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# SELF-LUBRICATING PLASMA-SPRAYED COMPOSITES FOR SLIDING-CONTACT BEARINGS TO 900° C

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16. Abstract

Plasma-sprayed composites which have good oxidation-resistance and self-lubricating characteristics to 900° C were developed. The composites are a Nichrome matrix containing dispersed glass for oxidation protection and calcium fluoride for lubrication. They are applied to bearing surfaces in layers about 0.050 cm thick by plasma-spraying; the layers are then machined to a thickness of 0.025 cm. Oscillating bearing tests were performed in air to 900° C at unit radial loads up to $3.5\times10^7$ N/m$^2$ (5000 psi) and a thrust load of 1960 N (440 lb). Bearings with a composite liner in the bore were in good condition after over 50 000 oscillating cycles accumulated during repeated bearing temperature cycles between 25° and 900° C.

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# SELF-LUBRICATING PLASMA-SPRAYED COMPOSITES FOR SLIDING-CONTACT BEARINGS TO 900$^{0}$ C

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## SUMMARY

Plasma-sprayed self-lubricating coatings were investigated for possible use to 900$^{0}$ C in Space Shuttle airframe bearings or other high-temperature applications such as automotive turbine regenerator seals. Composite coatings with good oxidation resistance as well as self-lubricating characteristics to 900$^{0}$ C were developed. The composites are a Nichrome matrix containing dispersed glass for oxidation protection and calcium fluoride for lubrication. The coatings are applied by plasma-spraying the bearing surfaces with a coating about 0.050 centimeter thick. The coatings are then machined to a thickness of 0.025 centimeter. Oscillating bearing tests were performed in air to 900$^{0}$ C at unit radial loads up to $3.5 \times 10^{7}$ newtons per square meter (5000 psi) and a thrust load of 1960 newtons (440 lb). Bearings with a composite liner in the bore were in good condition after over 50 000 oscillating cycles accumulated during repeated bearing temperature cycles in the range 25$^{0}$ to 900$^{0}$ C.

## INTRODUCTION

A need exists for the development of improved high-temperature, self-lubricating materials. In advanced aircraft, the aerodynamic heating at speeds of Mach 3 and higher can result in vehicle skin temperatures well above the temperature limitations of presently available airframe bearings. As an extreme case, a maximum skin temperature of about 1100$^{0}$ C has been predicted for the Space Shuttle Orbiter during reentry (ref. 1 and fig. 1)). Airframe bearings and control surface seals for the Oribter are near the heated surfaces. They must, therefore, either be capable of high-temperature operation or suffer the weight penalty of cooling or insulation. Other areas in which high-temperature lubrication is needed include sliding-contact seals for automotive turbine regenerators, shaft seals for turbupumps, piston rings for high-performance reciprocating compressors, and lubricants for hot-glass processing machinery.

Solid lubricants such as graphite, molybdenum disulfide, and graphite fluoride oxidize or dissociate below 500° C (refs. 2 to 5). Self-lubricating composites of sintered porous Inconel, in which the pore structure is impregnated with calcium fluoride ($CaF_2$) - barium fluoride ($BaF_2$) eutectic, have been successfully tested for long duration in nonoxidizing atmospheres to 900° C (refs. 6 to 8). In air, however, usefulness is limited to 650° C for long durations and 800° C for short durations because oxidation of the sintered metal structure occurs and causes swelling and distortion of the part. Attempts to reduce metal oxidation are described in reference 9. In that work, considerable improvement was achieved by partially filling the pore structure of the matrix with oxidation-protective glasses. The lubricating fluorides were introduced in a second infiltration. The resulting composites had improved oxidation resistance and were self-lubricating at 900° C. However, the double infiltration was complex and time-consuming. In the study described in this report, the potentially simpler alternative method of preparing the composite by plasma-spraying was explored. Work by Blampin in France (ref. 10) had indicated that adherent $CaF_2$ and $CaF_2$-graphite coatings could be applied to metal surfaces by plasma-spraying.

The present report describes the tribological and oxidative behavior of plasma-sprayed composites of $CaF_2$, glass, and metal that were developed in a program at the Lewis Research Center. The scope of the experiments included (1) basic friction and wear measurements using a pin-on-disk apparatus; (2) oxidation studies by thermogravimetric analysis (TGA) and measurement of dimensional changes; and (3) actual tests of self-alining, plain cylindrical bearings in which either the bore or the oscillating journal was coated with the plasma-sprayed composite. Bearing tests were at unit radial loads up to $3.5\times10^7$ newtons per square meter (5000 psi), a thrust load of 1960 newtons (440 lb), and temperatures to 900° C. Journal oscillation was $\pm15^\circ$ at a frequency of 1 hertz.

## PREPARATION OF COMPOSITE MATERIALS

The composites were deposited by plasma-spraying mixed powders of Nichrome, glass, and in some cases $CaF_2$. The coatings were applied to metal disks, bearing journals, and bearing bores. All substrates were made of the precipitation-hardened nickel-chromium alloy René 41.

### Preparation of Powders for Plasma-Spraying

Glasses have been used as oxidation protective coatings for metals (refs. 11 and 12). The glass used in the composites of the present study was based on one of the formulations originally developed under a NASA contract (ref. 11) to explore protective coatings for gas turbine blades. The composition of the mill batch or starting material from which the glass used in the present work was made and the calculated final composition of the glass are given in table I. The differences in mill batch and glass compositions are caused by the loss of carbon dioxide from the carbonates and water from the hydrated materials during preparation of the glass. The mill batch was melted in a nickel crucible at $1370^{0}$ C. About 10 minutes were allowed for complete decomposition of the carbonates and hydrated compounds. The melt was then poured into water to form readily pulverized, shotlike particles of glass frit. The frit was pebble-milled dry to a powder which would pass through a U.S. standard sieve size 120 (particle sizes less than 125 $\mu$m).

The powdered glass was then mixed with powdered Nichrome metal and, in one formulation, with $CaF_2$ to the desired compositions for plasma spraying. The two sprayed powders used had the following compositions (in wt. %): (1) 80 Nichrome - 20 glass and (2) 67 Nichrome - 16.5 glass - 16.5 $CaF_2$.

The substrate surfaces were grit blasted with coarse alumina grit. The composites were sprayed to a thickness of about 0.050 centimeter and subsequently machined back to a thickness of 0.025 centimeter.

During spraying, argon was used as the carrier gas and the arc gas. An arc current of 350 amperes was used.

## Machining the Plasma-Sprayed Coatings

The recommended machining procedure is very simple, but must be done correctly to prevent excessive smearing of the Nichrome metal over the machined surface. It is very important that the surface areas occupied by the nonmetallic components of the composite are not diminished by metal smearing during machining. The following procedure has produced the best surfaces to date with the least amount of smeared and folded metal:

(1) Machine dry.
(2) Use a single-point carbide tool.
(3) Machine at a low speed of 9 to 12 meters per minute (30 to 40 ft/min).
(3) Remove no more than 0.010 centimeter (0.004 in.) per cut.

## Postmachining Surface Treatments

Any machining smears that do occur can be removed, and the surface finish can be improved by wet sanding with waterproof sandpaper progressing from 150 grit through at least two intermediate grades to 600 grit.

For those composites containing $CaF_2$, the surface can be enriched in the lubricant phase by heat treating the specimens in air at 870° C for 4 hours. The heat treatment causes a solid-state migration of fluorides along the surface and serves the added beneficial purpose of mildly preoxidizing the exposed metal. The surface becomes entirely covered with a combined fluoride-oxide film which is very desirable to prevent direct metal-to-metal adhesive contacts during sliding. For those composites without $CaF_2$, the preoxidation alone is beneficial. Photomicrographs of a Nichrome-$CaF_2$-glass composite surface before and after heat treatment are given in figure 2.

## FRICTION APPARATUS

A diagram of the high-temperature friction apparatus is shown in figure 3. The riders (pins) and disks were made of René 41. The pins were hemispherically tipped with a radius of 0.476 centimeter. The plasma-sprayed coatings were applied to one flat surface of each 6.3-centimeter-diameter René 41 disk. The pin was loaded with standardized weights against the disk. The disk rotated at 600 rpm to give a linear sliding speed of 160 centimeters per second on a 5-centimeter-diameter circular track on the coated surface. The normal load applied to the riders was 1 kilogram.

The disk was heated by a high-frequency induction unit, and the temperature was monitored by an infrared optical pyrometer. A strain gage was used to measure frictional force.

## TEST BEARINGS

The design of the test bearing is illustrated in figure 4(a). The general design is that of a rod-end spherical bearing. However, in this program, the spherical element was not fastened to the journal but was allowed to float. The self-lubricating composite layer was plasma-sprayed on the journal or on the bearing bore and one thrust surface. The coatings were machined to a thickness of 0.0254 centimeter (0.010 in.), sanded to remove machining marks, and then heat-treated as previously described. All bearing elements and the journal were subjected to the heat treatment so that all exposed surfaces were mildly oxidized prior to operating the bearings. Although the ball was mounted to allow sliding on either the bore or the spherical surface, it was observed that all oscillation occurred in the bore because of (1) the lower friction coefficient of the composite liner and (2) the shorter radius of the bore relative to the spherical surface. However, the preoxidized ball and the contacting surfaces of the outer race could slide without seizing and therefore provided a self-alining characteristic to the bearings.

All bearing elements (except the self-lubricating layer in the bore) were made of René 41, a precipitation-hardened nickel alloy. The bearings were hardened to Rockwell C-32 (which is not reduced by the composite heat treatment). The lined bearing bore was 1.537 centimeters (0.605 in.) in diameter and 1.9 centimeters (0.75 in.) long. The spherical diameter was 2.92 centimeters (1.151 in.). The clearance between the journal and the composite-lined bore was 0.013 centimeter (0.005 in.), and the ball - outer-race clearance was 0.008 centimeter (0.003 in.).

## BEARING TEST MACHINE

A detailed description of the bearing test rig is given in reference 13; a drawing is given in figure 4(b). In essence, the bearing is mounted in an induction-heated bearing housing. The oscillating journal is taper-mounted into a drive shaft which is supported at both ends by roller bearings. Radial and thrust loads are applied to the test bearing by hydraulic actuators suitably linked to the drive shaft. The drive shaft is oscillated by means of a reversible hydraulic actuator which simulates the motion in an aircraft control surface actuator and bearing assembly. Thermocouples are press-mounted against the bearing outer race and in some cases embedded in the bearing ball (see fig. 4(a)).

## BEARING TEST PROCEDURE

The simulated reentry tests consisted of beginning bearing oscillation at room temperature under a nominal unit radial load of $4.5\times10^5$ newtons per square meter (65 psi) and then increasing the unit load in $4\times10^6$-newton-per-square-meter (1000-psi) increments (2 min at each increment) up to the test load of $3.5\times10^7$ newtons per square meter (5000 psi). Unit radial load is defined in this report as the total radial load per unit projected area of the bearing bore, where the projected area is obtained by multiplying bore diameter by bore length. A thrust load of 1960 newtons (440 lb) was also applied. The bearing temperature was controlled during the tests to obtain the temperature-time profile shown in figure 5. No attempt was made to simulate other reentry profiles such as load or atmospheric pressure. All tests were conducted in room air.

# RESULTS

## Oxidation Studies

The oxidation rate of the metallic structure in sintered or plasma-sprayed composites is an important factor in their high-temperature performance. Oxidation weakens the composite by the formation of relatively weak oxides at the expense of the supporting metallic structure. Perhaps, even more significantly, oxidation can cause swelling and other undesirable distortions. When the composites are used in bearings, these distortions ultimately cause a loss in working clearance and the bearing can jam. For self-lubricating composites, which are to be used to high temperatures in air, it is, therefore, important to control oxidation in order to maintain both the strength and the dimensional stability of the material.

The oxidation data, which were obtained by TGA for a number of Nichrome-glass and Nichrome-glass-$CaF_2$ composites, are given in figure 6. The TGA procedure and method of calculation for determining degree of oxidation from weight changes are given in the appendix. The highest oxidation rates were observed with porous sintered Nichrome which had been completely infiltrated with glass (about 10 wt. % glass) and then coated with a thin film of $CaF_2$-$BaF_2$ eutectic. Oxidation was about one-third lower when the fluoride eutectic overlay was omitted. This composite was previously shown to have excellent oxidation resistance at 816° C (ref. 9), but as indicated in figure 6, after 240 hours at 900° C, metal oxidation was almost 30 percent theoretically complete for the composite with the fluoride coating and almost 20 percent complete for the uncoated composite. Later plasma-sprayed composites containing 20 weight percent glass had better oxidation properties. For example, the data show that plasma-sprayed Nichrome with 20 weight percent glass oxidized to about 15 weight percent glass after 240 hours at 900° C; the addition of a fluoride overlay had no effect or was beneficial, although the differences in oxidation with and without the overlay are probably within the experiment error. The lowest oxidation rate was obtained with the plasma-sprayed coating containing Nichrome, $CaF_2$, and glass. Only about 7 percent of theoretically complete oxidation occurred after 240 hours at 900° C.

It is not clear why $CaF_2$ increases the oxidation rates of nickel alloy used in composites prepared by sintering and infiltration but actually appears to reduce metal oxidation in the plasma-sprayed composites. Increased oxidation in the first case can be explained by the occurrence of oxide solid-state diffusion away from the parent metal surface and into the fluoride filler. This oxide dilution at the metal surface reduces the efficiency of the oxide in forming protective films on the metal surfaces in the usual manner. Reduced oxidation rates when $CaF_2$ is introduced into the plasma-sprayed coatings appear to be contradictory. However, it was observed that plasma-sprayed

Nichrome-glass-$CaF_2$ coatings were denser (less porous) and more homogeneous than coatings containing only Nichrome and glass. It can only be speculated at this time that these physical improvements in coating quality imparted by $CaF_2$ had a beneficial effect on oxidation characteristics that outweighed any undesirable effects attributable to dilution of oxide films.

Table II gives the increases in thickness of composite coatings (initially 0.025 cm thick) during the first 4 hours and the next 236 hours of the $900^\circ$ C oxidation tests. The increase in thickness during the first 4 hours was about the same in most cases as it was during the next 236 hours. The increased thickness of the Nichrome-$CaF_2$-glass composite during the first 4 hours was partially caused by extrusion of $CaF_2$ from the surface pores. The extruded material forms microscopic mounds on the surface. The height of the mounds is included in the micrometer measurements of coating thickness. The extruded material not only forms mounds but also gradually migrates away from the mounds until the surface is entirely covered with a thin film of $CaF_2$ and metal oxide (fig. 2). Some increase in surface roughness occurs because the film is thicker at the mounds than elsewhere. (A smooth finish can be readily restored by lightly wet sanding with waterproof sandpaper. With care it is possible to restore a good finish without removing the beneficial surface film.) The increase in thickness during the remaining 236 hours was typically $1\times10^{-3}$ centimeter and was possibly caused by metal oxidation. This increase represents only 4 percent of the initial 0.025-centimeter coating thickness.

## Friction and Wear Tests Using Pin-on-Disk Apparatus

Typical friction coefficients for three plasma-sprayed composites are shown in figure 7. The tests involved unidirectional sliding of René 41 pins against plasma-sprayed coatings on René 41 disks at 160 centimeters per second (600 rpm) with a 1-kilogram load in an air atmosphere. The data show the importance of proper surface conditioning and the effect of $CaF_2$ addition to the composite on the friction coefficients at disk temperatures up to $900^\circ$ C. Considerably higher friction coefficients were observed with specimens in the as-machined condition than with those which were sanded and heat-treated after machining. Of the two composites which were sanded and heat-treated, the one containing $CaF_2$ gave lower friction coefficients over the entire temperature range. It is interesting, however, that proper surface conditioning was even more effective than $CaF_2$ addition, which indicated that the glass provides a lubricating function in these composites. The Nichrome-$CaF_2$-glass coatings had a friction coefficient of approximately 0.4 at room temperature, and this steadily decreased to about 0.2 at $900^\circ$ C. Photomicrographs of the sliding surfaces after testing are given in figure 8.

The wear track on the disk is covered with a transparent, very smooth glaze; the wear scar on the René 41 pin is covered with a similar glaze.

The wear coefficients for the Nichrome-$CaF_2$-glass coatings and for the René 41 pins at room temperature, 540° C, and 900° C are given in figure 9. These data are compared to data from reference 14 for the wear of brass sliding on hardened tool steel and the wear of hardened tool steel sliding on itself at room temperature. The wear of the composite at room temperature is comparable to that of brass sliding on tool steel, but drops to less than 0.2 of that value at 540° and 900° C. René 41 pin wear at room temperature and 540° C is very low, less than that of tool steel. René 41 wear at 900° C is about twice that of tool steel at room temperature. These reference data are given because it is often helpful to visualize the wear of the experimental material relative to the wear of more well-known combinations. The principal assumption here is that total wear is a linear function of load and sliding distance. The comparison is reasonable because the present data and the reference data were both obtained on bench wear test machines which employed a concentrated, counterform type of contact (pin-on-disk in the present work, crossed cylinders in Archard's work (ref. 14)). However, in the bearing tests described in the next section, which involved conforming cylindrical contact, wear coefficients of the composites were consistently much lower than those obtained on the wear testers.

## Bearing Tests

Wear. - The bearing temperature-time profile used in the bearing tests is given in figure 5. Table III gives the average wear of the plasma-sprayed composites over the entire temperature profile at a bearing unit radial load of $3.5\times10^7$ newtons per square meter (5000 psi) and a thrust load of 1960 newtons (440 lb). In some tests the journal was coated; in others the bearing bore was coated. The wear data given are total radial wear (cm increase in radial clearance due to wear) and calculated volume wear coefficient.

In bearings 1 to 5 (table III) the lubricant was Nichrome-glass bonded to the journal. One of the first observations with bearing 1 was that well-glazed rubbing surfaces were established early in the bearing test (during run-in). The glaze was very beneficial in reducing subsequent wear, but was effective only if the coating did not spall and if the initial wear debris were removed from the bearing. After the first $10^4$ oscillations, the radial wear of bearing 1 was $5\times10^{-3}$ centimeter. However, the wear debris was then cleaned from the bearing and no additional measurable wear occurred during subsequent tests of up to a total of $38\times10^3$ oscillations. Some coatings on the journals had a tendency to spall at the bond line in the region of high load. This was usually followed by a rapid increase in bearing wear and torque. In bearing 5, for example, wear could not be accurately measured because of the severe surface damage caused by the spalled material. It was observed that spalling did not occur in coatings applied to the bearing bore instead of the journal, for example, bearings 6 to 9.

The differences in the spalling behavior of coatings on the journal and on the bore are probably due to the following differences in mechanical stress distributions with the composites during bearing operations: When the coating is applied to the journal, the dense metal substrate reinforces the composite only against normal compressive stresses. Tangential stresses generated by sliding friction must be absorbed entirely by the coating and the coating bond to the substrate. On the other hand, when the coating is in the bearing bore, the bearing substrate material provides considerable lateral support to the coating and reinforces the composite against tangential as well as compressive stresses. When the difference in spalling behavior became clear, all subsequent bearings were coated in the bearing bore.

Favorable results were obtained with the Nichrome-$CaF_2$-glass composite as a self-lubricating liner in the bearing bore. In general, wear rates with this material were lower than those with the Nichrome-glass composites. In fact, after the first $12\times10^3$ oscillating cycles (three reentry tests) with bearings 7 and 9, no wear was detectable by micrometer measurements on either the bearing bore or the journal. However, when the bearing was subjected to repeated tests without cleaning the bearing between tests, wear debris eventually accumulated within the bearing. These wear particles then had an abrasive effect and caused an accelerating wear process. This is indicated by the increase in the average wear coefficient with total accumulated shaft oscillations. Therefore, wear is a self-accelerating process in this type of bearing unless some means are employed continuously to remove wear particles as they form. In fact, if wear debris is removed as previously indicated for bearing 1, the wear rate actually decreases with test duration.

The 0.025-centimeter-thick liner of Nichrome-$CaF_2$-glass in bearing 9 was almost worn through after 12 simulated reentries with no provision for wear debris removal. This quantity of wear is representative only for the test condition used. Most of the wear took place during the long period of operation below 500° C during the cooldown portion of the tests. Pin-on-disk wear data and the bearing wear data in table IV indicate that wear below 500° C is much more severe than it is above 500° C. Therefore, whether the bearing would survive 10 or a 100 reentries is strongly a function of the number of oscillations below 500° C in each reentry as well as whether or not provision is made for continuous wear debris removal.

Friction. - Bearing friction from room temperature to 900° C is given in figure 10. Data are given for a preoxidized but otherwise unlubricated bearing and for a bearing with a Nichrome-$CaF_2$-glass liner in the bore. At a radial load of $3.5\times10^7$ newtons per square meter (5000 psi), the unlubricated bearing exhibited higher friction throughout and seized at about 879° C. For the lubricated bearing, friction coefficients were about 0.35 at room temperature and steadily decreased to about 0.20 in the temperature range 500° to 900° C.

The friction coefficient was sensitive to bearing load. As shown in figure 11, friction at room temperature tended to decrease linearly with increasing load between $3.5 \times 10^6$ and $3.5 \times 10^7$ newtons per square meter (500 to 5000 psi). At 760° and 900° C bearing temperatures, friction increased sharply as loads were reduced below $1 \times 10^7$ newtons per square meter (1500 psi), but at room temperature the load effect is linear over the entire load spectrum.

The friction coefficients given in figures 10 and 11 are typical, but scatter occurred in the friction coefficients. Figure 12 gives the scatter bands for friction coefficients observed during 12 reentry tests on the same bearing. The friction-time and friction-temperature profiles are superimposed, and there is a common time scale on the abscissa. The general characteristic of lower friction at the higher temperature is apparent. Figure 12(a) gives the data during the first three tests, and figure 12(b) gives data for the remaining nine tests. Data scatter is less, and the average friction level tends to be lower in the last nine tests.

## SUMMARY OF RESULTS

A program was conducted to develop plasma-sprayed coatings with self-lubricating characteristics and good oxidation resistance in air to 900° C. Oxidation studies and preliminary friction and wear studies were made on the new coatings. Oscillating journal bearing tests were then performed with the coatings on either the journal or the bearing bore. The bearings were tested at a unit radial load of $3.5 \times 10^7$ newtons per square meter (5000 psi), a thrust load of 1960 newtons (440 lb), and oscillating frequencies of 1/3 to 1 hertz at an amplitude of ±15°. Bearing temperatures were increased from 25° to 900° C and then cooled to about 150° C during the total test time of 110 minutes. This temperature cycle was an estimate of the reentry temperature profile of Space Shuttle airframe bearings located in areas with little thermal protection. The following major results were obtained:

1. The best of the coatings formulated in this program is a plasma-sprayed composite of Nichrome - 16.5 weight percent calcium fluoride - 16.5 weight percent glass. In addition to good high-temperature friction and wear properties, this coating has good oxidation resistance to 900° C, is machinable, and has excellent bond strength on the substrate metal.

2. In general, better results were obtained with the coating on the bearing bore than with the coating on the journal surface.

3. Bearings were successfully operated during as many as 12 repeated temperature cycling tests. Friction coefficients were about 0.35 at room temperature and steadily decreased to about 0.20 in the temperature range 500° to 900° C. Wear rates were very low during the first few tests (with about 10-kHz journal oscillations), but tended to increase as wear debris accumulated in the bearing clearance. Most wear debris was generated below 500° C during the cooling portion of the bearing tests. Any reduction in required oscillating cycles below 500° C would increase bearing life. It is probable that the bearings could survive the desired 100 cyclic temperature tests if the bearing temperatures were not allowed to get below 500° C during cooling.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, November 9, 1973,
502-31.

## APPENDIX - OXIDATION STUDIES BY THERMOGRAVIMETRIC ANALYSIS

The data were obtained by thermogravimetric analysis. Composite specimens were accurately weighed and then placed in the 900° C zone of an air atmosphere furnace. The specimens were periodically removed, allowed to cool, and reweighed to determine the weight increase caused by oxidation. The fraction of Nichrome metal oxidized after each 900° C exposure was taken as the ratio of sample weight increase to the theoretical increase if the entire Nichrome metal content of the composite had been completely converted to the nickel oxide (NiO) and the chromium oxide ($Cr_2O_3$).

The primary assumptions were (1) that the only oxides formed in significant quantities are NiO and $Cr_2O_3$ or spinels of the two with the same metal-oxygen stoichiometry and (2) that $CaF_2$ and the glass are not involved in any chemical reactions which would influence sample weight. X-ray diffraction analysis of the composites and other related studies confirm the validity of these assumptions.

The weight increase at complete oxidation was therefore calculated by using the following simple equations:

$$Ni + \frac{1}{2} O_2 = NiO \tag{1}$$

$$2Cr + 1\frac{1}{2} O_2 = Cr_2O_3 \tag{2}$$

Nichrome is 80 weight percent nickel (Ni) - 20 weight percent chromium (Cr). Therefore, the weight of the oxide $W_{ox}$ formed by oxidation of a weight of Nichrome $W_{me}$ is

$$W_{ox} = \left(0.80 \frac{NiO}{Ni} + 0.20 \frac{Cr_2O_3}{Cr}\right) W_{me} \tag{3}$$

where the chemical formulas represent the molecular weights and atomic weights of the oxides and metals, respectively. Then the maximum weight increase due to metal oxidation is

$$W_{ox} - W_{me} = \Delta W_{max} \tag{4}$$

and the fraction oxidized is

$$\frac{W_t - W_0}{W_{ox} - W_{me}} = \frac{\Delta W_t}{\Delta W_{max}} \tag{5}$$

where $W_t$ is the weight of composite at any time $t$ of oxidation and $W_0$ is the initial composite weight.

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TABLE I. - COMPOSITION OF OXIDATION-PROTECTIVE GLASS

| Initial mill batch | | Final glass | |
|---|---|---|---|
| Compound | Concentration, wt. % | Compound | Concentration, wt. % |
| Silicon dioxide | 53.4 | Silicon dioxide | 58.0 |
| Barium oxide | 19.6 | Barium oxide | 21.2 |
| Calcium hydroxide | 9.5 | Calcium oxide | 7.8 |
| Potassium carbonate | 17.5 | Potassium oxide | 13.0 |

TABLE II. - SWELL OF NICHROME COMPOSITES AFTER HEATING IN 900° C AIR

| Composite composition, wt. % | Increase in thickness of composite (initially 0.025 cm thick), cm | | Comments |
|---|---|---|---|
| | During first 4 hr | During next 236 hr | |
| 67 Nichrome, 16.5 $CaF_2$, 16.5 glass | $2.5\times10^{-3}$ | $1.0\times10^{-3}$ | Initial increase was partly extrusion of fluoride from surface pores |
| 80 Nichrome, 20 glass | 1.3 | 1.3 | ------------------ |
| 80 Nichrome, 20 glass, with fluoride overlay | 1.5 | 1.3 | ------------------ |
| 90 Nichrome, 10 glass | .5 | 1.0 | Sintered Inconel, glass infiltrated |
| 90 Nichrome, 10 glass, with fluoride overlay | 1.5 | 2.0 | |

TABLE III. - WEAR AND AVERAGE WEAR COEFFICIENTS OF 0.025-CENTIMETER-THICK COMPOSITE COATINGS IN VARIABLE-TEMPERATURE BEARING TESTS

[Temperature range, 25° to 900° C; unit radial load, $3.5\times10^{7}$ N/m$^{2}$ (5000 psi); thrust load, 1960 N (400 lb); shaft oscillation at 1/3 or 1 Hz, ±15°.]

| Coating modification | Bearing | Total shaft oscillation, cycles | Total radial wear | | Average wear coefficient for test, cm$^{3}$/(cm)(kg) | Comments |
|---|---|---|---|---|---|---|
| | | | cm | in. | | |
| Nichrome - 20 wt. % glass on journal | 1 | $10.5\times10^{3}$ | $5\times10^{-3}$ | $2\times10^{-3}$ | $100\times10^{-11}$ | Bearing 1 was cleaned between each of three tests; additional wear after $10.5\times10^{3}$ cycles not detectable; this result shows beneficial effect of run-in if initial debris is removed |
| | | 23.2 | 5 | 2 | 46 | |
| | | 38.0 | 5 | 2 | 29 | |
| | 2 | $11.7\times10^{3}$ | $4\times10^{-3}$ | $1.5\times10^{-3}$ | $70\times10^{-11}$ | -------------------- |
| | 3 | 23.0 | 17.5 | 6.9 | 210 | Small amount of spalling |
| | 4 | 24.0 | 48 | 19 | 630 | Coatings spalled to cause high wear well into substrate metal |
| | 5 | 6.0 | (a) | (a) | (a) | |
| Nichrome - 20 wt. % glass in bearing bore | 6 | $3\times10^{3}$ | $5.4\times10^{-3}$ | $2.1\times10^{-3}$ | $384\times10^{-11}$ | -------------------- |
| Nichrome - 16.5 wt. % $CaF_2$ - 16.5 wt. % glass in bore | 7 | $12\times10^{3}$ | $<0.25\times10^{-3}$ | $0.1\times10^{-3}$ | $<2\times10^{-11}$ | Average wear coefficient increases with test duration because of abrasive action of entrapped wear debris (bearings ran full cycles shown without stops for removal of wear debris) |
| | 8 | 20 | 2.6 | 1 | 22 | |
| | 9 | 12 | <.25 | .1 | <2 | |
| | | 54 | 23 | 9.0 | 126 | |

[a] Severe surface damage.

## TABLE IV. - INFLUENCE OF TEMPERATURE ON WEAR OF 0.025-CENTIMETER-THICK NICHROME - 20-WEIGHT-PERCENT-GLASS COMPOSITE ON JOURNAL IN BEARING TESTS

[Unit radial load, $3.5\times10^{7}$ N/m$^{2}$ (5000 psi); thrust load, 1960 N (440 lb); shaft oscillation at 1/3 or 1 Hz, ±15°.]

| Bearing | Temperature, °C | Total shaft oscillation, cycles | Total radial wear | | Average wear coefficient, cm$^{3}$/(cm)(kg) |
|---|---|---|---|---|---|
| | | | cm | in. | |
| 10 | 25 to 500 | $7.1\times10^{3}$ | $10\times10^{-3}$ | $4\times10^{-3}$ | $360\times10^{-11}$ |
| 11 | 25 to 500 | 7.3 | 7.6 | 3 | 250 |
| [a]1 | 25 to 900 | 10.5 | 5 | 2 | 100 |
| 12 | 650 | 7.9 | 2.6 | 1 | 57 |

[a] See table III.

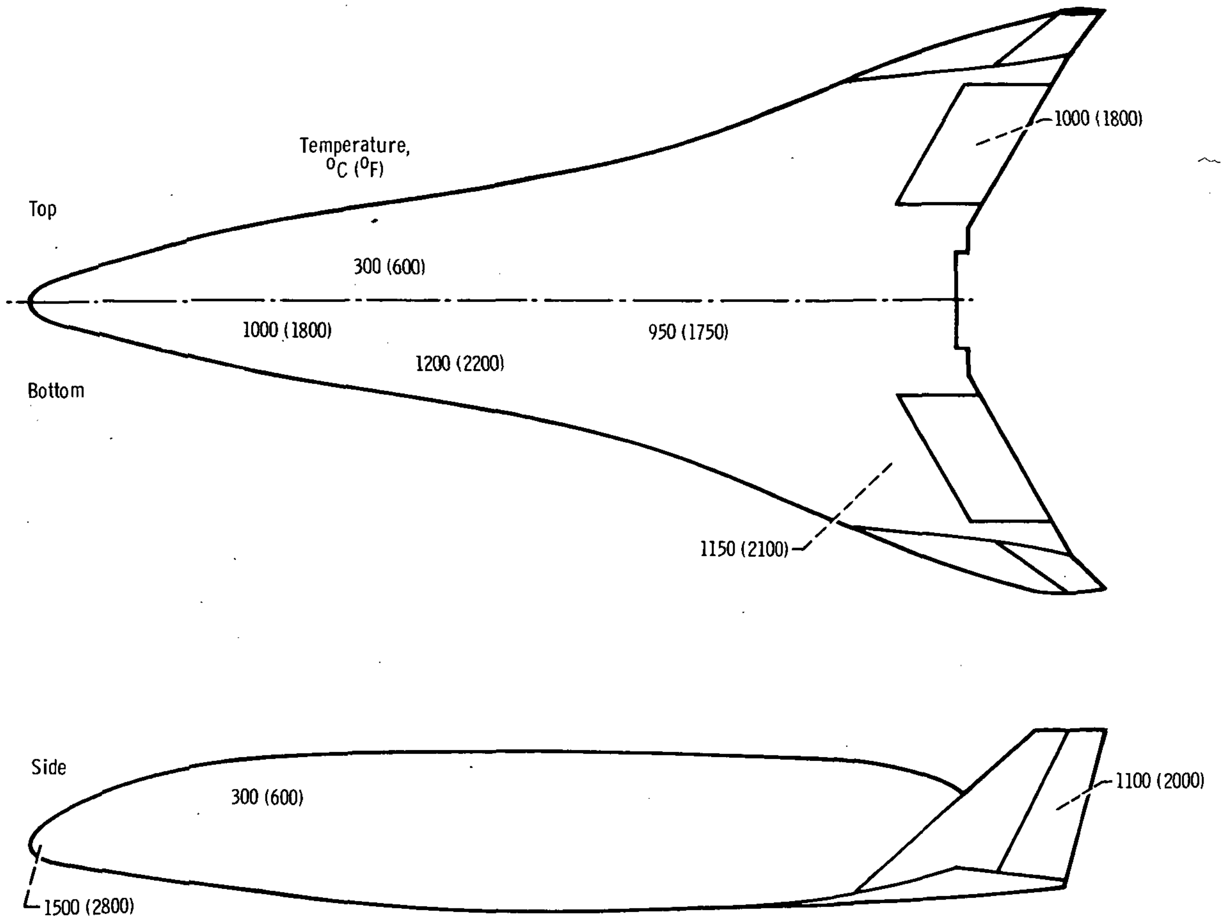
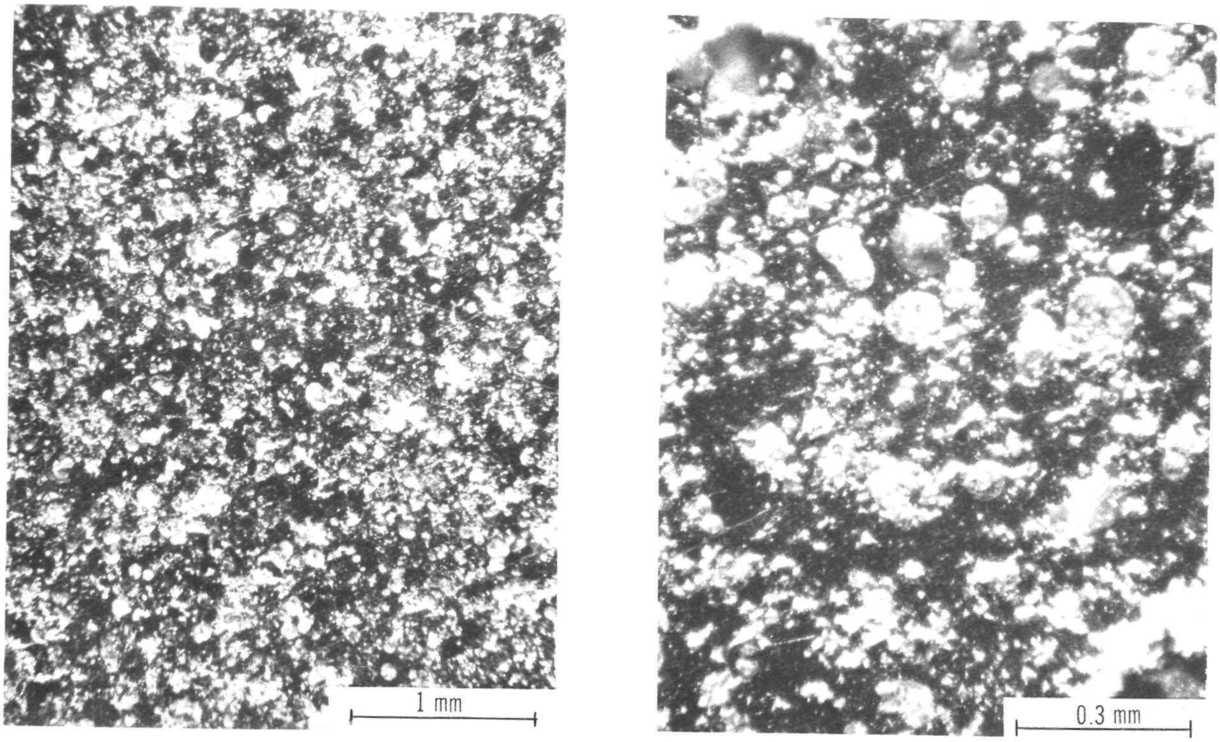
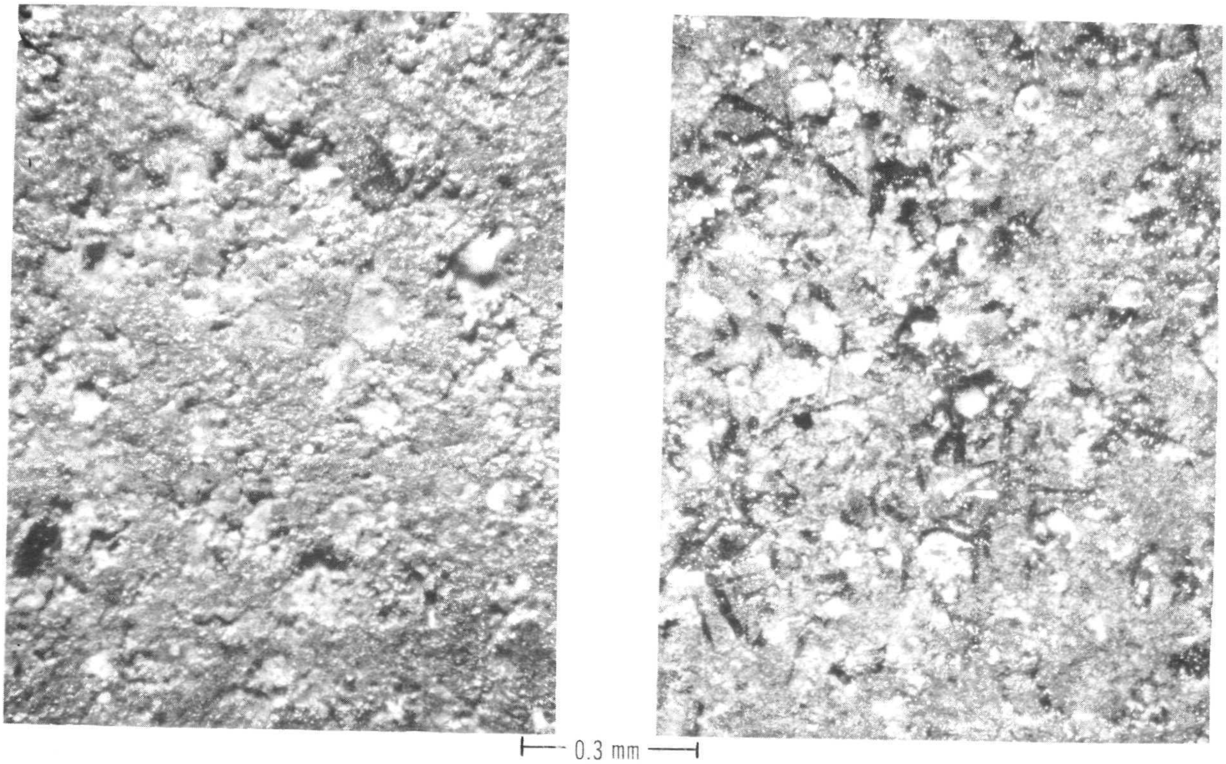


Figure 1. - Approximate temperature distribution for one concept of Space Shuttle Orbiter (ref. 1).



(a) Machined and sanded.

(b) Same as (a), at higher magnification.



(c) Machined, sanded, and heat-treated in air for 4 hours at 816° C.

(d) Machined, sanded, and heat-treated in air for 20 hours at 816° C.

Figure 2. - Photomicrographs of plasma-sprayed Nichrome-$CaF_2$-glass composite after different surface-conditioning pretreatments.

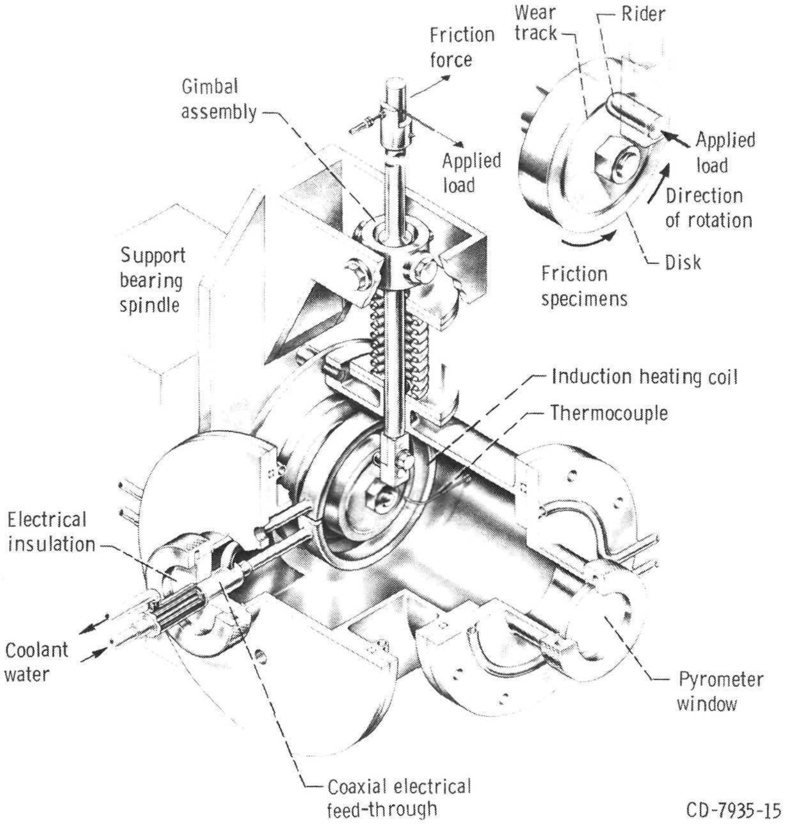
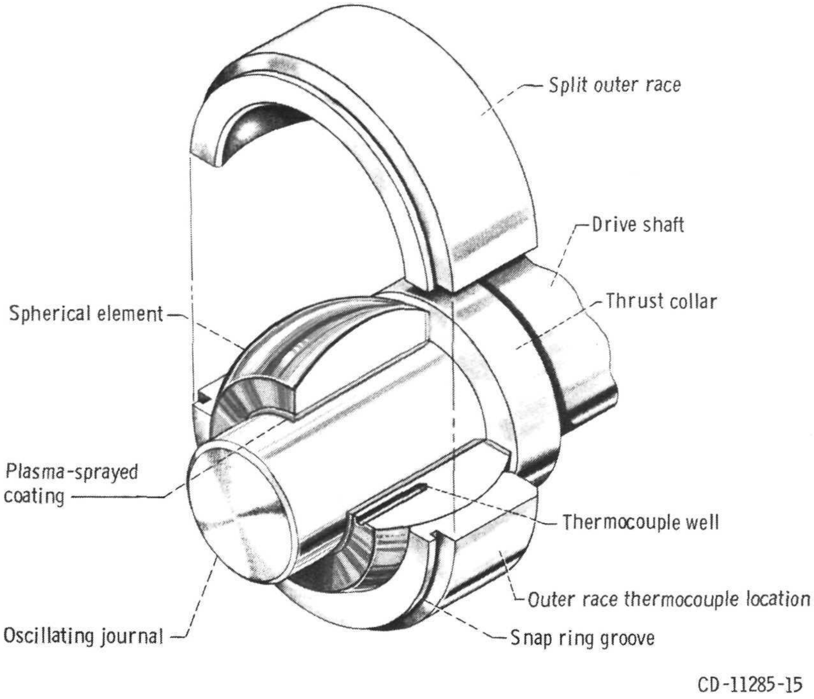
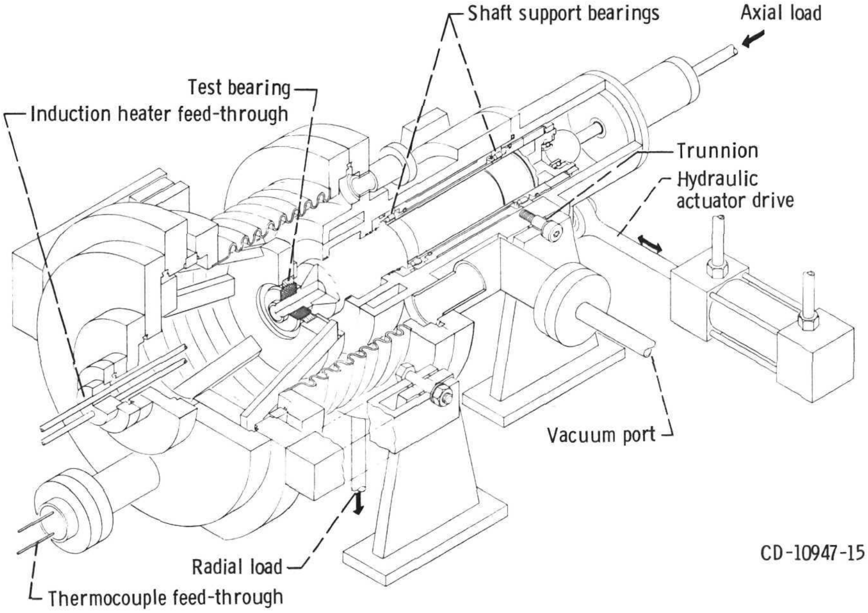


Figure 3. - High-temperature friction apparatus.



(a) Bearing.



(b) Test rig.

Figure 4. - Spherical test bearing and high-temperature oscillating bearing test rig.

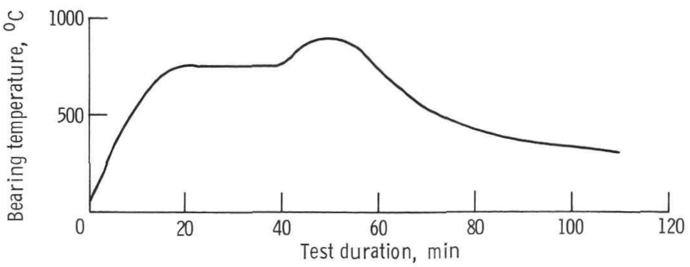


Figure 5. - Bearing test temperature profile. This is estimated reentry temperature profile for space shuttle airframe bearings without thermal protection.

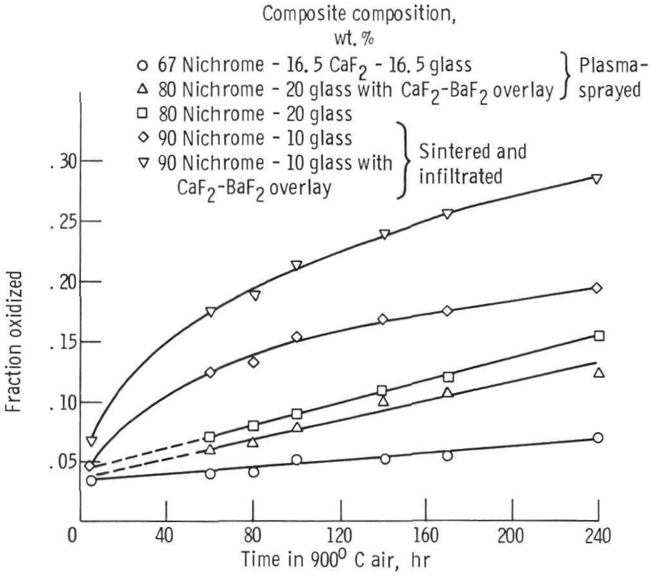


Figure 6. - Oxidation of Nichrome matrix in various self-lubricating composites.

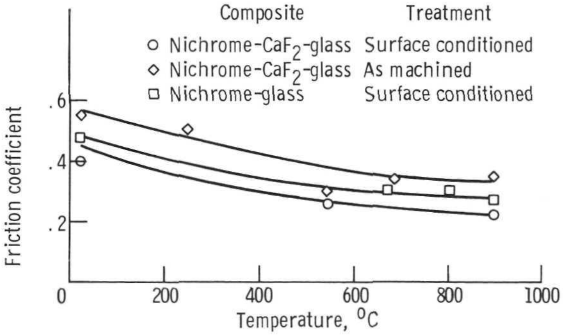
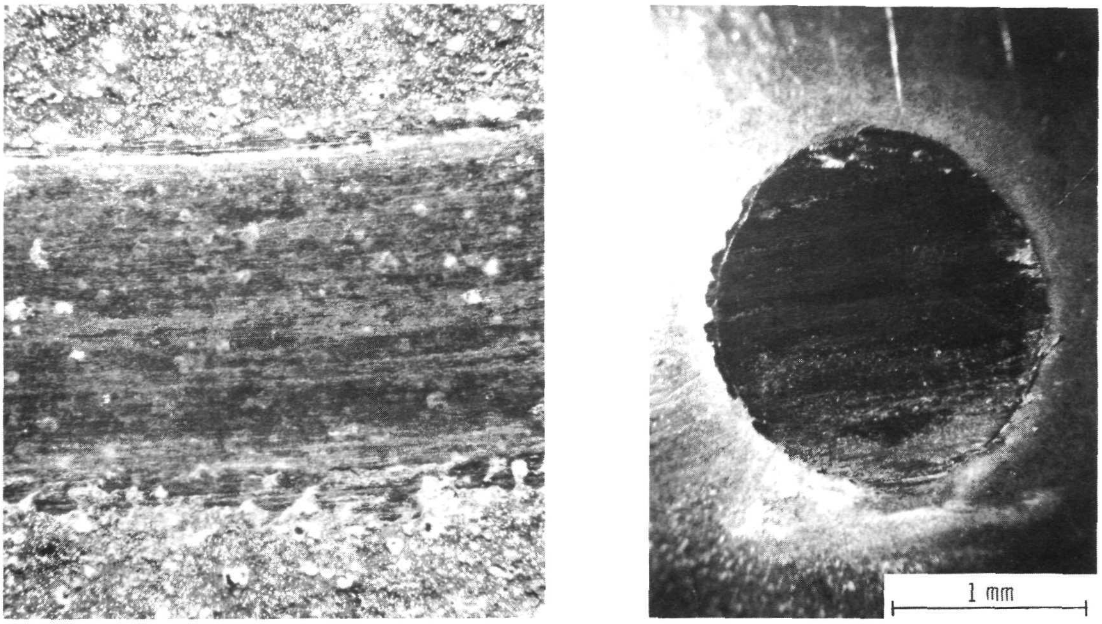


Figure 7. - Friction of some plasma-sprayed composites in pin-on-disk experiments. Load, 1 kilogram; sliding velocity, 160 centimeters per second (600 rpm).



(a) Disk. (b) Pin.

Figure 8. - Photomicrographs of sliding surfaces on plasma-sprayed disk and René 41 pin. Load, 1 kilogram; sliding velocity, 160 centimeters per second (600 rpm); test temperature, room temperature to 900° C; coating composition: Nichrome - 16½ weight percent $CaF_2$ - 16½ weight percent glass; composite heat-treated for 4 hours at 816° C before friction and wear test.

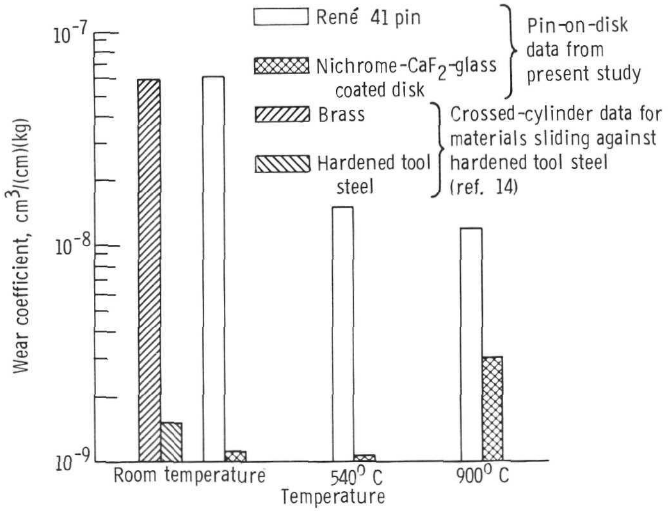


Figure 9. - Wear during pin-on-disk experiments. Load, 1 kilogram; sliding velocity, 160 centimeters per second (600 rpm).

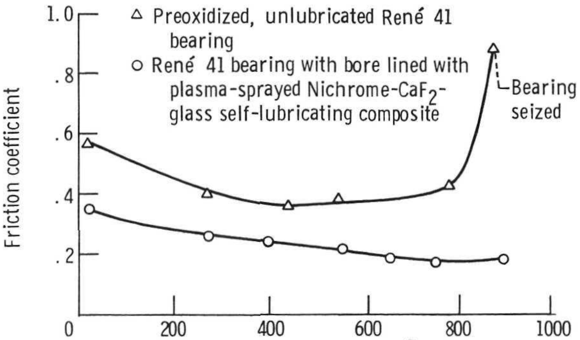


Figure 10. - Friction of self-alining plain cylindrical bearings. Unit radial load, 3.5x10$^7$ newtons per square meter (5 ksi); thrust load, 1960 newtons (440 lb); journal oscillating ±15° at 1/2 hertz.

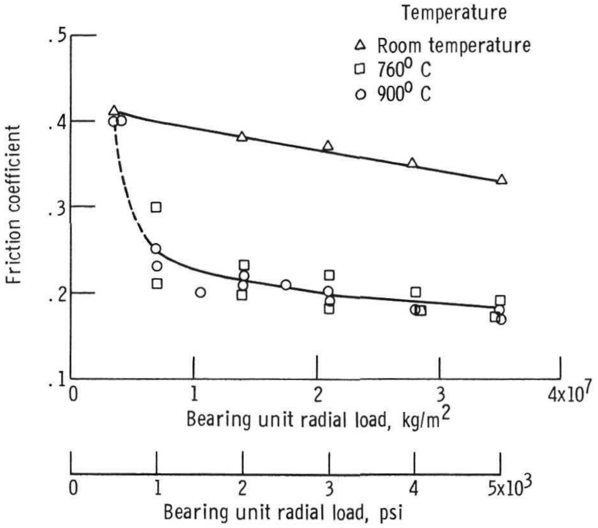
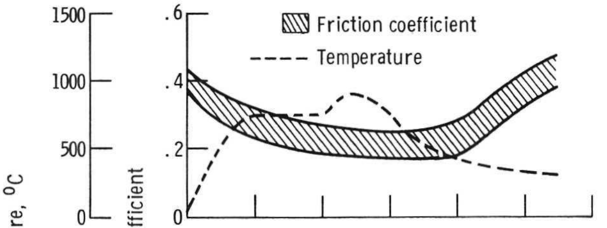
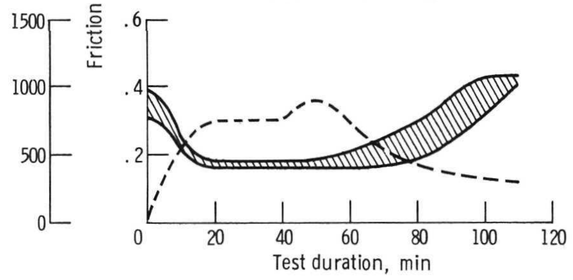


Figure 11. - Effect of load on friction of bearings with Nichrome-CaF$_2$-glass composite liner in bore.



(a) First three tests.



(b) Last nine tests.

Figure 12. - Bearing friction scatter during 12 simulated reentry temperature tests with same bearing. Composition of liner in bearing bore: Nichrome - $16\frac{1}{2}$ weight percent CaF$_2$ - $16\frac{1}{2}$ weight percent glass.

NASA-Langley, 1974 E-7574

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