N82-17263

NASA Technical Memorandum 82779

Performance of PTFE-Lined Composite Journal Bearings

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Prepared for the
Annual Meeting of the American Society
of Lubrication Engineers
Cincinnati, Ohio, May 10-13, 1982

NASA

E-1110

PERFORMANCE OF PTFE-LINED COMPOSITE JOURNAL BEARINGS

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ABSTRACT

Plain cylindrical journal bearings consisting of aramid fiber reinforced epoxy outer shells and glass fiber reinforced PTFE lubricating liners were evaluated. All materials in these bearings are electrically nonconductive; thus eliminating the problem of galvanic corrosion sometimes encountered with metal bearings installed in dissimilar metal mountings. Friction and wear characteristics were determined for loads, temperatures, and oscillating conditions that are typical of current airframe bearing applications. Friction and wear characteristics were found to be compatible with most airframe bearing requirements from -23° to 121° C. Contamination with MIL H-5606 hydraulic fluid increased wear of the PTFE liners at 121° C, but did not affect the structural integrity of the aramid/epoxy composite.

INTRODUCTION

Self lubricating, polymer-base composite materials are used extensively in oscillating bearings for aircraft. Examples are hinge pivot bearings for control surfaces and bushings for variable stator vanes in jet engine compressors. Glass or polyester-fiber-reinforced PTFE liners are bonded to metal substrates in cylindrical or plain spherical bearings for use to about 175° C (ref. 1). Graphite fiber reinforced polyimide (GFRPI) is used to about 350° C (refs. 2 to 4). GFRPI is strong enough to be used either as a free-standing bearing or as a self-lubricating bonded liner in metal bearings.

In the past, these bearings were always mounted in metallic structures. However, with the increasing new application of polymer base composites for aircraft structures, some bearings must be mounted in direct contact with structural composite materials such as graphite fiber reinforced epoxy (GFRE) for use to about 150° C or graphite fiber reinforced polyimide (GFRPI) for use to about 300° C. These composites are attractive for flight hardware because of their outstanding strength and stiffness characteristics combined with their light weight.

Unfortunately, a galvanic corrosion problem can occur when graphite fiber reinforced composites are in contact with certain common aircraft metals. This is generally not a problem with GFRPI because it is selected for use at high temperatures and the contacting metals are very corrosion-resistant. However galvanic corrosion occurs in low temperature applications where bearing metals such as aluminum bronze, cadmium or chromium plated steel, or anodized aluminum are in contact with GFRE structural composites (ref. 5).

One way to avoid this corrosion is to use only, highly alloyed, corrosion-resistant bearing metals in contact with graphite fiber composites. A less costly approach is to employ nonmetallic, composite bearings. These bearings would be very light weight, noncorrosive, less costly, and have the added advantage of acting as a dielectric barrier between the graphite reinforced structural composite and the metallic journals or pins on which the bearings pivot.

This paper describes an experimental composite bearing design which contains only polymeric materials. It consists of an epoxy shell reinforced with high modulus aramid fibers and a bonded self-lubricating liner of woven PTFE and polyester. The experimental bearings are simple cylindrical bushings. Preliminary test results for this bearing concept were reported in reference 5. The research reported herein is to more thoroughly evaluate the concept and to provide a data base for the designer.

Bearings were tested from -23° to 121° C at unit loads from 69 MPa (10 000 psi) to 276 MPa (40 000 psi), while oscillating ±25° at 5 to 20 cpm. Friction torque, wear, and load carrying capability were determined for the clean bearings and for bearing contaminated with MIL H-5606 paraffinic base, hydraulic oil. The bearings were tested at the North American Division of Rockwell International under NASA Contract NAS 3-22123.

TEST SPECIMENS AND MATERIALS

The experimental bearings are plain cylindrical bushings consisting of an aramid fiber reinforced epoxy outer shell and a woven PTFE/polyester self-lubricating liner. The bearing bore is 25.4 mm (1-in.) in diameter and 13 mm (0.5 in.) long. The bearing outside diameter is 30.2 mm (1.189 in.). The clearance between the test shaft and the bearing bore is 0.013 mm (0.0005 in.). Sketches of the bearing and test shaft are shown in figure 1. The test shafts are fabricated of 17-4 PH steel and are heat treated to a hardness of R_C 45-47. The O.D. surfaces are ground and buffed to obtain a surface finish of 0.1 to 0.15 micrometer (4 to 6 μin.) rms.

The fabricating technique for the filament-wound composite bushings were as follows:

1. A woven fabric, tubular PTFE liner was placed over an appropriately sized and finished cylindrical mandrel that was treated with a parting agent. Heat was applied to the liner to shrink it snugly to the mandrel. The liner fabric was a satin weave of PTFE and polyester yarns. This type of weave produces a fabric that is predominantly PTFE yarn on the live bearing surface, with more polyester on the bond side surface. A limited number of bushings with taffeta weave liners were also prepared. This weave has the same amount of PTFE on both sides of the liner. The nominal thickness of the liners was 0.381 mm (0.015 in.).

2. The in-place liner was thoroughly coated with a three-part epoxy resin.

3. The mandrel with the liner in place was helically wound with continuous filament yarns of aramid fibers. The yarns were led through a container of the resin to maintain saturation of the layup.

4. The preceding process was continued until the appropriate dimensional buildup was obtained, the mandrel and filament-wound tube were then removed from the winding machine. For the wall thickness of the bushings used in this program, five to six plies were required.

5. Drying, curing, and postcuring were accomplished after removal of the wound tubes from the mandrel.

6. After complete curing, the tube O.D. was machined to the proper dimension, and the tube was parted into a number of appropriate-length bearings.

7. The final operation was trimming of the edges on the I.D. of the bushing.

Photomicrographs of cross sections through the bearing shell and liner are shown in figure 2.

BEARING TEST EQUIPMENT AND PROCEDURE

The basic components of the three identical plain bearing testers used in this program are shown in figure 3. The test bearing (bushing) is held with a 0.013 mm (0.0005 in.) nominal interference fit in a 17-4 PH steel housing which positions the bushing and transmits load during cycling. The design is such that axial and rotational motion of the bearing in the housing is prevented. The test shaft is held mechanically (fixed) in a holder with transmits the rotational motion.

The test bearing is supported on each side by three large, grease-lubricated ball bearings (a total of six) mounted in fixed housings. The drive mechanism transmits motion through the support and test bearings.

The bearing frictional torque is obtained from a strain gage between the support bearings and the drive mechanism, which measures the combined frictional torque of the test and the support bearings. The torque magnitude of the support bearings remains constant and is significantly lower than the test bearing. Any change in the total torque system, therefore, is the result of frictional changes in the test bearing. The machines are instrumented to allow complete machine shutdown at predetermined torque cut-off points when failure occurs in the test bearings.

Bearing wear during cycling is monitored by a dial indicator mounted below the bushing holder, which measures changes in holder position due to wear of the bushing and/or shaft. In addition to the dial gage wear readings, "before and after" measurements of the bores are made with a taper bore gage. This gage consists of two tapered bars with radiused outer edges, used in conjunction with a standard outside diameter micrometer. These wear measurements cannot distinguish between wear due to material removal and to creep or plastic deformation of the bearing material. However, they do give the increase of internal clearance which is important in this type of bearing. The clearance determines bearing backlash which is a critical factor in oscillating airframe bearings, particularly control surface bearings.

Loading of the test bearing is accomplished with a pneumatic loading cylinder. The cylinder is connected to the bearing holder through a lever system so that a maximum of 1.3×10^5 N (30 000 lb) can be applied to the test bearing. The shaft is crank driven by a motor and gearbox unit. In this program, the shaft oscillated $\pm25^\circ$ at controlled frequencies from 5 to 20 cpm (0.0018 to 0.0074 k/sec).

The test bearing and shaft are heated with resistance heaters. For initial calibration, a special test shaft is used with a thermocouple installed through a hole drilled into the shaft and brazed to the shaft O.D. on the top (load) side. The controller thermocouple is tack-welded to the edge of the test bearing housing as close as possible to the bearing. The control thermocouple output is then calibrated as a function of shaft temperature. Shaft temperatures are the reported bearing test temperatures with the exception of the room temperature (21° C) tests where the bearing temperature is variable depending on the amount of frictional heating.

For fluid contamination tests, the shaft O.D. and the bearing bore are wiped with hydraulic fluid prior to installation in the test machine. During the test, hydraulic fluid is continuously dripped onto the shaft adjacent to both edges of the bearing bore.

RESULTS AND DISCUSSION

Friction, wear, and dynamic load capacities of composite bearings were determined. A relevant standard by which to judge the results is the military specification MIL B-81934 "Bearings, Sleeve, Plain and Flanged, Self-Lubricating." In order to qualify under this speficiation, bearings must pass the performance test summarized below:

MIL B-81934 OSCILLATING TEST REQUIREMENTS FOR METAL-RACKED

PTFE-LINED CYLINDRICAL BEARINGS

Temperature	Room (ambient)	163° C (bearing)
Maximum liner wear, mm (in.)	0.11 (0.0045)	0.15 (0.0060)
Unit load, MPa (psi)	250 (36 000)	190 (27 000)
Duration, oscillating cycles	25 000	25 000
Oscillating condition	±25° C at 10 cpm	±25° C at 10 cpm

A proposed specification under consideration for composite bearings relaxes the above requirements to 0.15 mm (0.006 in.) maximum wear at room temperature and at 121° C at a 207 MPa (30 000 psi) unit load with no requirement at 163° C. These relaxation are necessary because of excessive creep of the aramid/epoxy bearing shell under high loads at 163° C. Bearings satisfying this relaxed specification however would satisfy most requirement for bearings mounted in GFRE composite structure because the structure themselves have about the same load and temperature limits as the composite bearings.

Effect of Load on Wear and Friction

All bearings in this series were tested for a toal of 25 000 oscillating cycles. In most cases, three bearings were used for each combination of load and temperature. The data for replicate tests were not averaged; therefore each data point represents the wear of a single bearing.

Low temperature (-23° C) performance. - Figure 4 gives the liner wear and the friction coefficients of composite bearings at radial loads from 69 to 276 MPa (10 000 to 40 000 psi). Twelve bearings (three at each of four loads) with satin weave PTFE/polyester liners were tested. On the average, the total wear after 25 000 oscillating cycles increased approximately linearly with load. This linearity indicates that the dynamic load capacity of the bearings was not exceeded at the highest load employed (exceeding the dynamic load capacity is generally indicated by an exponential rise in the wear vs. load curve). The wear of one bearing with a taffeta weave at 276 MPa (40 000 psi) was at the low end of the scatter band for bearings with satin weave liners.

The friction coefficients decreased linearly with increasing load at -23° C. This is uncharacteristic of PTFE at higher temperatures. However, it has been reported that PTFE undergoes on adverse friction transition below room temperature that is probably related to a disorder transition in PTFE at 20° C (ref. 6). The friction coefficient is generally less than 0.1 above 20° C, but can be much higher below the transition temperature. In figure 5, the decrease of friction coefficient with increasing load at the nominal bearing temperature of -23° C is probably caused by frictional heating of the PTFE surface in the sliding contact. It will be seen that for the tests at bearing temperatures above 20° C, the friction coefficient is low and relatively insensitive to variations of load and temperature.

Room temperature bearing performance. - AT room temperature, figure 5, the average liner wear increased linearly with load in a manner very similar to the wear behavior at -23° C. One bearing with a taffeta weave liner had much lower wear than the satin weave liners at 276 MPa (40 000 psi), but results from reference 4 with a taffeta weave liner at 248 MPa (36 000 psi) are scattered above and below the wear curve. The MIL B-81934 requirements for metal-backed PTFE bearings is also shown in the figure. It is clear that the composite bearings would not meet this requirement but could meet the previously discussed requirement of the proposed specification for composite bearings.

Wear data obtained from the continuous dial gage measurements during some typical bearing tests at 21° C are shown in figure 6. All bearings characteristically had a higher wear rate during run-in (which may include some plastic deformation especially at the higher loads) followed by constant, steady state wear rates. This behavior is typical of most wear trends for both boundary lubricated systems (ref. 7) and self-lubricating solids (ref. 8).

Unlike the downward trend at -23° C, (fig. 4) the friction coefficients at 21° C (fig. 5) were almost constant at about 0.06 for all loads. The surface temperatures were obviously above the friction transition temperature and the increasing frictional heating associated with increasing load, therefore, had little effect on the friction coefficient.

Bearing performance at 93° C. - There is considerable scatter in the wear data shown of figure 7. However, the trend of wear with increasing load, indicates that the dynamic load limit of these bearings is about 207 MPa (30 000 psi) because there is a repeatable and disproportionate increase in wear rate as the load is increased from 207 to 276 MPa. The continuous dial gage measurement of wear during the bearing tests showed the typical early run-in wear followed by a constant, lower, steady state wear rate. The curves are not included because they are identical in trend to those on figure 6.

The friction coefficients were in the range of 0.04 to 0.06. There appears to be a mild upward trend with increasing load, but it is within the data scatter and probably is not significant.

Bearing performance at 121° C. - Figure 8 shows that wear rates increase abruptly between 207 MPa (30 000 psi) and 276 MPa (40 000 psi) and therefore the limiting dynamic load capacity is between those unit loads. As at room temperature, wear is higher than required by MIL B-81934 for metallic bearings, but meets the wear requirement in the proposed specification for composite bearing. No significant difference was apparent in the performance of satin wear liners compared to taffeta weave liners. The shapes of the continuous wear curves were the same as on figure 6 for room temperature wear. Clearly differentiated run-in and steady-state segments are indicated. Only the slopes differ from the room temperature case.

Again, friction coefficients are reasonably constant, around 0.06, with the exception of an unexplained consistently low values of 0.04 at 69 MPa (10 000 psi).

Comparison with metal-backed bearings. - In figure 9 the wear of conventional metal backed and composite PTFE-lined bearings is compared. At 276 MPa (40 000 psi) the wear of the metallic bearings was within the same scatter band as the composite bearings at -23° and 121° C, but was much lower in the room temperature tests. At 207 MPa (30 000 psi) and 121° C wear of the metal backed bearings was much less than the wear of the composite bearings.

Effect of temperature. - Cross plots of wear data from previous figures are presented in figure 10. They illustrate the effect of temperature on wear and friction of composite bearings at various constant loads. The wear is unaffected by temperature at loads up to 207 MPa (30 000 psi), but wear increases in an apparently linear manner with temperature at 276 MPa (40 000 psi). This again indicates that the dynamic load capacity is between those two load levels, and that a specification for loads up to 207 MPa (30 000 psi) should be reasonable for the composite bearings.

Friction coefficients average about 0.06 at all loads and temperatures except at -23° C where the friction coefficients are 0.17 at 69 MPa (10 000 psi) and continuously decrease to 0.10 at 269 MPa (40 000 psi).

The effect of cycle rate. - Figure 11 gives the effect of cycle rate on bearing liner wear. As might be expected, at the low sliding velocities used, total wear after 25 000 oscillating cycles at 207 MPa (30 000 psi) was not significantly influenced by a 4 to 1 variation in cycles rates from 20 to 5 cpm.

Hydraulic fluid contamination. - The effect of continuous contamination with MIL H-5606 hydraulic fluid on bearing wear at 21° and 121° C is shown in figure 12. The contamination had no significant effect on liner wear at 21° C. At 121° C, hydraulic fluid contamination tended to increase average liner wear. The aramid fiber/epoxy outer shell did not appear to be damaged in any way by exposure to the hydraulic fluid.

Static load (creep) tests. - Static load tests were performed to determine the short-term creep characteristics of the composite bearings at room temperature and 121° C. Three tests were at loads of 300 MPa (44 000 psi) and five were at 458 MPa (66 600 psi). The bearings were statically loaded while mounted on the bearing test apparatus. The loads were maintained for at least 96 hours or until the onset of obvious gross damage to the bearing. The results are summarized in table I. At 458 MPa (66 600 psi) the load exceeded the static load capacity of the bearings at both temperatures. With one exception, the composites extruded, then were crushed before completion of the 96 hour test. The one bearing that was not crushed at this load was deformed excessively after 192 hours. At 300 MPa (44 000 psi), the bearings were undamaged with only a moderate permanent set after 96 hours but excessive deformation occurred during 168 hours at 121° C. It therefore appears that the bearings have a static load capacity of at least 300 MPa (44 000 psi) up to 121° C in regard to short term creep (up to 96 hr).

CONCLUSIONS

Friction, wear, and load-carrying capability of nonmetallic composite bearings were measured in this program. The bearings were plain, cylindrical bushings consisting of an aramid fiber reinforced epoxy shell with a bonded, self-lubricating woven liner of PTFE and polyester fibers. The major results are:

1. The composite bearings have lower load capacities and temperature capabilities than those of conventional PTFE-lined metallic bushings. However, they have very respectable dynamic load capacities of at least 207 MPa (30 000 psi) from -23° C to 121° C. This is compatible with the load and temperature limits of graphite fiber/epoxy structural materials for which the composite bearings were primarily developed.

2. As expected, the friction characteristics are typical of PTFE liner materials which have low friction coefficients of about 0.06 above 20° C. However, higher friction is observed at -23° C where the friction coefficients are about 0.17 at 69 MPa (10 000 psi) and decrease to about 0.10 at 276 MPa (40 000 psi).

3. Although the composite bushings have a lower load capacity and temperature limitation than metallic bearings, they also have a number of advantages. They are completely polymeric and therefore inert to galvanic corrosion when in contact with dissimilar materials. They are lighter and potentially cheaper than metallic bearings and they can be adhesively bonded in structural composite parts.

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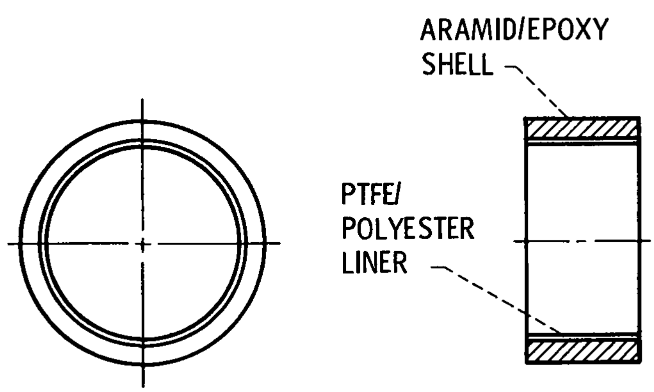
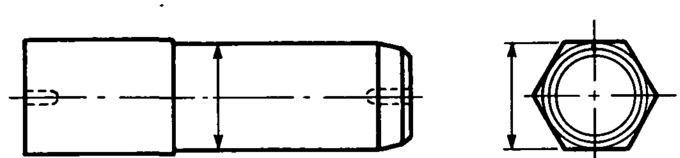
TABLE I. - SUMMARY OF STATIC LOAD (CREEP) TESTS, PTFE LINED BUSHINGS

[Bushing bore: 2.54×10^{-2} meters (1.000 in.); PTFE liner: satin weave, PTFE/polyester fiber; Mating shaft: 17-4 PH CRES, R_c 45, surface finish = 4-6 RMS (buffed after grinding.]

Load		Temperature		Permanent set				Duration of test	Comments
				Dial indicator		Measured			
MPa	psi	°C	°F	$M \times 10^{-2}$	Inch	$M \times 10^{-2}$	Inch		
306	45 000	+21	+70	0.0033	0.0013	0.0117	0.0046	96 hours	Liner and composite in good condition
306	45 000	+121	+250	.0135	.0053	.0130	.0051	96 hours	Light extrusion of composite at first ply
306	45 000	+121	+250	.0229	.0090	.0620	.0244	168 hours	Moderate extrusion of composite at first ply with extrusion of liner
458	67 000	+21	+70	------	------	------	------	72 hours	0.0030×10^{-2} meters (0.008 in.) permanent set after 48 hours. Failed by crushing after 72 hours.
↓	↓	+21	+70	0.0231	0.0091	0.0406	0.0160	192 hours	Light extrusion of composite at first ply
↓	↓	+93	+200	------	------	------	------	42 min.	Began to fail in first five minutes. Composite crushed.
↓	↓	+121	+250	------	------	------	------	1 hour	Began to fail in first minute. Composite crushed.
↓	↓	+121	+250	------	------	------	------	1 min.	Began to fail as soon as the load was applied. Composite crushed.



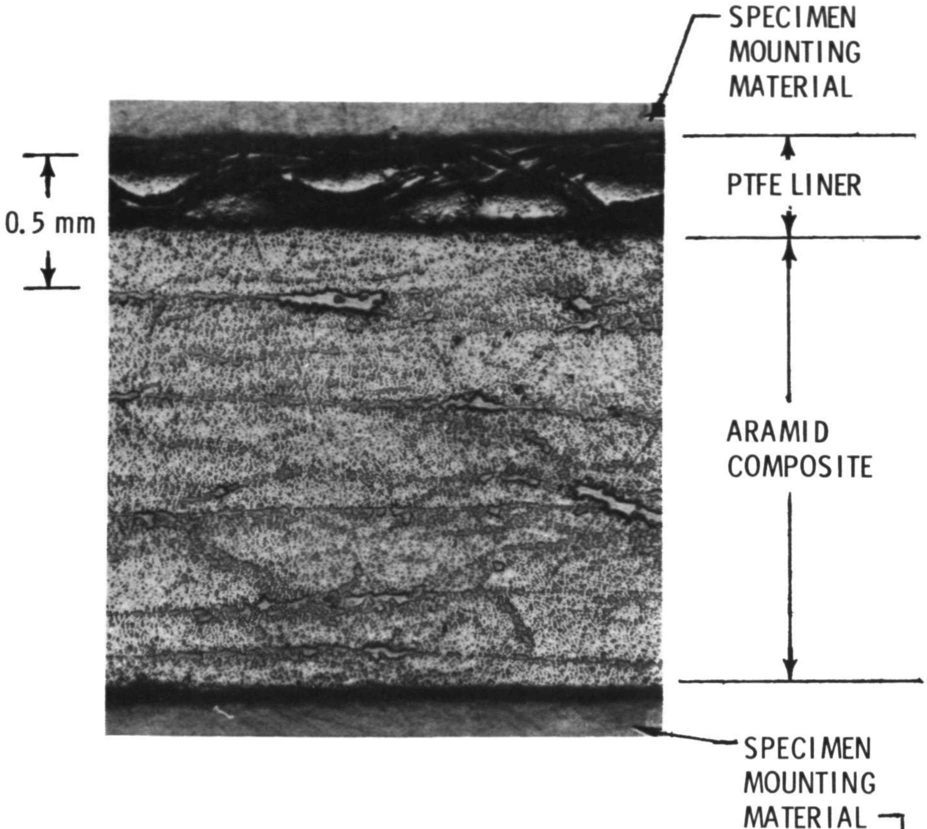
(a) BUSHING.



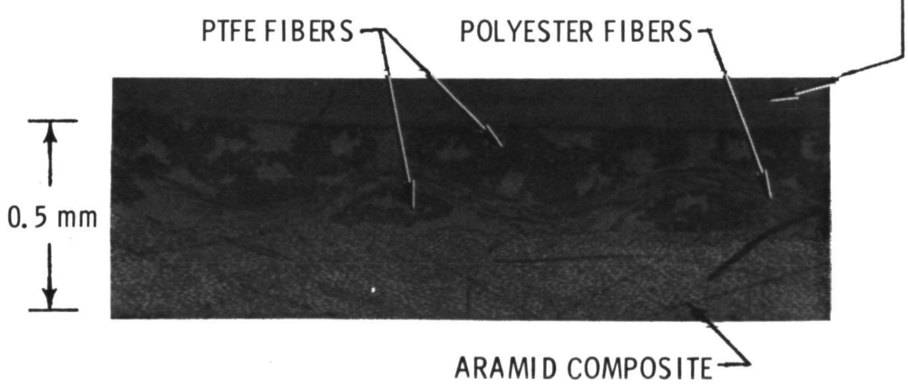
MAT'L. 17-4 PH CONDITION H-900

(b) TEST SHAFT.

Figure 1. - Test specimens.



(a) CROSS SECTION OF BEARING SHELL AND LINER.



(b) CROSS SECTION OF SATIN WEAVE LINER.

Figure 2. - Photomicrographs of composite bearing materials.

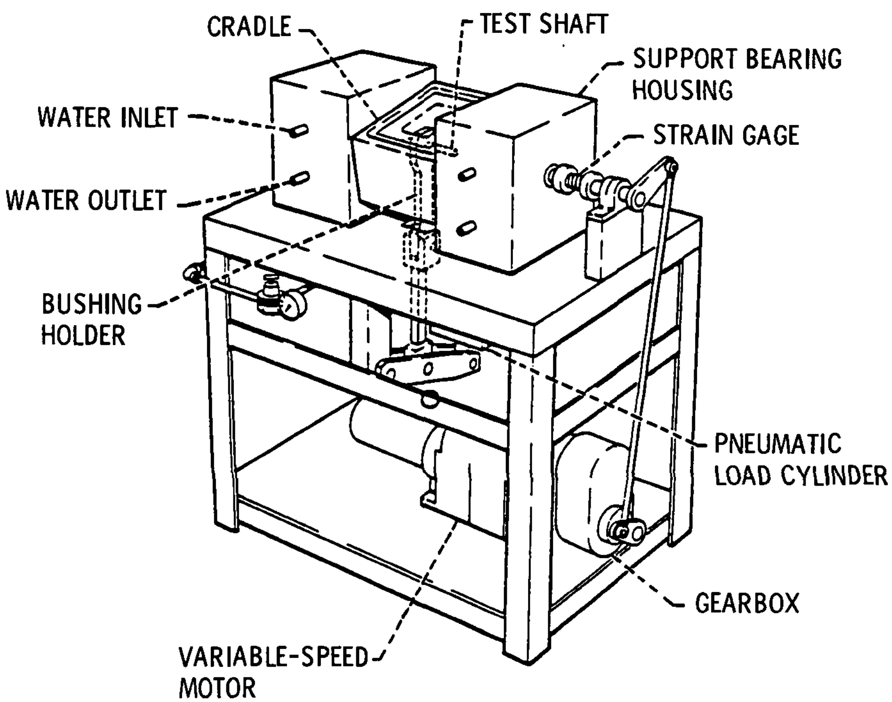


Figure 3. - Plain bearing tester.

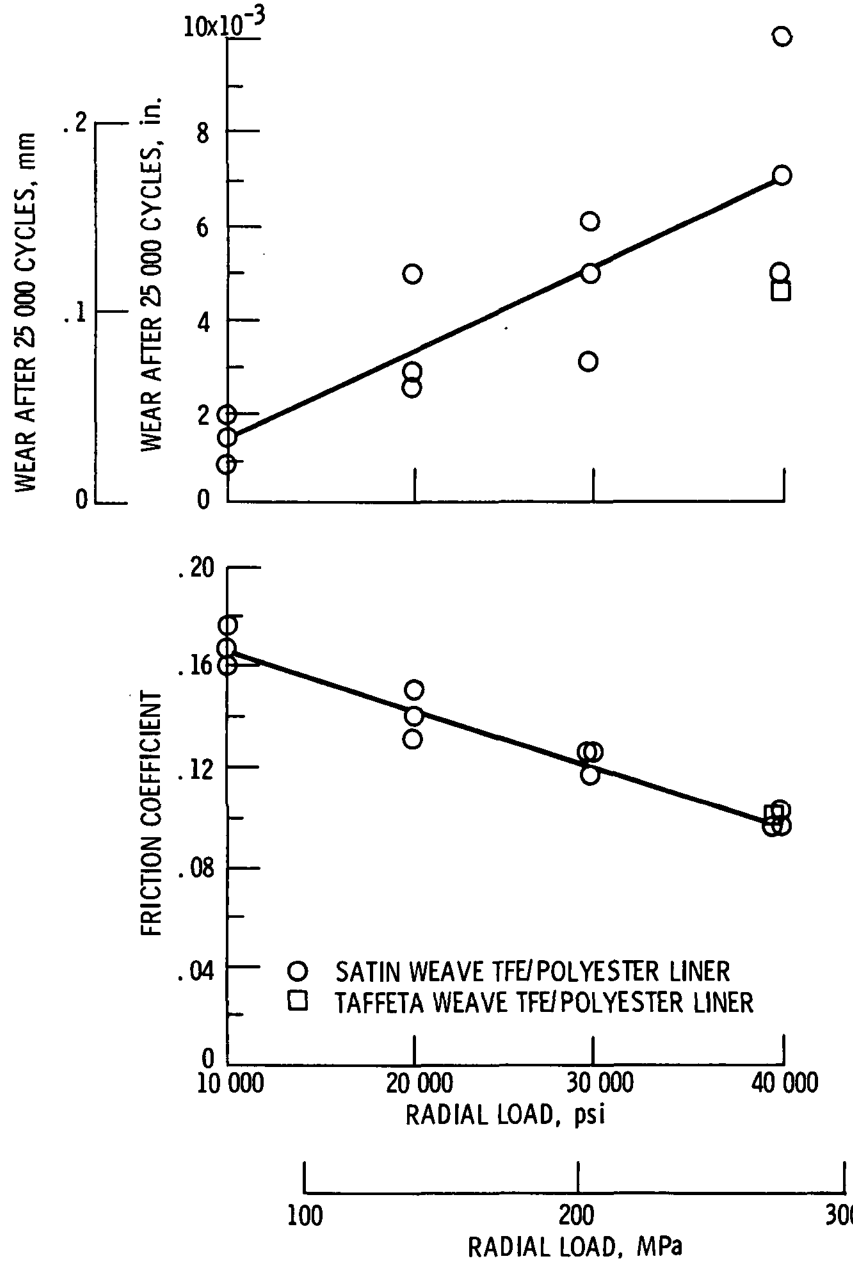


Figure 4. - Effect of load on wear and friction of composite bushings at -23° C.

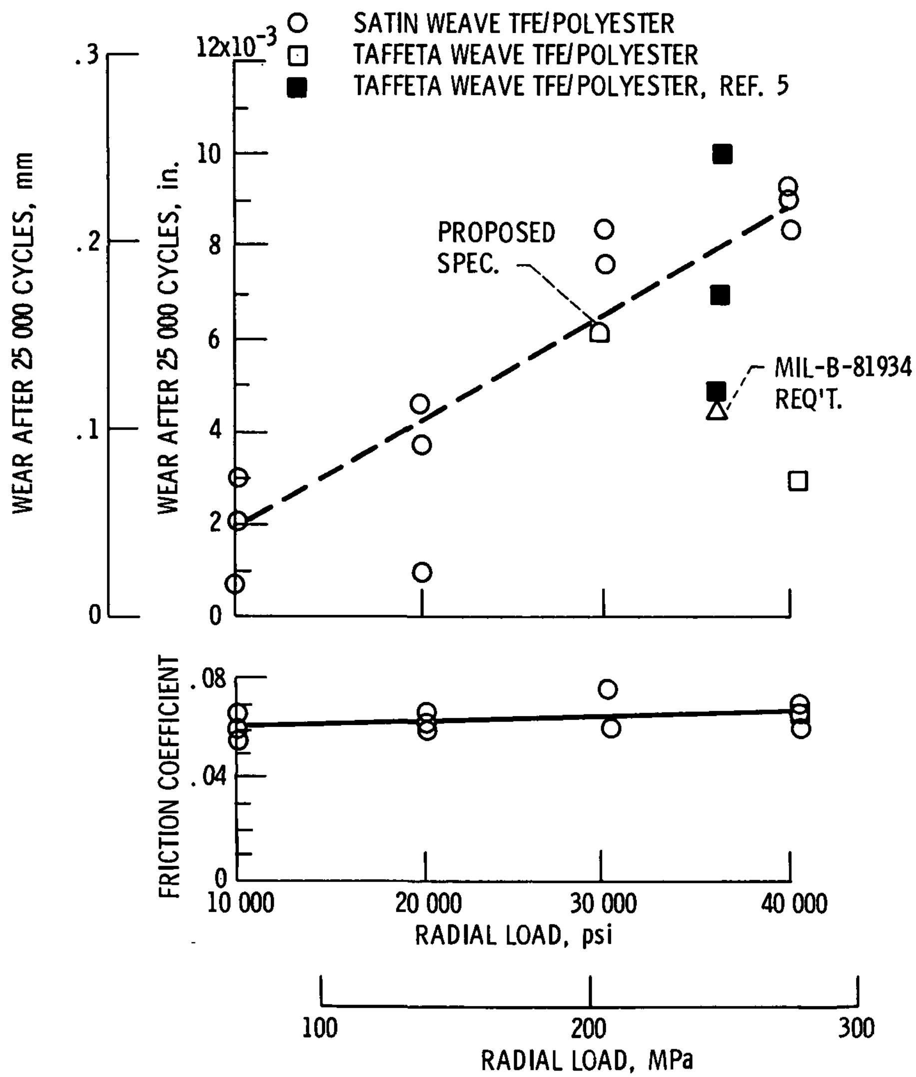


Figure 5. - Effect of load on wear and friction of composite bushings at 21° C.

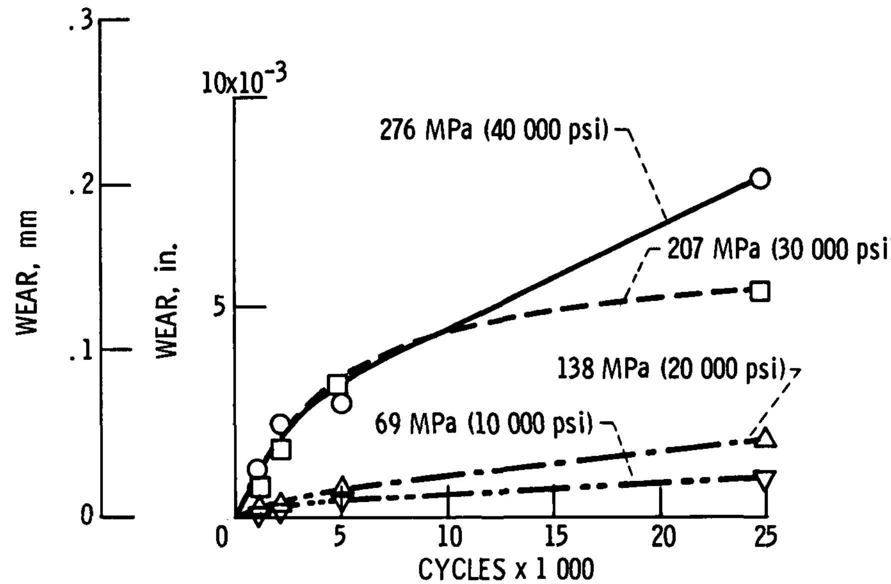


Figure 6. - Wear curves of TFE-lined Kevlar/epoxy one-inch bore composite bushings at +21° C (+70° F) based on dial indicator readings.

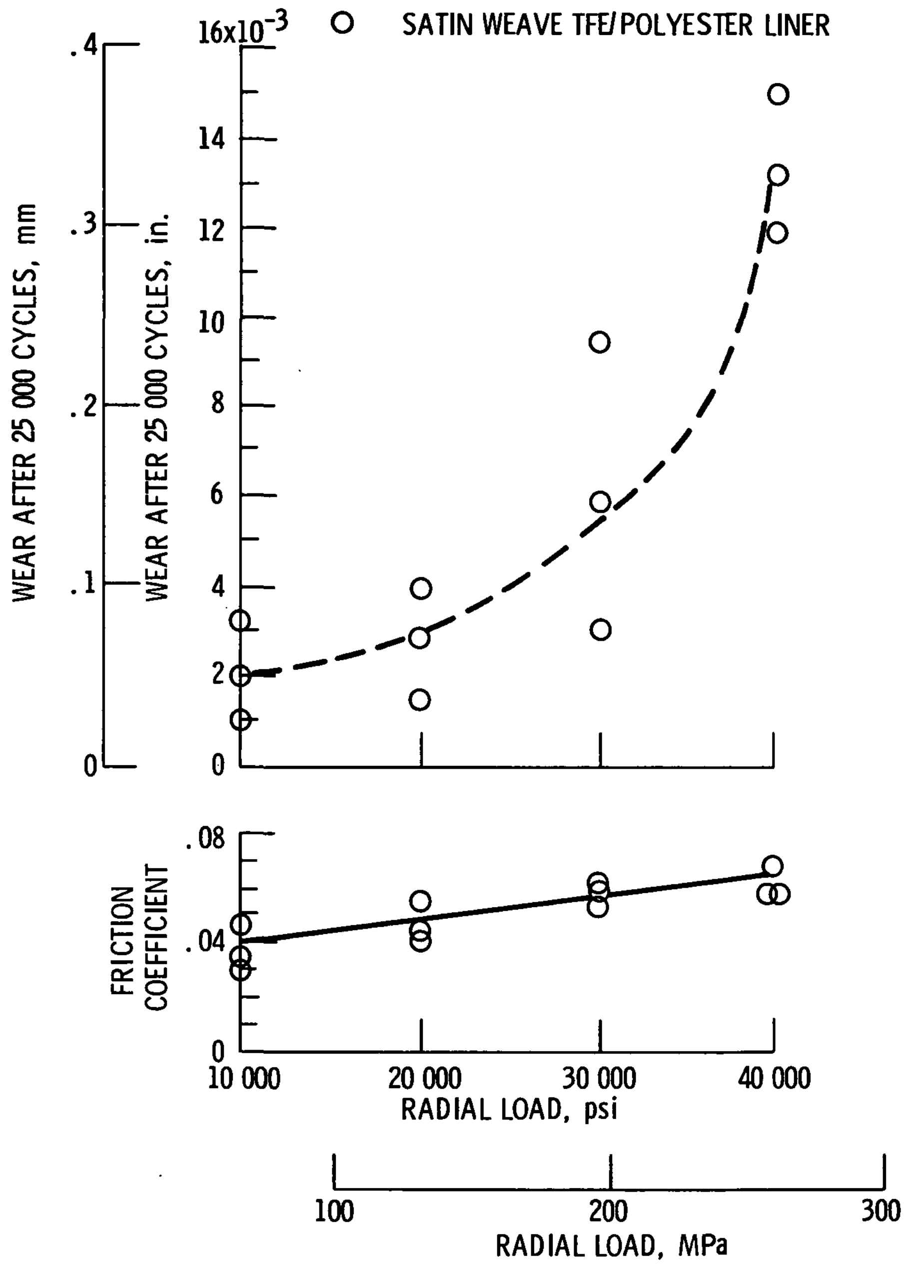


Figure 7. - Effect of load on wear and friction of composite bushings at 93° C.

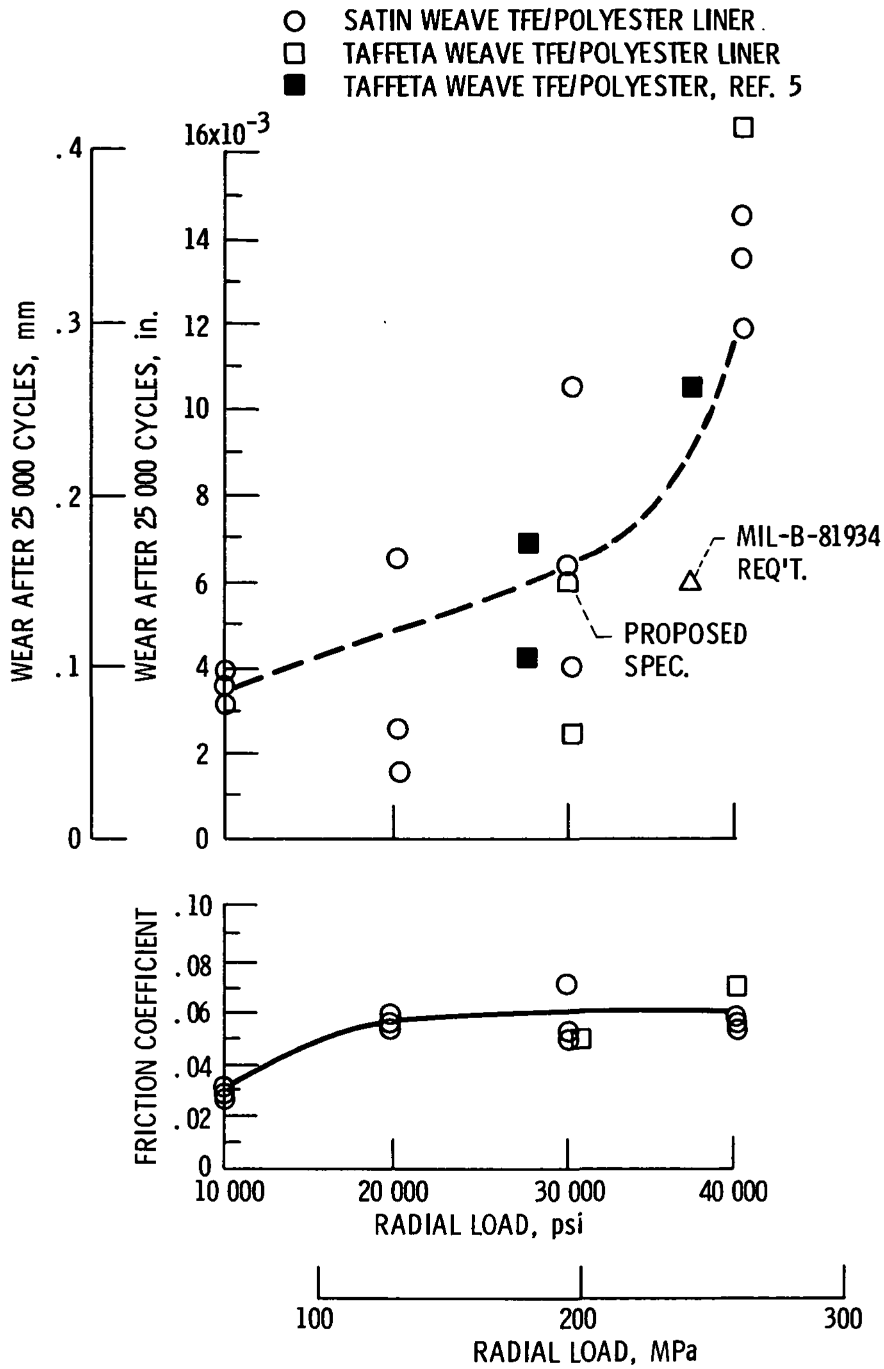


Figure 8. - Effect of load on friction and wear of composite bushings at 121° C.

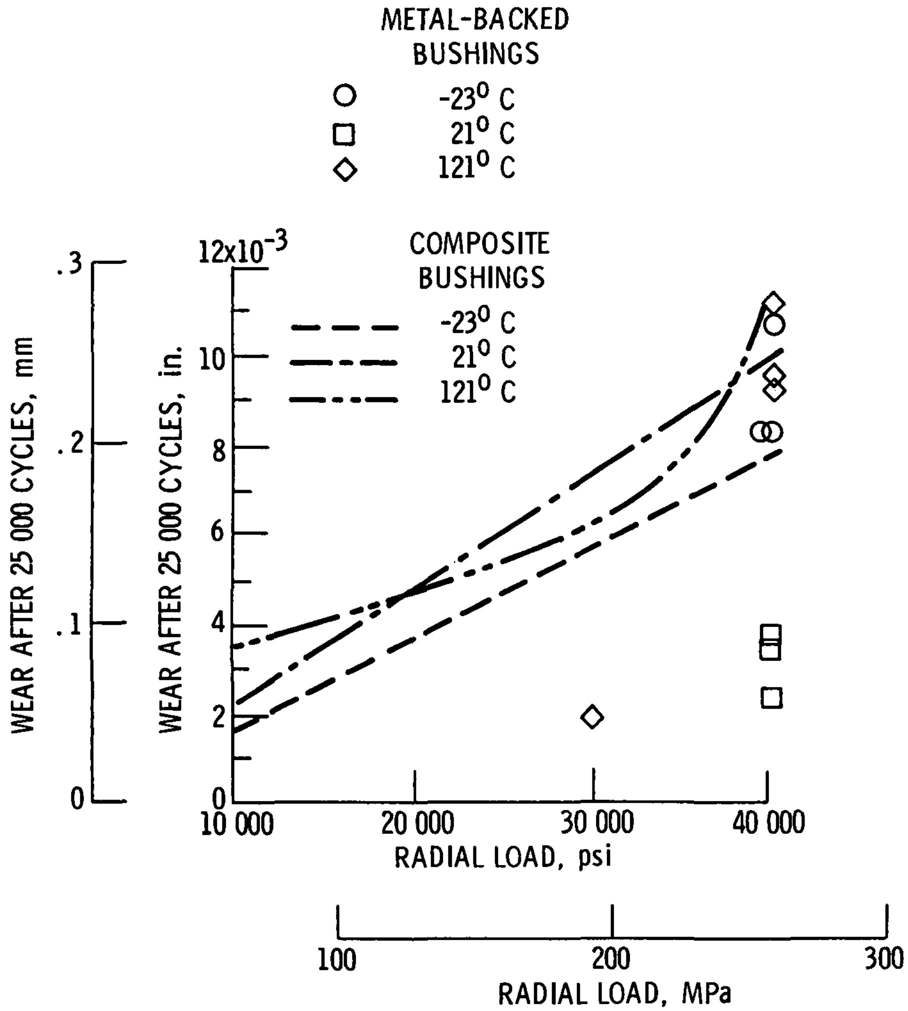


Figure 9. - Wear of metal-backed bushings compared to averaged wear curves for composite bushings. (All bushings with TFE/ polyester self-lubricating liners.)

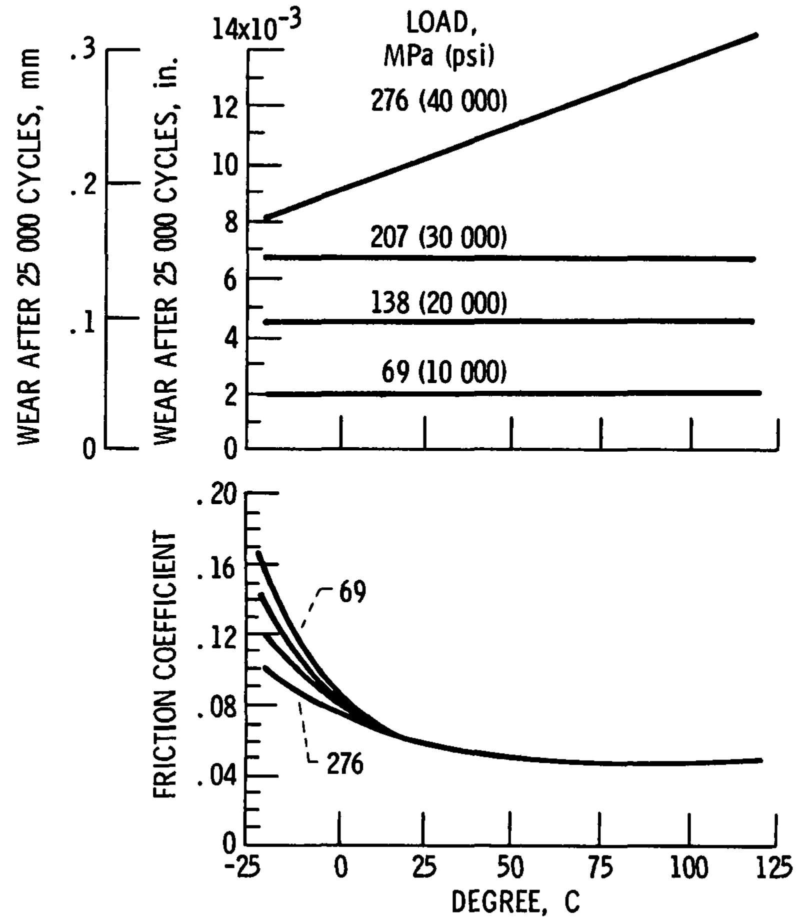


Figure 10. - Cross-plot of figures 4, 5, 7, and 8 showing effect of temperature on wear and friction of TFE-lined composite bushings.

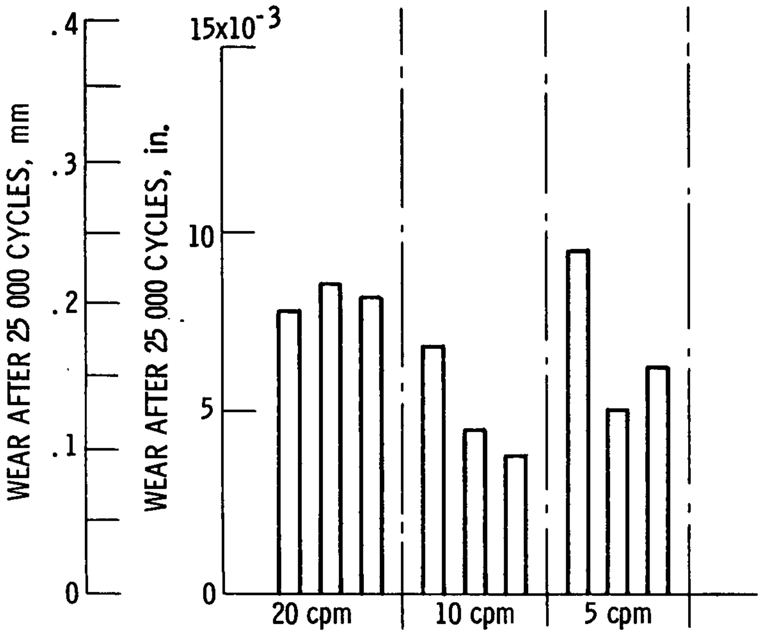


Figure 11. - Wear comparison at 207 MPa (30 000 psi) at various cycle rates - one-inch bore TFE-lined composite bushings.

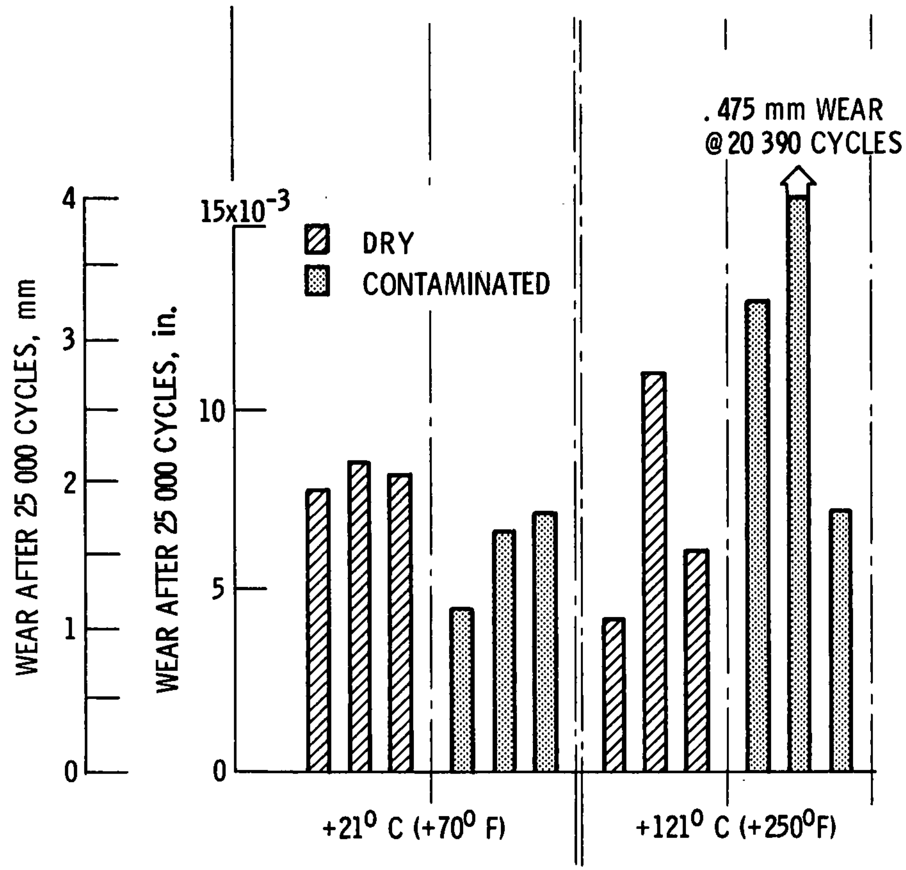


Figure 12. - Wear comparison at 207 MPa (30 000 psi) between dry and fluid contaminated test specimens - one-inch bore TFE-lined composite bushings.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-82779		

4. Title and Subtitle	5. Report Date
PERFORMANCE OF PTFE-LINED COMPOSITE JOURNAL BEARINGS	6. Performing Organization Code 505-32-42
7. Author(s) Harold E. Sliney and Frank J. Williams	8. Performing Organization Report No. E-1110
	10. Work Unit No.
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code

15. Supplementary Notes

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Prepared for the Annual Meeting of the American Society of Lubrication Engineers, Cincinnati, Ohio, May 10-13, 1982.

16. Abstract

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Composite bearings Airframe bearings Self-lubricating polymers	Unclassified - unlimited STAR Category 23

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
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