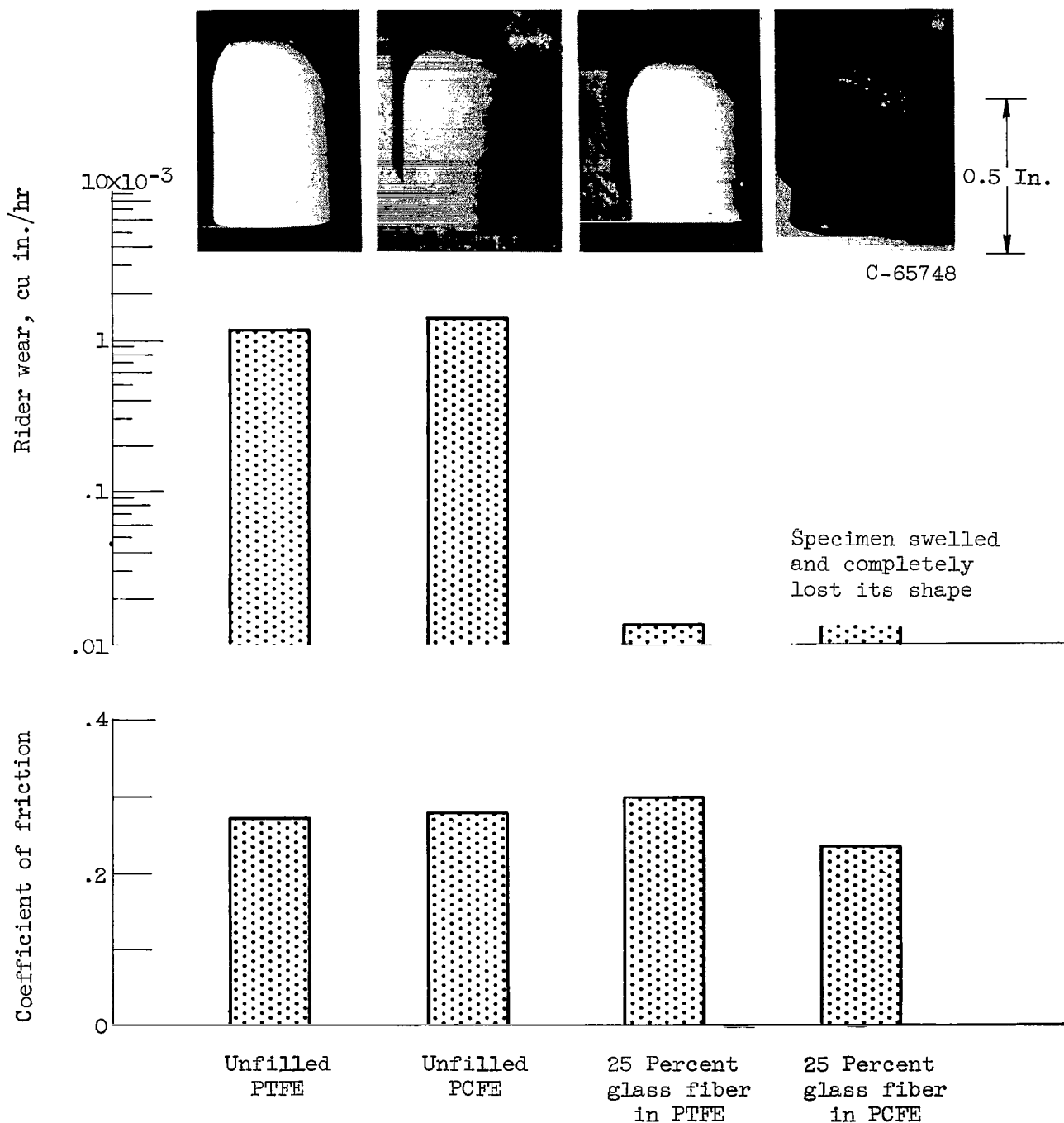
Figure 2. - Coefficient of friction and rider wear of polytetrafluoroethylene and polychlorotrifluoroethylene sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 grams; duration of run, 1 hour; no external specimen heating.

0.10 In.

(a) PTFE.

(b) PCFE.

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Figure 3. - Photomicrographs of polytetra-
fluoroethylene and polychlorotrifluoro-
ethylene wear debris on 440-C stainless
steel. Sliding velocity, 390 feet per
minute; load, 1000 grams; ambient pressure,
10^{-9} millimeter of mercury; no external
specimen heating.

14

0.05 In.

C-65749
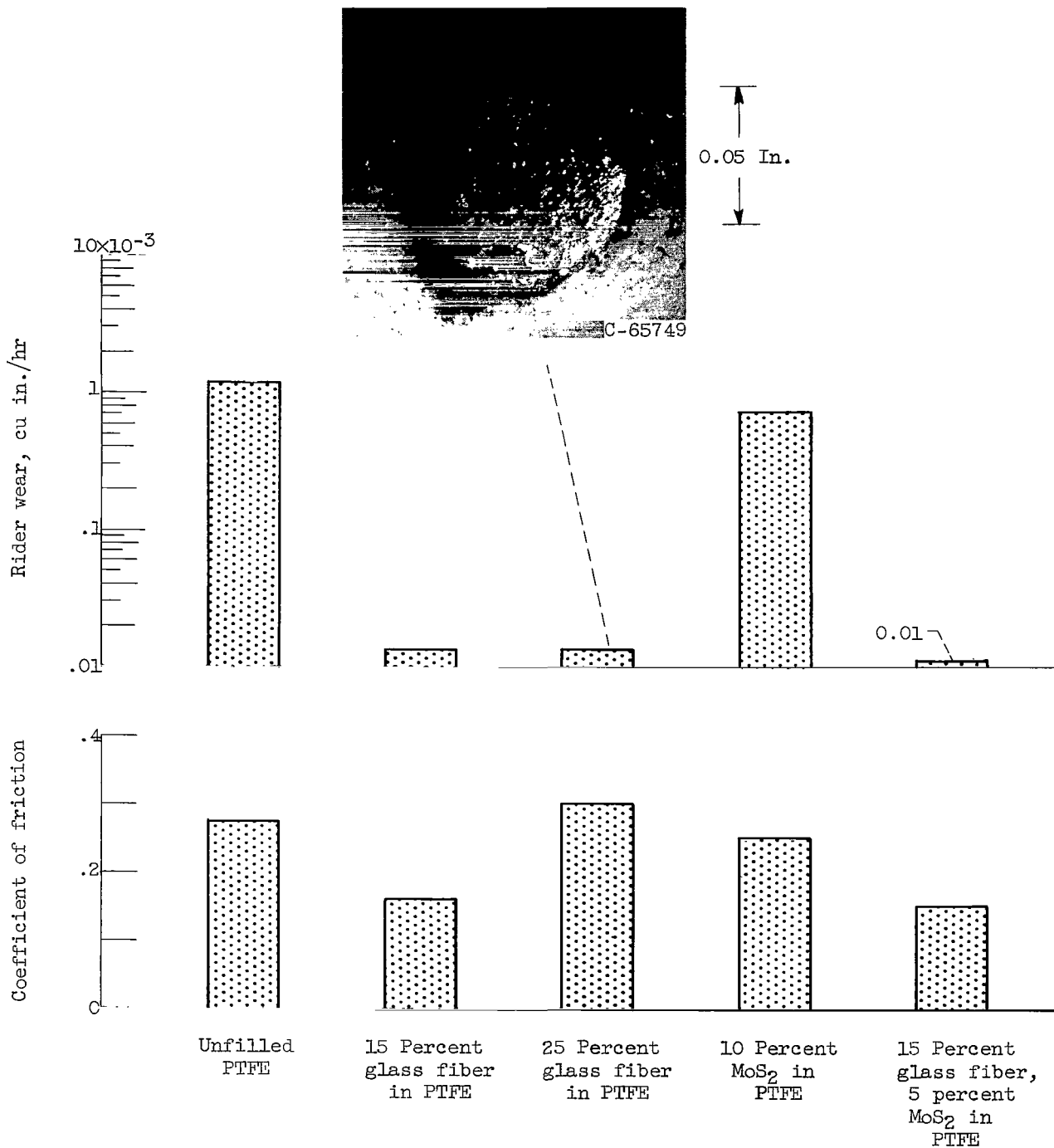
Figure 4. - Coefficient of friction and rider wear for various polytetrafluoroethylene compositions sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; duration of run, 1 hour; no external specimen heating.

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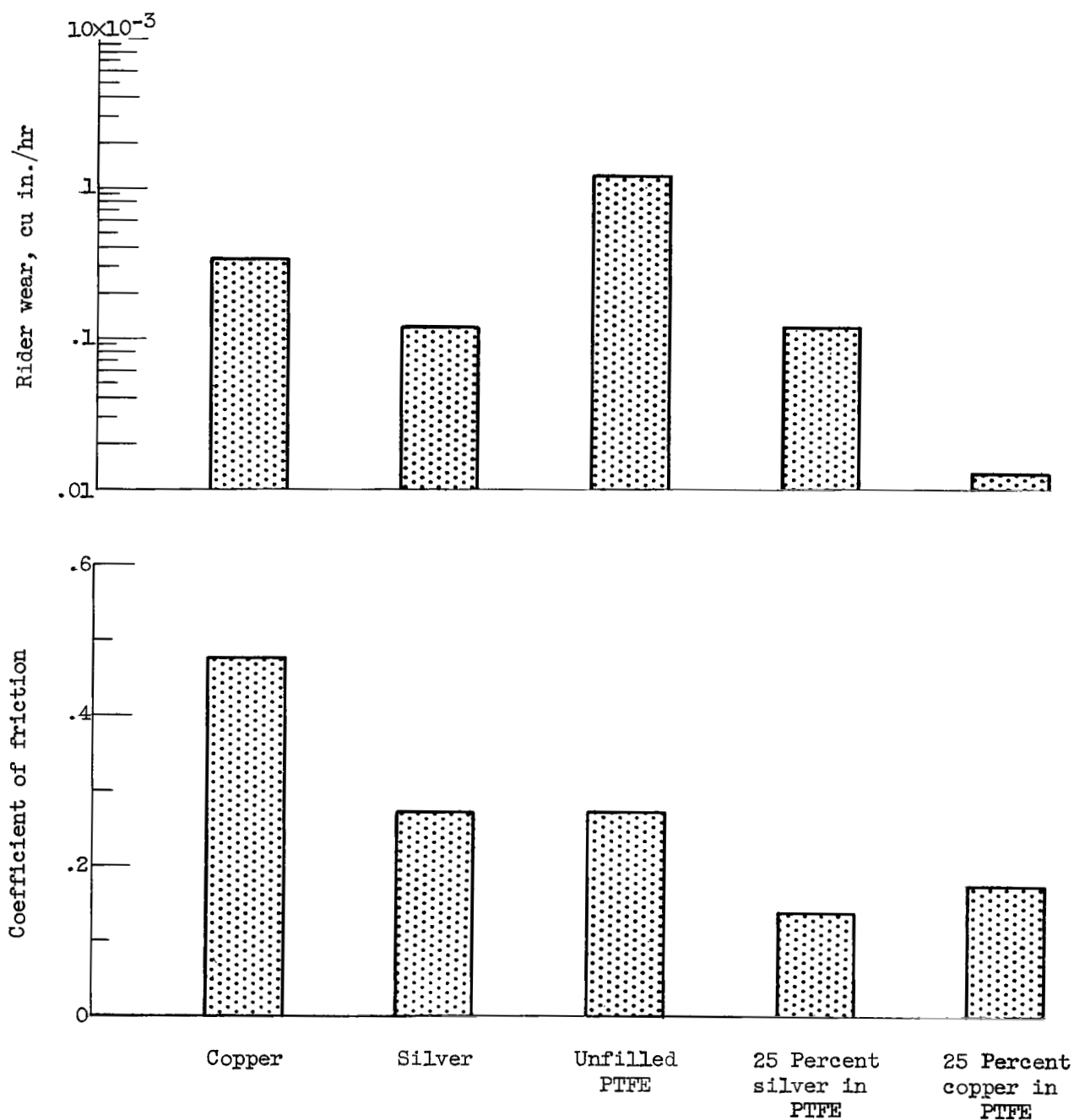
Figure 5. - Coefficient of friction and rider wear for various materials sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg.) Sliding velocity, 390 feet per minute; load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; duration of run, 1 hour; no external specimen heating.

0.01 In.
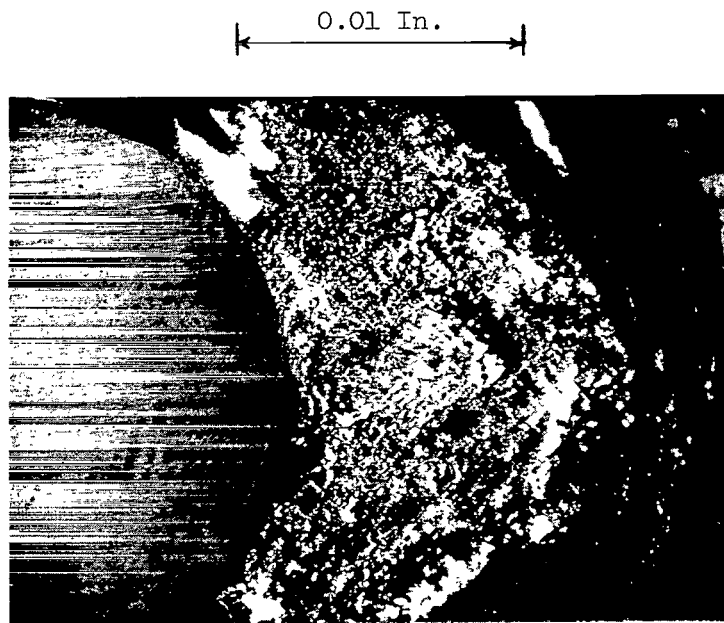
(a) Electrolytic copper.
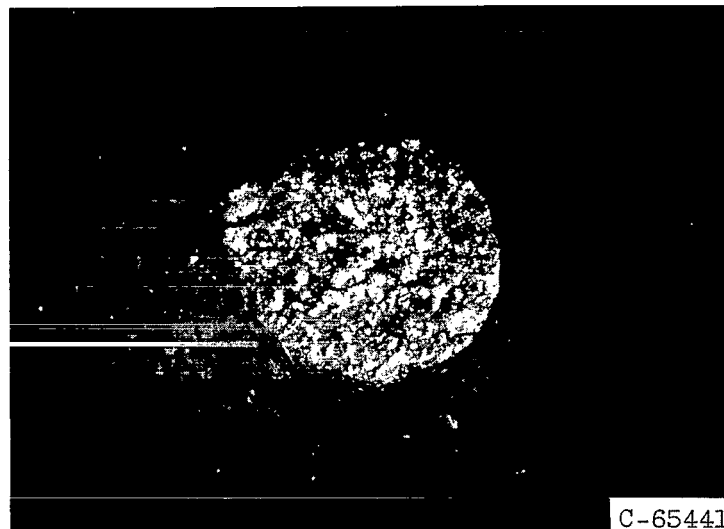
(b) 25 Percent copper in PTFE.

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Figure 6. - Photomicrographs of electrolytic copper and 25 percent copper-filled polytetrafluoroethylene rider wear areas. The disk specimen was 440-C stainless steel. Sliding velocity, 390 feet per minute; load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; no external specimen heating.
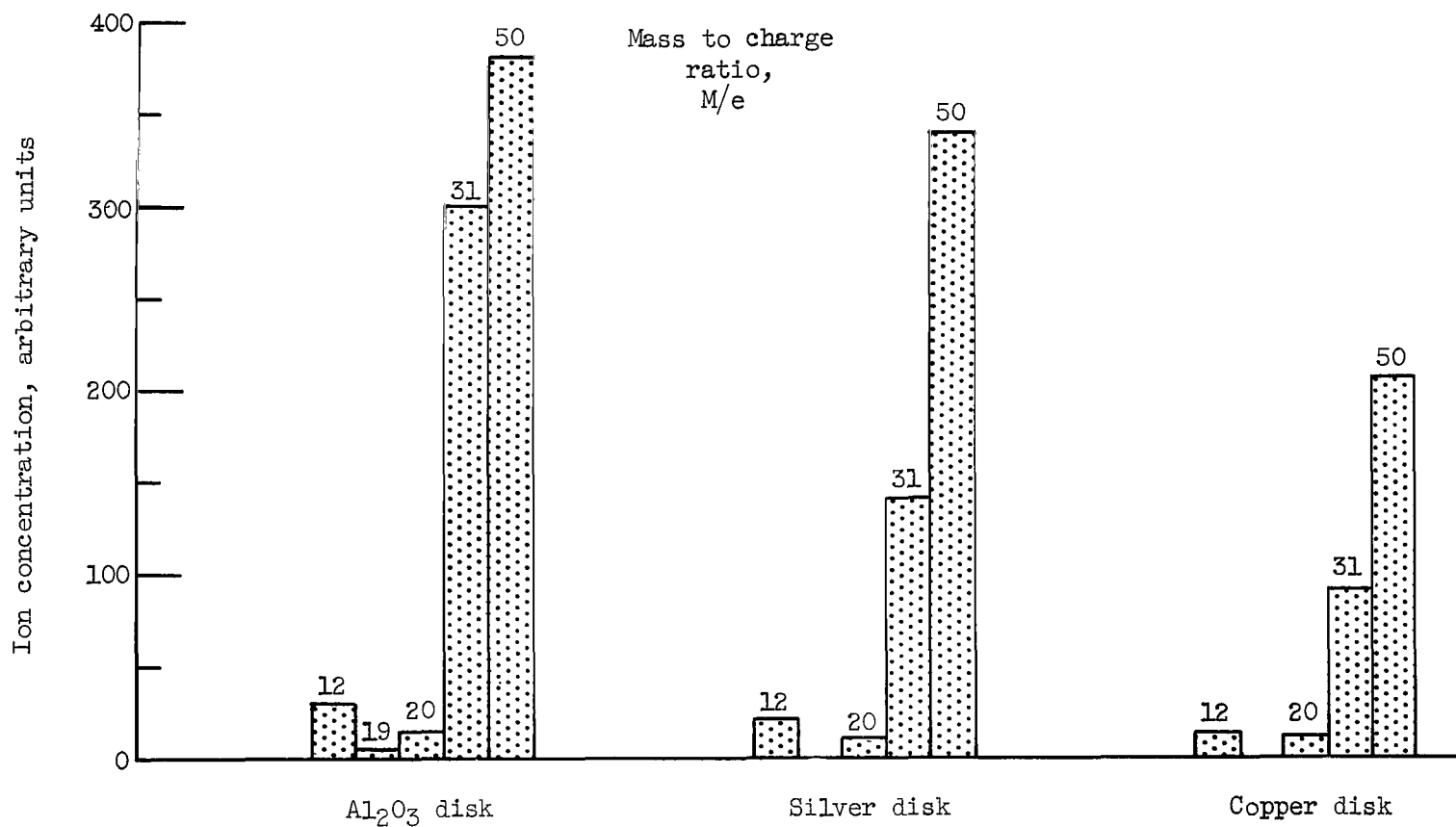
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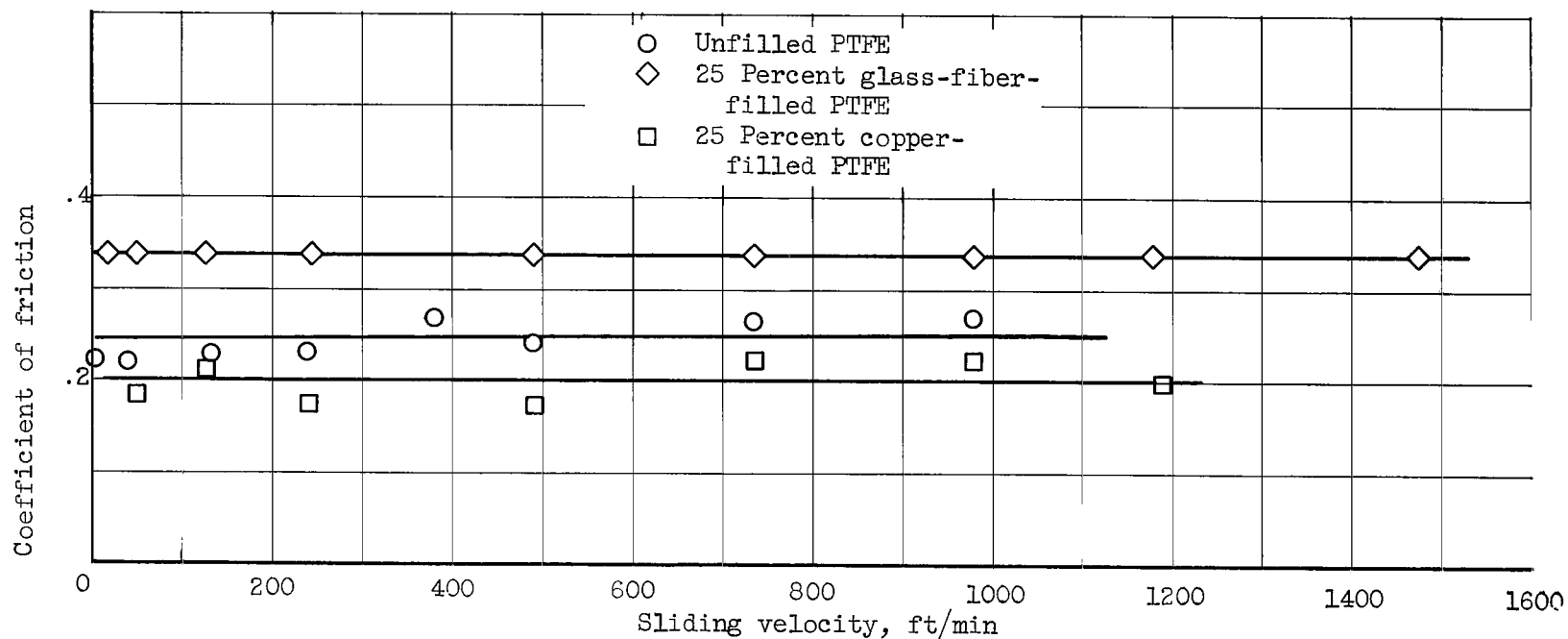
Figure 7. - Coefficient of friction for compositions of polytetrafluoroethylene sliding on 440-C stainless steel in vacuum (10^{-9} mm Hg). Load, 1000 grams; no external specimen heating.
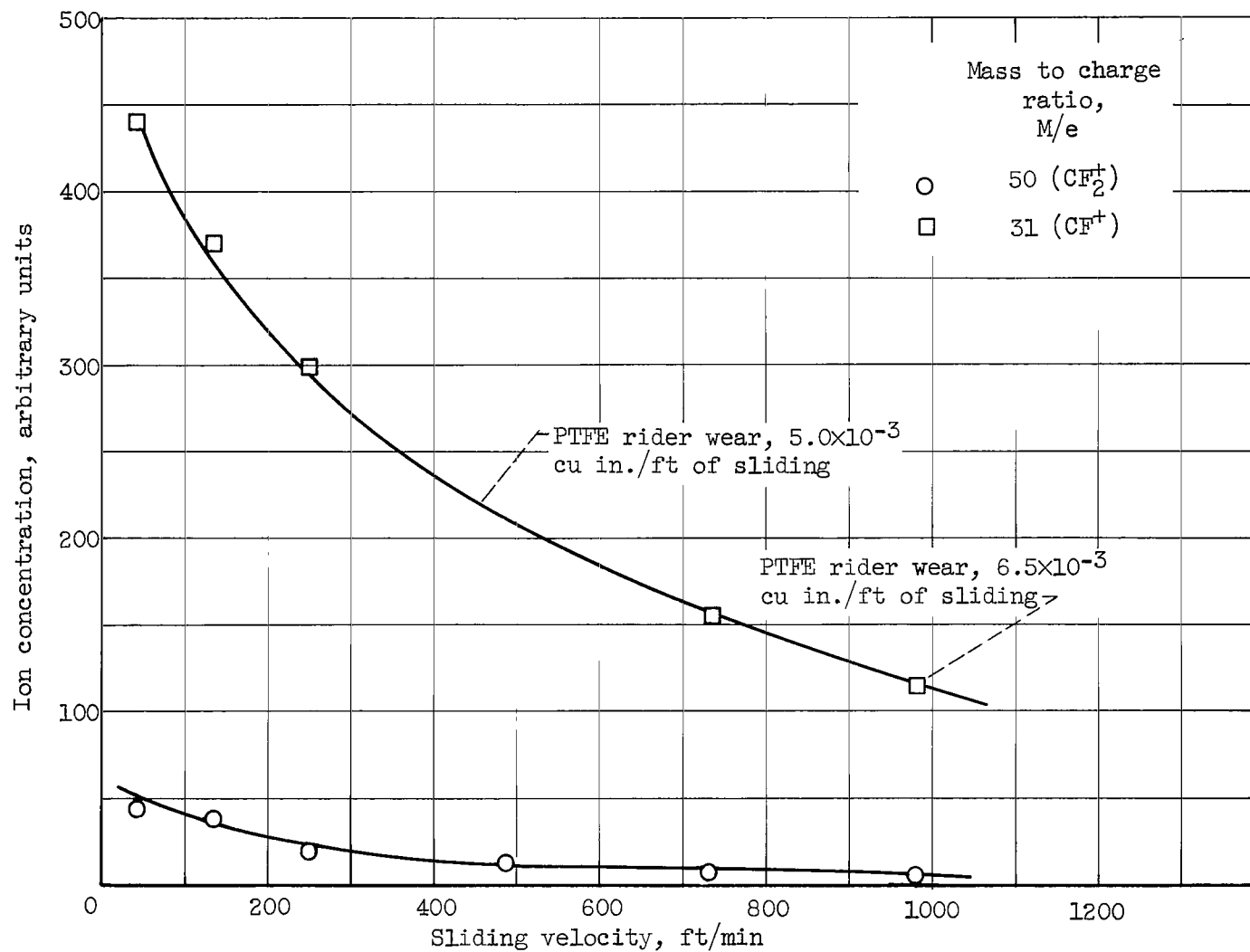
(a) Polytetrafluoroethylene.

Figure 8. - Ion concentration at various sliding velocities for some decomposition products obtained with three polytetrafluoroethylene compositions sliding on 440-C stainless steel. Load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; no external specimen heating.
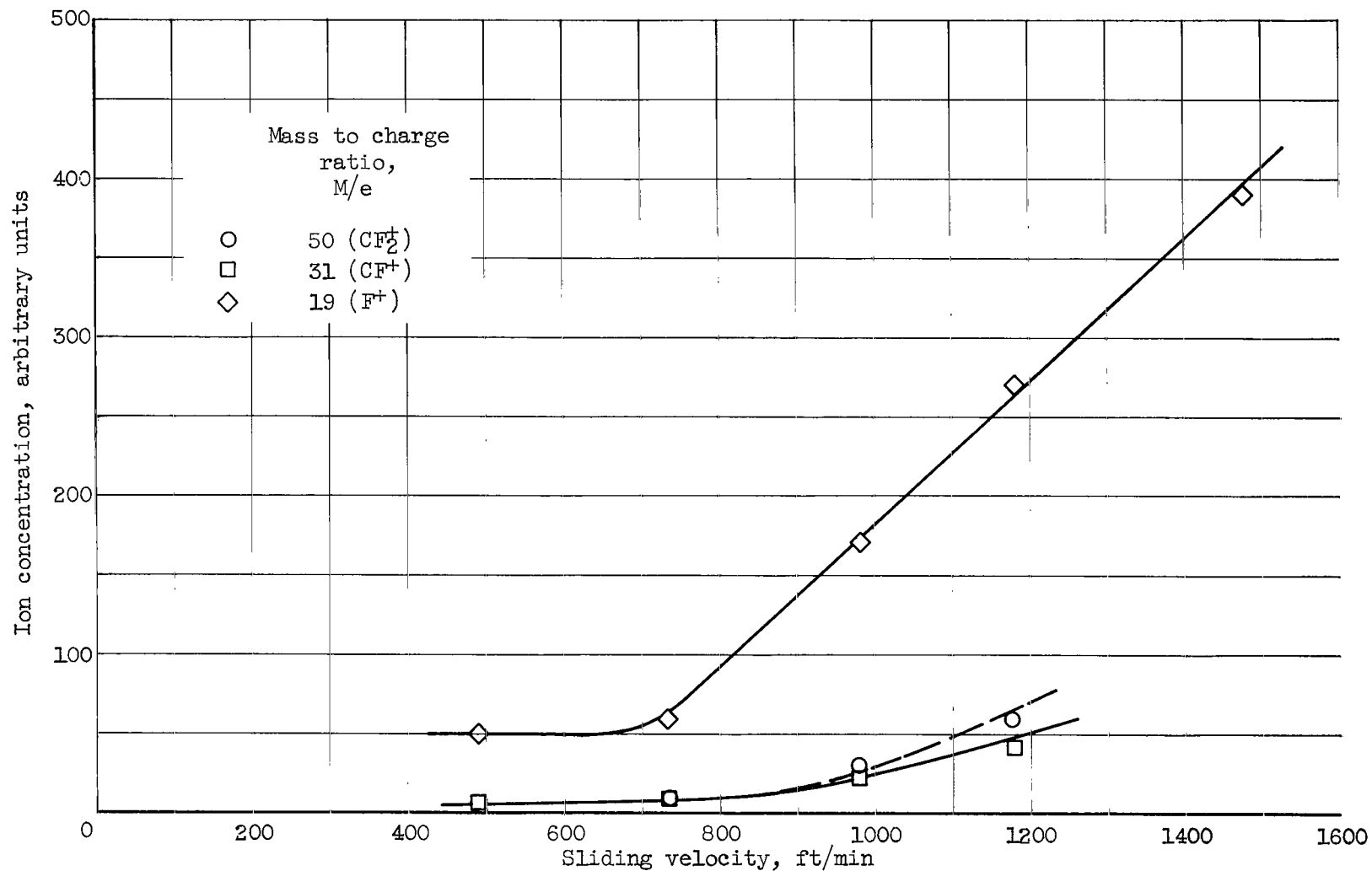
(b) 25 Percent glass-fiber-filled polytetrafluoroethylene.

Figure 8. - Continued. Ion concentration at various sliding velocities for some decomposition products obtained from three polytetrafluoroethylene compositions sliding on 440-C stainless steel. Load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; no external specimen heating.
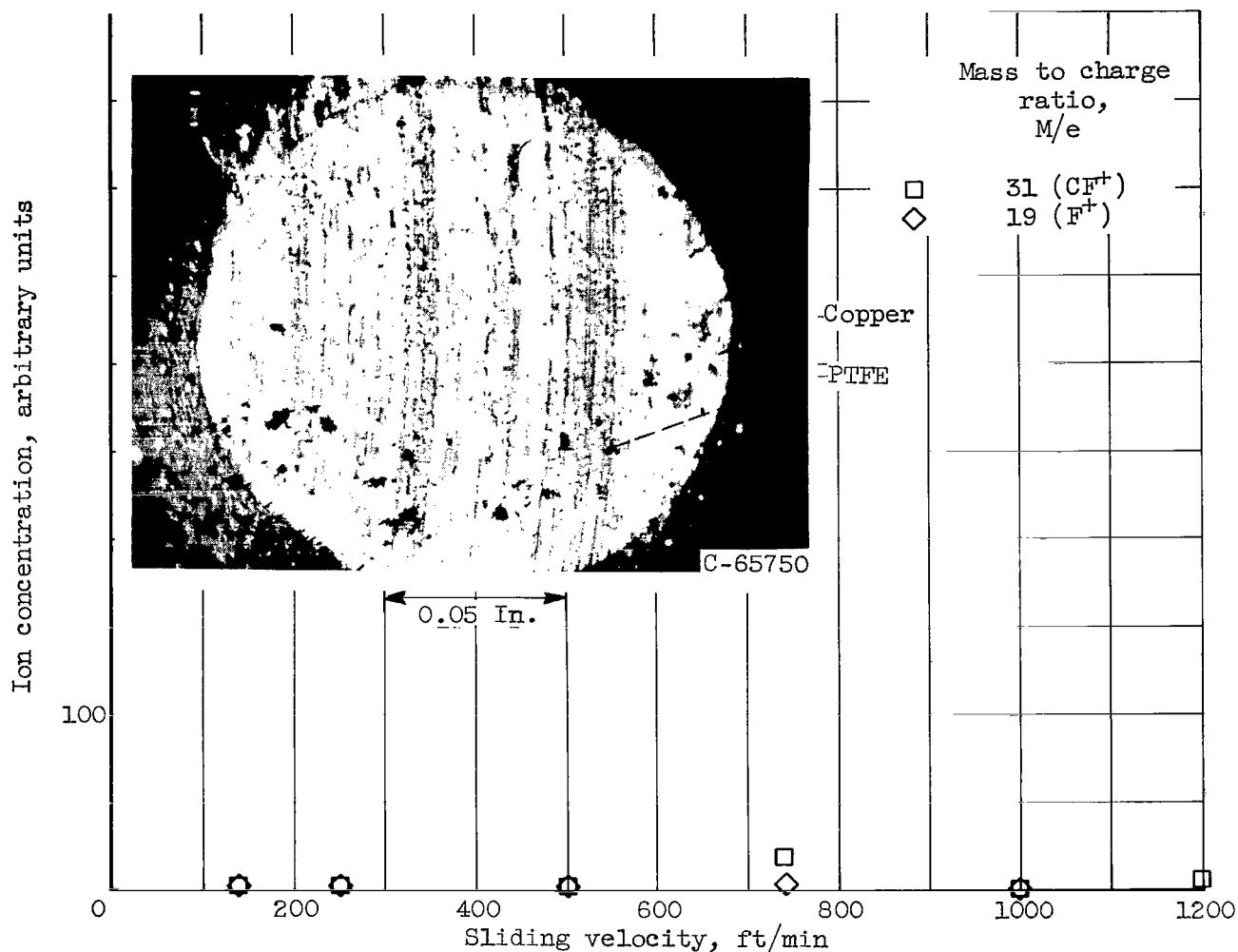
(c) 25 Percent copper-filled polytetrafluoroethylene.

Figure 8. - Concluded. Ion concentration at various sliding velocities
for some decomposition products obtained from three polytetrafluoro-
ethylene compositions sliding on 440-C stainless steel. Load, 1000
grams; ambient pressure, 10^{-9} millimeter of mercury; no external speci-
men heating.
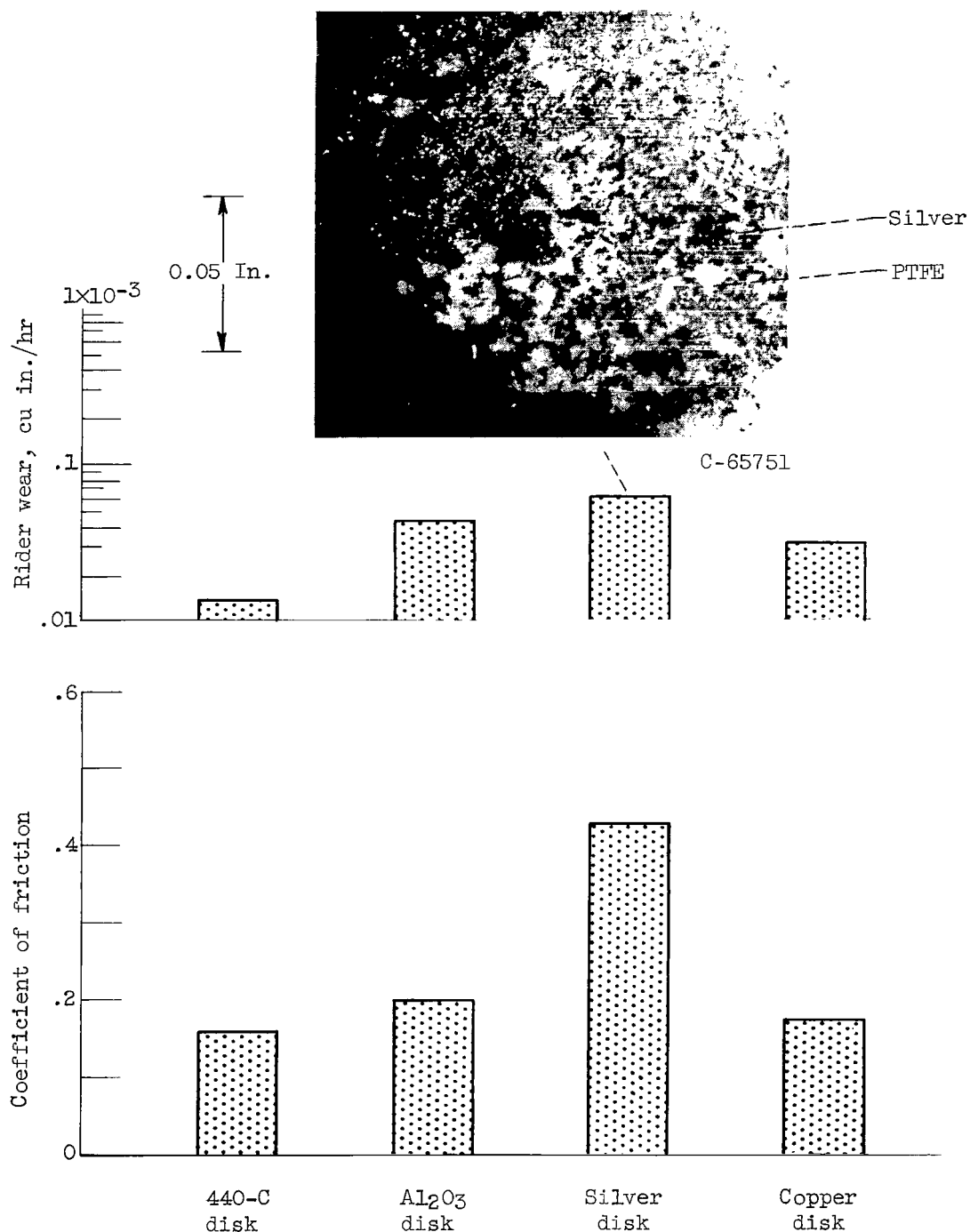
Figure 9. - Coefficient of friction and rider wear for 15 percent glass fiber in polytetrafluoroethylene sliding on various disk materials in vacuum (10^{-9} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; duration of run, 1 hour; no external specimen heating.

Figure 10. - Ion concentration for decomposition products of 15 percent glass fiber in polytetrafluoroethylene sliding on various disk materials in vacuum (10^{-9} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 grams; duration of run, 1 hour; no external specimen heating.
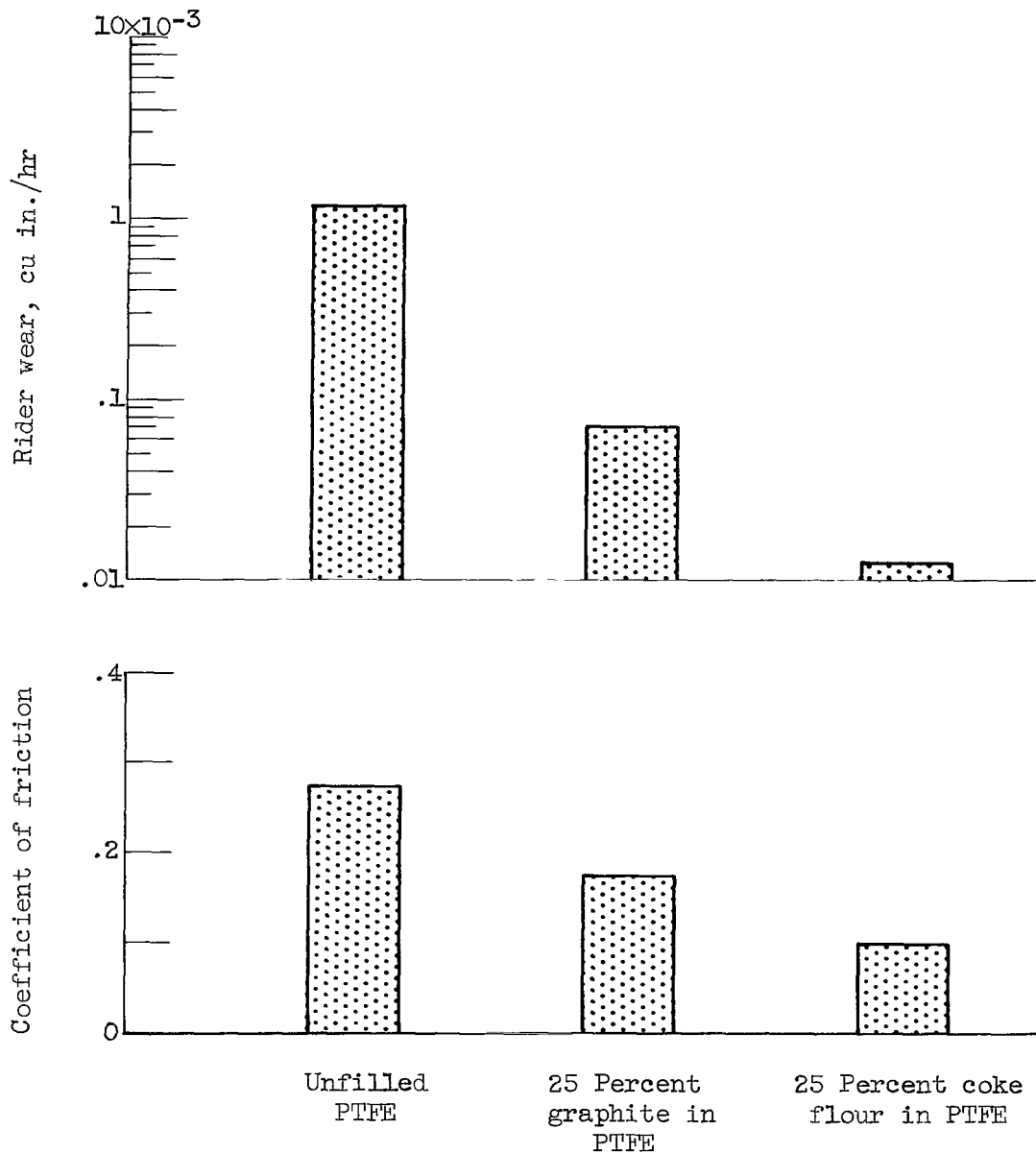
Figure 11. - Coefficient of friction and rider wear for poly-
tetrafluoroethylene compositions sliding on 440-C stainless
steel in vacuum (10^{-9} mm Hg). Sliding velocity, 390 feet
per minute; load, 1000 grams; ambient pressure, 10^{-9} milli-
meter of mercury; duration of run, 1 hour; no external
specimen heating.
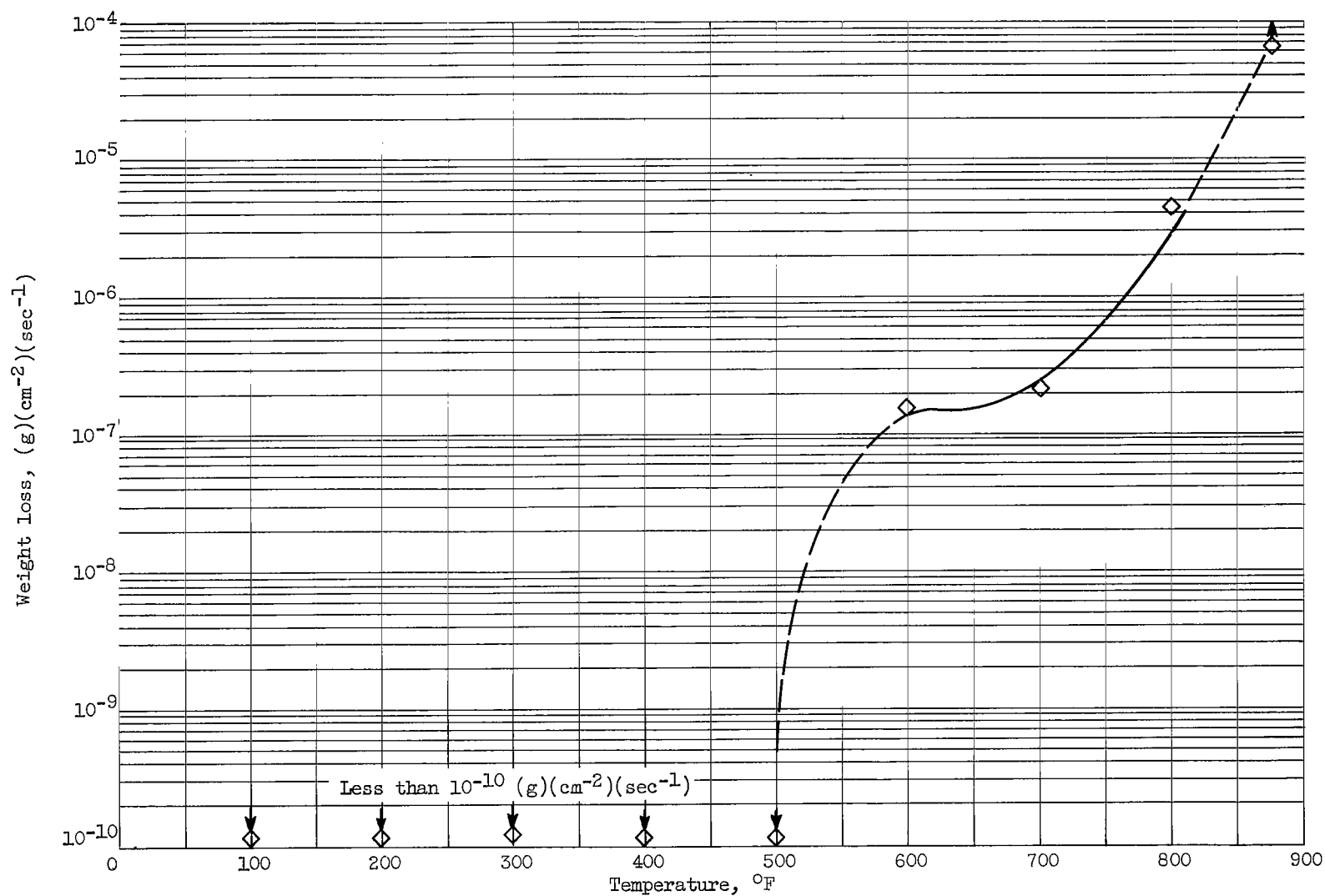
Figure 12. - Weight loss of polyimide in vacuum as a function of specimen temperature. Ambient pressure, 10^{-7} to 10^{-8} millimeter of mercury.
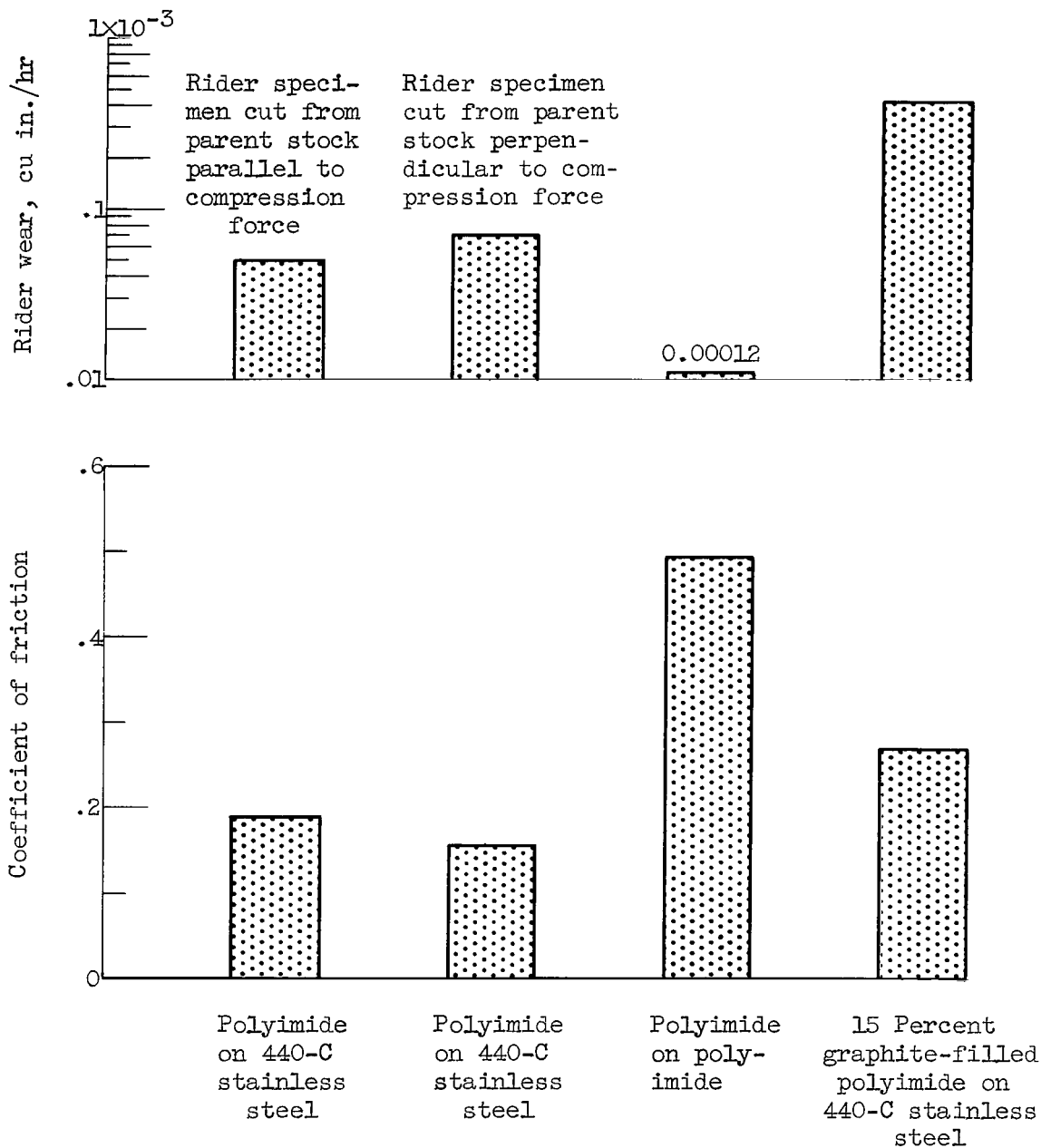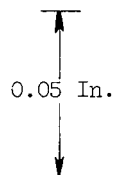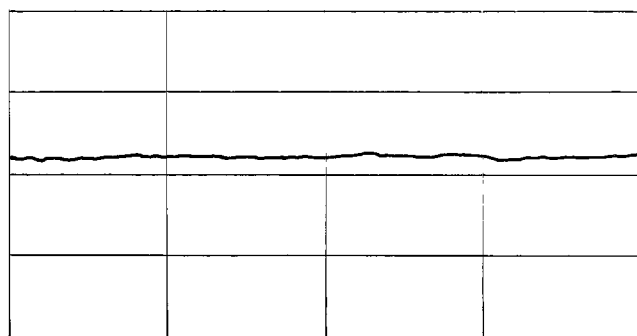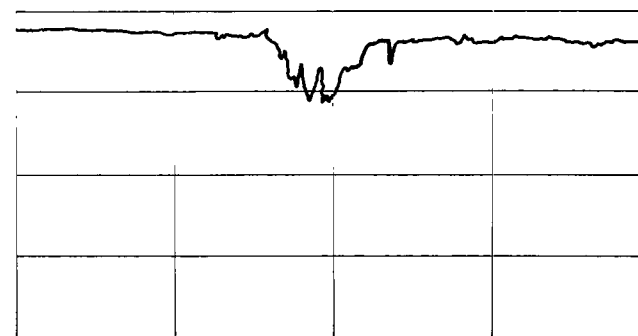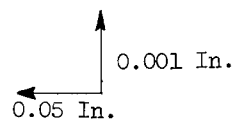
Figure 13. - Coefficient of friction and rider wear for various material combinations in vacuum (10^{-9} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 grams; duration of run, 1 hour; no external specimen heating.

0.05 In.

C-65752

0.001 In.

0.05 In.

(a) Polyimide on 440-C.

(b) Polyimide on polyimide.

Figure 14. - Photomicrographs and surface profile traces for polyimide sliding on 440-C stainless steel and polyimide in vacuum (10^{-9} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; duration of run, 1 hour; no external specimen heating.
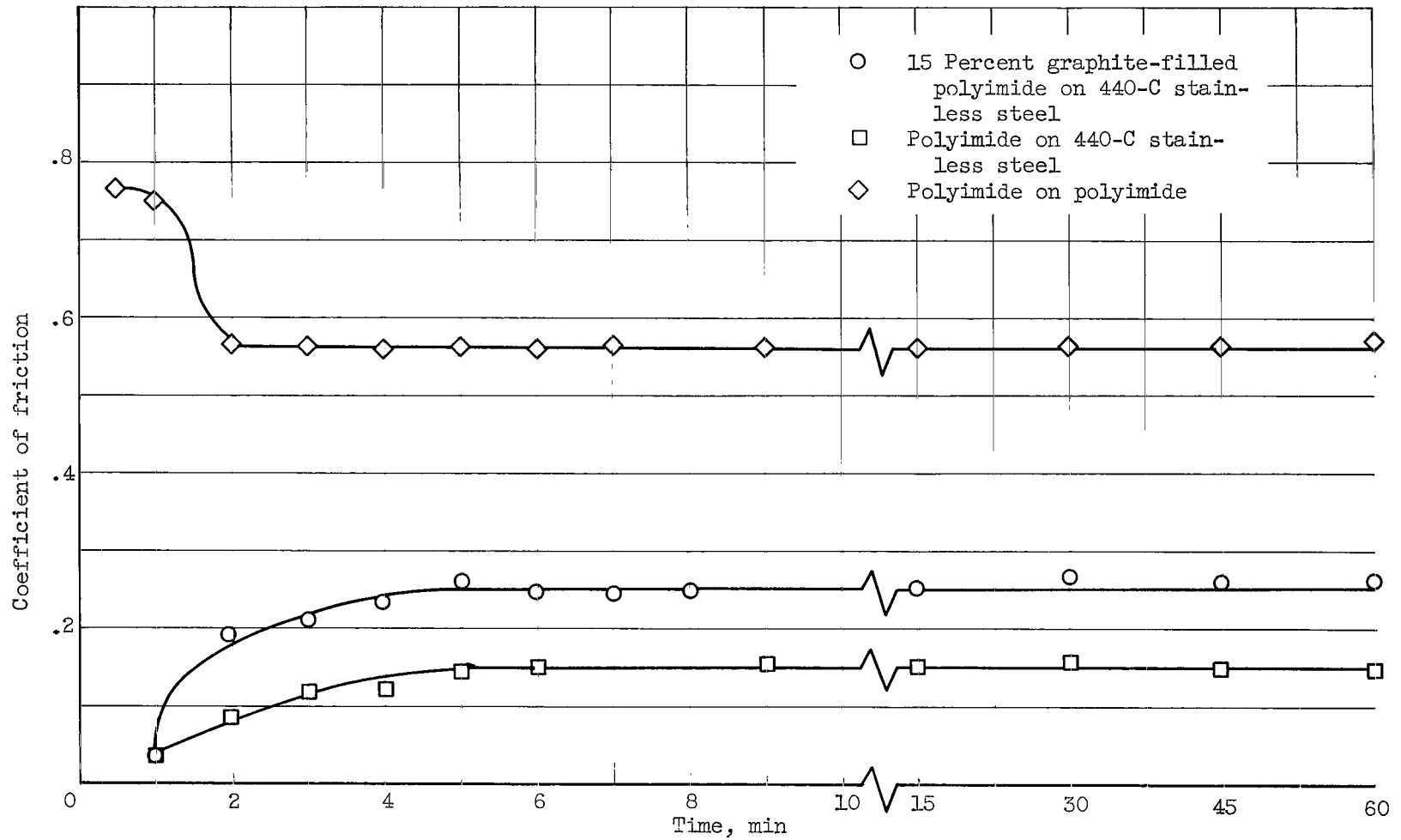
Figure 15. - Coefficient of friction as a function of time for polyimide sliding on polyimide and on 440-C stainless steel in vacuum (10^{-9} mm Hg). Sliding velocity, 390 feet per minute; load, 1000 grams; ambient pressure, 10^{-9} millimeter of mercury; no external specimen heating.

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