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GRAPHITE-FIBER-REINFORCED POLYIMIDE LINERS OF VARIOUS COMPOSITIONS IN PLAIN SPHERICAL BEARINGS

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GRAPHITE-FIBER-REINFORCED POLYIMIDE LINERS OF VARIOUS COMPOSITIONS IN PLAIN SPHERICAL BEARINGS

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Abstract

A plain spherical bearing design with a ball diameter of 28.6 mm, a race length of 12.7 mm, and a 1.7-mm-thick, molded composite liner was evaluated. The liner material is a self-lubricating composite of graphite-fiber-reinforced polyimide resin (GFRPI). The liner is prepared by transfer molding a mixture of one part chopped graphite fiber and one part partially polymerized resin into the space between the bearing ball and the outer race and then completing the polymerization under heat and pressure. Several liner compositions were evaluated: two types of polyimide, condensation and addition; two types of graphite fiber, low and high modulus; and four powder additives - cadmium oxide (CdO), cadmium iodide (CdI_2), graphite fluoride $(CF_{1.1})_n$, and molybdenum disulfide (MoS_2). The bearings were oscillated ±15° at 1 Hz for 20 kilocycles under a radial unit load of 29 MN/m^2 (4200 psi) in dry air at 25°, 200°, or 315° C. Both types of fiber and polyimide gave low friction and wear. Friction and wear were high during "run-in" but stabilized at lower values during the rest of the test. The average increase in radial clearance (initially zero) was 40±15 μm (1.6±0.6 mil). A simple equation was developed to fit the wear-time data and adequately predicted wear to 100 kilocycles. Wear coefficients increased 8×10^{-7}, 17×10^{-7}, and 23×10^{-7} mm^3/N-m and friction coefficients decreased 0.15, 0.10, and 0.06 with temperature: 25°, 200°, and 315° C. Additives were helpful only with very high loads or extremely dry environments.

INTRODUCTION

Self-lubricating composites of polymers with various solid lubricant powders and other fillers or reinforcing fibers are an important class of bearing material. Thermoplastic polymers such as the acetals and polyamides are commonly used partly because they are conveniently formed by injection molding (1, 2). Molybdenum disulfide (MoS_2) and graphite powders, which are often used as fillers to reduce friction, usually weaken the structure. Graphite fiber fillers, on the other hand, both lubricate and reinforce (3). The graphite-fiber-reinforced thermoplastics can therefore provide both good lubrication and high strength.

One important use of polymer composites is for self-lubricating liners in plain spherical, oscillating bearings. In aircraft, plain spherical bearings are used extensively throughout the airframe as control surface bearings and as pivot bearings in hydraulically actuated, mechanical linkages as well as in actuator linkages for engine controls.

Because of the aerodynamic heating in supersonic aircraft, airframe bearings with upper temperature limits above 300° C are needed. Engine control bearings can also be exposed to high temperatures from the engine. Most polymers in current use are limited to service temperatures below 260° C. For higher temperatures, a more thermally stable polymer such as a polyimide can be used. Although the self-lubricating behavior of polyimides with a graphite powder filler has been known for some time (4-6), tribological studies of graphite-fiber-reinforced polyimides (GFRPI) are a more recent development (7-9). Polyimide materials can be used at light loads to perhaps 390° C (6), but for high loads and long duration the temperature limit is about 300° to 340° C for those polyimides evaluated so far as bearing materials (10).

A preliminary study of GFRPI composites in plain spherical bearings showed the feasibility of using this composite as the ball material in such bearings (8). For fiber contents to 60 weight percent, the best combination of strength and tribological properties was achieved with a fiber-resin weight ratio of approximately 1. Later work (10, 11) showed that the dynamic unit load capacity of a plain spherical bearing with a GFRPI ball is about 7.0×10^7 N/m^2 (10 000 psi) at 25° C and about one-half that value at 340° C. Plain cylindrical bearings with thin-wall GFRPI liners had a higher load capacity than a plain spherical bearing with a GFRPI ball, 2.8×10^8 N/m^2 (40 000 psi), at 25° C - with only a moderate decrease at higher temperatures. Therefore, GFRPI alone may be used as the ball material in plain spherical bearings for light to moderate loads, but higher loads require a metal ball and a GFRPI-lined outer race.

Experimental, GFRPI-lined, plain spherical bearings were designed at NASA Lewis and made by a bearing manufacturer[1] who also developed the necessary molding and other fabrication procedures. Addition (A) and condensation (C) polyimides, as well as high-strength (H) and low-strength (L) graphite fibers, were compared. Also studied were the solid lubricant additives molybdenum disulfide (MoS_2) and graphite fluoride $(CF_{1.1})_n$ and the lubricating adjuvants cadmium iodide (CdI_2) and cadmium oxide (CdO). The effects of a vacuum degassing pretreatment and atmospheric moisture were determined.

Bearing tests were performed to determine wear and friction at 25°, 200°, and 315° C. In most tests, the load was 29 MN/m^2 (4200 psi), but a few tests were run at unit loads to 100 MN/m^2 (14 500 psi). The balls were oscillated against the GFRPI liner at a frequency of 1 Hz and an amplitude of ±15°.

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[1] Marlin Rockwell Division of TRW, Jamestown, N.Y.

STAR Category 27

MATERIALS

The composites used in this study were made from a mixture of graphite fibers and polyimide resin at a weight ratio of 1. The fibers were chopped into lengths of 6.4×10^{-3} m (0.25 in.) and were dispersed as randomly as possible throughout the polyimide matrix. (Although the fiber orientation was multiaxial, it probably was not perfectly random because some preferred ordering is likely during the molding process.) Two types of graphite fibers were evaluated. Typical properties are listed in Table I. The fiber L had a low tensile strength and a low elastic modulus. The fiber H had a medium tensile strength and a high elastic modulus.

Two types of polyimide resins were also evaluated. Both were formulated to eliminate voids in the final cured polymer. Polyimide A was an addition polyimide that was highly crosslinked. Polyimide C was a condensation polyimide that was linear, amorphous, and essentially noncrosslinked.

Four combinations of these fibers and polyimides were evaluated: the addition polyimide with the low-modulus fiber (composite AL), the addition polyimide with the high-modulus fiber (composite AH), the condensation polyimide with the low-modulus fiber (composite CL), and the condensation polyimide with the high-modulus fiber (composite CH). In addition to these four materials, composites were prepared in which 10 percent (by weight) of either $(CF_{1.1})_n$ powder, CdI_2 powder, or CdO powder was added to the CH composites. Type CH composites with 16-percent $(CF_{1.1})_n$ or 20-percent MoS_2 were also made. These solid lubricant additives were incorporated into the polyimide/graphite-fiber mixture before polymerization.

The bearing ball and ring material was 440C high-temperature stainless steel hardened to Rockwell C60. The balls had a surface finish of 10^{-7} m (4 μin.). The outer ring was machined with an internal spherical radius with a slip-fit clearance with the ball diameter (no swaging). The resulting thickness of the composite liner was 1.7 mm (68 mil). The test bearing design, with additional relevant dimensions, is shown in Fig. 1. The projected area of this bearing (ball diameter times liner length) is 363 mm^2 (0.563 in^2).

MOLDING PROCEDURES

The liners were made by transfer-molding the polymer/graphite-fiber mixture into the space between the ball and race and then completing the polymerization under heat and pressure. The ball and race were mounted for accurate concentricity and functioned as the main elements of the mold. The ball was precoated with a mold-release to minimize adhesion between the ball and the composite. Molding procedures for mixtures with either the condensation or addition polymer are detailed in Table II.

TEST PROCEDURE

Apparatus

The apparatus for testing self-alining, plain spherical bearings is shown in Fig. 2. The test bearing was held in a housing that can be heated by an induction coil. The ball was oscillated ±15° at 1 Hz by a reciprocating hydraulic drive. Oscillation of the ball against the liner was at a uniform speed with rapid direction reversal. The average speed was 15 mm/s. The standard test duration was 20 kilocycles (5.6 hr). A slight axial load was hydraulically applied to aline the journal. The test load, a radial load to the test bearing, was pneumatically applied to the journal. The load, 10 500 N (2350 lb), on the bearing projected area produced a radial unit load of 29 MN/m^2 (4200 psi). Thus, the operating P-V was 0.43 MN/m-s.

Measurements

Friction force was measured by a preloaded piezoelectric load cell mounted in the drive arm. This signal, proportional to the tension and compression during the stroke, was recorded on a strip chart. Wear was measured by two methods: (1) radial displacement of the journal as measured with a dial gage on the shaft assembly; and (2) bearing weight loss.

Since bearing weight changes were complicated by moisture adsorption and desorption, all pre- and post-test weighings were done after prolonged storage in the same atmosphere. Storage and weighings were repeated until the weight remained constant, to insure that equilibrium with the storage atmosphere had been achieved.

Two test sequences were used in this program: the first sequence involved testing each bearing, as received from the manufacturer, in dry air: first at 25° C, then at 200° C, and finally at 315° C. The second involved degassing each bearing for 16 hours at a vacuum of 100 millitorr at about 120° C before testing it.

Wear Coefficient Calculation

The wear coefficient, wear volume per unit load per unit sliding distance, was calculated from both weight loss measurement and journal displacement. Wear volume was calculated both as the net weight loss divided by the composite density (1.5 g/cm^3) and as the radial wear multiplied by the projected area of the bearing (363 mm^2). These wear volumes were then divided by the bearing load (10^4 N) and the sliding distance (15 mm per oscillating cycle). The lower limit and accuracy of the wear coefficient are 5×10^{-7} mm^3/N-m, based on a journal displacement of 4 μm in 20 kilocycles of oscillation, and 1×10^{-7} mm^3/N-m, based on a weight loss of 0.5 mg in 20 kilocycles.

RESULTS AND DISCUSSION

Wear of GFRPI Composites Without Additives

The increase in radial clearance (initially zero), as measured by journal displacement, during bearing oscillation are shown in Fig. 3 for the four base compositions at the three test temperatures: 25°, 200°, and 315° C. Because the wear was widely scattered during the run-in period, arbitrarily taken as the first 2000 cycles, stabilized wear was defined as that occurring between 2 and 20 kilocycles of oscillation.

Total wear, run-in wear, and the calculated wear rates for both run-in and stabilized conditions are given in Table III. Neither type of polyimide or filler gives a clear advantage. The average total wear depths for the four GFRPI composites are: 56 μm at 25° C, 28 μm at 200° C, and 42 μm at 315° C. Excluding the lowest (15 μm) and highest (81 μm), the average increase in radial clearance was 40 ± 15 μm (1.6 ± 0.6 mil). However, since the same bearing was used progressively in testing first at 25° C and then at 200° and 315° C, the effect of run-in predominated at 25° C. This is substantiated by weight loss measurements, which are presented later in this section.

An algebraic expression of the form

$$y = aN^b \ . \ . \ . \qquad (1)$$

can be fit to the wear data of Fig. 3 and Table I. In this expression, y is radial wear depth, N is the number of bearing oscillations, and a and b are evaluated constants. The constants are determined by simultaneously solving equation (1) using the experimental values (Table II) of radial wear, y, at N of 2 and 20 kilocycles. The constant, a, is the controlling term during early wear and equals y at $N = 1$ kilocycle. The constant, b, assumes more importance at high values of N; for b much less than unity, steady-state wear rates are much lower than run-in wear rates.

Figure 4 gives calculated curves for CH liners at 25° C and for AL liners at 315° C, all at a 29 MN/m^2 (4200 psi) unit load. These curves were selected for this figure because they establish typical, but not extreme, upper and lower boundaries of wear for the composite liners at all three temperatures.

The equation for the upper wear curve is

$$y = 44\ N^{0.046}\ \mu\text{m} \qquad (2)$$

The equation for the lower wear curve is

$$y = 6.8\ N^{0.29}\ \mu\text{m} \qquad (3)$$

The data points at 2 and 20 kilocycles that were used to calculate the constants for equations (2) and (3) are shown in Fig. 4. The calculated curves were extended to $N = 100$ kilocycles. Wear data for six experiments, which were each run for 100 kilocycles, are superimposed on this figure. They all fall within the range predicted by the calculated curves.

Friction of GFRPI Composites Without Additives

Friction coefficients measured during bearing oscillation are shown in Fig. 5 for the four GFRPI compositions at the three test temperatures. In general, friction coefficients initially were 0.12 to 0.18. At 25° C they remained relatively constant; but at higher temperatures they stabilized at lower levels: 0.08 to 0.12 at 200° C, and 0.04 to 0.08 at 315° C. This friction reduction may be associated with the transfer film that forms on the contacting metallic ball surface, lubricating wear debris trapped between the ball and the liner, and possibly the crystallographic orientation of graphite and polyimide at the sliding interface.

The beneficial effect of nonabrasive wear debris on subsequent sliding has been studied by Play and Godet (12). In their model, nonabrasive wear debris becomes compacted within the sliding contact and acts as a "third body" to supplement lubrication of the primary rubbing surfaces. This model appears to be applicable to GFRPI composite liners.

Wear of GFRPI Composites With Additives

Ten percent by weight of a powdered compound - either CdO, CdI_2, or $(CF_{1.1})_n$ - was added to CH composites (condensation polyimide and high-modulus graphite fiber). Cadmium oxide and cadmium iodide were chosen because they have long been known to improve lubrication of graphite in dry air (13, 14). Graphite fluoride was chosen because it is an intercalation compound of graphite that has low friction and long endurance when used as a polyimide-bonded, dry film lubricant at temperatures to 315° C and above (15).

Wear-time data for these three composites are compared in Fig. 6 with the base composite at the three test temperatures. The wear data are summarized in Table IV. The results show that the additives give no clear advantage under these bearing test conditions. In general, the wear of composites with additives fell within the band for base composites in Fig. 4 (15 to 50 μm). The insensitivity of graphite-fiber-reinforced polymers to solid-lubricant additives has also been observed by Giltrow (14).

Average Wear Coefficients of GFRPI Composites

To consolidate the data, we averaged the wear of the four base composites and the CH composite with 10 weight percent of either CdO, CdI_2, or $(CF_{1.1})_n$ for each of the three test temperatures (fig. 7). Coefficients calculated from weight loss data and from displacement measurements of equilibrium wear correlate well with each other. Wear coefficients increase moderately with temperature in dry air: 8×10^{-7}, 17×10^{-7}, and 23×10^{-7} mm^3/N-m at 25°, 200°, and 315° C, respectively. The higher wear coefficient at 25° C (15×10^{-7} mm^3/N-m) is due to the larger journal displacement during the initial test of these bearings.

These data agree reasonably well with the bearing wear coefficient of 12×10^{-7} mm^3/N-m reported in Ref. 10 for AL-type GFRPI composites tested in 25° C air with about 50-percent relative humidity. In that study, the temperature effect was even less: wear coefficients were typically 12×10^{-7} mm^3/N-m at both 25° and 315° C. In tests by Fusaro (7) involving 440C pins sliding on GFRPI disks in air of 50-percent relative humidity, the wear coefficients for GFRPI composites were $(13 \pm 4) \times 10^{-7}$ mm^3/N-m at 25° C and $(15 \pm 3) \times 10^{-1}$ mm^3/N-m at 300° C.

Friction With GFRPI Composites Containing Additives

The continuous friction coefficient - time data for the CH composite containing 10 weight percent of either CdO, CdI_2, or $(CF_{1.1})_n$ are compared in Fig. 8 with data for the base composite at the three test temperatures. In no case did the additives reduce friction and in some cases they significantly increased it. However, the friction coefficients did not exceed about 0.19.

Several bearings were also tested with composite liners that contained either more $(CF_{1.1})_n$ - 16 weight percent - or 20-weight-percent MoS_2. In these experiments the effect of load on friction was studied. Some preliminary data are shown in Fig. 9. Of the three materials (the base composite and the two composites with an additive), friction was lowest for the base composite at loads to 38 MN/m^2 (5500 psi). At higher loads, the $(CF_{1.1})_n$ additive reduced friction slightly. The MoS_2 additive gave lower friction than the base composite at loads above 69 MN/m^2 (10 000 psi). That MoS_2 reduces friction with load has long been well known (16-18). Therefore, it may be a desirable additive to GFRPI composites for very high load applications, but it does not show any beneficial effect at lighter loads.

Bearing Pretreatment and Moisture Effects

Adsorbed moisture usually enhances the lubricating properties of self-lubricating composites that contain a substantial amount of graphite (19, 20). However, as previously discussed, the GFRPI composites were not adversely affected by testing in dry air. This observation and the lack of additive response raised the question of whether the residual adsorbed moisture in the as-received bearings might be functioning as a beneficial additive. To answer this, we pretreated a set of bearings in a vacuum oven (100 millitorr at 120° C) to degas them and then tested them in dry air (<20-ppm H_2O) and in vacuum.

Figure 10 shows the combined effects of bearing pretreatment and atmospheric moisture on the friction and wear of GFRPI composites without additives at 25° C. The degassing pretreatment increased both friction and wear when the bearings were tested in dry air. The increase was even greater when the bearings were tested in vacuum. However, when the pretreated bearings were tested under ambient humidity conditions (30- to 50-percent relative humidity), friction decreased with test time and wear was low (about the same as for the as-received bearings tested in dry air). Thus, some moisture is rapidly readsorbed from the ambient air although (as water adsorption studies have shown) adsorption equilibrium is achieved very slowly. Conversely, the desorption that takes place during testing of as-received bearings in dry air is not sufficient to affect bearing friction and wear. (Material must be exposed for over a week in a dry air to achieve desorption equilibrium (10).) Therefore, both a degassing pretreatment and a very dry test atmosphere are required to deteriorate the lubricating properties of GFRPI at 25° C.

We then determined the effect of additives on degassed bearings in dry air at 25° C. The friction and wear data are given in Fig. 11. The $(CF_{1.1})_n$ additive reduced friction but increased wear. The CdO and CdI_2 additives only slightly reduced friction but considerably reduced wear.

We concluded that GFRPI composites are self-lubricating under all but the most extreme moisture-free conditions at 25° C. Even under those conditions, CdO or CdI_2 are helpful in restoring the self-lubricating characteristics of the composite.

SUMMARY OF RESULTS

Composites made of graphite-fiber-reinforced polyimide (GFRPI) with a fiber-resin ratio (by weight) of about 1 were evaluated as molded outer-race liners in plain spherical bearings. Several compositions were studied: two types of polyimide (addition and condensation polymers), two types of graphite fiber (high and low modulus), and four powder additives (CdO, CdI_2, $(CF_{1.1})_n$, and MoS_2). Friction and wear were measured during oscillation (±15° at 1 Hz) at three temperatures: 25°, 200°, and 315° C. The main results were as follows:

1. All compositions provided good lubrication in dry air: after run-in, all compositions at 25°, 200°, and 315° C, respectively, had average wear coefficients of 8×10^{-7}, 17×10^{-7}, and 23×10^{-7} mm^3/N-m and average friction coefficients of 0.15, 0.10, and 0.06.

2. Despite individual differences in the lubrication behavior of the various compositions, neither type of polyimide or graphite fiber nor the additives gave a clear advantage.

3. Only under extremely dry conditions, when the bearings were first vacuum degassed and then tested in dry air or vacuum, did lubrication behavior deteriorate. Under these conditions, CdO and CdI_2 additives reduced friction and wear.

4. Wear rates (as determined by the rate of increase in bearing radial clearance) were always higher during run-in, before conditions stabilized. Wear equations were developed which defined a scatter band that fit the 20-kilocycle test data and adequately predicted wear to at least 100 kilocycles.

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TABLE I. - TYPICAL PROPERTIES OF GRAPHITE FIBERS

Property	Fiber L[a]	Fiber H[b]
Tensile strength, N/m^2 (lb/in^2)	6.2×10^8 (9.0×10^4)	2.0×10^9 (2.8×10^5)
Elastic modulus, N/m^2 (lb/in^2)	3.0×10^{10} (5.0×10^6)	3.9×10^{11} (5.7×10^7)
Length, cm (in.)	0.64 (0.25)	0.64 (0.25)
Diameter, μm (mil)	8.4 (0.33)	6.6 (0.26)
Specific gravity	1.4	1.4

[a] Low tensile strength and low elastic modulus.

[b] Medium tensile strength and high elastic modulus.

TABLE II. - PROCEDURES FOR MOLDING GRAPHITE-FIBER-REINFORCED POLYIMIDE BEARING LINERS

Procedure	Liner composition	
	Graphite-fiber-reinforced condensation polymers	Graphite-fiber-reinforced addition polymers
Mixing fibers and polymer precursor solution	Ambient	Ambient
Drying (solvent evaporation)	4 hr; 200° C	1 hr; 200° C
Precuring (B-stage polymerization)	15 hr; 230° - 260° C	1 hr; 230° C
Molding[a]	10 min; 430° C; 6.9×10^7 N/m^2 (10 000 psi)	1 hr; 320° C; 6.9×10^7 N/m^2 (10 000 psi)
Postcuring	4 hr; 260° C	4 hr; 200° C

[a] Hold under pressure and cool to 260° C before releasing mold.

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TABLE III. - WEAR DATA FOR GRAPHITE-FIBER-REINFORCED COMPOSITES

[Fiber-resin weight ratio, 1.]

Test temperature, °C	GFRPI composition code[a]	After 2 kilocycles (run-in)	After 20 kilocycles (total)	0 - 2 kilocycles (run-in)	2 - 20 kilocycles (stabilization)
		Wear (as determined from journal displacement), μm		Wear rate, μm/kilocycle	
25	AL	28	51	14	1.3
	AH	71	81	36	.56
	CL	33	48	17	.83
	CH	47	51	24	.22
200	AL	5	25	3	1.1
	AH	11	38	6	1.5
	CL	15	34	8	1.1
	CH	13	16	7	.17
315	AL	8	23	9	0.83
	AH	28	38	14	.72
	CL	38	40	19	.22
	CH	40	56	20	.89

[a] A = addition polyimide; C = condensation polyimide; H = high modulus fiber; L = low modulus fiber.

TABLE IV. - WEAR DATA FOR A GRAPHITE-FIBER-REINFORCED POLYIMIDE COMPOSITE WITH ADDITIVES

Test temperature, ^{o}C	Additive to CH-type[a] GFRPI composite	After 2 kilocycles (run-in)	After 20 kilocycles (total)	0 - 2 kilocycles (run-in)	2 - 20 kilocycles (stabilized)
		Wear (as determined from journal displacement), μm		Wear rate, μm/kilocycle	
25	None	47	51	24	0.22
	CdO	43	55	23	.67
	CdI_2	25	35	13	.56
	$(CF_{1.1})_n$	35	38	18	.17
200	None	13	16	7	0.11
	CdO	31	33	17	.11
	CdI_2	31	41	17	.56
	$(CF_{1.1})_n$	20	30	10	.56
315	None	40	56	20	0.89
	CdO	18	46	9	1.6
	CdI_2	38	56	19	1.0
	$(CF_{1.1})_n$	25	53	13	1.6

[a] CH = condensation polyimide with weight ratio 1 of high modulus fiber.

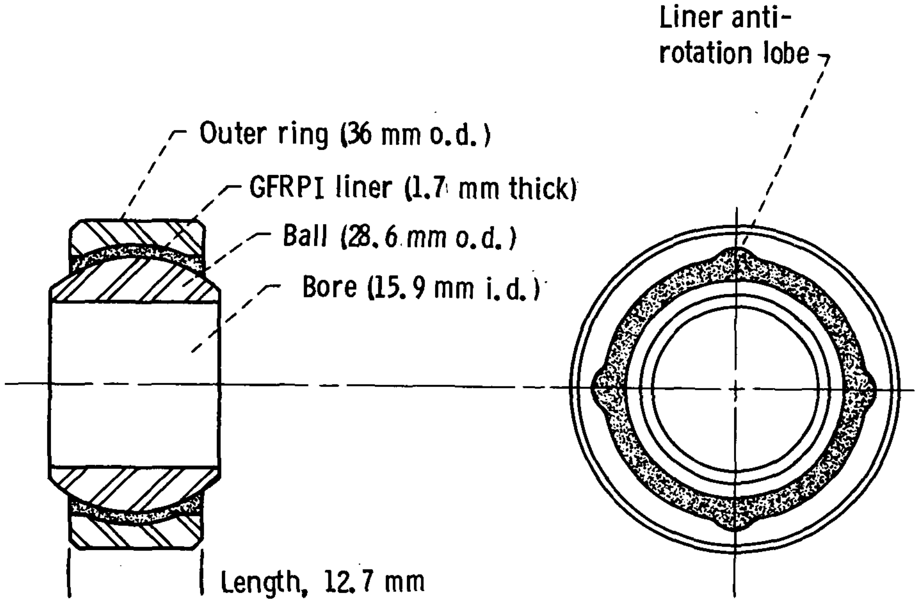


Figure 1. - Design of test bearing.

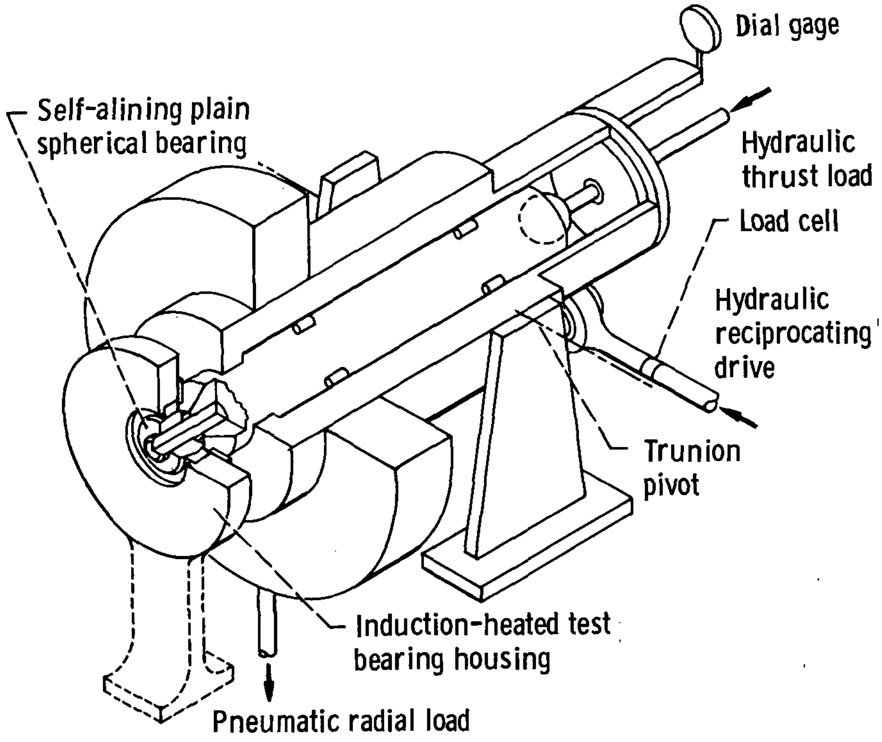
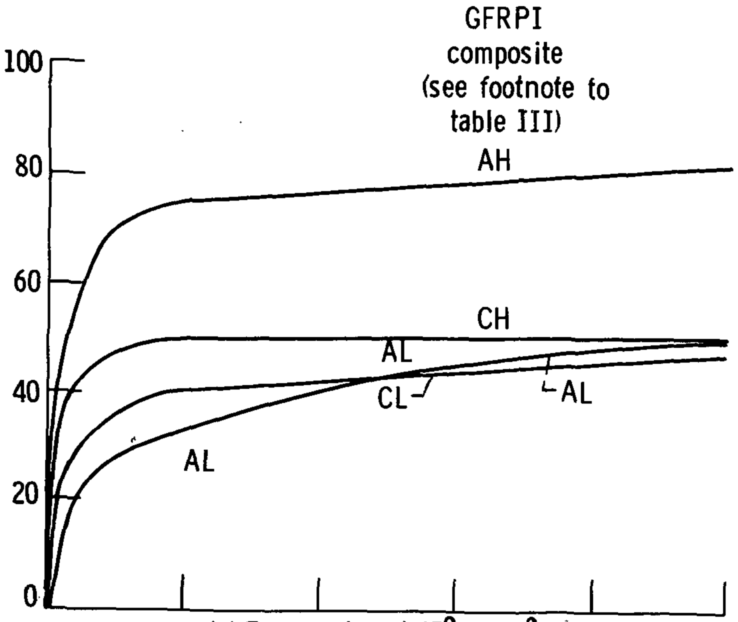
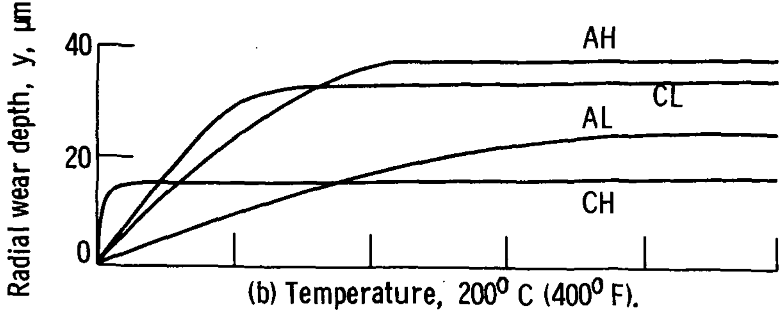


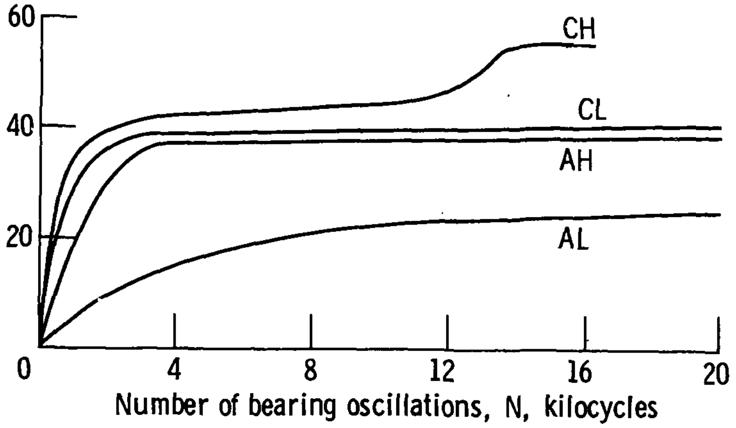
Figure 2. - Schematic of apparatus for testing self-alining, plain spherical bearings.



(a) Temperature, 25° C (85° F).



(b) Temperature, 200° C (400° F).



(c) Temperature, 315° C (600° F).

Figure 3. - Continuous wear characteristics of four graphite-fiber-reinforced composites. Unit load, 2.9×10^7 N/m^2 (4200 psi); oscillation of ±15 degrees at 1 hertz in dry air (<20-ppm H_2O).

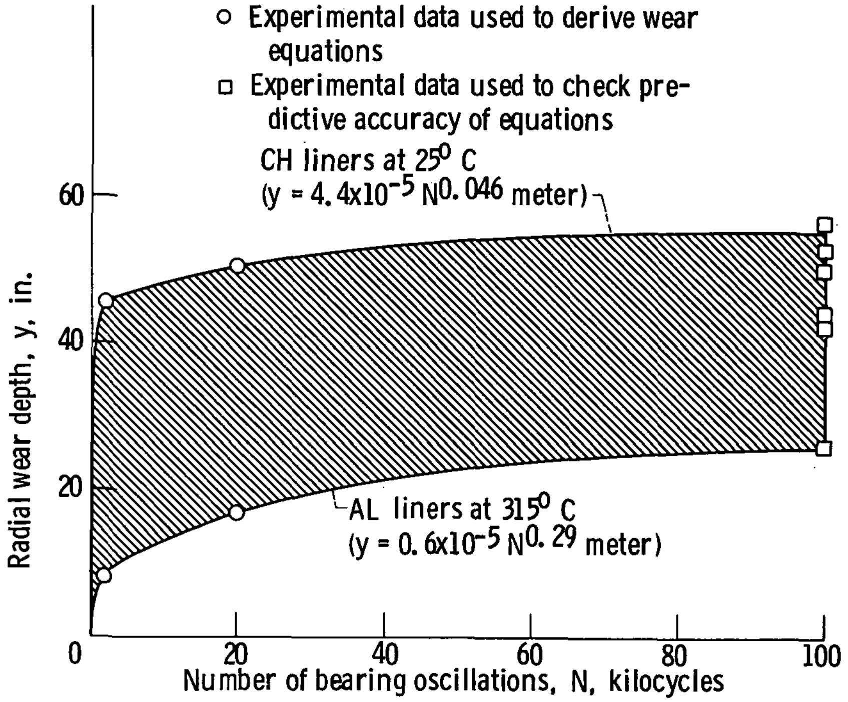
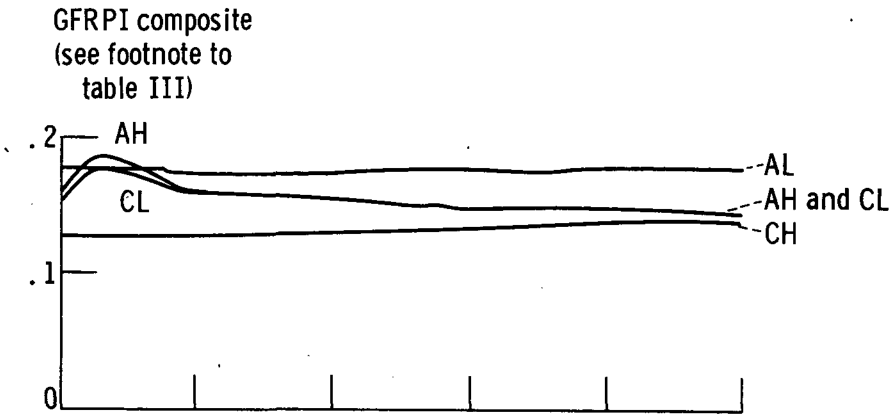
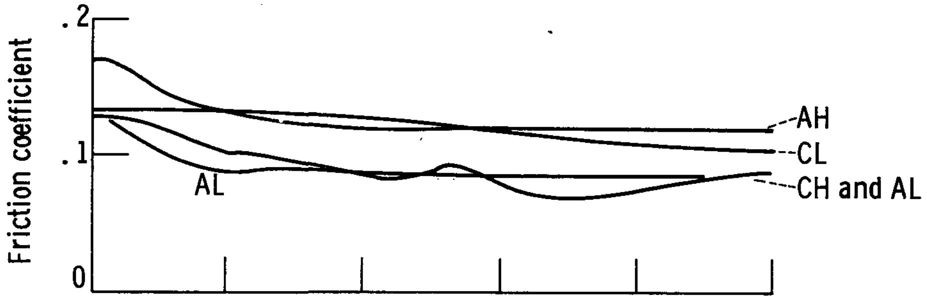


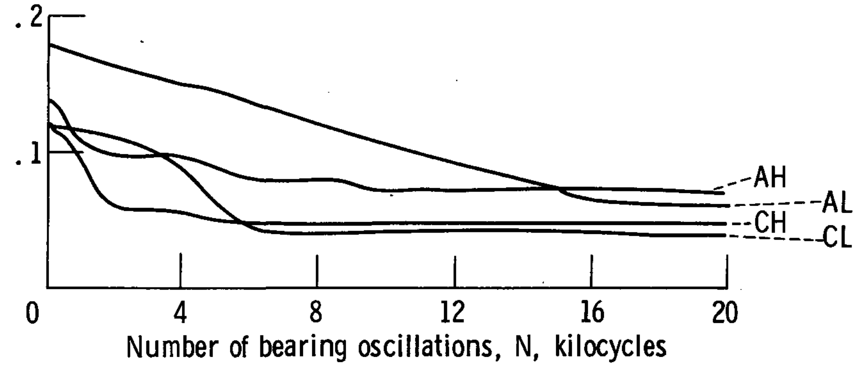
Figure 4. - Probable wear range for graphite-fiber-reinforced polyimide composite liners at temperatures from 25° to 315° C and at a unit load of 2.9×10^7 N/m^2 (4200 psi). (Constants for data fit equations calculated from experimental wear data at 2 and 20 kilocycles.)



(a) Temperature, 25° C (85° F).

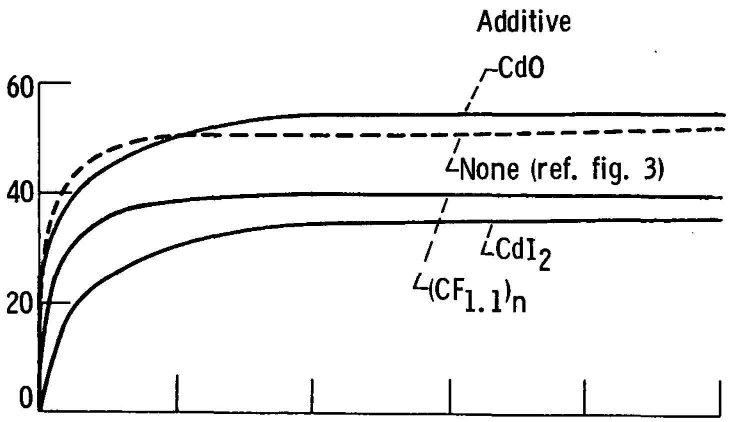


(b) Temperature, 200° C (400° F).

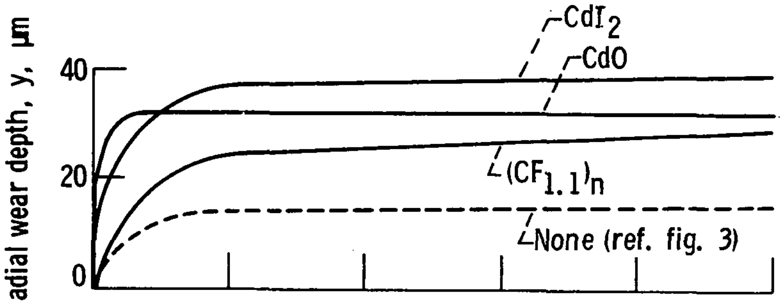


(c) Temperature, 315° C (600° F).

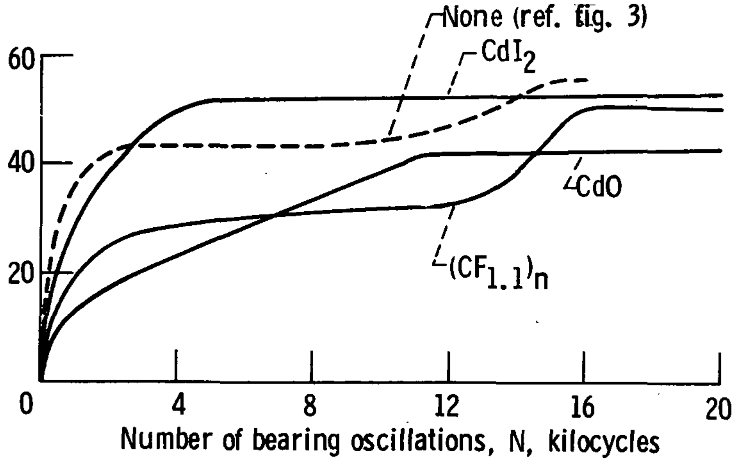
Figure 5. - Continuous friction characteristics of four graphite-fiber-reinforced polyimide composites. Unit load, 2.9×10^7 N/m^2 (4200 psi); oscillation of ± 15 degrees at 1 hertz in dry air (< 20-ppm H_2O).



(a) Temperature, 25° C (85° F).



(b) Temperature, 200° C (400° F).



(c) Temperature, 315° C (600° F).

Figure 6. - Effect of 10-weight-percent additives on continuous wear characteristics of graphite-fiber-reinforced polyimide bearing liners made of condensation polymers with medium-tensile-strength and high-elastic-modulus fibers (CH composites). Unit load, 2.9×10^7 N/m^2 (4200 psi); oscillation of ±15 degrees at 1 hertz in dry air (<20-ppm H_2O).

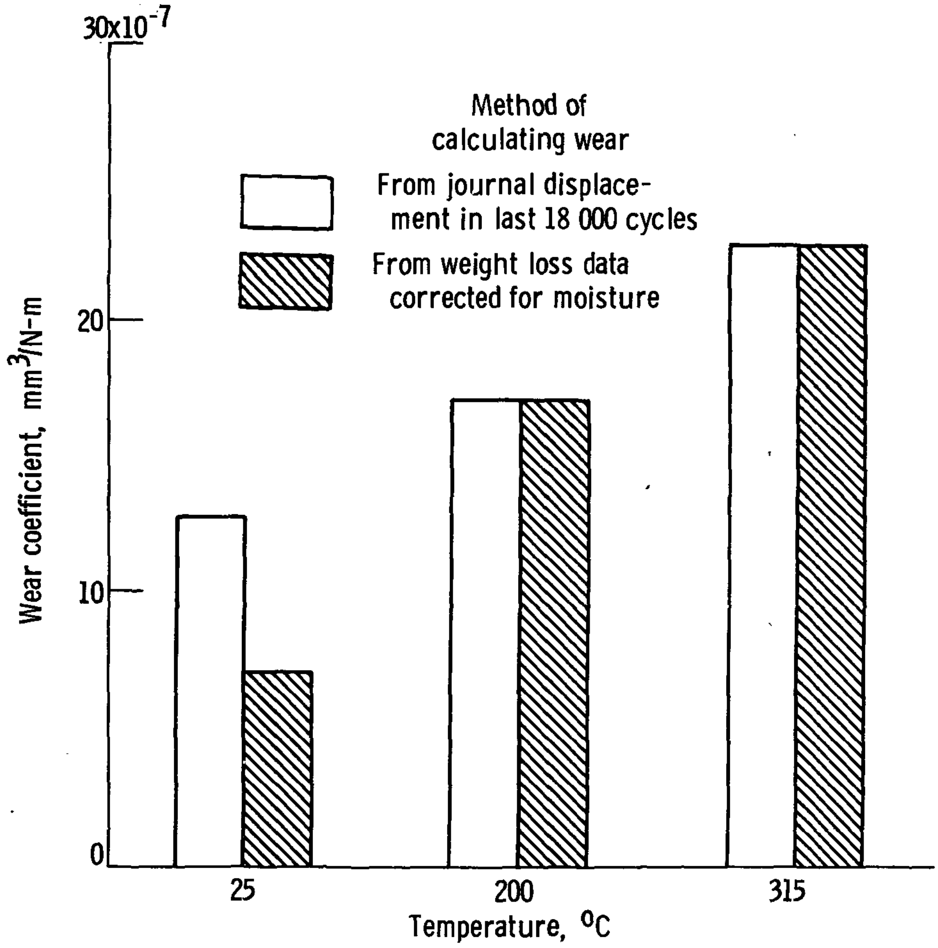
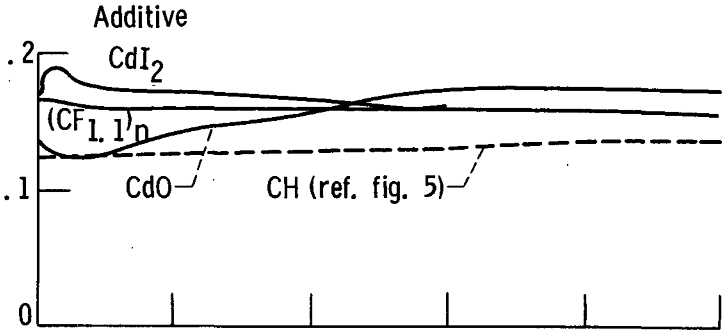
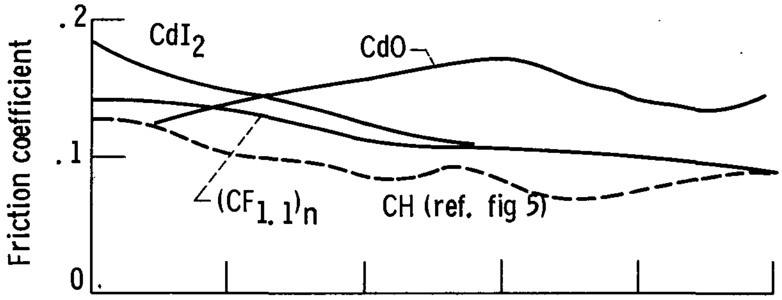


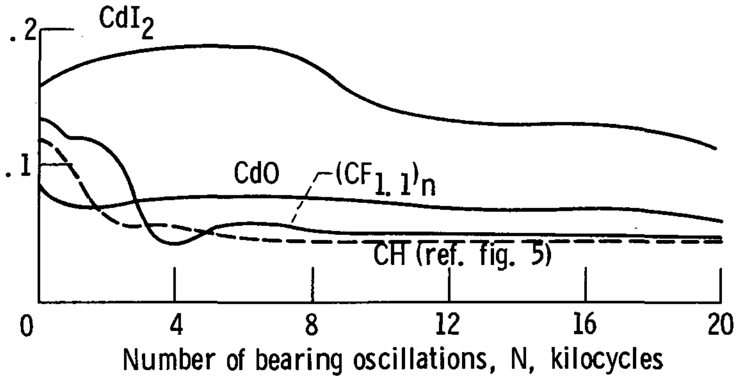
Figure 7. - Average wear coefficients for seven graphite-fiber-reinforced polyimide composites tested at 25°, 200°, and 315° C as outer-race liners in plain, spherical bearings. Unit load, 2.9×10^7 N/m^2 (4200 psi); oscillation of ± 15 degrees at 1 hertz in dry air (< 20-ppm H_2O).



(a) Temperature, 25° C (85° F).



(b) Temperature, 200° C (400° F).



(c) Temperature, 315° C (600° F).

Figure 8. - Effect of 10-weight-percent additives on continuous friction characteristics of graphite-fiber-reinforced polyimide bearing liners made of condensation polymers with medium-tensile-strength and high-elastic-modulus fibers (CH composites).

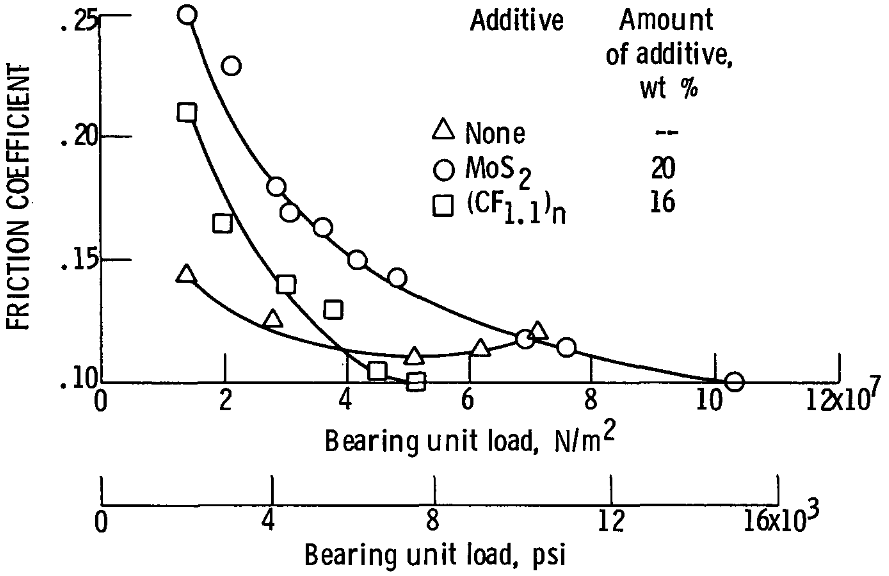


Figure 9. - Effects of load and additives on friction of as-received bearings. Test temperature, 25° C (85° F); relative humidity; 50 percent, oscillation of ±15 degrees at 1 hertz.

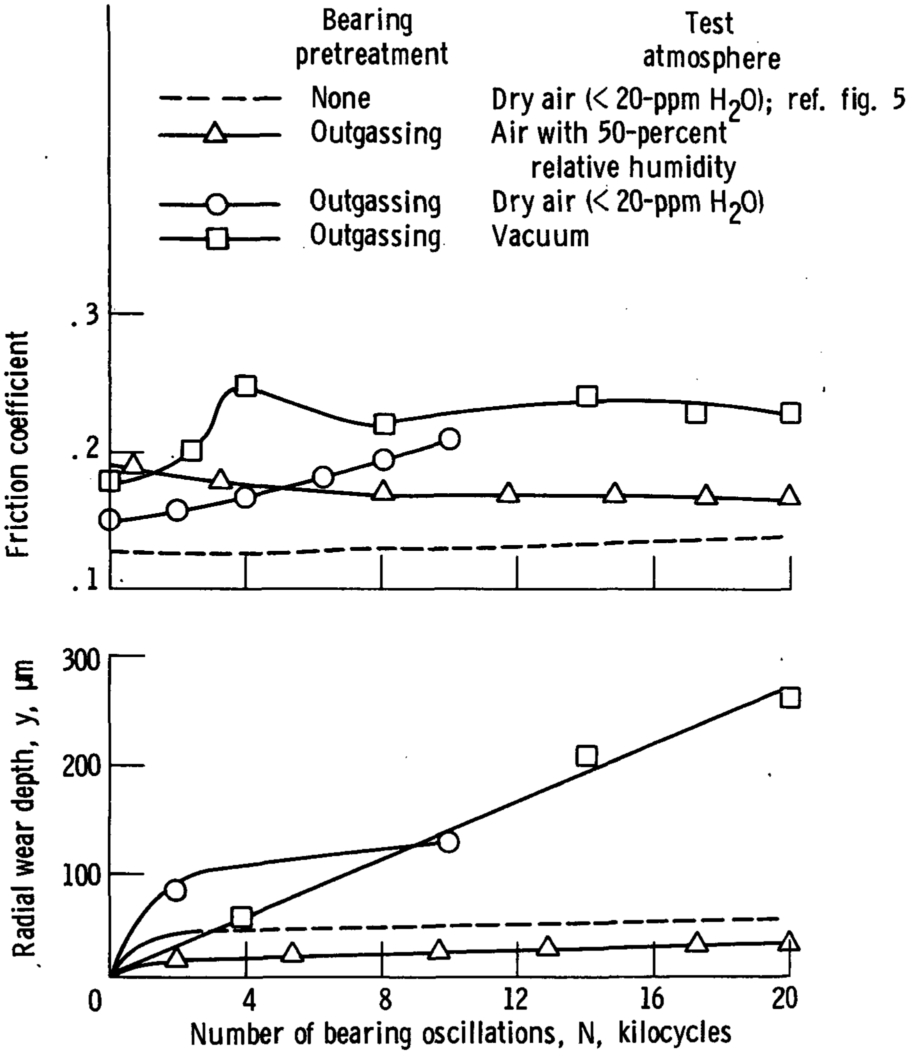


Figure 10. - Effects of bearing pretreatment and atmospheric moisture on friction and wear at 25° C (85° F).

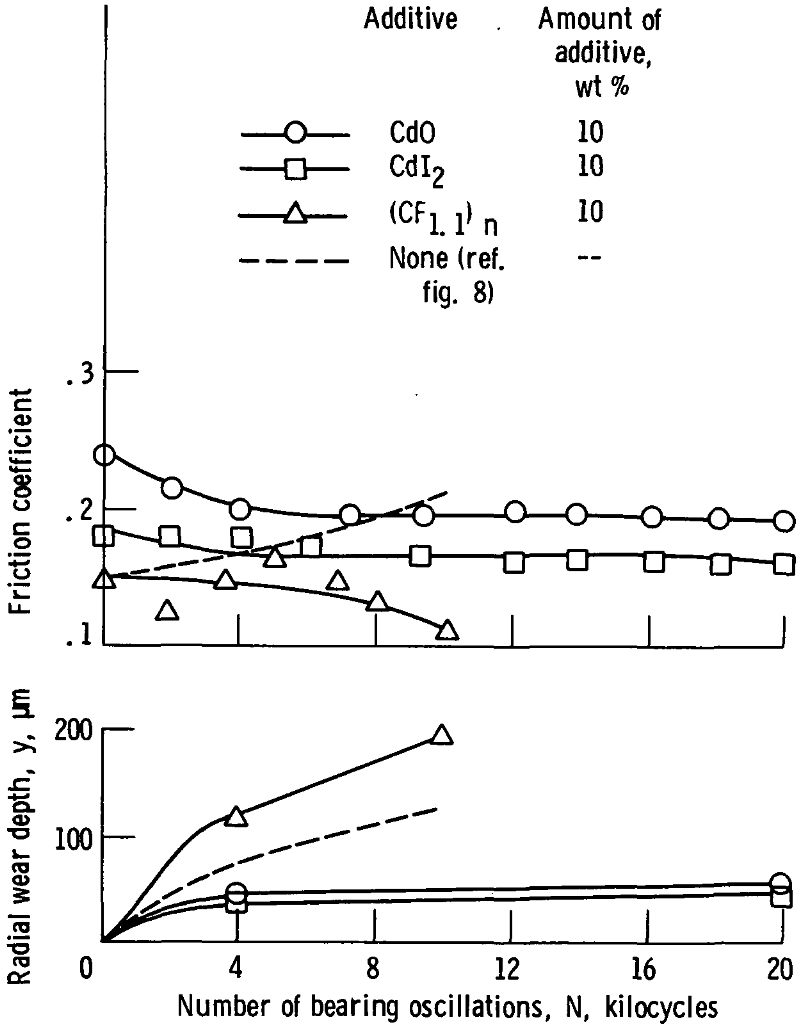


Figure 11. - Effect of additives on friction and wear of outgassed bearings. Test temperature, 25° C (85° F); dry air atmosphere, <20-ppm H_2O.