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TECHNICAL NOTE 4211

FRICTION STUDIES OF VARIOUS MATERIALS IN LIQUID NITROGEN

By D. W. Wisander, W. F. Hady, and R. L. Johnson

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4735

CF-1

SUMMARY

Friction, wear, and surface-failure properties of various materials were determined in liquid nitrogen. Data were obtained at a sliding velocity of 2300 feet per minute and a load of 1000 grams with a hemisphere (3/16-in. radius) sliding on the flat surface of a rotating disk.

Various metals and nonmetals including carbon, phenolic laminates, and filled Teflon were run against metals. Filled Teflon gave lower friction coefficients (0.15) and wear than any of the other materials studied, and should be useful as a seal and bearing material in some cryogenic applications. A carbon seal material with a phenolic impregnant wore rapidly. A metal-haloid impregnant gave the best wear properties to molded carbon. Phenolic laminates formed thin smear films on mating metal surfaces and gave relatively high friction coefficients (>0.5). A cermet that has been used successfully as a high-temperature seal ring failed because of subsurface brittle fracture during sliding. Decreasing the load to 800 grams reduced the tendency toward brittle fracture.

INTRODUCTION

Friction, wear, and surface-failure properties of materials sliding together in cryogenic liquid are vitally important to the development of efficient pumps for advanced powerplant systems. Bearings and shaft seals in particular have critical sliding surfaces and are used in all types of pumps. Positive-displacement pumps have additional parts such as vanes, pistons, or gears with surfaces in sliding contact.

The physical and chemical properties of most cryogenic liquids of interest are such that they might be expected to have very poor lubricating properties. The data of reference 1, however, indicate that conventional bearings and seals may operate without difficulty in liquid nitrogen and hydrogen. In reference 2 failures were reported for some miniature ball bearings operating in gaseous hydrogen at temperatures

approaching those of liquid nitrogen and hydrogen. In the same investigation, bearings of type 440 stainless steel were made to operate without difficulty by using thick Micarta retainers.

Temperature might be expected to play a vital role in the sliding properties of metals. Complete surface failure and high wear of bearing metals are usually characterized by surface welding. Reference 3 advances the theory that there is a "transition temperature" for sliding metallic couples in any given fluid above which welding is observed and below which "sliding by shear" without welding occurs. The transition temperature was found to depend on the liquid, the metallic couples, and the sliding velocity. This concept too might suggest that it would not be difficult to obtain satisfactory materials for sliding contact in cryogenic liquids.

The generally accepted adhesion concept of sliding friction (refs. 4 and 5) considers that cold welding occurs between sliding metals in close contact and that frictional force is the product of the cross-sectional area of the welded junction and the shear strength of the metal in the plane of shear. Static friction experiments reported in reference 6 support the adhesion theory of friction at temperatures ranging from that of liquid helium (4.2° K) up to 600° K. With most materials, friction did not change significantly with the various temperatures.

Surface films of oxides have a primary influence on the friction, wear, and surface-failure properties of metals in sliding contact (ref. 7). The literature contains numerous instances where formation of oxide films during sliding prevented surface welding of mutually soluble metal couples. Many cryogenic liquids, including nitrogen and hydrogen, prevent the reformation or repair of surface oxides, once these oxide films are broken or disrupted. The probability of metallic welding could therefore be greater when the original oxide layer is worn away during sliding. The selection of slider materials in cryogenic engineering, therefore, might be more critical than for applications in room atmosphere. Nonsoluble metal couples and couples including a nonmetallic material might be of particular interest for cryogenic sliding surfaces.

The present investigation was an exploratory study to determine the friction, wear, and surface-failure properties of various types of slider materials operating in liquid nitrogen. The data were obtained with a sliding-friction apparatus consisting of a hemisphere-tipped (3/16-in. radius) rider specimen sliding in a circumferential path on the flat surface of a rotating disk ($2\frac{1}{2}$-in. diameter) submerged in liquid nitrogen. A surface speed of 2300 feet per minute was chosen as representative of conditions in some positive-displacement pumps for cryogenic liquids. The test load of 1000 grams gave an initial Hertz surface stress of approximately 150,000 pounds per square inch with steel specimens.

4735

Experimental samples of some of the slider materials used in this investigation were provided by The Formica Company, Plastics Division of The Garlock Packing Company, Pure Carbon Company, Micarta Division of Westinghouse Electric Corporation, and Koppers Company, Inc.

APPARATUS AND PROCEDURE

The apparatus used in this investigation is shown in figure 1. The basic elements consist of a rotating-disk specimen ($2\frac{1}{2}$-in. diameter, 1/2-in. thick) and a hemisphere-tipped (3/16-in. radius) rider specimen. The rider specimen slides in a circumferential path on the lower flat surface of the rotating disk. Unless otherwise specified, the specimens were run submerged in liquid nitrogen.

The disk specimen was driven by a 5-horsepower hydraulic motor assembly through a 6:1 speed increaser capable of shaft speeds as high as 29,000 rpm. Surface speed was usually 2300 feet per minute (5000 rpm) for the data reported herein; some data are reported, however, with surface speeds up to 6400 feet per minute. Two sets of helium-purged shaft seals prevented leakage from the test chamber. The lower seal was a double-bellows face seal with carbon seal rings sliding on both faces of a shoulder that was an integral part of the shaft. The shaft was made of type 304 stainless steel, as were most internal parts of the apparatus. The upper seal was a double controlled-gap seal that had two closely fitted carbon rings sliding on the rotating shaft.

The rider specimen was supported by an arm assembly that allowed both application of load and measurement of friction force outside the test chamber. The vertical shaft of this assembly was pivoted through gimbal bearings mounted in the top housing. The shaft was sealed at the top and bottom of the gimbal mounting by flexible metallic bellows and, in operation, the enclosed volume was pressurized (7 lb/sq in. gage) with helium. Friction force was measured by a strain-gage dynamometer ring assembly connected to the top of the shaft. The deflection necessary for friction measurement was so small (< 0.003 in.) that the restraining spring action of the bellows was negligible. The spring properties of the bellows were important, however, where extreme wear of rider specimens necessitated considerable (> 0.040 in.) displacement of the arm toward the center of the rotating specimen. This deflection of the bellows reduced the true load on the wearing surface. Deflection of the top of the arm in the direction of loading was measured with a fixed micrometer. The runs were terminated if excessive wear caused 20-percent unloading of the specimens. Previous calibration made it possible to determine true load with any amount of deflection. Load was applied by a pulley and dead-weight system.

4735

CF-1 back

The top housing of the apparatus was insulated by foamed-in-place urethane. The lower housing and the transfer line were insulated by vacuum jackets. The static heat leak in the apparatus resulted in vaporization of less than 1/2 liter of liquid nitrogen per hour. In operation, however, the vaporization was primarily a result of friction heat from the test specimens and the shaft seals. In most cases, a 25-liter Dewar of nitrogen was sufficient to precool the apparatus and make a 1-hour run; a 100-liter Dewar was sufficient for a 5-hour run.

The liquid nitrogen was transferred to the apparatus, as shown in figure 2, by pressurizing the storage Dewar with gaseous helium at 2 to 6 pounds per square inch gage. Nitrogen was forced through the vacuum-jacketed 1/4-inch-diameter stainless-steel tubing about 20 feet to the test chamber. Gaseous nitrogen was vented through a 3/4-inch-diameter tube with a pressure relief valve set at $1\frac{1}{2}$ pounds per square inch gage. The vent line was insulated by block urethane foam for 3 feet beyond the test chamber. About 2 liters of liquid in the test chamber was required for proper operation. The liquid level was determined by carbon resistors at different levels in the test chamber. Although the remotely operated valves in the transfer line were either fully open or closed, it was possible to maintain the desired flow rate for the proper liquid level (about 3 in. above the test specimens) by controlling the Dewar pressure. A safety circuit made it impossible to close both valves in the transfer line at the same time.

Stainless-steel O-rings were originally included in the apparatus design. Where possible, thin sections were used in the apparatus to minimize heat leak. This type of design made the apparatus too flexible to allow the high clamping pressures that are necessary with stainless-steel O-rings. Hence, all the static seals were made of either Teflon or Kel-F. No trouble except cold flow has been experienced with Teflon and Kel-F static seals. Two concentric Kel-F O-rings were used as a seal between the lower and upper housings when they were bolted together before each experiment. These rings were reused 45 times or more before replacement was necessary.

The experimental materials used in these studies are listed in table I; they include several metal couples and several series of nonmetallic rider specimens usually in combination with type 304 stainless steel. The reasons for selecting the various rider and disk materials are discussed as the results are presented.

The methods of specimen finishing were necessarily varied because of the great difference in materials. The metal disks were all finish-ground on the test surfaces and had a surface roughness of 4 to 8 rms as measured with a profilometer. The rider specimens were usually finished on a lathe, the tools and procedures depending on the material.

Extremely hard materials were finished by grinding. The radius (3/16 in.) of each rider specimen was checked with a radius gage and a strong light source prior to the experiment.

The metal specimens were cleaned by the following procedure:

4735

(1) Washing in a solution of 50 percent acetone and 50 percent benzene

(2) Repeated scrubbing with moist levigated alumina

(3) Washing in tap water

(4) Washing in distilled water

(5) Washing in 95 percent ethyl alcohol or c.p. acetone

(6) Drying in a stream of warm air and storing in a desiccator

Nonmetallic specimens were cleaned with suitable solvents and stored in a desiccator.

After the experimental specimens were installed, the lower housing was securely bolted in place. The seals were pressurized with helium, and the transfer tube, the test chamber, and the vent were purged for 15 minutes with gaseous helium or nitrogen. The storage Dewar was pressurized at 6 pounds per square inch gage with gaseous helium or nitrogen. It required at least 20 minutes to cool the transfer lines and apparatus and obtain about 2 liters of liquid to submerge the specimens in the test chamber. The gaseous nitrogen was vented outside the building through a pressure relief valve set at $1\frac{1}{2}$ pounds per square inch gage.

With the liquid level stabilized, the drive motor was turned on and a predetermined rotative speed (5000 rpm) obtained. The 1000-gram load was then applied and the experiment begun. Frictional force was measured by a recording potentiometer used as a strain indicator. Dewar pressure was adjusted to maintain the desired liquid level in the test chamber.

Displacement of the vertical arm was checked with a vernier micrometer, and the run was terminated if wear was sufficient to cause partial (more than 20 percent) unloading of the specimens. Specimens that gave acceptable wear were usually run for 1 to 5 hours. The occurrence of welding and surface failure was indicated by high and unstable friction; such runs were terminated after a few minutes of operation.

After completion of the run, the lower housing was removed and the specimens were heated with an electric air heater to prevent condensation

of atmospheric moisture. It was necessary to remove some of the specimens quickly to minimize corrosion.

The wear of the specimens was determined by: (1) measuring the diameter of the wear area and calculating wear volume, and (2) measuring weight loss with an analytical balance. Wear was also checked during the run by the micrometer-displacement method. The specimens were carefully studied and photographed at low magnification after each run. Unless noted, all photographs were made under oblique illumination.

RESULTS

Metals and Metal Compounds

Austenitic stainless steel is perhaps the most thoroughly studied (e.g., ref. 8) and most generally used structural material for cryogenic equipment. It is also widely known as an extremely poor alloy as far as sliding friction, wear, and surface-failure properties are concerned. The catastrophic type of surface failure that occurs with austenitic stainless steel in sliding contact with metals is explained (ref. 5, p. 81) by the fact that the completely homogeneous austenite does not provide any contaminating phase to inhibit surface welding and adhesion. If, however, the "transition-temperature" criterion of reference 3 were applicable (and thus result in no welding), the problem of selecting slider materials for cryogenic applications might be more easily solved.

Results obtained from sliding austenitic stainless steel (type 304) on itself in liquid nitrogen are given in figure 3. The appearance of the specimens indicated that surface welding was characteristic of this slider couple. High friction ($\mu = 0.78$), rapid wear (6.2×10^{-3} cu in./hr), and catastrophic metal transfer occurred. It was apparent that the "transition-temperature" criterion did not apply in this case. Other runs at room temperature in dry air and in dry gaseous nitrogen produced similar friction results, but surface failure was more severe than in liquid nitrogen.

Many commercial ball bearings have cages of pressed mild steel and balls and races of SAE 52100 or similar chrome steel. The results of reference 1 under nonsevere operating conditions indicate that bearings of this type will run in cryogenic fluids without difficulty for short periods. In general service, most ball-bearing failures result from wear or galling of cage surfaces that operate in pure sliding.

The results of sliding mild steel (SAE 1020) against chrome steel (SAE 52100) are given in figure 4(a). Friction coefficient (0.59) and wear (1.18×10^{-3} cu in./hr) were significantly lower than those obtained

with the austenitic stainless-steel couple. The disk surface showed evidence of metal transfer from the rider specimen. The feathered metal on the trailing edge of the rider wear area indicated that plastic flow occurred at the contacting interface. Although the initial Hertz surface stress was very high (≈150,000 lb/sq in.), the final unit pressure based on projected wear area was low (<120 lb/sq in.). It is interesting that plastic flow continued to occur under low nominal load and at extremely low temperatures. At room temperatures, similar sliding experiments in air did not produce plastic flow so severe as that shown in figure 4.

Two specimens of hardened chrome steel (SAE 52100) were run together for a very short time in liquid nitrogen to obtain the data of figure 4(b). The friction coefficient was 0.52, which is about the same as that obtained at room temperature. It might be expected that, in a run of such short duration (0.2 min), the normal oxide film initially present on the metal specimens would be capable of preventing surface welding. The disk surface, however, showed metal transfer; also the slight feather on the trailing edge of the rider specimen was indicative of plastic flow at the interface.

Surface welding and metal transfer with these metal couples indicate that the low temperature and any boundary lubricating influence of the liquid nitrogen were not sufficient to make the use of these combinations practicable under the conditions reported herein. As previously mentioned, with a surface oxide film worn away, the mutual solubility of metal couples should be of increased importance in the occurrence of surface welding. Silver has little or no solubility in the primary alloy constituents of type 304 stainless steel (refs. 9 and 10). Therefore, runs were made with cast electrolytic silver riders sliding on type 304 stainless steel; the results are shown in figure 5(a). Severe plastic flow of the silver was indicated by the extensive feather edge. This detritus was separated from the rider specimen as a result of handling after the run. The initial friction coefficient was 0.80 and the wear was 0.63×10^{-3} cubic inch per hour.

Surface welding in the usual sense did not occur, but a thin plastically smeared film of metallic silver was formed on the steel disk. There is no doubt, however, that the true sliding surfaces during much of the run were solid silver against a transferred silver film. Chemical spot tests were used to verify that the film was silver and to etch it away from the base metal. The underlying metal suffered little or no welding deformation. The metal transfer experienced in this case might be partly explained by the theory (ref. 11) that metal transfer can be due to mechanical interlocking of metal surface asperities or roughness.

As discussed in detail in reference 12 (p. 548), tangential forces between bodies in contact produce plastic yielding and contribute to the growth of the contact area. Reducing the effective shear strength (based on the friction process) at the interface can thus inhibit plastic

flow, contact area growth, and possibly the formation of a transferred smear film. A hot-pressed silver, copper, and MoS_2 composition, reported in reference 13 as a self-lubricating bearing material, should have less plastic deformation than solid silver because the MoS_2 should reduce the effective shear strength at the interface.

Data for a composition containing 85 percent silver, 5 percent copper, and 10 percent MoS_2 given in figure 5(b) can be compared with the data of figure 5(a) for solid silver. There was a marked reduction in the amount of silver smeared on the mating surface, and no evidence of welding deformation of the base metal could be detected. The friction coefficient (0.34) was more constant and significantly lower than with solid silver. Wear (0.66×10^{-3} cu in./hr) was essentially the same as for the solid silver. It appears that the improved lubrication by the MoS_2-containing material was sufficient only to compensate for the poorer physical strength. The cast silver would have greater strength than the hot-pressed body weakened by the inclusion of a solid lubricant.

4735

Observation of the plastic behavior (ductility) of the various metal combinations during sliding in liquid nitrogen indicates that materials normally considered brittle at room temperature might continue to be useful in cryogenic applications. In unreported NACA experiments, a titanium carbide-base cermet was found to have low wear and to resist surface failure when run against tool steel at temperatures from 80° to 700° F. Experiments were performed in liquid nitrogen with the cermet (K162B) sliding against hardened 440-C stainless steel. High hardness (Rockwell C-54) of the mating disk was utilized in order to obtain the minimum real area of contact and sustain the high contact stresses that should provide a continuing severe test of a brittle material. The data shown in figure 6(a) indicate that the test was too severe with the 1000-gram normal load.

Subsurface brittle fracture appeared to have occurred in the cermet rider. Both high friction ($\mu = 0.63$) and high Hertz surface stress (>150,000 lb/sq in.) probably contributed to the surface deterioration. The nominal wear rate, based on volume calculated from the projected diameter of the wear area, indicates that wear was relatively low (0.05×10^{-3} cu in./hr). The surface of the rider showed several furrows where local fracture occurred. The considerable depth of the furrows, however, makes the wear rate of questionable significance. The rider irregularities cut grooves in the wear track on the disk. There was no evidence of surface welding; however, this could have been masked by the surface fracture.

Figure 6(b) shows the result of reducing the initial load to 800 grams for the combination of K162B cermet on 440-C steel. Friction

remained high, wear was low (0.014×10^{-3} cu in./hr), but the severity of surface fracture was reduced. The disk showed some evidence of transferred particles, which may have been embedded fragments from the rider.

Nonmetals

The use of nonmetals in cryogenic bearings and seals would seem practicable because, as a group, they are considered inherently nonwelding to metal surfaces. Molded carbon products should be of particular interest because they are used for sliding contact seals on rotating shafts more often than any other type of material. Molded carbons impregnated with phenol resins are frequently used in all types of seals, including some for cryogenic applications. These and other carbons and their high-temperature wear properties are described in reference 14.

During the preliminary operation of the apparatus, an observation worthy of comment was made with a carbon material. Some experiments were run with an open Dewar instead of the closed test chamber. The open Dewar was raised into place to submerge the test specimens, thus quenching them rapidly from room temperature. Runs made with a phenol-impregnated carbon (Purebon P5J) sliding on type 304 stainless steel gave very low wear (0.009×10^{-3} cu in./hr) as indicated in figure 7(a). There was no surface disturbance on the disk and only slight evidence of solid contact. When the same combination was run in the closed test chamber, entirely different results were observed (fig. 7(b)). Seven duplicate runs gave extremely high and erratic wear values from 34×10^{-3} to 91×10^{-3} cubic inch per hour. Comparing these data with those obtained with the open Dewar (0.009×10^{-3} cu in./hr) shows that the closed system resulted in up to 10,000 times greater wear rate. The apparent explanation for this difference is that with the open Dewar adsorbed moisture films on both the carbon and the metal surfaces and within the carbon body were frozen *in situ* when the specimens were plunged into liquid nitrogen. The standard closed system, however, provided for prepurging of the transfer lines, the test chamber, and vent lines with helium gas. During the precooling period before liquid contacted the specimens, gaseous nitrogen of decreasing temperature flowed through the system. The flow of gas through the system was believed to have removed the moisture films adsorbed by the test specimens during the brief exposure to room atmosphere that was necessary for installation in the apparatus.

The same basic grade of carbon was also run with no impregnant (Purebon P5), with a double phenolic impregnant (Purebon 652), and with an organic-metallic complex impregnant (Purebon P5HT). In addition, data were obtained with another phenolic-impregnated carbon material (Graphitar 39) that is comparable with Purebon P5J. The surfaces of these carbon materials after test were very similar to that shown in figure 7(b); the wear rates were all high (from 10×10^{-3} to 30×10^{-3} cu in./hr); and the

initial friction coefficients were 0.84 for the nonimpregnated carbon, 0.53 to 0.62 for the phenolic-impregnated carbon, and 1.08 for the organic-metallic complex impregnated material.

Service experience with carbon brushes of aircraft-engine generators has shown that rapid wear can occur at high altitudes. Laboratory experience (ref. 15) indicated that this wear phenomenon, called "dusting", occurred in the absence of moisture and oxygen. In some instances dusting was eliminated by the use of a metal-haloid impregnant that was capable of forming a protective surface film. A carbon material having such a metal-haloid impregnant (Purebon P5N) was run against type 304 stainless steel. It gave much lower wear (1.04×10^{-3} cu in./hr) than the phenolic-impregnated carbon, but the friction ($\mu = 0.59$) was about the same. The metal-haloid impregnated material was the best carbon run in liquid nitrogen, but was not so good as other nonmetals to be discussed later.

4735

Fabric-laminated phenolic resins (for example, Micarta and Formica) have found numerous applications as sliding surfaces. Rolling-contact-bearing retainers made of phenolics have given excellent service in high-speed, normal-temperature ($<275^{\circ}$ F) applications and may have promise at cryogenic temperatures (ref. 2).

Several laminated phenolics (see table I(b)) were run against type 304 stainless steel. It was felt that varied fineness of the fabric and additions of solid lubricants to the materials might influence wear and friction properties. The lowest initial friction coefficient obtained with a cotton-fabric-laminated phenolic sliding against type 304 stainless steel in liquid nitrogen was 0.49. The addition of graphite and molybdenum disulfide neither reduced wear nor lowered friction. For example, Formica LN gave a wear rate of 0.11×10^{-3} cubic inch per hour, and the addition of graphite or MoS_2 resulted in wear rates from 0.28×10^{-3} to 0.42×10^{-3} cubic inch per hour. The additives also had an adverse effect on friction, resulting in initial friction coefficients from 0.81 to 1.40.

A fiber glass-filled melamine resin (Formica FF-55) was reported by the manufacturer to have good strength properties at cryogenic temperatures and was therefore considered as a slider material. The results indicated extremely high wear (10.6×10^{-3} cu in./hr), high friction ($\mu = 1.04$), and abrasion of the metal surface by the glass particles.

The surfaces of all the phenolic materials were good after sliding contact. (See fig. 8, for example.) The mating metal surface usually had a slightly burnished transfer film. As mentioned, high friction was noted for the phenolic materials. The burnished appearance and high

friction suggest that heat dissipation from the interface may be a problem in spite of the low temperature of liquid nitrogen.

Teflon (polytetrafluoroethylene) and Kel-F (polytrifluorochloroethylene) have found considerable application in cryogenic static seals. These materials also have excellent friction properties under low-speed sliding conditions (ref. 16). The limiting factors in the use of Teflon for high-speed sliding applications appear to be its poor ability to conduct heat from the sliding interface and its tendency to cold-flow under load. Kel-F has somewhat less tendency to cold-flow than Teflon. Fillers, such as graphite or metals, can be added to Teflon to decrease cold-flow tendencies and should also increase thermal conductivity. Reference 17 reports the friction and wear properties of a variety of filled Teflon compositions. Some of the most effective uses of Teflon in lubrication have developed from its applications in thin films on metals, such as those described in reference 18.

4735

Figures 9(a) and (b) show surfaces that were typical of Teflon and filled Teflon compositions sliding on type 304 stainless steel in liquid nitrogen. The rider specimens were always very smooth, usually highly reflective to light, and showed no evidence of any adverse sliding conditions. The highly reflective character of the wear surfaces made it possible to detect elastic recovery that was at a maximum in the center of the contact area. A quantitative evaluation of this elastic behavior is beyond the scope of this investigation. The disk specimens had very smooth highly polished surfaces in most cases. However, thin uniform transfer films of the Teflon compositions were visible on the disks after operation. Etching of the disk surfaces that had been run with unfilled Teflon showed that the transfer film on the disk was highly protective to the base metal.

CF-2 back

Figure 10 summarizes wear and friction data for most of the materials studied. As figure 10 shows, the wear and friction for these Teflon compositions was, in general, lower than for any other type of material considered. The behavior was somewhat erratic in different experiments with one of the best compositions, as indicated by the hatched area in the bar graphs. Wear of the graphite-filled material in one run (0.011×10^{-3} cu in./hr) was nearly ten times greater than in another essentially identical experiment (0.0013×10^{-3} cu in./hr). Friction force also had periodic fluctuations during the individual runs. Close examination of the specimens showed a lack of homogeneity, which is the probable explanation of these varying results. In many cases it was easy to identify very large aggregates (approximately 1/16-in. diameter) of Teflon particles.

Glass-filled Teflon had relatively good characteristics but did not give as low wear or friction as a graphite-filled Teflon (fig. 10). The glass-filled Teflon did not abrade the mating metal surface in contrast to the results with the glass-filled melamine resin.

Miscellaneous Observations

The lubricating ability of liquid nitrogen was not evaluated, per se. Significant differences were observed, however, when several materials were run in dry air at room temperature, in dry gaseous nitrogen at room temperature, or in dry gaseous nitrogen at temperatures approaching that of the liquid. In particular, wear was significantly higher for the nonmetals running in the gases. The relative effect of the gases and the liquid on friction was not so well defined as the effect on wear in these limited experiments. 4735

Isolated experiments with both SAE 52100 and type 440-C steel disks were run with a few of the rider materials. With the various types of nonmetals studied, the rider specimens in liquid nitrogen always showed less wear sliding against SAE 52100 and type 440-C than against type 304 steel.

The effect of sliding velocity on wear was determined for the Teflon composition containing 10 percent graphite. Figure 11 shows the wear per unit distance of sliding. Below 3000 feet per minute, the curve indicates that wear increased linearly with the sliding velocity, as would be expected with adhesive wear. The curve shows that, at sliding velocities above 3000 feet per minute, wear increases exponentially with sliding velocity.

EVALUATION OF RESULTS

Liquid nitrogen does not have the ability to form the strongly adsorbed interface film that is basic to effective boundary lubrication, but it does provide an excellent heat sink for frictional energy. This characteristic probably accounts for the good performance of filled Teflon compositions in these experiments. Some results indicate that the wear of one of these compositions increased at a greater-than-linear rate as sliding velocities increased. A similar increase in wear with greater loads might be expected. At higher rates of heat rejection from the specimen, heat transfer from the interface may not be adequate to prevent thermal degradation of the Teflon.

The Teflon compositions reported were samples of commercial products and did not give consistent results. There was a marked lack of homogeneity in these materials, which was also true for similar commercial materials from other sources. Homogeneous materials can be obtained by more careful processing and should give consistent results. The worst results for the filled Teflon compositions were better than the most favorable data obtained with the other types of materials studied.

Metal couples sliding together in liquid nitrogen gave friction coefficients that were similar in most cases to those obtained at

atmospheric temperatures. Adhesion of metals by welding occurred in spite of the low ambient temperature. Frictional heating at the interface undoubtedly caused surface asperities to experience high flash temperatures. Reference 5 (p. 57) indicates that, during sliding at light loads and low speeds and in the presence of a liquid, surface temperatures of metals may be several hundred degrees Centigrade above the ambient temperature. This suggests that the thermal aspects of surface welding (ref. 19) may be important during sliding contact, even at the temperature of liquid nitrogen.

4735

Solid solubility, alloying characteristics, and similar criteria are not sufficient guides for selecting metal couples to slide in liquid nitrogen. Transfer of rider materials to the metal disks occurred both with nonsoluble metals and with nonmetals. In such cases smear films were formed on the disks but there was no detectable distortion of the base metal.

Smearing and the plastic growth of sliding junctions may have progressed as a result of thermal softening. The metal sliding surfaces exhibited surprising ductility. The literature suggests, however, that this ductility need not be associated with thermal softening in any way. For example, it was demonstrated (ref. 20, p. 26) that some austenitic stainless steels had better ductility at subzero temperatures than at room temperature. Reference 20 suggests that the cohesive strength of the metal increases rapidly at subzero temperatures, with the result that the metal resists fracture until the plastic deformation is considerably greater than would be possible at room temperature. This observation should not be confused with the property of impact strength at low temperature.

CONCLUDING REMARKS

An exploratory study was made of the friction, wear, and surface-failure properties of various metallic and nonmetallic materials sliding together in liquid nitrogen. Data were obtained at a sliding velocity of 2300 feet per minute with an initial load of 1000 grams on a hemisphere-tipped (3/16-in. radius) rider specimen sliding on the flat surface of a rotating disk (usually type 304 stainless steel).

Filled Teflon compositions, such as one containing 10 percent graphite, gave low friction (μ = 0.12 to 0.15) and wear. They may be useful as slider and bearing surfaces in cryogenic liquids. Failure of Teflon in slider applications at room temperature has previously been associated with thermal degradation accentuated by poor thermal conductivity. Cooling by the liquid nitrogen probably played a vital role in the good results obtained with Teflon compositions.

Friction and surface-failure properties of metal combinations in liquid nitrogen were basically the same as at room temperature. Metal transfer either by welding or by mechanical adhesion occurred with both soluble (304 on 304) and nonsoluble (silver on 304) metal combinations. Considerable plastic deformation was observed, and interface ductility was greater than at room temperature. Except for a silver composition containing MoS_2 ($\mu = 0.34$), all metal combinations, including SAE 1020 on SAE 52100, gave friction coefficients greater than 0.52. A cermet suffered subsurface brittle fracture; the depth of fracture was considerably reduced by decreasing the load to 800 grams.

4735

Molded-carbon materials that are commonly used in sliding seals wore very rapidly in liquid nitrogen. Wear of the carbons was decreased significantly by a metal-haloid impregnant of the type used to inhibit "dusting" of aircraft generator brushes at high altitude.

Laminated phenolic compositions had high friction, developed a burnished transfer film on the mating surface, and wore considerably more than Teflon compositions. Additives such as graphite and MoS_2 did not improve the performance of the phenolic materials.

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
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TABLE I. - EXPERIMENTAL MATERIALS

(a) Metals and metallic compounds

Type	Manufacturer or source	Typical analysis, percent by weight		Average hardness
304 Stainless steel	NACA stock	C	0.07	Rockwell B-63
		Cr	18.40	
		Si	0.29	
		Ni	8.41	
		Fe	Remainder	
440-C Stainless steel	Allegheny Ludlum Steel Corp.	C	0.95 to 1.20	Rockwell C-54
		Mn(max)	1.00	
		Si(max)	1.00	
		P(max)	0.04	
		S(max)	0.03	
		Cr	16.00 to 18.00	
		Mo(max)	0.75	
		Fe	Remainder	
SAE 52100 chromium steel	NACA stock	C	0.95 to 1.10	Rockwell C-60
		Mn	0.25 to 0.45	
		P(max)	0.025	
		S(max)	0.025	
		Si	0.20 to 0.35	
		Cr	1.30 to 1.60	
		Fe	Remainder	
SAE 1020 mild steel	NACA stock	C	0.18 to 0.23	Rockwell A-50
		Mn	0.30 to 0.60	
		P(max)	0.04	
		S(max)	0.05	
		Fe	Remainder	
Silver, cast electrolytic	NACA stock	Ag	99.9+	--------
Hot-pressed silver composition with MoS_2	Formed by NACA	Ag	85	--------
		Cu	5	
		MoS_2	10	
Kentanium K162B (titanium carbide cermet)	Kennametal, Inc.	Ni	25	--------
		Mo	5	
		(Cb,Ta,Ti)C	8	
		TiC	Remainder	

TABLE I. - Concluded. EXPERIMENTAL MATERIALS

(b) Nonmetals

Type of material	Manufacturer or source	Manufacturer's designation	Description of material	Average hardness
Molded carbon	Pure Carbon Co., Inc.	Purebon P5J	Amorphous carbon plus small amount of graphite; phenolic impregnant	Scleroscope 90
		P5	No impregnant	----------
		652	Double phenolic impregnant	----------
		P5HT	Organic-metallic complex impregnant	----------
		P5N	Metal-haloid impregnant	----------
	U.S. Graphite Co.	Graphitar 39	Amorphous carbon plus small amount of graphite; phenolic impregnant	Scleroscope 95
Molded plastic	The Formica Co.	CN	Coarse-weave cotton-fabric laminate; phenolic resin	----------
		LN	Fine-weave cotton-fabric laminate; phenolic resin	----------
		L-84	Fine-weave cotton-fabric laminate; phenolic resin; molybdenum-disulfide additive	----------
		CH-9	Medium-weave cotton-fabric laminate; phenolic resin; graphite additive	----------
		CH-93	Same as CH-9 except for higher graphite content	----------
		FF-55	Continuous-filament fiber glass laminate; melamine resin	----------
	Micarta Division, Westinghouse Electric Corp.	221	Fine-weave cotton-fabric laminate; phenolic resin	Rockwell M-113
		273	Fine-weave cotton-fabric laminate; phenolic resin (bearing-retainer material)	Rockwell M-115
		286	Medium-weave cotton-fabric laminate; phenolic resin	Rockwell M-108
Teflon and filled Teflon	Plastics Division, The Garlock Packing Co.	9507	Teflon filled with approx. 3 percent graphite	----------
		9291	Kel-F unplasticized (no filler)	----------
		8764	Teflon plain (no filler)	Durometer 50 to 65
		9412	Teflon filled with approx. 10 percent graphite	----------
		9429	Teflon filled with copper	----------
		9453	Teflon filled with MoS_2	----------
	Koppers Co., Inc.	----	Teflon filled with fiber glass (cut from molded piston rings)	----------

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CF-3 back

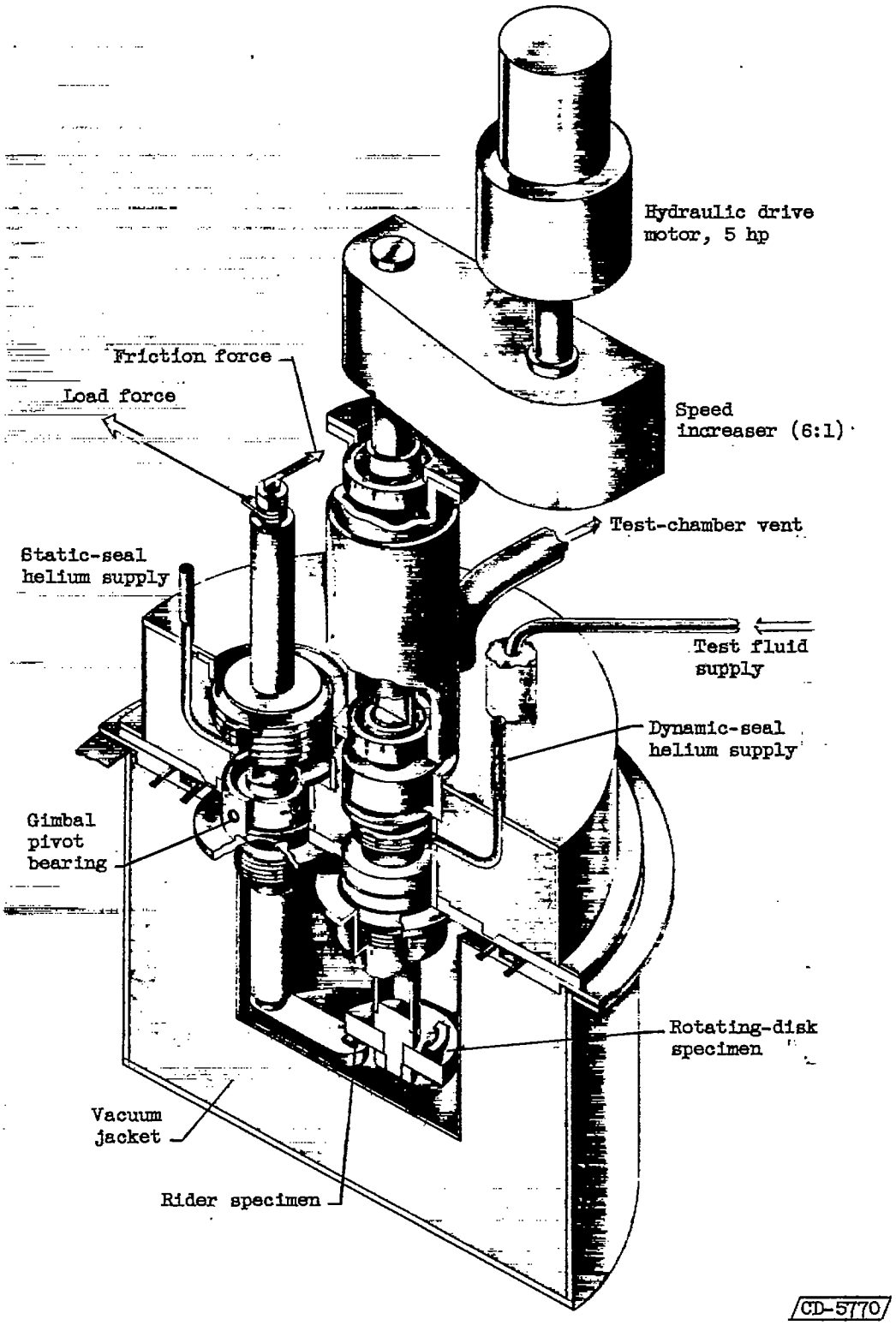


Figure 1. - Cryogenic friction-and-wear apparatus.

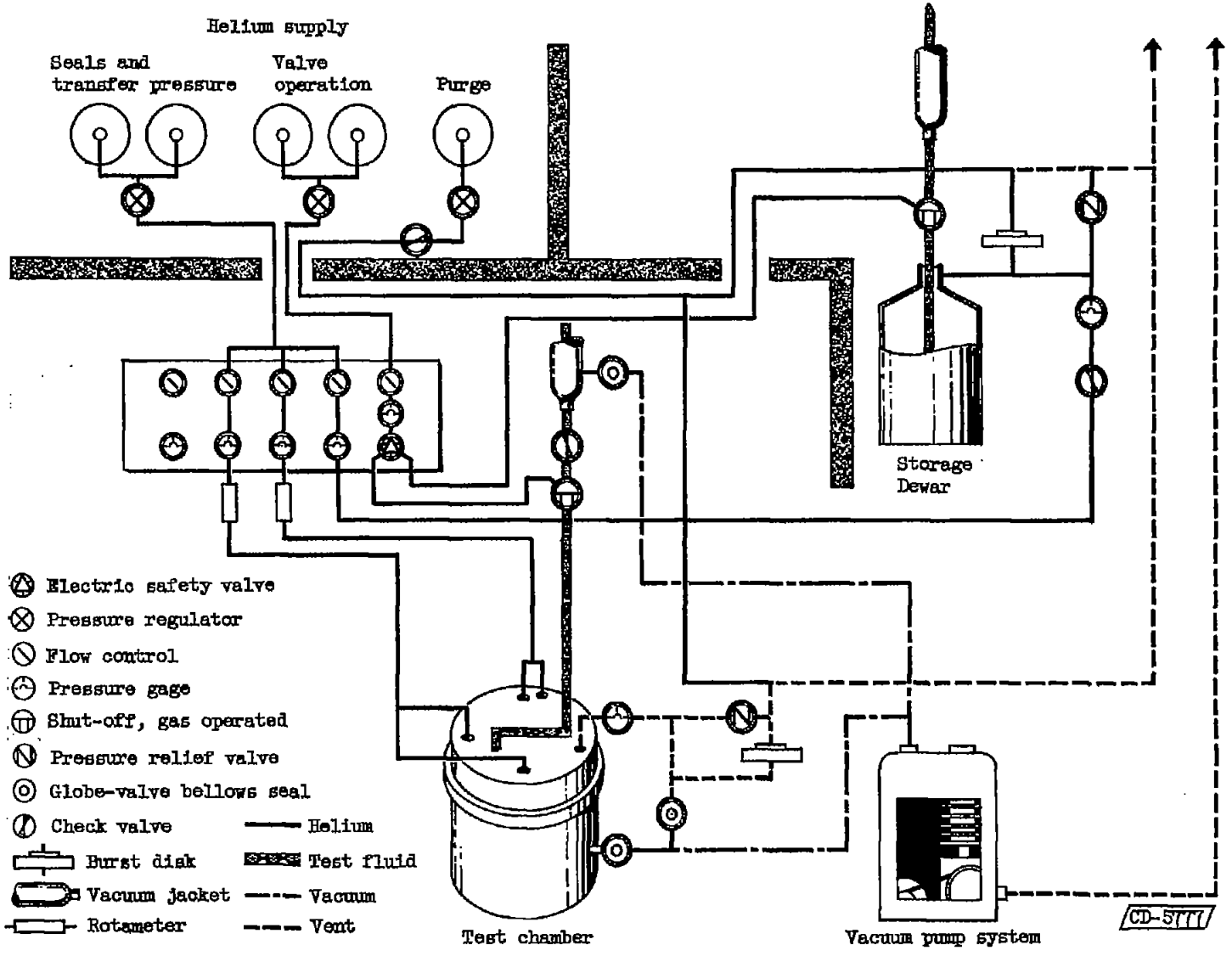
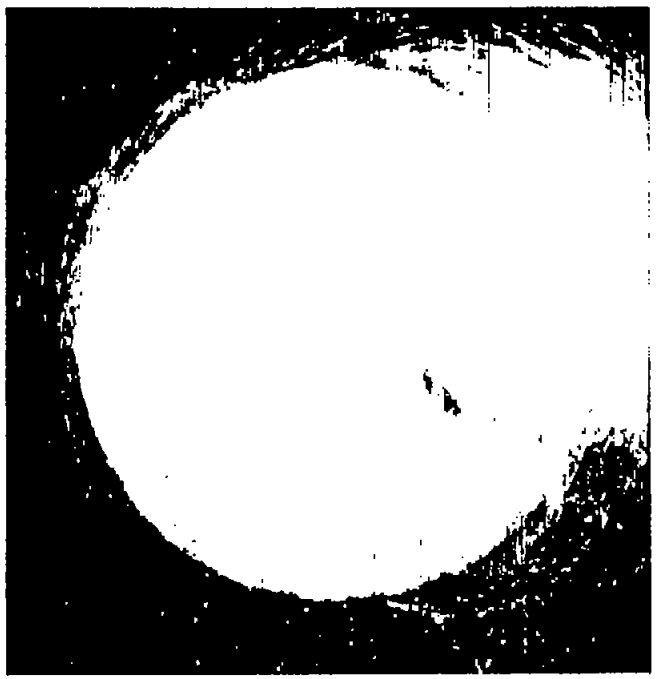
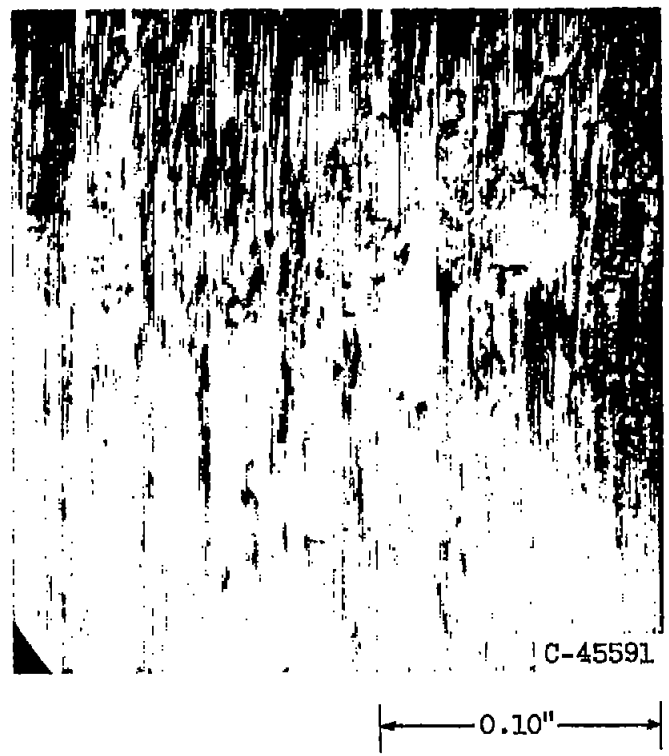


Figure 2. - System for transfer of cryogenic fluid to test chamber of friction-and-wear apparatus.



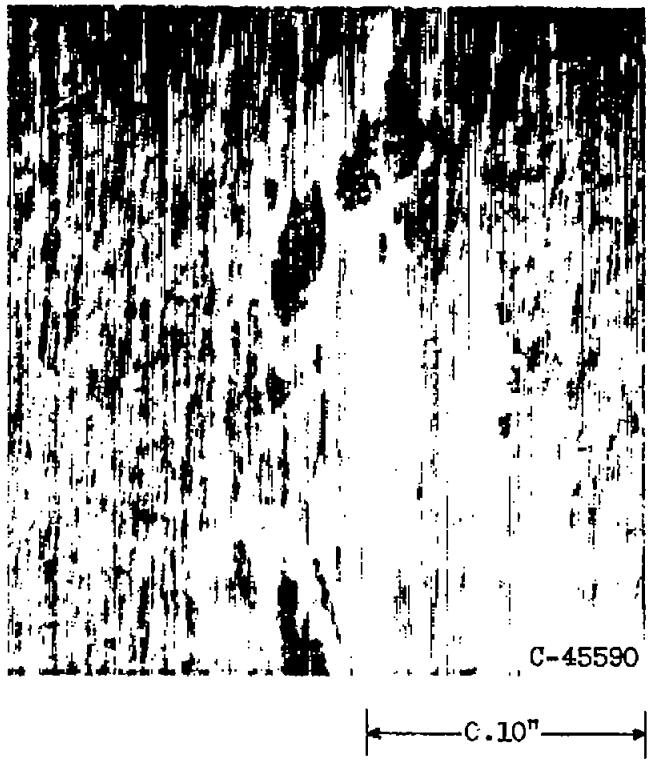
Rider wear area



Disk wear track

Figure 3. - Surfaces of austenitic type 304 stainless-steel rider on type 304 stainless-steel disk after sliding in liquid nitrogen. ×15. Duration, 4.75 minutes; rider wear rate, 6.2×10^{-3} cubic inch per hour; initial friction coefficient, 0.78; sliding velocity, 2300 feet per minute; initial load, 1000 grams.

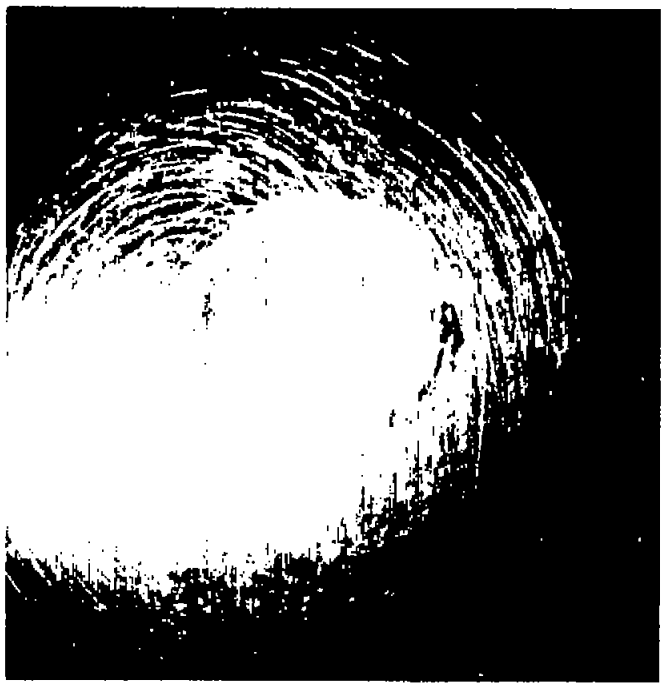
Rider wear area



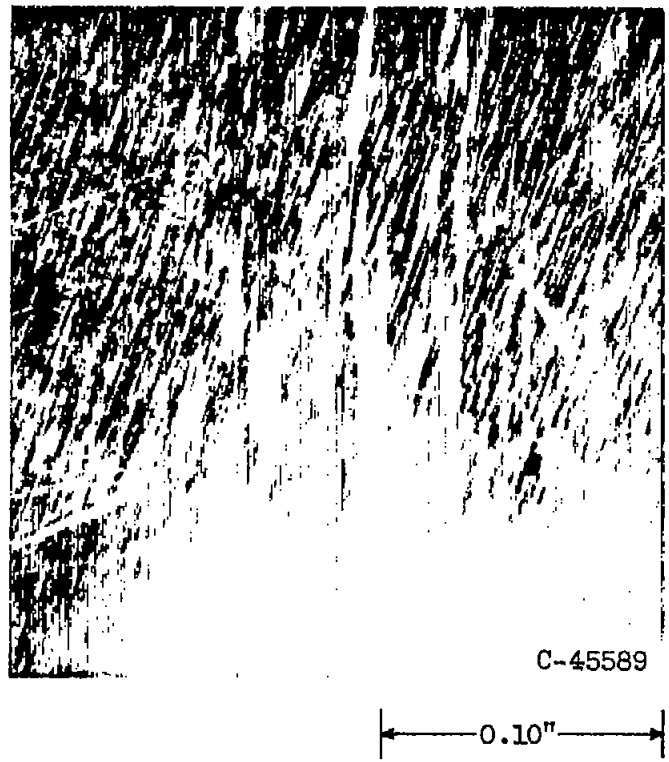
Disk wear track

(a) SAE 1020 rider on SAE 52100 disk. Duration, 10.78 minutes; rider wear rate, 1.18×10^{-3} cubic inch per hour; initial friction coefficient, 0.59.

Figure 4. - Surfaces of conventional bearing materials after sliding in liquid nitrogen. ×15. Sliding velocity, 2300 feet per minute; initial load, 1000 grams.



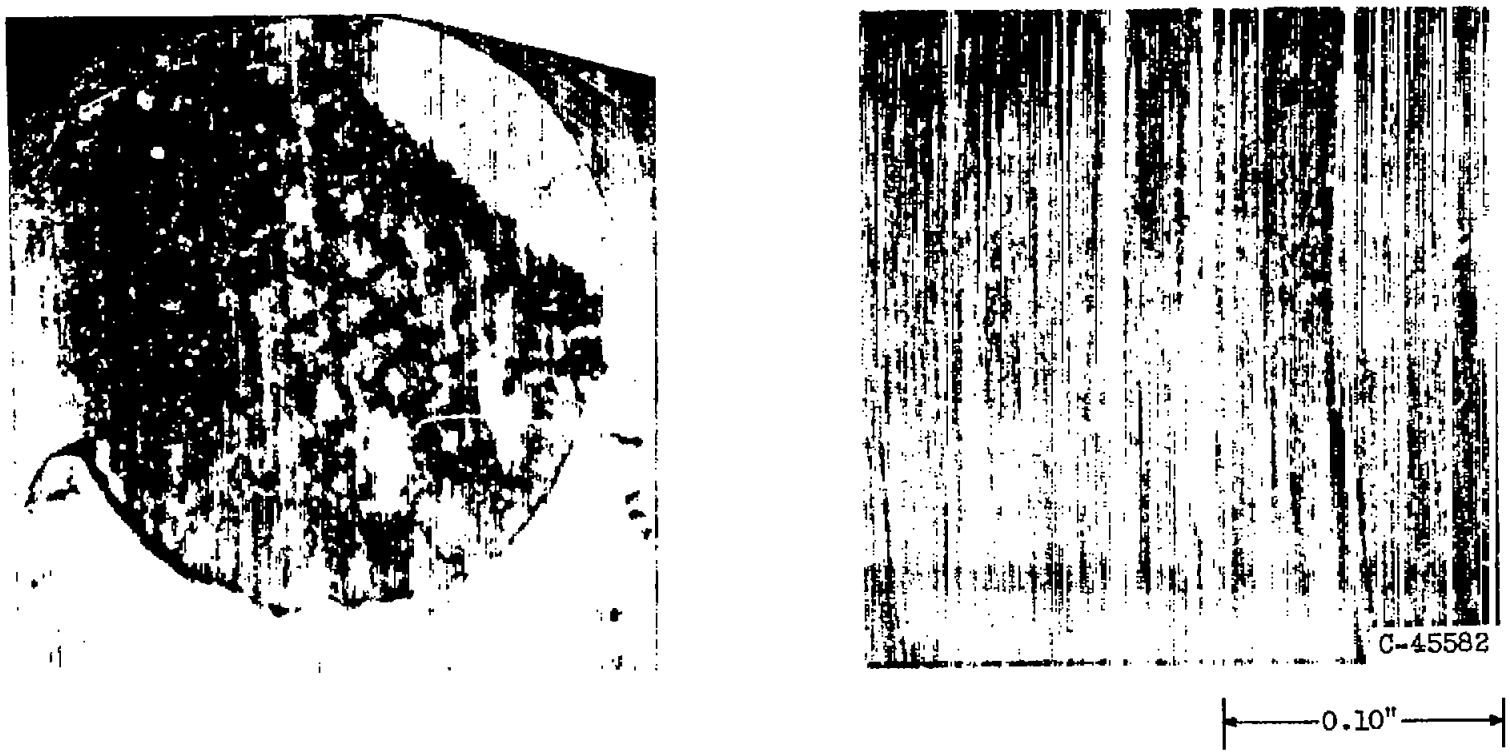
Rider wear area



Disk wear track

(b) SAE 52100 rider on SAE 52100 disk. Duration, 0.2 minute; rider wear rate not significant because of short duration; initial friction coefficient, 0.52.

Figure 4. - Concluded. Surfaces of conventional bearing materials after sliding in liquid nitrogen. ×15. Sliding velocity, 2300 feet per minute; initial load, 1000 grams.



Rider wear area

Disk wear track

(a) Cast electrolytic silver rider on type 304 stainless-steel disk. Duration, 60 minutes; rider wear rate, 0.63×10^{-3} cubic inch per hour; initial friction coefficient, 0.80.

Figure 5. - Surfaces of solid silver and a silver composition and the mating metal after sliding in liquid nitrogen. ×15. Sliding velocity, 2300 feet per minute; initial load, 1000 grams.

Rider wear area

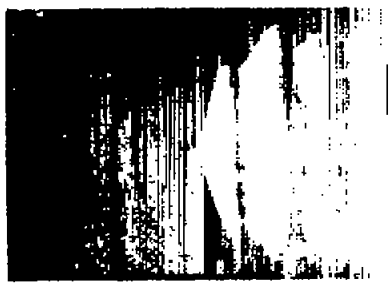
0.10"

Disk wear track

(b) Hot-pressed silver (85 percent), copper (5 percent), and MoS_2 (10 percent) composition rider on type 304 stainless-steel disk. Duration, 48.5 minutes; rider wear rate, 0.66×10^{-3} cubic inch per hour; initial friction coefficient, 0.34.

Figure 5. - Concluded. Surfaces of solid silver and a silver composition and the mating metal after sliding in liquid nitrogen. ×15. Sliding velocity, 2300 feet per minute; initial load, 1000 grams.

Vertical illumination



Oblique illumination

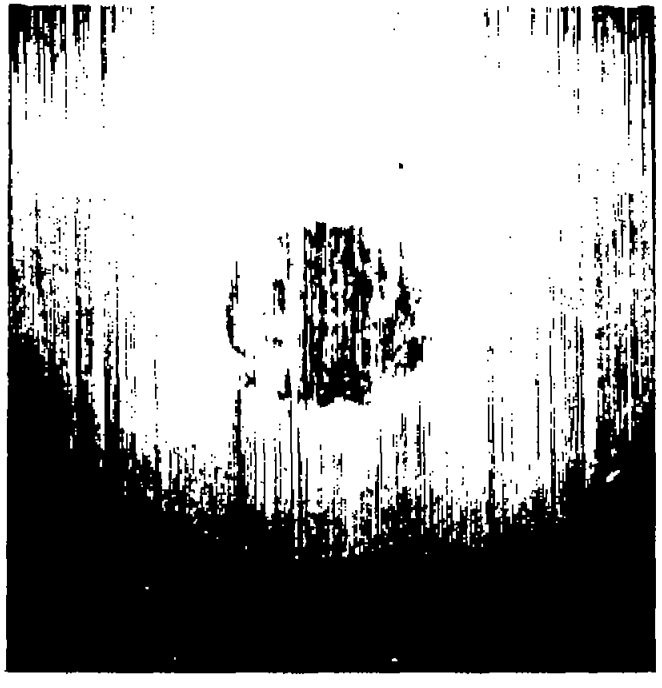
Rider wear area

0.10"

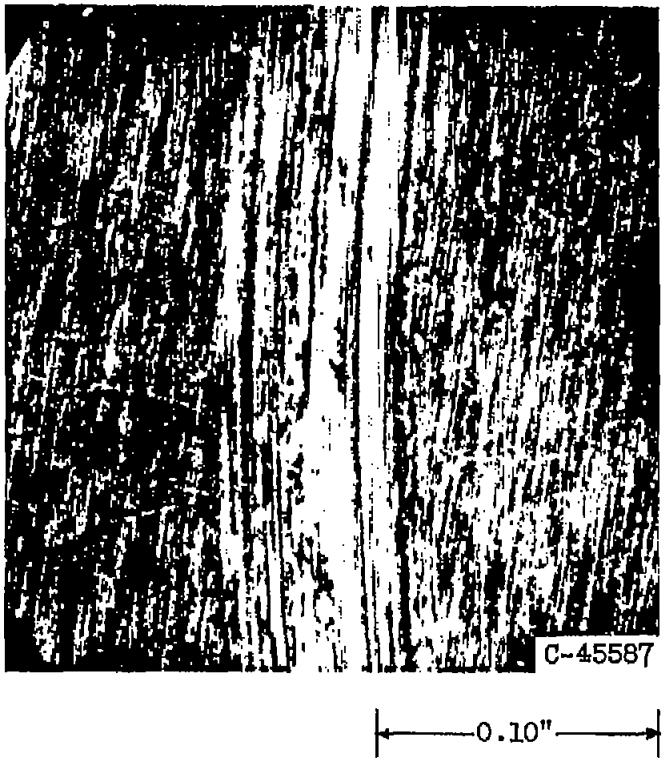
Disk wear track

(a) Titanium carbide cermet (K162B) rider on type 440-C stainless-steel disk. Duration, 22.4 minutes; rider wear rate (0.051×10^{-3} cu in./hr) is not significant because of subsurface brittle fracture; initial friction coefficient, 0.63; initial load, 1000 grams.

Figure 6. - Surfaces of titanium carbide-base cermet and mating metal after sliding in liquid nitrogen. X15. Sliding velocity, 2300 feet per minute.



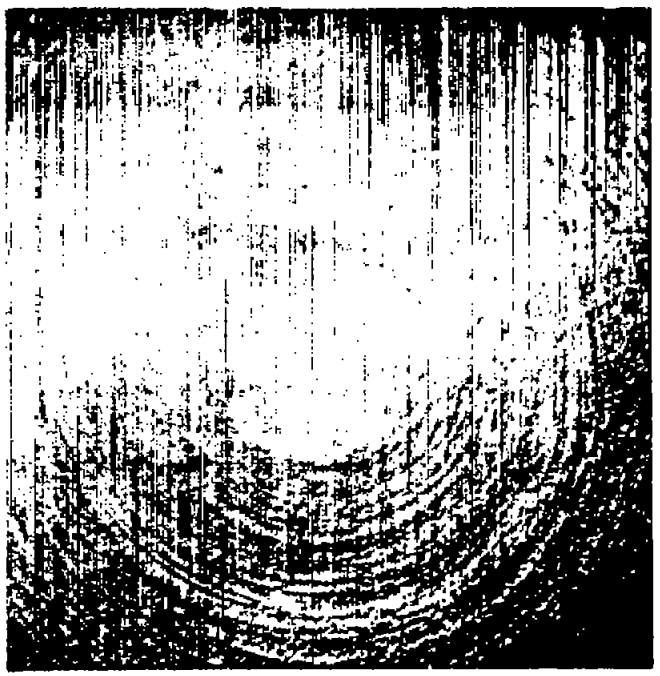
Rider wear area



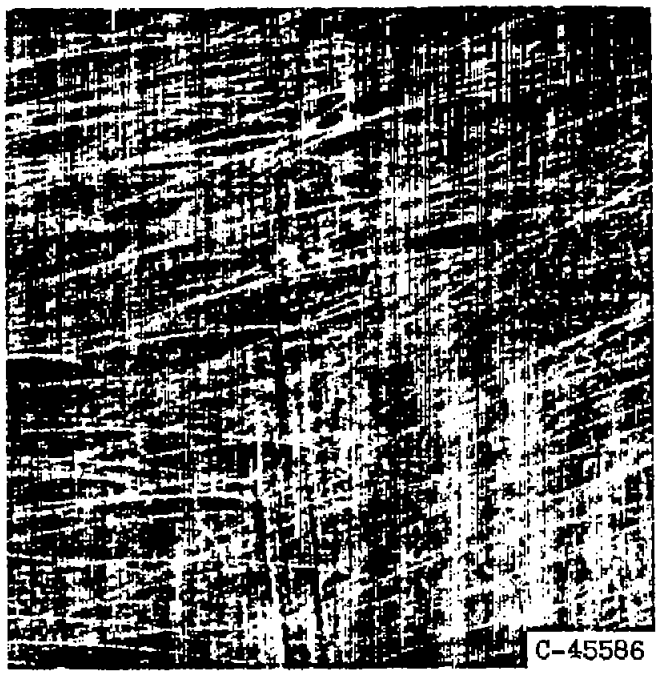
Disk wear track

(b) Reduced-load experiment with titanium carbide cermet (K162B) rider on type 440-C stainless-steel disk. Duration, 31.44 minutes; rider wear rate (0.014×10^{-3} cu in./hr) is not significant because of subsurface brittle fracture; initial friction coefficient, 0.69; initial load, 800 grams.

Figure 6. - Concluded. Surfaces of titanium carbide-base cermet and mating metal after sliding in liquid nitrogen. ×15. Sliding velocity, 2300 feet per minute.



Rider wear area

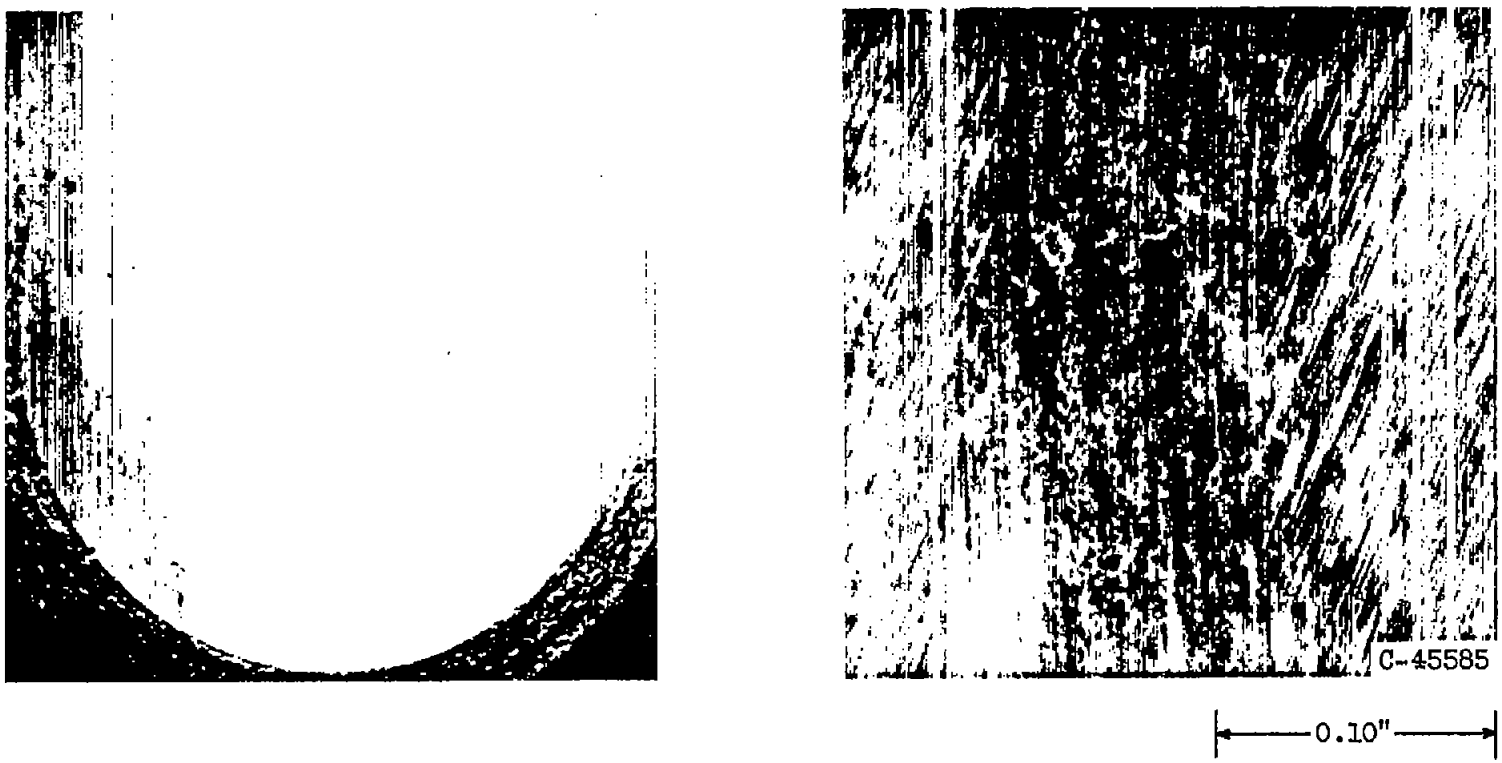


0.10"

Disk wear track

(a) Phenol-impregnated molded carbon (Purebon P5J) rider on type 304 stainless-steel disk. Duration, 60 minutes; rider wear rate, 0.009×10^{-3} cubic inch per hour; initial friction coefficient, 0.35. Surfaces believed contaminated with frozen adsorbed moisture film when specimens were plunged into liquid nitrogen in open Dewar.

Figure 7. - Surfaces of molded carbon and mating metal after sliding in liquid nitrogen. ×15. Sliding velocity, 2300 feet per minute; initial load, 1000 grams.

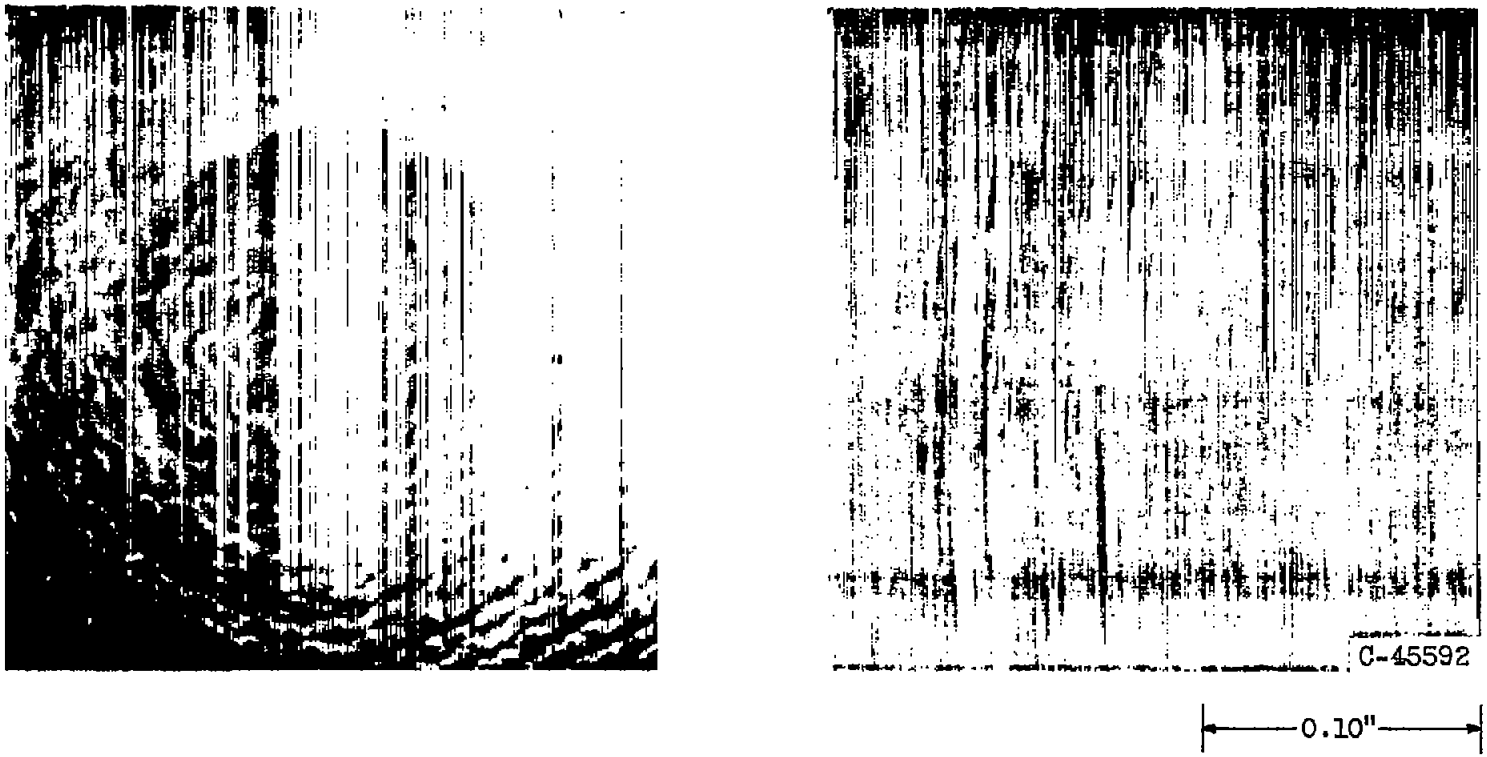


Rider wear area

Disk wear track

(b) Phenol-impregnated molded carbon (Purebon P5J) rider on type 304 stainless-steel disk. Duration, 1.4 minutes; rider wear rate (91.3×10^{-3} cu in./hr) not quantitatively significant because of short duration; initial friction coefficient, 0.40. Standard experimental procedure.

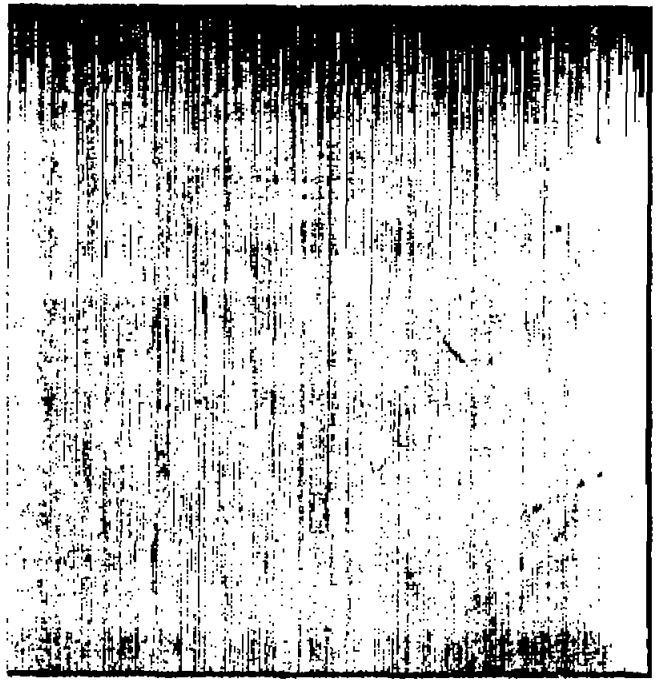
Figure 7. - Concluded. Surfaces of molded carbon and mating metal after sliding in liquid nitrogen. ×15. Sliding velocity, 2300 feet per minute; initial load, 1000 grams.



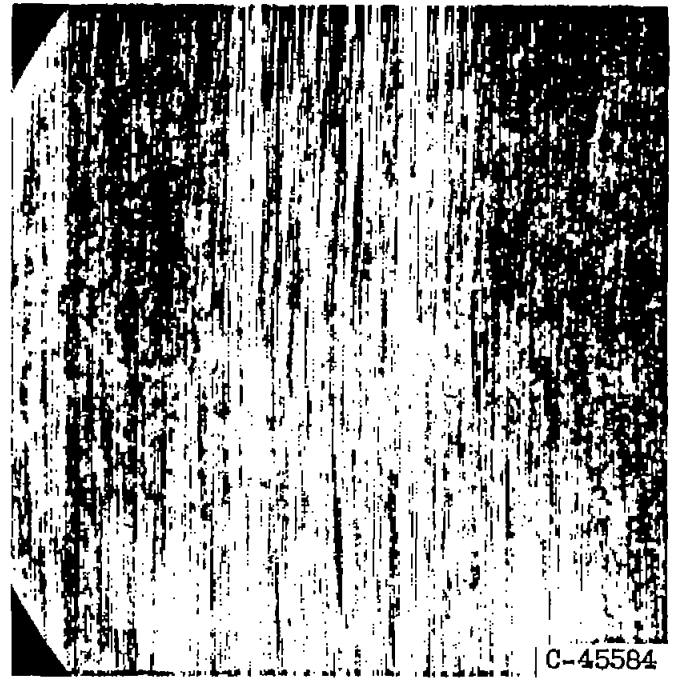
Rider wear area

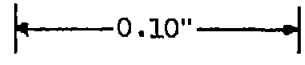
Disk wear track

Figure 8. - Surfaces of laminated phenolic resin (Formica LN) rider on type 304 stainless-steel disk after sliding in liquid nitrogen. ×15. Duration, 60.25 minutes; rider wear rate, 0.11×10^{-3} cubic inch per hour; initial friction coefficient, 0.70; sliding velocity, 2300 feet per minute; initial load, 1000 grams.



Rider wear area

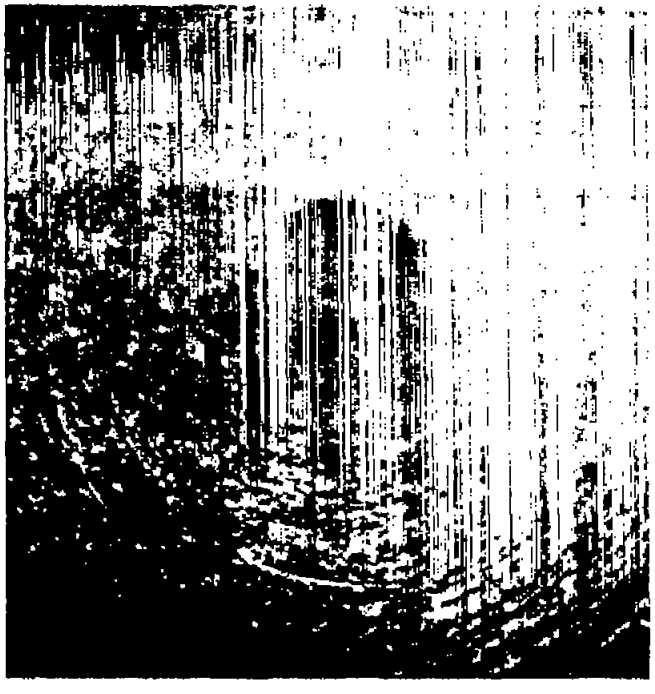




Disk wear track

(a) Molded Teflon (Garlock 8764) rider on type 304 stainless-steel disk. Duration, 15.25 minutes; rider wear rate, 0.31×10^{-3} cubic inch per hour; initial friction coefficient, 0.27.

Figure 9. - Surfaces of Teflon and filled Teflon after sliding in liquid nitrogen. ×15. Sliding velocity, 2300 feet per minute; initial load, 1000 grams.



Rider wear area

0.10"

Disk wear track

(b) Molded graphite-filled Teflon (Garlock 9412) rider on type 304 stainless-steel disk. Duration, 61.0 minutes; rider wear rate, 0.011×10^{-3} cubic inch per hour; initial friction coefficient, 0.14.

Figure 9. - Concluded. Surfaces of Teflon and filled Teflon after sliding in liquid nitrogen. X15. Sliding velocity, 2300 feet per minute; initial load, 1000 grams.

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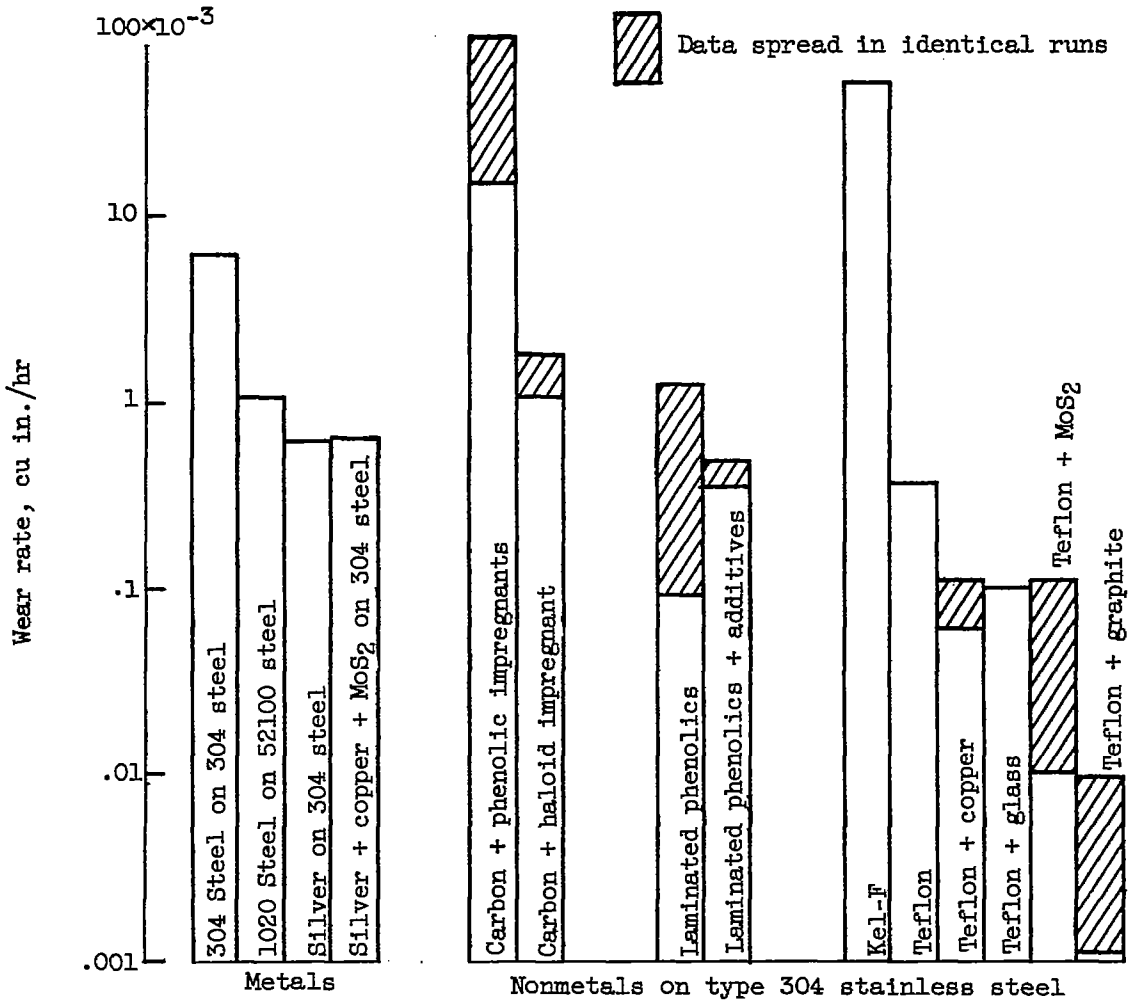
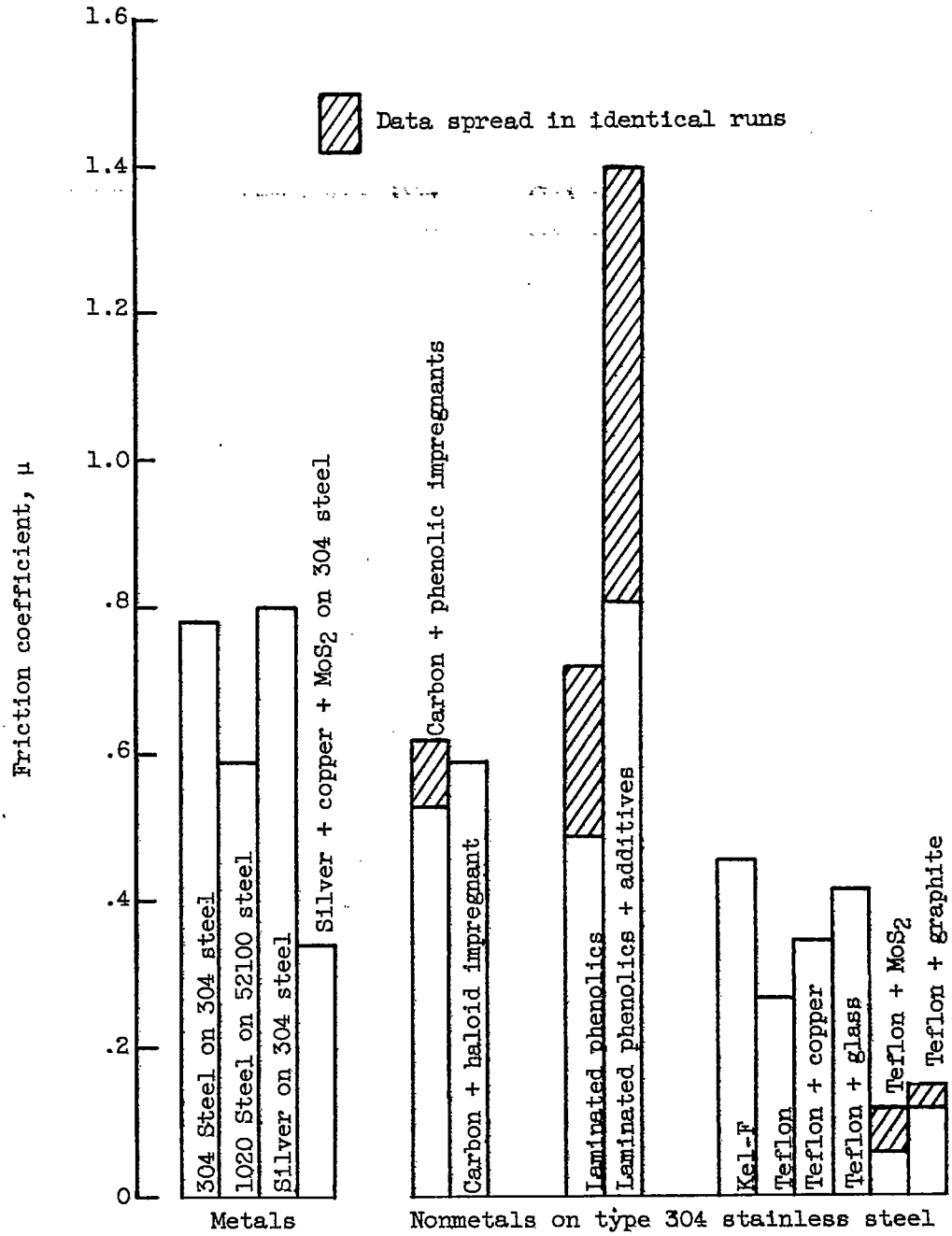


(a) Wear.

Figure 10. - Wear and friction properties of various types of materials sliding in liquid nitrogen. Sliding velocity, 2300 feet per minute; load, 1000 grams; duration, from 5 minutes to 5 hours depending on wear rate.



(b) Friction.

Figure 10. - Concluded. Wear and friction properties of various types of materials sliding in liquid nitrogen. Sliding velocity, 2300 feet per minute; load, 1000 grams; duration, from 5 minutes to 5 hours depending on wear rate.

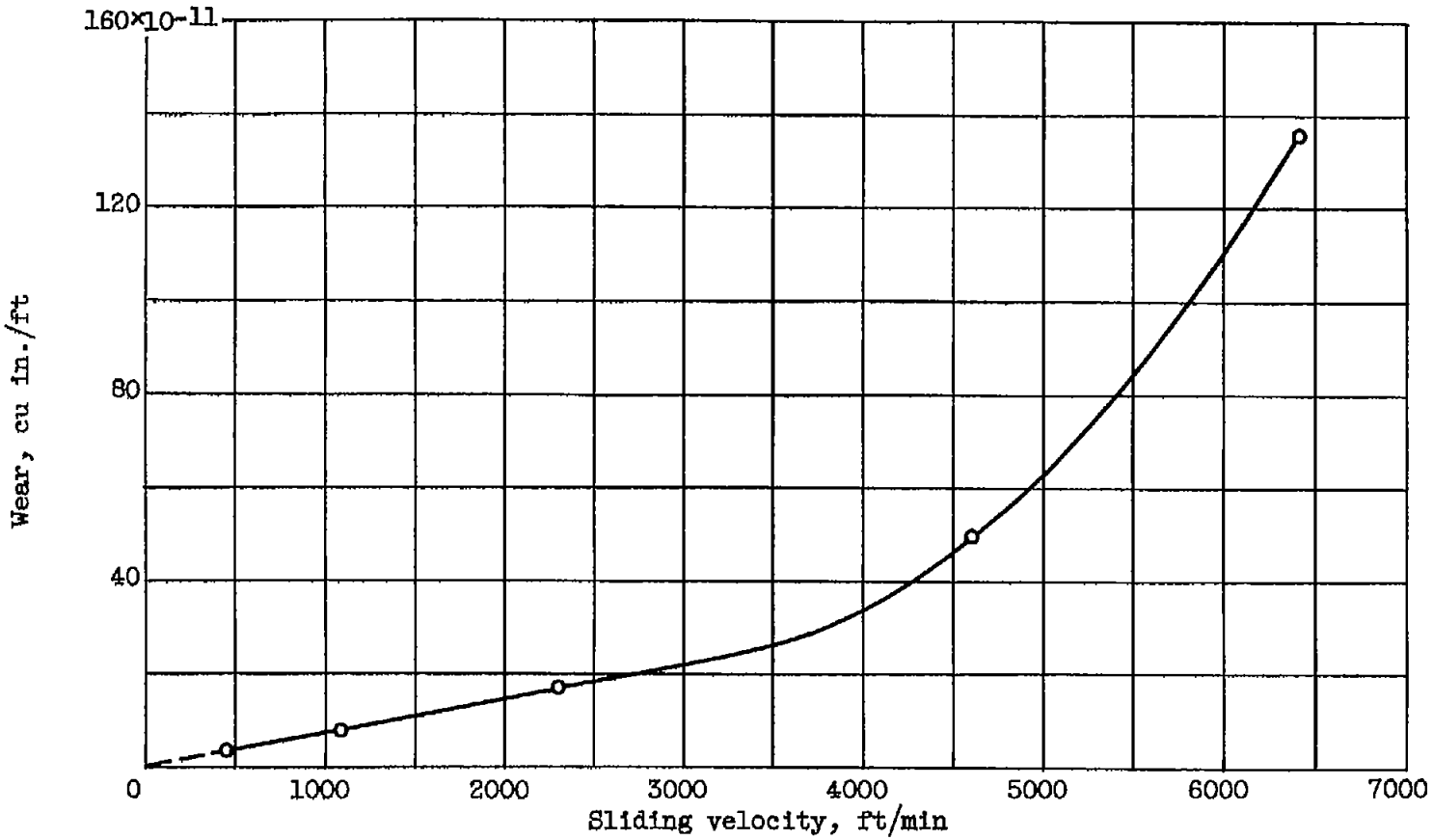


Figure 11. - Effect of sliding velocity on wear per unit distance of sliding for molded graphite-filled Teflon rider on type 304 stainless-steel disk submerged in liquid nitrogen. Initial load, 1000 grams; radius of rider tip, 3/16 inch.

NACA - Langley Field, Va.