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SUMMARY

An experimental investigation was undertaken to determine the feasibility of operating journal bearings in cryogenic liquids at surface speeds comparable to those of current generation oxidant turbopumps. Tests were conducted with 1.0- and 1.5-inch-diameter bearings.

Results from tests in liquid nitrogen and liquid oxygen were generally poor due to the difficulty of maintaining a hydrodynamic film. It is hypothesized that boiling of the cryogenic fluids may have occurred within the bearing clearance area, creating a two-phase-flow condition. A sharp decrease in the effective viscosity and in the bearing load-carrying capacity resulted.

The best performance from tests with journal bearings fully immersed in liquid-oxygen was obtained with (1) fused polytetrafluoroethylene (PTFE) coated wrought-nickel-copper alloy sleeves, (2) a 15-percent glass-filled PTFE liner on steel, and (3) PTFE plus lead in sintered bronze. These materials were capable of sustaining moderate loads at surface speeds to 76 feet per second for a short duration. Liquid-oxygen pressure fed to the bearings at approximately 5 pounds per square inch gage above atmospheric pressure (boiling point, -302° F) did not improve performance over the tests fully immersed at atmospheric pressure.

Results of screening tests conducted in a low-viscosity hydrocarbon with a number of materials showed good agreement with hydrodynamic theory. Hydrodynamic films were maintained over a range of surface speeds to 107 feet per second at unit loads to 200 pounds per square inch.

INTRODUCTION

Present generation liquid-chemical-propulsion systems utilize high-speed turbopumps to transfer cryogenic liquid propellants from storage tanks to the rocket-engine combustion chamber. It is desirable to operate the shaft bearings immersed in the working fluid. Two decided advantages immediately apparent are (1) weight reduction by the elimination of a separate lubrication system and (2) simplification of design by the overall reduction in the number of shaft seals normally required with conventional lubricants. To achieve maximum weight reduction and reduce complexity, it is necessary to use the propellants both to lubricate and to cool the bearings in the fuel and the oxidant systems. This report is concerned with journal bearings that would be suitable for operation in cryogenic oxidants.

The decision to evaluate plain journal bearings rather than rolling-contact bearings was based primarily on the greater number of candidate materials for sliding bearings that are potentially compatible with strong oxidizers. Secondly, lower unit pressures are obtained in sliding bearings as compared with a rolling bearing at the same load.

Basically, an ideal bearing lubricant performs two functions: (1) it prevents intimate contact of journal and bearing surfaces, and (2) it carries away the heat generated in shearing the film. Liquid oxygen, for example, at its boiling point of -297° F affords an excellent heat sink; however, its extremely low viscosity of 0.0274×10^{-6} reyn (lb-sec/sq in.) limits the amount of load pressure that can be supported with a realistic film thickness. Hydrodynamic bearing theory states that load-carrying capacity varies directly with lubricant viscosity and journal speed. Because of the low viscosity of liquid oxygen as compared with conventional lubricants, it is reasonable to assume that bearings will, at times, operate under boundary lubrication conditions. This being the case, material selection under these conditions is of prime importance.

A preliminary two-phase screening program was conducted to evaluate qualitatively a number of promising materials. The object of these screening tests was to determine the speed and load limitations of the candidate materials. In the initial phase, a low-viscosity hydrocarbon (hexane), which has an absolute viscosity of 0.043×10^{-6} reyn at 75° F, was used as a lubricant. The second phase was conducted in liquid nitrogen (absolute viscosity, 0.023×10^{-6} reyn at -320° F) with those materials that had exhibited good performance in the room-temperature hexane tests. In addition to possessing good bearing properties, the materials chosen for testing would have to be resistant to chemical attack by strong oxidizers (such as liquid O_2 and liquid F_2) used as high-energy propellants. Consideration also had to be given to dimensional stability and retention of certain desirable physical properties at low temperatures.

The low-temperature-test results reported herein are for journal bearings operating fully immersed in liquid nitrogen and liquid oxygen at atmospheric pressure. Some tests were also conducted with journal bearings pressure-fed with liquid oxygen.

The object of this investigation was to determine the load-carrying capabilities and the speed limitations of various materials that have potential as bearings in cryogenic oxidant pumps. Based on a typical turbopump application, these bearings would have to sustain steady loads of 68 to 151 pounds per square inch (shaft diam., 1.5 in.; bearing length, 1.5 in.) at a speed of 12,000 rpm.

A qualitative evaluation was made of bearing and journal wear. Bearing friction torque at varying speeds and loads was recorded for the low-viscosity-hydrocarbon tests. Various lubricating groove arrangements were tested, and the diametral clearance was varied in an attempt to establish a load-carrying hydrodynamic film.

Nominal $1\frac{1}{2}$-inch-bore by $1\frac{1}{2}$-inch-length bearings were tested in hexane at radial loads to 500 pounds and journal speeds to 17,100 rpm. Nominal 1-inch-bore by 1-inch-length bearings were tested in liquid nitrogen and liquid oxygen at radial loads to 200 pounds per square inch and journal speeds to 25,000 and 17,500 rpm, respectively.

SYMBOLS

c_d	diametral bearing clearance, in.
c_r	radial bearing clearance, in.
d	bearing diameter, in.
F	frictional force, lb
f	coefficient of friction, F/W, dimensionless
$f(r/c_r)$	friction variable, dimensionless
l	bearing length, in.
p'	unit load on projected area, P/ld, lb/sq in.
r	bearing radius, in.
S	Sommerfeld number, $\frac{\mu N'}{p'}\left(\frac{r}{c_r}\right)^2$, dimensionless
N'	journal speed, rps
N_T	transitional journal speed from laminar to turbulent regime, $\frac{41.1\nu}{\pi d c_r}\sqrt{\frac{d}{2c_r}}$, rps
W	applied load, lb
μ	absolute viscosity, reyns (lb-sec/sq in.)
ν	kinematic viscosity, centistokes (sq in./sec)

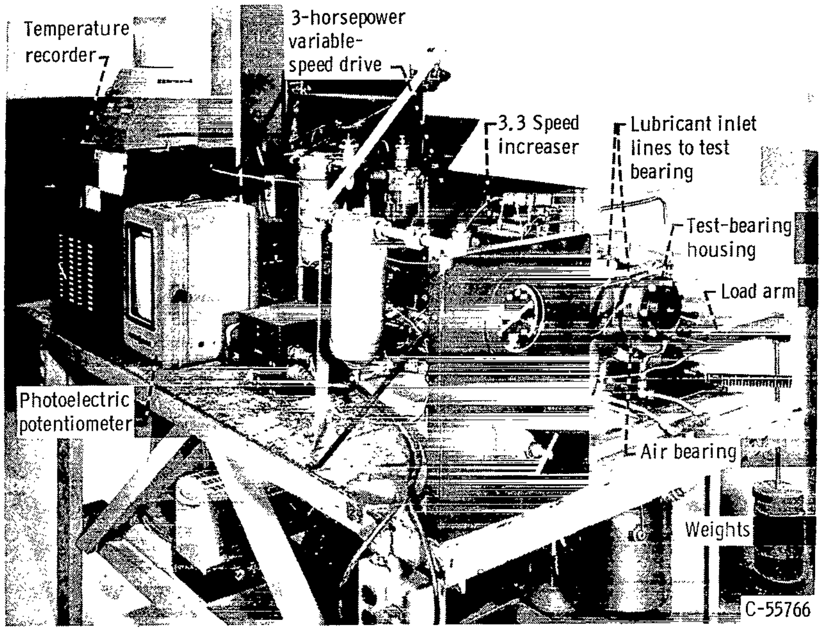


Figure 1. - Bearing screening rig used in tests with hexane.

APPARATUS

Screening Rig

The apparatus used in conducting the screening tests with hexane is shown in figure 1. A 3.3 speed increaser is coupled to a 3-horsepower variable-speed drive motor on one end and to the test shaft on the other through a shear pin and flexible coupling. The speed range of the test shaft was from 2000 to 17,100 rpm; shaft speed was measured by a chronometric tachometer.

Static weights positioned at one end of a lever arm with a ratio of 10 were used to apply a radial load to the test bearing. This load was transmitted to the test-bearing housing through an externally pressurized air bearing so that the housing was free to rotate for measurement of bearing friction torque. The tangential friction force produced in the bearing was sensed by an electrical-resistance strain-gage beam and recorded on a photoeletric potentiometer. To minimize any spurious torques in the system, the test lubricant was introduced to the bearing housing through two pieces of flexible tubing. The tubing was arranged in symmetric coils, one on each side of the housing centerline, to cancel out any reaction couples produced by the lubricant flow. The lubricant flow from the bearing was collected and returned to the sump by means of catch basins. A three-way valve in the return line provided a means for flow measurement. Bearing back and lubricant temperatures were measured by iron-constantan thermocouples.

The bearings were 1.5 inches (nominal) in inside diameter by 1.5 inches (nominal) long. The lubricant was introduced to the bearing through a 0.125-inch-diameter hole into an axial spreader groove opposite the applied load as in reference 1. A three-axial-groove configuration was tested to determine the effects, if any, on inhibiting half-frequency whirl (ref. 2). These two bearing-groove designs are shown in figures 2(a) and (b). Test journals in most cases were SAE-4340 steel treated to a Rockwell C hardness of 35 and finished to 5 to 10 microinches rms.

Cryogenic Rig

Drive and load system. - A 10-horsepower variable-speed direct-current drive motor is coupled to a 14.35 speed increaser through a flexible coupling. The vertical test shaft is supported by a ball and roller bearing and is

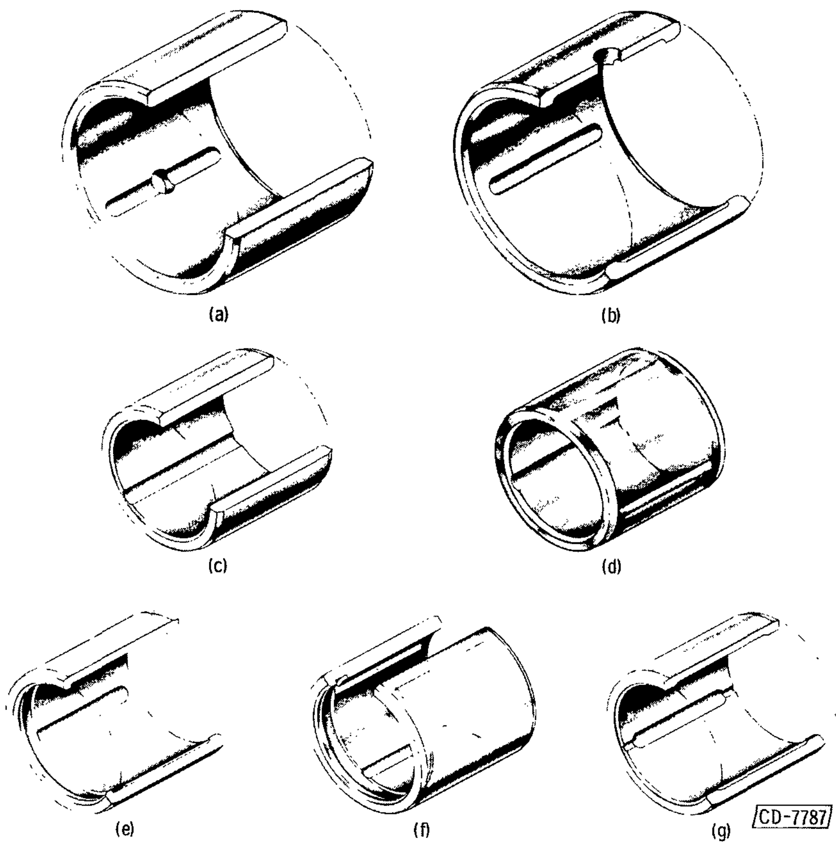
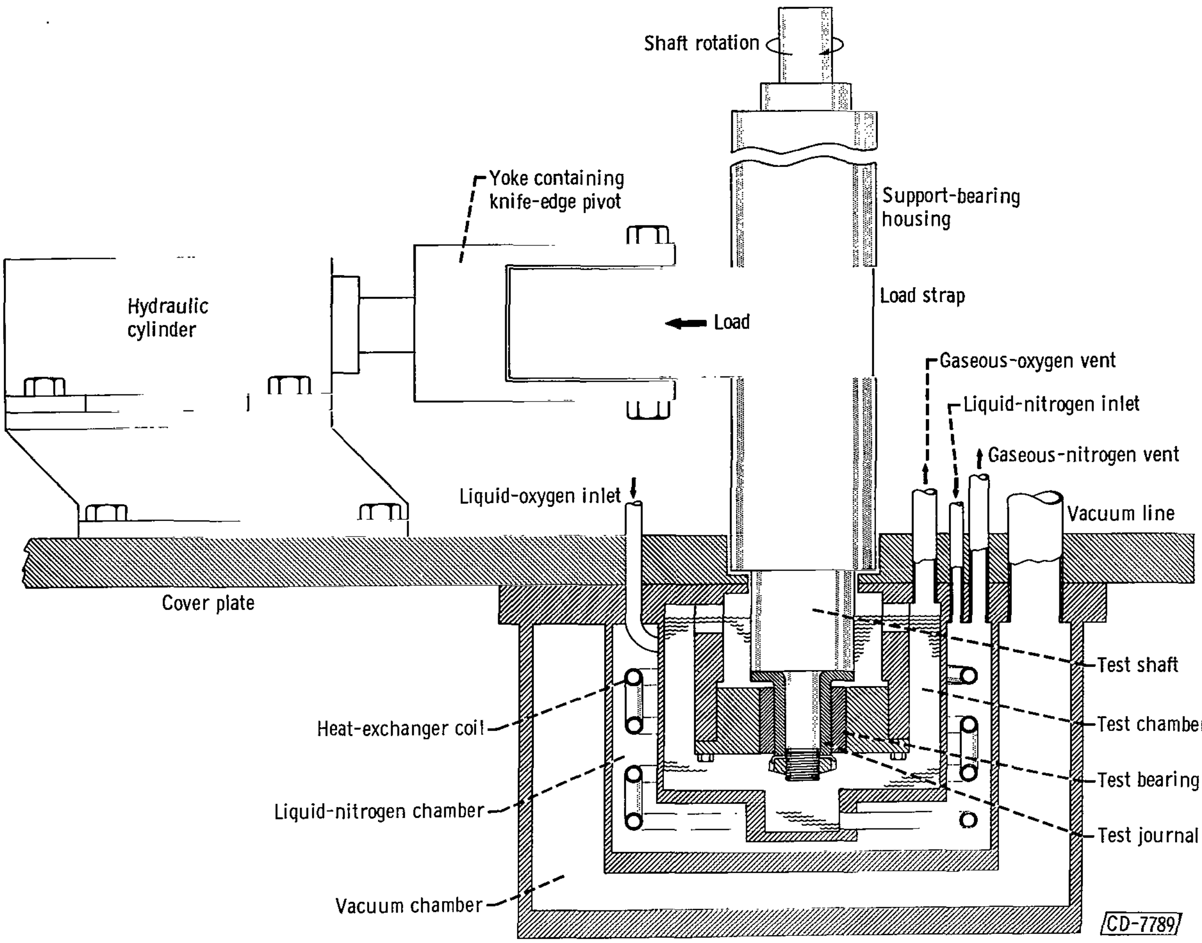


Figure 2. - Types of lubricant supply grooves investigated in hexane, liquid nitrogen, and liquid oxygen.

coupled to the speed-increaser output shaft by a gear coupling. The test-shaft speed range was varied from 400 to 50,000 rpm. The output from a magnetic pickup in proximity to a 60-tooth gear on the test shaft was fed into an electronic counter to measure shaft speed. A radial load was applied to the test bearing by pressurizing a precision hydraulic cylinder. The force was transmitted to the test bearing through the support-bearing housing and test shaft as shown in figure 3(a).

Cryogenic supply system. - A cylindrical weldment consisting of three concentric chambers completely encloses the test-bearing assembly (fig. 3(a)). The innermost chamber contains the oxidant that is introduced through a heat-exchanger coil immersed in liquid nitrogen in the center chamber. The outermost chamber is a vacuum jacket to minimize boiloff of the cryogenic liquid. The cryogenic liquid (nitrogen or oxygen) was transferred from a 100-liter Dewar to the test chamber by gas pressurization. The liquid level in the test chamber was sensed by a specially designed capacitance probe and was read on a milliammeter. In the tests where the liquid oxygen was supplied to the bearing at approximately 5 pounds per square inch gage, the heat exchanger and the nitrogen jacket were removed and a transfer line was added that introduced the test fluid directly to the bearing as shown in figure 3(b).

Test bearings. - The bearings tested in liquid nitrogen and liquid oxygen were 1.0 inch (nominal) in inside diameter by 1.0 inch (nominal) long. These bearings were tested fully immersed in liquid nitrogen and both fully immersed and pressure-fed in liquid oxygen. Various lubricant-groove configurations, both circumferential and axial, were tested and are shown in figures 2(c) to (g). The test journals in most cases were made of hardenable stainless steel; however, a wrought nickel-copper alloy and a hardenable alloy steel were also tested.



(a) Bearing fully immersed at atmospheric pressure.

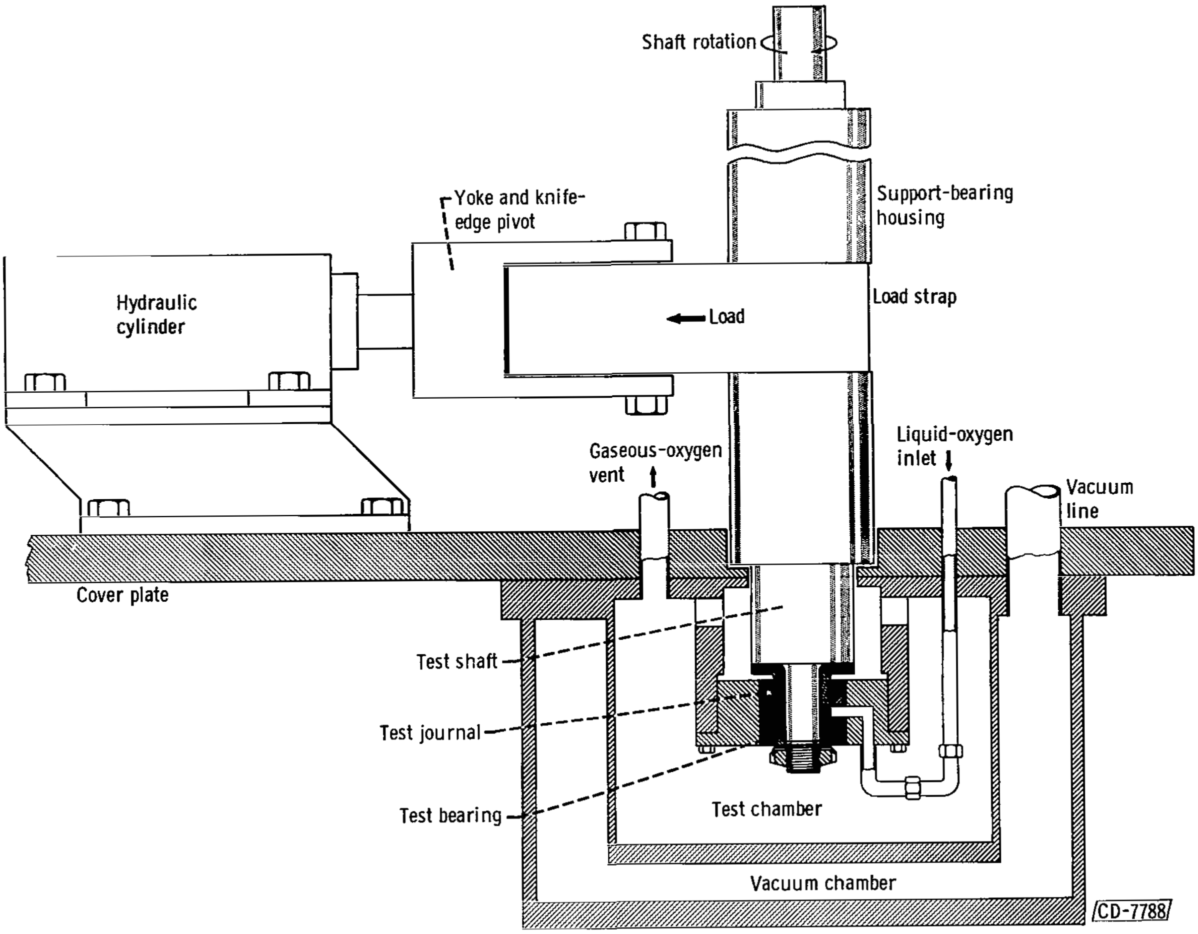
Figure 3. - Schematic drawing of cryogenic bearing-test rig.

PROCEDURE

Screening Tests

Prior to each test series a bearing was assembled in a housing with a radial interference fit. An average of nine measurements with a dial bore gage determined the bearing inside diameter to within 0.0001 inch. From this measurement a journal diameter was specified to give a predetermined running clearance for any given test.

The test-lubricant pump was started and the inlet pressure to the bearing adjusted to 10 pounds per square inch gage. To prevent galling or scoring of the bearing and journal surfaces, the drive motor was started prior to the application of any radial load. With the test shaft running at its minimum speed of 2000 rpm, weights were added to the load arm and the torque readings checked to see whether or not the bearing was running with a hydrodynamic film. For a given radial load, the speed was increased in nominal 2500-rpm increments up to a maximum nominal speed of 15,000 rpm. The load was then increased by



(b) Pressure-fed system.

Figure 3. - Concluded. Schematic drawing of cryogenic bearing-test rig.

100 pounds on a succeeding run and the speed varied as before. This procedure was repeated until a maximum load of 500 pounds was reached or until a failure terminated the test. A run was considered successful if the maximum speed was attained under a given radial load for 30 minutes.

Cryogenic Bearing Tests

The test bearing inside diameter was measured and a journal size was specified to provide a predetermined running clearance at liquid-bath temperature. To ensure the removal of any organic contaminants, each component of the test bearing was thoroughly cleaned in 1, 1, 1,-trichloroethane and then rinsed in acetone. Journals were scrubbed with levigated alumina until tap water would completely wet the surface indicating the absence of any organic films.

Liquid nitrogen was introduced into the chamber surrounding the oxidant or test chamber. Sufficient time was allowed for chamber walls to reach temperature equilibrium before the low-temperature test fluid was introduced into the test chamber. Once a stable liquid level of approximately 2 inches above the test bearing could be maintained at a Dewar gas pressure of 3 pounds per square inch gage, the drive motor was started. At startup, the test shaft would accelerate to a minimum value of 400 rpm. The speed was slowly increased to at least 1000 rpm before any load was applied. With a given load applied the speed was increased in nominal 2500-rpm increments to a maximum of 25,000 rpm. The load was varied in 25-pound increments whenever possible. Motor input volts and amperes were recorded at each speed and load change. A test was terminated if (1) the armature current exceeded 125 percent of the rated amperes for more than 5 minutes, (2) the ammeter surged, (3) severe noise and/or vibrations occurred, or (4) seizure of the test bearing occurred.

RESULTS AND DISCUSSION

Screening Tests in Hexane

The results of preliminary tests with hexane as a lubricant are listed in table I. The metal combination exhibiting the best performance under hydrodynamic and boundary lubricating conditions was a high-lead-bearing bronze running against an SAE-4340 journal. Satisfactory performance was also obtained with an SAE-64-bearing bronze against an SAE-4340 journal.

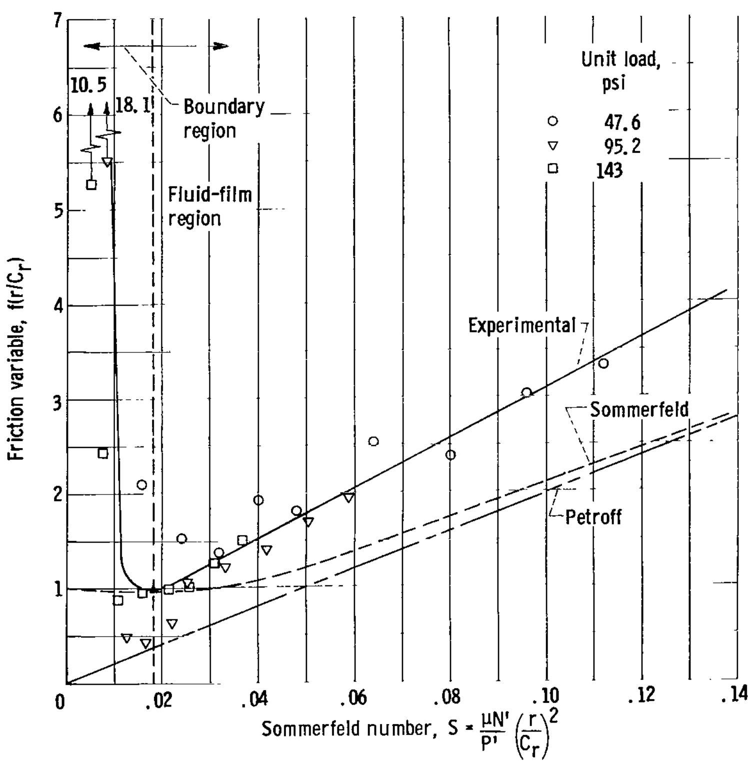


Figure 4. - Comparison of experimental data with theoretical data for loads of 100, 200, and 300 pounds. Bearing, high-lead-bearing bronze; bearing diameter, $1\frac{1}{2}$ inches; journal, steel; diametral clearance, 0.0021 inch; hexane inlet pressure (fed through 1/2-in.-diam. hole), 10 pounds per square inch gage; absolute viscosity, 0.043×10^{-6} reyns at 75° F; speed, 2000 to 14,000 rpm.

Metallic materials. - The high-lead-bearing bronze material, because of its reliable performance, was used in several investigations to obtain friction-torque data for comparison with hydrodynamic theory. Experimental values of friction variable are plotted against Sommerfeld number in figure 4. Also plotted in figure 4 are friction variables against Sommerfeld number by using the Petroff, Ocvirk (ref. 3), and Sommerfeld theories (ref. 4). The high experimental values of friction variable show that a rupture of the hydrodynamic film occurred at values of the Sommerfeld number less than 0.02. For values less than 0.02, boundary lubrication conditions existed; for

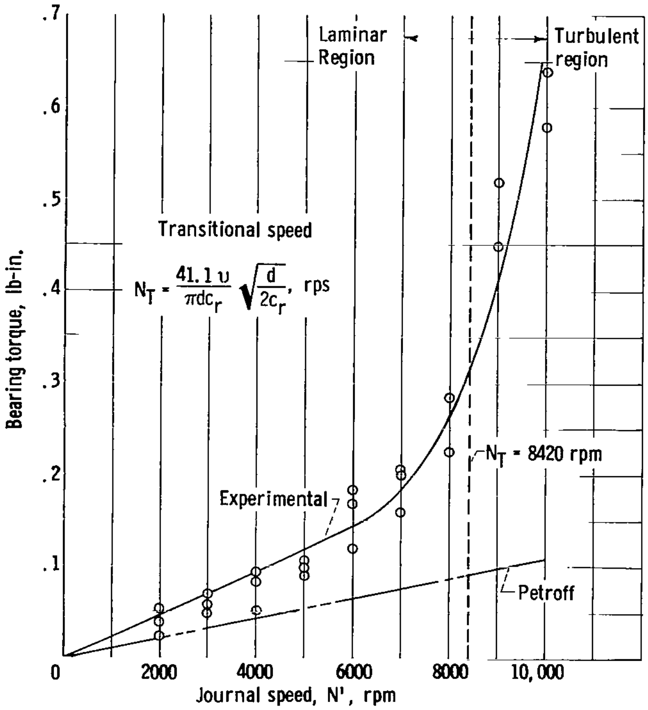


Figure 5. - Zero-load friction torque plotted against journal speed in hexane for comparison of experimental data with theoretical data. Bearing, high-lead-bearing bronze; bearing diameter, $1\frac{1}{2}$ inches; bearing length, $1\frac{1}{2}$ inches; journal, steel; diametral clearance, 0.0021 inch; hexane inlet pressure (fed through 1/8-in.-diam. hole), 10 pounds per square inch gage; absolute viscosity, 0.043×10^{-6} reyns at 75° F; journal speed, 2000 to 10,000 rpm.

values above 0.02, this bearing operated with a full fluid film. The knee of this curve is dependent upon the frictional characteristics of the bearing material (ref. 5).

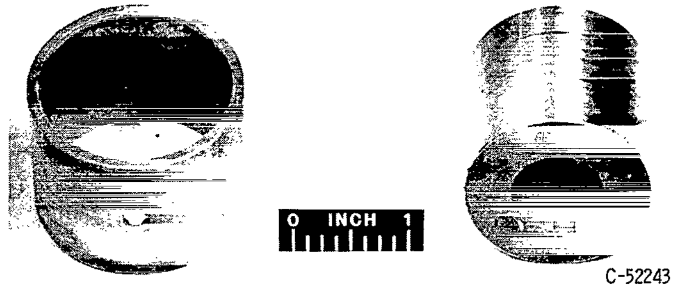
Bearing friction torque was obtained over a range of speeds to determine the onset of turbulence. These data are plotted in figure 5. The general shape of the curve is in good agreement with data obtained in references 6 and 7 for turbulent flow investigations. A critical or transitional shaft speed was calculated for this bearing by using Taylor's criterion (ref. 8) as modified by Wilcock. The calculated value is shown in figure 5 as a dotted line and falls close to the actual shaft speed where friction torque no longer increases linearly with an increase in speed.

Plastic materials. - Of the various plastic materials tested in hexane (table I(b)), the fused polytetrafluoroethylene (PTFE) on wrought nickel-copper alloy performed the best. The test conducted at a maximum journal speed of 107 feet per second and a maximum unit pressure of 204 pounds per square inch was completed without any indication of bearing distress. The only visual evidence of the material having been tested was a slight glazed appearance of the surface in the load-carrying area (fig. 6(a)). Satisfactory performance was also obtained with a commercially available material (PTFE plus Pb in sintered bronze). This bearing was in excellent condition at the conclusion of the test series, and only a light polishing of the surface was evident as a result of contact with the journal on starting and stopping (fig. 6(b)).

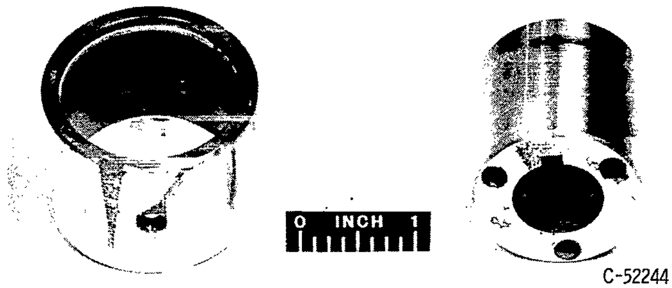
Ceramic and cermet materials. - The results of screening tests with two ceramic materials and one cermet material are shown in table I(c). The performance of these materials was poor. Failure in all cases was due to seizure, indicating that these materials, when used in plain journal bearings, will not perform satisfactorily in the boundary lubrication regime.

Screening Tests in Liquid Nitrogen

The results of these tests are presented in table II. The bearing of fused PTFE on wrought nickel-copper alloy, as in the hexane tests, again demonstrated performance superior to that of either the SAE-64 and the lead-bearing bronzes or the bearing of PTFE plus lead in sintered bronze. A maximum unit load of 215 pounds per square inch was sustained by the fused-PTFE on wrought nickel-copper alloy bearing for 5 minutes at 15,000 rpm. The motor armature current during this run fluctuated excessively, indicating operation in the boundary lubrication regime. Examination of the bearing at the completion of the test showed the PTFE liner to be completely worn away and the wrought nickel-copper alloy sleeve to be deeply scored in the load zone (fig. 7(a)). PTFE and metal debris were present in the test chamber.



(a) Fused polytetrafluoroethylene on wrought nickel-copper alloy.

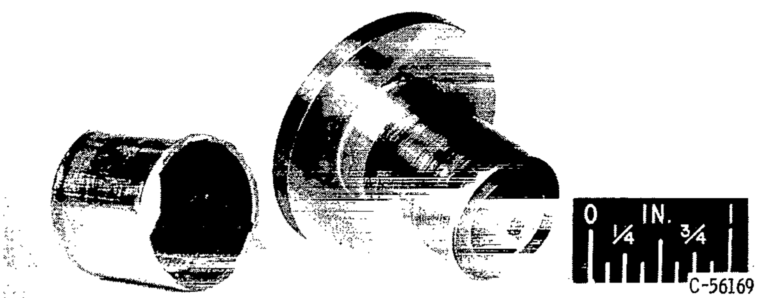


(b) Polytetrafluoroethylene plus lead in sintered bronze.

Figure 6. - Results of screening tests in hexane.

The overall performance of the bearing of PTFE plus lead in sintered bronze was superior to that of either the SAE-64- or the lead-bearing bronzes. In one test a load of 45 pounds per square inch was carried at a surface speed of 87.5 feet per second with the bearing fully immersed in liquid nitrogen. Diametral clearances were increased, and three equally spaced axial spreader grooves (fig. 2) were added to increase the supply of lubricant to the bearing clearance area. These changes resulted in some improvement as shown in table II. The bearing was able to support a load of 45 pounds per square inch at a surface speed of 87.5 feet per second. The extent of bearing wear and journal scoring are shown in figure 7(b). Test results for

(a) Fused polytetrafluoroethylene on wrought nickel-copper alloy.



(b) Polytetrafluoroethylene plus lead in sintered bronze.

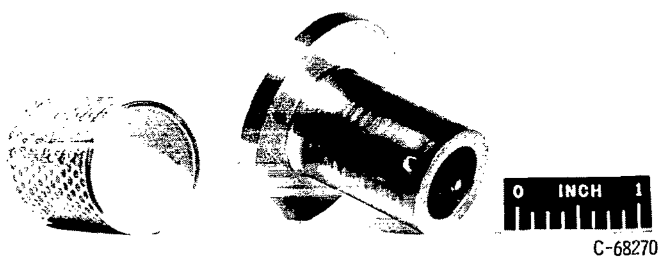
Figure 7. - Results of screening tests in liquid-nitrogen.

the SAE-64- and the lead-bearing bronzes show that the SAE-64 phosphor bronze was superior to the high-lead-bearing bronze that was unable to carry any load at all.

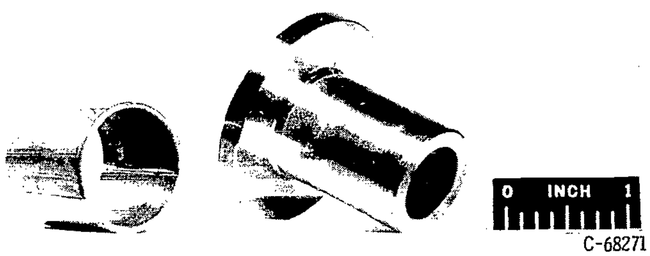
Tests in Liquid Oxygen

Fully immersed at atmospheric pressure. - Results of these tests are presented in table III(a). The fused-PTFE coating on wrought nickel-copper alloy and the glass-filled-PTFE on steel bearings, as in the hexane and liquid-nitrogen tests, performed better than the other materials tested; however, there were no tests that reached both objectives of a surface speed of 78.5 feet per second and a load of 100 pounds per square inch. One exception was a PTFE liner (15-percent glass-filled) on perforated steel that carried a load of 160 pounds per square inch at 65.5 feet per second for approximately 7 minutes, at which time impending seizure dictated a reduction in the load and speed. Performance on a second test of this material was not nearly as good. This test was run on a split bushing that is shown with the journal in figure 8(a). A white powdery wear debris was evident in the test chamber and on the adapter parts. The journal was darkened indicating that high temperatures were generated at the journal and bearing interface at the high rubbing speeds.

The bearings of fused PTFE on wrought nickel-copper alloy and PTFE plus lead in sintered bronze were capable of sustaining only moderately light loads at surface speeds considerably less than the original test objectives. The latter material showed only light wear in the load zone, whereas the fused-PTFE coating in one test at the maximum surface speed of 76.5 feet per second and load of 36 pounds per square inch was completely worn through to the wrought nickel-copper alloy backing sleeve. The bearing and journal of PTFE plus lead in sintered bronze are shown in figure 8(b). The single axial groove in the bearing can be seen. The 1/8-inch-diameter hole located in the journal midway between the ends was drilled coincident with radial passageways in the shaft that led to a central shaft recess. This was done in an effort to improve the flow of liquid oxygen to the bearing by exploiting the centrifugal pressure head developed in the entrapped fluid in this recess.



(a) Polytetrafluoroethylene liner (15-percent-glass-filled) on perforated steel.



(b) Polytetrafluoroethylene plus lead in sintered bronze.

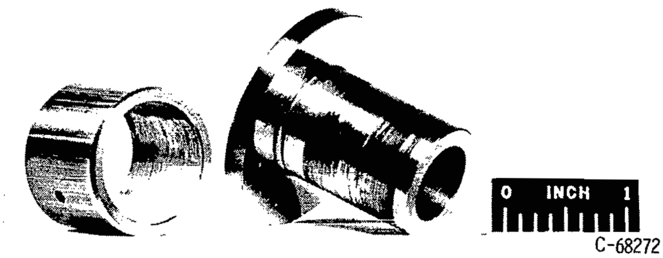
Figure 8. - Results of tests in liquid oxygen (fully immersed at 14.7 lb/sq in.).

Two phenolic-impregnated mechanical-carbon bearings were tested. One test was terminated after a short time due to excessive drive torque even at very nominal loads. The second test on a bearing with a significantly larger clearance seized at 2500 rpm without any load being applied.

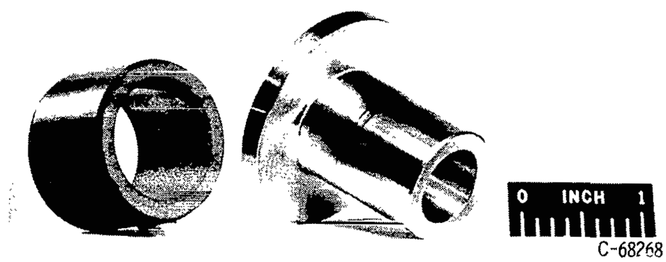
<u>Pressure-fed tests.</u> - The results of these tests are presented in table III(b). Several mechanical-grade carbon materials with phenolic-resin, halide-salt, and PTFE impregnants were tested and compared with fused PTFE on wrought nickel-copper alloy. The latter material performed slightly better than the carbon materials. In two of the pressure-fed tests, the general performance was poorer than in the fully immersed tests. The maximum speed attainable was 44 feet per second at a load of 41 pounds per square inch compared with 76.5 feet per second at 36 pounds per square inch in the fully immersed tests. All bearings of carbon compositions experienced seizure at moderate speeds and loads, or tests were terminated because of high motor armature current. The fused-PTFE liners in both cases were worn away and the journal was badly scored (fig. 9(a)). The bearing of halide-salt-impregnated carbon is shown in figure 9(b). The bearing of PTFE-impregnated carbon that showed light scoring and polishing is shown in figure 9(c).

It is hypothesized that the generally poor performance of these materials in the cryogenic fluids is due primarily to the fact that these fluids are at or near their boiling points. Any energy input into the fluid, for instance, through surface contact at startup or from viscous shear, causes it to flash into a vapor, resulting in two-phase flow within the bearing. The presence of a two-phase flow would sharply decrease the load-carrying capacity by a further reduction in the viscosity.

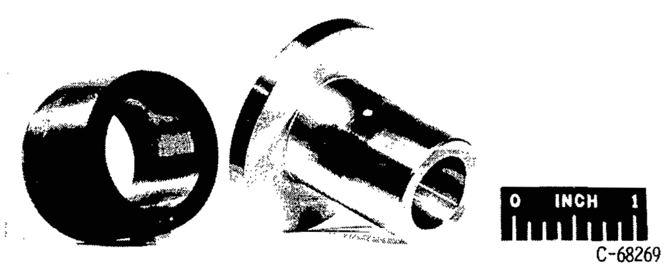
In order to ensure a full fluid film in the bearing, liquid oxygen was supplied directly to the clearance area 180° opposite the applied radial load at a pressure of 5 pounds per square inch gage above atmospheric. The boiling point of liquid oxygen at this pressure was -302° F. The test results did not indicate any improvement, and, in some cases, performance was not as good. Results of tests when liquid oxygen was subcooled to approximately -304° F by means of the liquid-nitrogen jacket were also negative.



(a) Fused polytetrafluoroethylene on wrought nickel-copper alloy.



(b) Halide-salt-impregnated mechanical-grade carbon.



(c) Polytetrafluoroethylene-impregnated mechanical-grade carbon.

Figure 9. - Results of tests in liquid oxygen (externally pressurized at 5 lb/sq in. gage).

For any given bearing geometry the load-carrying capacity is a direct function of lubricant viscosity and shaft speed in the hydrodynamic regime. In boundary lubrication as applied to journal bearings, however, the load capacity varies inversely as the speed and is dependent on certain physical characteristics of the material as well as bearing geometry, surface finishes, and the amount of wear that can be tolerated in the bearing (refs. 5 and 9).

SUMMARY OF RESULTS

A number of tests were conducted with 1.0- to 1.5-inch-diameter journal bearings of various materials with a low-viscosity hydrocarbon, liquid nitrogen, and liquid oxygen as lubricants. The three fluids had comparable viscosities at test conditions. These tests, which were run over a range of journal surface speeds to 109 feet per second (25,000 rpm) and loads to 220 pounds per square inch, revealed the following results:

1. The generally poor bearing performance experienced in liquid oxygen was in direct contrast to the relatively good results obtained with several material combinations in the hydrocarbon screening tests. This poor performance is attributed to the operation of the bearings in the cryogenic fluids while at or near their boiling points, where only a slight energy input causes the fluid to flash into a vapor, resulting in two-phase flow.

2. Fully immersed tests in liquid oxygen for six different materials showed that only three were capable of sustaining even nominal loads (36 psi) at shaft speeds of 10,000 rpm (44 ft/sec) and above for short durations. These materials were (1) fused PTFE on wrought nickel-copper alloy, (2) 15-percent-glass-filled PTFE on perforated steel, and (3) PTFE plus lead in sintered bronze. Thermal degradation of the liners through frictional heating at high rubbing speeds caused excessive wear and ultimate failure of the bearing.

3. Two pressure-fed tests in liquid oxygen of a bearing of fused-PTFE coating on wrought nickel-copper alloy showed load-carrying capabilities of 36 and 41 pounds per square inch at a maximum speed of 10,000 rpm (44 ft/sec). Impregnated carbon bearings generally did not perform as well under these conditions as did the fused-PTFE-coated wrought nickel-copper alloy bearings.

4. Experimental values of friction variable at varying Sommerfeld numbers obtained in screening tests conducted in a low-viscosity (0.043×10^{-6} reyn at 75° F) hydrocarbon (hexane) correlated well with the theory. The bearing material used in these tests was a high-lead-bearing bronze operating against an SAE-4340 steel journal. A definite rupture of the lubricating film occurred in some tests at a Sommerfeld number of less than 0.02. The experimental curve of friction variable as a function of Sommerfeld number is of the same general shape as that obtained by many other investigators.

5. Experimental values of bearing friction torque at zero load established a shaft speed for a given bearing geometry where transition from laminar to turbulent flow occurs. The plotted curve is in good agreement with results published by other investigators.

6. A number of tests were conducted in liquid nitrogen on those materials that performed satisfactorily in hexane. The bearings of fused-PTFE coating on wrought nickel-copper alloy and PTFE plus lead in sintered bronze were able to sustain higher loads at higher surface speeds and for longer periods of time than the SAE-64- and the high-lead bearing bronzes.

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio, August 26, 1964

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TABLE I. - RESULTS OF SCREENING TESTS IN LOW-VISCOSITY HYDROCARBON.

[Bearing I.D., $1\frac{1}{2}$ in. (nominal); bearing length, $1\frac{1}{2}$ in. (nominal); journal materials, SAE 4340 and chromium plating on SAE 4340; surface finish, 5 to 10 µin. (rms); groove type, see fig. 2(a).]

(a) Metals

Bearing material	Room-temperature diametral clearance, in.	Maximum journal speed		Maximum unit-bearing load, psi	Time at maximum speed and load, min	Total test time, min	Reason for stopping test	Bearing surface condition
		rpm	ft/sec					
SAE-64-bearing bronze (80% Cu + 10% Pb + 10% Sn)	0.0024	15,000	107	81	30	225	Test objective attained	Did not examine
		15,000	107	122	30	105	Test objective attained	Did not examine
		5,000	35	122	30	50	Bearing seized when increasing speed to 7500 rpm	Bearing and journal scored and galled
	0.0019	15,000	107	40	30	120	Test objective attained	Bearing and journal lightly scored
		12,300	87	81	---	90	High torque	Bearing scored; surface polished in load zone
High-lead-bearing bronze (70% Cu + 26% Pb + 4% Sn)	0.0015	15,000	107	43	30	90	Test objective attained	Did not examine
				88	30	90	Test objective attained	Did not examine
				132	30	90	Test objective attained	Did not examine
				176	30	90	Test objective attained	Did not examine
				220	30	90	Test objective attained	Bearing surface excellent, light polishing in load zone

Silver plating on wrought nickel-copper alloy (67% Ni + 30% Cu + 1.4% Fe + 1% Mn + 0.05% Si + 0.15% C + 0.035% S)	0.0016	15,000	107	17	30	150	Test objective attained	Did not examine
		15,000	107	40	30	90	Test objective attained	Did not examine
		14,000	100	81	---	60	Bearing seized when increasing speed to 15,000 rpm	Silver wiped and scored in localized areas, approximately $3\frac{1}{8}$ in. from each end
Cold-pressed and sintered iron alloy (70% Fe + 15% Mo + 15% Co)	0.0014	5,000	35	17	---	2	Bearing seized at this speed and load	Deep score in bearing surface
		5,000	35	44	30	30	Seized after approximately 1 min at 8000 rpm	Bearing surface badly galled
Beryllium copper (wrought) (2% Be + 98% Cu)	0.0018	10,000	66	44	30	30	Bearing seized at this speed and load	Distress in localized areas at bearing extremities; journal evidenced material pickup
Aluminum bearing alloy (6.5% Sn + 1% Cu + 1% Ni, bal. Al)	0.0020	14,000	93	44	15	105	High torque and rough operation generally	Bearing lightly scored near ends
		15,000	106	88	5	60	High torque and rough operation generally	Additional scoring
		4,000	26	132	10	10	Seized	Bearing galled; heavy scoring in load zone
Rhodium plating on wrought nickel-copper alloy (ASTM B164)	0.0018	15,000	99	44	2	120	High torque and rough operation	Light scoring
		15,000	99	44	15	90	Seized when attempting increase in load at 2000 rpm	Galled areas at ends of bearing
Gold plating on wrought nickel-copper alloy (ASTM B164)	0.0021	14,000	92	44	10	80	Rig noisy; high torque	Did not examine
		4,000	36	88	---	---	Seized	Narrow band of galled surface in center extending 360° in circumference

TABLE I. - Continued. RESULTS OF SCREENING TESTS IN LOW-VISCOSITY HYDROCARBON

[Bearing I.D., $1\frac{1}{2}$ in. (nominal); bearing length, $1\frac{1}{2}$ in. (nominal); journal materials, SAE 4340 and chromium plating on SAE 4340; surface finish, 5 to 10 μin. (rms); groove type, see fig. 2(a).]

(b) Plastics

Bearing material	Room-temperature diametral clearance, in.	Maximum journal speed		Maximum unit-bearing load, psi	Time at maximum speed and load, min	Total test time, min	Reason for stopping test	Bearing surface condition
		rpm	ft/sec					
PTFE[a] resin (extruded tubing)	0.0015	2,500	16.5	17	2	2	Seized	Darkened area in load zone indicating high heating
	0.0083	10,000	66	17	10	85	Rough operation	Darkened area in load zone indicating high heating
PTFE resin plus 20 percent copper (extruded tubing)	0.0064	14,500	96	17	30	90	Test objective attained	Did not examine
		14,500	96	44	30	120	Test objective attained	Did not examine
		5,000	33	87	2	120	High torque; motor overload	Polished area in load zone; copper transfer to journal surface
	[b]0.0050	15,000	99	44	15	120	High torque	Wear pattern indicated probable misalinement
		10,000	66	87	30	90	Seized in attempt to increase speed	Distressed area on one end only; large amount of copper wear debris
Fused PTFE resin on wrought nickel-copper alloy (ASTM B164)	0.0025	15,000	107	40	30	150	Test objective attained	Did not examine
				81	30	105	Test objective attained	Did not examine
				122	30	90	Test objective attained	Did not examine
				163	30	90	Test objective attained	Did not examine
				204	30	90	Test objective attained	Bearing surface excellent; light polishing in load zone (fig. 6)

Fused PTFCE[c] resin on wrought nickel-copper alloy (ASTM B164)	0.0037	15,000	107	40	30	120	Test objective attained	Did not examine
				81	30	90	Test objective attained	Did not examine
				122	30	90	Test objective attained	Did not examine
		14,000	100	163	---	60	Rapid torque increase 14,000 rpm	Liner wiped in narrow band at center extending 360°; evidence of high temperature material breakdown
PTFE plus lead in sintered bronze	0.0038	15,000	99	53	30	90	Test objective attained	Did not examine
				107	30	90	Test objective attained	Did not examine
				160	30	90	Test objective attained	Did not examine
				213	30	90	Test objective attained	Lightly polished area in lead zone, otherwise surface condition excellent (fig. 7)

[a]Polytetrafluoroethylene.

[b]Three axial grooves, see fig. 2(b).

[c]Polytrifluorochloroethylene.

TABLE I. - Concluded. RESULTS OF SCREENING TESTS IN LOW-VISCOSITY HYDROCARBON.

[Bearing I.D., $1\frac{1}{2}$ in. (nominal); bearing length, $1\frac{1}{2}$ in. (nominal); journal materials, SAE 4340 and chromium plating on SAE 4340; surface finish, 5 to 10 μin. (rms); groove type, see fig. 2(a).]

(c) Ceramics and cermets

Bearing material	Room-temperature diametral clearance, in.	Maximum journal speed		Maximum unit-bearing load, psi	Time at maximum speed and load, min	Total test time, min	Reason for stopping test	Bearing surface condition
		rpm	ft/sec					
Aluminum oxide on flame-sprayed wrought nickel-copper alloy (ASTM B164)	0.0022	5,000	33	17	---	1	Seized	Bearing surface darkened in load zone. Metal transferred from journal to bearing surface
Crystallized glass ceramic	0.0011	10,000	66	44	---	30	Seized	Bearing and journal welded together
	0.0032	8,000	53	44	---	30	Seized	Darkened circumferential bands 1/4 in. in from ends
Platinum-bonded titanium carbide	0.0022	9,000	59	44	---	90	Seized	Distressed area localized at bearing ends extending around circumference
	0.0018	9,000	59	44	---	45	Seized	Distressed area localized at bearing ends extending around circumference

TABLE II. - RESULTS OF SCREENING TESTS IN LIQUID NITROGEN

[Bearing I.D., 1 in. (nominal); bearing length, 1 in. (nominal); journal surface finish 5 to 10 μin. (rms); nitrogen absolute viscosity μ, 0.023×10^{-6} reyns at -320° F (b.p.).]

Bearing material	Journal material	Groove type, see -	Diametral clearance, in.		Maximum journal speed		Maximum unit load, psi	Time at maximum speed and load, min	Total test time, min	Reason for stopping test	Bearing surface condition
			Room temperature	Liquid-nitrogen temperature (a)	rpm	ft/sec					
SAE-64-bearing bronze (80% Cu + 10% Pb + 10% Sn)	SAE 4340	Fig. 2(e)	0.0040	0.0025	20,000	87.5	25	5	95	Ran out of liquid nitrogen	Wear pattern in upper half of bearing load zone, journal surface excellent
		Fig. 2(e)	0.0035	0.0022	7,500	32.7	25	5	60	Seized at 10,000 rpm and 25 psi	Distressed area in load zone; bearing had rotated in its housing
		Fig. 2(g)	0.0041	0.0025	2,000	8.8	36	5	25	Excessive motor amperes	Surface galled and scored at bearing extremities
		Fig. 2(e)	0.0033	0.0020	1,100	4.8	25	2	20	Excessive motor amperes	Uneven wear indicating misalinement
High-lead-bearing bronze (70% Cu + 26% Pb + 4% Sn)	Precipitation hardened stainless steel	Fig. 2(e) but only one axial	0.0035	------	2,700	11.8	---	15	25	High motor amperes	Wear at bearing upper end only
		Fig. 2(e)	0.0037	------	5,000	21.8	---	10	25	Seized after 1 min at 5000 rpm and 30 psi load	Lead smeared on surface in loaded half of bearing. Journal scored and polished
		Fig. 2(e)	0.0038	------	5,000	21.8	---	20	43	High motor amperes	Bearing surface galled, moved in housing
		Fig. 2(f)	0.0030	------	2,500	10.9	---	3	30	High motor amperes	Distressed area on upper half of bearing
Fused PTFE resin on wrought nickel-copper alloy	Wrought nickel-copper alloy (ASTM B164)	Fig. 2(e)	0.0070	0.0045	25,000	109	36	15	105	Test objective obtained	Bearing surface good, slight polishing in load zone
		Fig. 2(e)	0.0070	0.0045	7,500	32.7	18	5	40	Severe vibrations	PTFE liner worn through to wrought nickel-copper alloy sleeve
		Fig. 2(e)	0.013	0.0105	15,000	65.5	215	5	85	Test objective obtained	Liner worn excessively in bonded area (fig. 7(a))
PTFE plus lead in sintered bronze	Precipitation hardened stainless steel	None	0.0011	------	8,000	34.9	36	7	90	High motor amperes	Lead-PTFE overlay worn away in loaded area of bearing surface
		None	0.0016	------	1,000	4.4	36	15	60	High motor amperes	Slight wear in loaded half
		Fig. 2(d)	0.0052	------	20,000	87.5	45	2	95	High motor amperes	Bearing was found to have lost its initial pressure. Fitting was loose in housing (Fig 7(b))
		None	0.0068	------	7,500	32.7	17	3	65	Excessive noise; high amperes	Wear in load zone through to sintered-bronze underlay

[a]Calculated.

TABLE III. - RESULTS OF TESTS IN LIQUID OXYGEN

[Bearing I.D., 1 in. (nominal); bearing length, 1 in. (nominal) except where noted; journal surface finish, 5 to 10 μin. (rms); absolute viscosity μ, 0.0274×10^{-6} reyns at -297° F (b.p.).]

(a) Fully immersed at atmospheric pressure

Bearing material	Journal material	Groove type, see -	Diametral clearance, in.		Maximum journal speed		Maximum unit load, psi	Time at maximum speed and load, min	Total test time, min	Reason for stopping test	Bearing surface condition
			Room temperature	Liquid-oxygen temperature (a)	rpm	ft/sec					
SAE-64-bearing bronze	Precipitation hardened stainless steel	Fig. 2(g)	0.0040	0.0035	1,000	4.4	---	---	3	Seized when increasing speed	Distressed area upper one-third surface, loaded half
High-lead-bearing bronze	Precipitation hardened stainless steel	Fig. 2(g)	0.0052	0.0044	1,000	4.4	---	4	10	Seized when increasing speed	Extensive scoring on bearing surface near upper end
Fused PTFE[b] on wrought nickel-copper alloy	Precipitation hardened stainless steel	Fig. 2(d)	0.0037	0.0047	17,500	76.5	36	5	63	High motor amperes, noise	Bearing-liner worn through to wrought nickel-copper alloy sleeve
		None	0.0092	0.0115	10,000	44	36	10	37	Lower test shaft seal failure	Light polishing in load zone; journal surface highly polished
PTFE plus lead in sintered bronze	Precipitation[c] hardened stainless steel	Fig. 2(d)	0.0029	0.0005	10,000	44	36	5	55	Seized at 12,800 rpm	Light wear in load zone; clearance too small (fig. 8(b))
		None	0.0088	0.0013	6,000	26.2	37	7	93	High motor amperes when applying load	Light wear in load zone; surface good
PTFE on steel[d] (15% glass filled)	Precipitation hardened stainless steel	None	0.0080	0.0049	15,000	65.5	160	7	57	Seized at 25,000 rpm and 44 psi load	PTFE liner worn excessively; journal shows evidence of heating
		None	0.012	0.006	10,000	44	14	3	34	High motor amperes	High wear in load zone 0.004 out of round (fig. 8(a))
Mechanical carbon phenolic-resin impregnate	Chromium plating on steel	Fig. 2(e) only one groove	0.0022	0.0012	2,600	11.3	---	13	25	High motor amperes	Surface rough and pitted in loaded area; journal shows carbon material transfer
		Fig. 2(e)	0.0050	0.0018	1,000	4.4	---	3	3	Seized at 2500 rpm; no load	Surface rough and pitted in loaded area; journal shows carbon material transfer

[a]Calculated.

[b]Polytetrafluroethylene.

[c]Radial hole in journal wall, 1/8-in. diameter.

[d]Bearing length, 1.25 in. (nominal; split bushing).

TABLE III. - Concluded. RESULTS OF TESTS IN LIQUID OXYGEN

[Bearing I.D., 1 in. (nominal); bearing length, 1 in. (nominal) except where noted; journal surface finish, 5 to 10 μin. (rms); absolute viscosity μ, 0.027×10^{-6} reyns at -297° F (b.p.).]

(b) Externally pressurized at 5 pounds per square inch gage (b.p., - 302° F)

Bearing material	Journal material	Groove type, see -	Diametral clearance, in.		Maximum journal speed		Maximum unit load, psi	Time at maximum speed and load, min	Total test time, min	Reason for stopping test	Bearing surface condition
			Room temperature	Liquid-oxygen temperature (a)	rpm	ft/sec					
Fused PTFE on wrought nickel-copper alloy	440-C stainless steel	None	0.0096	-----	8,000	34.9	36	10	55	High motor amperes and rig vibration	Liner completely worn away in loaded area
		None	0.0087	-----	10,000	44	41	8	50	High motor amperes and rig vibration	Liner completely worn away in loaded area (fig. 9(a))
Mechanical carbon phenolic-resin impregnate	Chromium plating on steel	Fig. 1(a)	0.0038	-----	10,000	44	20	2	37	Seized	Roughened band extending 360° circumferentially at bearing center
		Fig. 1(a)	0.0030	-----	1,100	4.8	---	---	20	High motor amperes	Polished area in load zone; journal evidences resin stain
		Fig. 2(d)	0.0030	-----	6,000	26.2	26	2	54	Seized	Polished area in load zone, roughened band extending 360° circumferentially. Journal evidences high heating
Mechanical carbon plus halide-salt impregnate	Chromium plating on steel	Fig. 2(a)	0.0034	-----	460	2	---	10	10	High motor amperes	Brown film at lower end of bearing. Journal had excessive taper
		Fig. 2(a)	0.0025	-----	6,000	26.2	26	2	54	Fluctuating motor amperes; rig noisy	Highly polished area in load zone; circumferential scoring at bearing ends
Mechanical carbon plus halide-salt impregnate and PTFCE film	Chromium plating on steel	Fig. 2(a)	0.0031	-----	8,000	34.9	36	15	65	Seized at 10,000 rpm and 36 psi load	Wear bands extending 360° and 1/4 in. from ends; debris in groove (fig. 9(b))
Mechanical carbon plus PTFE impregnate	Chromium plating on steel	Fig. 2(a)	0.0032	-----	2,000	8.7	17	12	55	Fluctuating motor amperes; rig noisy	Highly polished area, lower one-half of bearing. Journal has carbon pickup
			0.0032	-----	8,000	34.9	20	8	48	High armature amperes	Highly polished area in center of load zone; film transfer in journal center
			0.0032	-----	2,000	8.7	27	5	47	High armature amperes	Highly polished area in center of load zone; film transfer in journal center (fig. 9(c))

[a]Did not calculate because bearings were not fully immersed in liquid oxygen.

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