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PERFORMANCE OF HIGH-SPEED BALL BEARINGS WITH LEAD- AND LEAD-ALLOY-PLATED RETAINERS IN LIQUID HYDROGEN AT 1.2 MILLION DN

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TECHNICAL PAPER proposed for presentation at
Joint Lubrication Conference cosponsored by the American
Society of Lubrication Engineers and the American
Society of Mechanical Engineers
Atlanta, Georgia, October 16-18, 1973

E-7573

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ABSTRACT

Forty-millimeter-bore ball bearings with lead- and lead-alloy-coated retainers were operated in liquid hydrogen at 30 000 rpm under a thrust load of 1780 Newtons (400 lb). Bearing lives were compared using different (1) lead- and lead-alloy coatings, (2) coating thicknesses, (3) substrate materials, (4) retainer locating surfaces, and (5) plating techniques. Longer bearing run times were achieved using retainers with a lead-tin-copper alloy coating electroplated onto a leaded-bronze material (22.5 hr) and an aluminum-bronze alloy (19.3 hr). Thirty percent of the bearings tested achieved the desired objective of 10 hours. All of the lead-alloy coated retainers exceeded this objective. A coating thickness of at least 36 microns (0.0014 in.) was used for all bearings exceeding the 10-hour goal.

INTRODUCTION

Rolling-element bearing technology for high-speed, cryogenic turbomachinery has advanced considerably during the past decade. Bearing designs have been directed mainly toward chemical-rocket-engine turbopumps that pump liquid hydrogen [1 to 3] for which bearing running times are only a few minutes. In a rocket-engine turbopump, the bearings are normally cooled by direct contact with the cryogenic hydrogen. The bearings are usually lubricated by transfer films provided by the retainer, which is fabricated from a self-lubricating material such as polytetrafluoroethylene (PTFE) [4]. The PTFE is compounded with additives such as glass fibers, bronze or molybdenum disulfide to provide the necessary strength and wear-resistance properties [5 and 6].

The NERVA (Nuclear Engine for Rocket Vehicle Application) engine turbopump requires bearings with a radiation-resistant, nonspalling, solid lubricant having extended life capabilities. The integrated gamma radiation dose for the current NERVA engine design is estimated at 10^3 to 10^4 joules per gram of carbon in the area of the turbine bearing [7]. Ball bearings with retainers made from a polymer-glass laminate material have been run in liquid hydrogen in a radiation environment [8]. In two separate tests, each lasting 60 minutes, at an integrated gamma dose of 100 joules per gram of carbon, the retainer material suffered severe radiation damage. Therefore, PTFE materials seem to be unsuitable for use in a high radiation environment.

The friction and wear studies reported in [9] indicated that several low-shear-strength metallic coatings applied to a 440C stainless-steel substrate can provide adequate lubrication in liquid hydrogen. The best results were obtained with a lead coating. The lead coating formed a transfer film by a mechanism similar to that of PTFE materials used in cryogenic hydrogen. The results of [9] suggest that lead-coated retainers can be used as a means of providing lubrication for ball bearings operating at high speed in liquid hydrogen. Furthermore, lead coatings appear promising for use in bearings operating in a radiation environment.

The objectives of this investigation were (1) to achieve a 10-hour bearing operating life with a lead or lead-alloy coating on a metal retainer, (2) to determine an optimum thickness of the lead or lead-alloy coating necessary for a 10-hour run, and (3) to improve the wear resistance of the coating and the retainer substrate material while maintaining lubrication.

Experiments were conducted with 40-millimeter-bore ball bearings operating at 30 000 rpm in liquid hydrogen with a 1780-newton (400-lb) thrust load. Bearing lubrication was effected by the transfer of lead or lead-alloy film from the retainer ball pockets to the race grooves. The bearing retainers were fabricated from two aluminum-bronze alloys, a leaded-bronze alloy, and AISI 440C stainless steel. The retainers were then ion-plated or electroplated with lead or lead alloys.

APPARATUS

Bearing Test Rig

The test apparatus is shown in figure 1. The test bearing was driven through a gear assembly by a variable-speed, direct-current motor. Automatic speed control (to within ±0.1 percent) was provided over a range of test-shaft speeds from 900 to 30 000 rpm. The test shaft was supported at its lower end by the test bearing and at its upper end by an oil-lubricated ball bearing, not shown. Thrust load was applied to the test-bearing housing by a dead-weight load. The test-bearing outer-race temperature was monitored with a platinum resistance sensor (fig. 1) and continuously recorded on a strip chart. Speed was indicated on a digital frequency meter. Motor power consumption was determined from readings of a voltmeter and an ammeter (armature power).

Liquid-Hydrogen Supply and Exhaust System

The test bearing was cooled by liquid hydrogen supplied from a 1.89-cubic-meter (500 gal) Dewar. The liquid-hydrogen flow rate to the test bearing was approximately 0.0076 cubic meter per minute (2 gal/min). The liquid-hydrogen flow from the Dewar was regulated by the Dewar pressure and the flow valve setting.

Test Bearings and Retainers

The bearings used in these tests were 40-millimeter-bore (108 series), deep-groove ball bearings manufactured to ABEC-5 tolerances. Two types of bearings were used to accommodate both inner- and outer-race located retainers. To make the bearings separable, one shoulder was relieved at the outer- (inner-) race for inner- (outer-) race located retainers (fig. 2). The inner- and outer-race curvatures were both 0.54. The average internal radial clearance was 0.063 millimeter (0.0025 in.). The ball and race material was AISI 440C stainless steel. The bearings contained ten 9.53 millimeter (0.375 in.) diameter balls manufactured to grade 10 specifications. The retainers were one-piece construction machined from one of four different substrate materials. Composition and hardness of substrates are given in table I. The diametral clearance between the retainer and the race locating shoulder (i.e., the land clearance) and the ball-pocket clearance are indicated for each bearing in table II.

Retainer Coatings

Lead or lead-alloy plated on the retainer substrate material, served as the bearing lubricant in the liquid-hydrogen environment. Coatings were applied by either an ion-plating or electroplating process. Two sets of bearing races were also ion plated with lead. The ion-plating process is described in detail in [10]. Coating composition, method of application, and coating thickness are also given in table II. Ion-plated coating thickness was assumed uniform on the retainer surface and was determined by dividing the weight gain by the product of the material density and the surface area. The lead-tin-copper alloy was electroplated on the retainer surfaces to a thickness of 50.8 microns (0.002 in.) over a flash coating of 90 percent lead and 10 percent tin. The flash coating served as a primer to improve adherence to the substrate.

PROCEDURE

In preparation for testing, the bearings were first degreased with three solvents (trichloroethylene, acetone, and alcohol). Next, they were inspected and measured for clearances. Finally, individual components of the bearings were weighed.

After the test bearing was installed, the test chamber and all hydrogen lines were purged for 15 minutes with helium gas. The dewar was then pressurized and liquid hydrogen flowed through the bearing and test chamber. The test shaft was rotated at 900 rpm during the 10-minute cool-down period. The thrust load (400 lb or 1780 N) was applied immediately after the start of rotation. When the system reached liquid-hydrogen temperature (20.3 K), the shaft speed was increased to the test speed of 30 000 rpm in increments of 5000 rpm every 5 minutes.

The operating life of a test bearing was defined as the run time accumulated at 30 000 rpm at the above test conditions until failure. Failure was defined as either (1) bearing seizure, (2) excessive (10 kilowatts) power input to the drive system, or (3) wear-through of the coating on the retainer to the substrate material. This latter criteria could only be ascertained during intervals between testing which usually occurred after three to four hours of continuous testing. Consequently, bearing lives based on this criteria may be inaccurate to this extent.

After each run, the test bearing was inspected for wear. Periodically, the bearing was washed with three solvents (trichloroethylene, acetone, and alcohol), and dried and weighed to determine the weight change (in.mg) of each component. The balls, races, and retainers were examined visually and with optical microscopy to determine the extent of wear and surface damage. Photographs of the retainers were made to illustrate the wear patterns that occurred during the test period.

RESULTS AND DISCUSSION

The lead- and lead-alloy-coated retainers are discussed separately. The sixteen pure lead-coated retainers which are first discussed are either inner- or outer-race guided; whereas, all four of the lead-alloy-coated retainers are outer-race guided.

Lead Coated Retainers

Evidence of lead transfer film. - Among the sixteen retainers coated with pure-lead, twelve were ion-plated by the technique described in [10] and four were electroplated. Both electroplated and ion-plated lead transferred from the retainer surfaces to form a lubricating film on the balls and race grooves. Figure 3 is a profile trace across the inner-race groove, normal to the ball-rolling direction, of bearing 4. The maximum transfer-film thickness measured was 6.1 microns (240 μin.). These lead films are considerably thicker than the films obtained from PTFE composition retainers [4]. The lead transfer films were normally deposited uniformly around the circumference of the race groove.

Effect of retainer coating thickness. - The lead-coating thickness is an important consideration in the design of this type of bearing for longer life. Seven bearings with a retainer coating thickness less than or equal to 10.2 microns (0.0004 in.) had the lowest average life of 2.9 hours. Five retainers had coatings less than 50 micron thickness but equal to or greater than 27.4 microns and resulted in an average life of 4.7 hours. The highest average life (7.3 hr) was achieved with 4 bearings using a retainer coating thickness of 50 microns (0.002 in.). Among the 16 bearings only two surpassed the objective 10 hour life. These two bearings had lives of 12.4 hours and 14.9 hours with retainer lead-coating thickness of 35.8 and 50.0 microns (0.0014 and 0.0020 in.) respectively. Both bearings required a shutdown since the power input to the bearing exceeded 10 kilowatts. Examination of the retainers showed that the lead coating had worn through in the ball pockets and at the inner locating diameter. Consequently these bearings were discontinued from further testing. It is not evident what caused the high bearing torque leading to the shutdown.

According to [9], ion-plated lead adheres more tenaciously to the substrate than does electroplated lead. All of the 50 micron (0.002 in.) thick coatings were electroplated. Therefore, the higher average life achieved with the 50 micron (0.002 in.) thick coatings is attributed to the thickness of the coating and not to the plating technique.

Although thicker lead coatings appear to result in longer bearing life, these bearings are more susceptible to jamming due to excessive lead accumulation. Figure 4 shows excessive lead accumulation adjacent to the rubbing area of the ball pocket of bearing 5. Figure 5 shows an excess of lead debris transferred to a ball surface of bearing 8. This type of accumulation of lead has the potential of jamming the bearing at high speeds and causing a catastrophic failure of the bearing.

Lead blisters. - Examination of the inner race of bearing 6 at a low magnification revealed a transfer film with a blistered appearance (fig. 6(a)). Blisters were also observed on the ball set of bearing 9. The lead-transfer film thickness on bearing 16 was excessive and caused the lead to blister and peel off in ribbons as shown in figure 6(b). These blisters may have resulted from fatigue of the transfer film or may indicate that the lead transfer film was excessively thick and poorly adherent to the race groove.

Effect of retainer clearances on wear. - Tests were made with 4 bearings (4, 6, 7, and 8) using inner-race guided retainers to determine the effect of inner-land and/or ball-pocket clearance on wear.

Wear occurred in a 360° arc of the retainer ball pockets of the first few bearings tested, possibly indicating insufficient ball-pocket clearance. However, increasing the ball pocket clearance from 0.33 mm (0.013 in.) to 0.61 mm (0.024 in.) did not significantly reduce the circumferential wear within the pockets.

Further, an attempt was made to determine if the retainer-race land clearance affected the wear at the inner land of the retainer. Bearings 7 and 8 were both run with retainers that were ion plated with equal thicknesses of lead (10 microns) and balanced dynamically before running. They both survived only 2 hours of running. However, bearing 8 had 10 times more retainer wear (weight loss) than did bearing 7 (table III). The inner-land clearance of bearing 8 was 60 percent greater than that of bearing 7. The excessive inner-land clearance in bearing 8 was probably conducive to uneven wear and, therefore, to increasing dynamic unbalance. Inner-race-riding retainers are not self-balancing as wear progresses; therefore, any unbalance is compounded by uneven wear.

Effect of ion plating of bearing races. - In addition to coating the retainers, the races of bearings 1 and 2 were ion plated with lead to a thickness of 0.51 microns (20 μin.). These two bearings showed no noticeable improvement in bearing life or performance over bearings with lead coatings on only the retainers (see table III). For example, bearings 1, 3, and 9 had retainers with 50-microns (0.002-in.-) thick, electroplated lead coatings on the retainers, with the same clearances. The life of bearing 1 (5.8 hr) was equivalent to that of bearing 9 (5.4 hr). However, these lives were less than the life of bearing 3 (14.9 hr).

Wear resistance. - The retainer of bearing 15 fractured after running 2.7 hours. The failure mode for all other bearings (1-16) was by wear of the lead coating through to the substrate material. Run times for bearings in this group (with exception of bearings 3 and 16) were less than 10 hours, as shown in table III. These test results indicate that the lead coating was not sufficiently wear resistant to provide lubrication for the desired 10-hour run time. A harder coating should improve the wear resistance and thereby increase the operating life of the bearing.

Lead Alloy Coated Retainers

Lead can be hardened by alloying [11]. Therefore several lead alloys were plated onto the retainers [12] to determine the effect on the bearing life. A lead alloy coating containing 3 percent antimony showed some improvement in wear resistance but proved to be too abrasive. A lead-tin-copper alloy showed the most promise.

A lead-tin-copper alloy was electroplated onto the retainers of four bearings. Two different retainer substrate materials were used. The leaded-bronze alloy (material B, table I) was used with bearings 17 and 20, and the hard aluminum-bronze alloy (material D, table I) was used with bearings 18 and 19.

The lead-tin-copper alloy coatings provided the longest bearing run times of the coatings evaluated. All four bearings completed the objective 10-hour run time at 30 000 rpm in liquid hydrogen. The run times of bearings 17 and 19 were 22.5 and 19.3 hours, respectively. These runs were discontinued because post-test examination of retainers revealed wear-through of the lead-alloy coating on the rails and in the ball pockets. Bearings 18 and 20 also exceeded the objective of 10 hours (12.2 and 15.2 hr, respectively). These runs were terminated because of fracturing of the retainer. The cause for these fractures is not known. Some additional discussion concerning this is given under Post-Test Analysis.

The coating was somewhat abrasive, since wear grooves formed in the outer-race lands of bearings 18 and 19. Evidence of this high wear is indicated in table III by noting the outer-race percent weight loss of these two bearings. This wear is similar to that discussed in [12] with the antimony-lead-alloy coating.

The 50.8-micron- (0.002-in.-) thick lead-alloy coating in the ball pockets of bearing 19 tended to extrude into the wear track and jam the balls. This occurred during the initial bearing run and prevented the bearing from achieving the 30 000-rpm test speed. After the extruded material was removed from the retainer, the bearing was reassembled and testing was continued. Thus the extrusion observed with the lead coatings can also be a problem with the harder lead-alloy coatings.

Post Test Analysis

Fractures. - Three of the twenty bearing retainers failed by fracture. All three were outer-race riding retainers. All fractures occurred at the cross section through the center of the ball pockets as illustrated in figure 7. The maximum hoop-stress due to the centrifugal force on the retainer occurs at the sidewall of the ball pocket. But a calculation of the maximum hoop-stress indicates that this by itself could not be responsible for the fracture. Large ball-retainer forces apparently contributed to the fractures, as indicated by the wear and deformation within the ball-pockets of these retainers. Ball-retainer forces large enough to cause retainer fracture have been hypothesized in [13] as resulting from ball speed variation (BSV). Accordingly, BSV can result from (a) misalinement plus pure thrust load, (b) deviations in ball diameter, and (c) conditions of high speed (usually above 0.5 million DN) under radial load combined with a small thrust load. No misalinement was indicated in the ball tracks of the failed bearings. Ball diameter variation was no greater than 0.25 microns (10 μin.), and no radial loads were applied in these tests. Consequently, it is likely that none of the above considerations would have led to ball-retainer forces sufficiently large to cause failure.

Momentary ball-retainer forces, or race-retainer forces could develop if any of the balls would roll over a piece of lead-alloy that had become dislodged from an area of accumulation as described previously. If the dislodged material were large enough, it could slow-down the orbital velocity of the ball sufficiently to produce a large ball-retainer force. This force would create additional stress to the hoop stress and possibly cause fracture at the weakest section.

Eccentric retainer motion could also be caused by lead-alloy debris lodging between the guiding race shoulder and the retainer land. If sufficient wear has occurred so as to open up the race-retainer land clearance, then the potential of the balls jamming between the retainer and race exists. It is possible bearings 15 and 20 failed in this manner. Examination of the ball pockets of these retainers revealed wear patterns indicating several balls had become jammed between the upper edge of the ball pockets and outer-race.

The retainer of bearing 18 fractured into 4 pieces. In addition, the outer race had several cracks that had propagated along planes normal to the rolling direction of the ball set. Also the film on the balls and races had an unusal shiny, melted appearance. The melted alloy film was evidence of high heat generation that was probably caused by loss of bearing radial clearance prior to retainer failure.

Retainer and coating wear rate. - Table III shows the retainer wear for each bearing as the weight change in percent of the original retainer weight.

The wear on the inner-race riding retainers was uniform around the land periphery. In contrast, the wear on the rail-lands of half of the outer-race riding retainers was uneven around the periphery. Among all retainers seven showed uniform, moderate coating wear and minimal substrate wear in the lands and ball pockets. Further, the retainer wear was less than 2 percent for these bearings.

The wear rate of the various retainer coating and substrate materials can be compared by observing the bar graph in figure 8. Bearings that failed as a result of a broken retainer or peeled coating were excluded from the plot. In general, the lead-alloy coated retainers had lower wear rates than those with the pure-lead coating. Not all of the wear rates shown in figure 8 accurately represent coating wear since some retainers had minimal substrate wear. Bearings using retainers 3 and 16, with lead coating, and retainers 17 and 19 with lead-tin-copper-alloy coating, achieved the required 10-hour life with relatively low wear rates. The leaded-bronze alloy (material B) or the aluminum-bronze alloy (material D) served equally well as retainer substrate materials.

CONCLUDING REMARKS

Of the 20 bearings discussed in this report, 8 failed from high, uneven wear on the lands of the retainer. The ball pockets of the failed retainers showed moderate wear and deformation. Three retainers failed by cracking or fracturing. These problems with the substrate indicate that the retainer material may not have been ductile enough even though it had good wear resistance and was nongalling. Since some of the lead- and lead-alloy-coated retainers operated for more than 10 hours, it is apparent that lead does lubricate at liquid-hydrogen temperatures. However, the effectiveness of this method of lubrication was masked by the tendency of the lubricant coating to accumulate in the ball pockets. These accumulations then dislodge and cause the bearing to jam.

SUMMARY OF RESULTS

Coatings of lead and lead alloys on metal retainer substrates were investigated for use with high-speed ball bearings operating in liquid hydrogen. The bearings were 40-millimeter-bore size and were run at 30 000 rpm with a 1780-newton (400-lb) thrust load. The liquid-hydrogen flow through the bearing was approximately 0.0076 cubic meter per minute (2 gal/min). Coatings of lead were ion-plated and electroplated onto the retainer substrate. An electroplated lead-tin-copper-alloy coating was also used. These coatings were applied to substrates made of two different aluminum-bronze alloys, a leaded bronze alloy, and AISI 440C stainless steel. The study produced the following results:

1. Both lead and lead-alloy retainer coatings transferred from the retainer surfaces to form a lubricant transfer film on the balls and in the race grooves.

2. The lead-tin-copper alloy proved to have better wear resistance than the pure-lead coating. All four bearings using this alloy coated retainer successfully completed the objective 10-hour run time with an average life of 17.3 hours.

3. Increasing the coating thickness up to 50 microns (0.002 in.) resulted in higher average bearing life for bearings with lead-coated retainers. A coating thickness of at least 36 microns (0.0014 in.) was used for all bearings exceeding the 10 hour goal.

4. Three of the twenty bearing retainers failed by fracture. All three were outer-race riding retainers. Deformation and wear within the ball pockets indicated the presence of large ball-cage forces.

5. Two bearings were run with 0.51-micron- (20-μin.-) thick, ion-plated lead coatings on the races in addition to the lead coatings of the retainers. This ion-plating of the races produced no significant improvement in bearing performance or life.

6. All three bronze-alloy retainer materials had good wear resistance and were nongalling.

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TABLE I. - RETAINER SUBSTRATE MATERIALS

Substrate	Material	Composition		Brinell hardness number	Equivalent Rockwell A hardness
		Element	Percent		
A	Aluminum-bronze alloy	Copper Aluminum Iron Other	85.3 10.5 3.5 .7	187	55.7
B	Leaded-bronze alloy	Copper Lead Tin	75.0 20.0 5.0	57	----
C	AISI 440C stainless steel	---------	----	560	79.0
D	Hard aluminum-bronze alloy	Copper Aluminum Iron Other	82.0 13.1 4.4 .5	285	65.6

TABLE II. - RETAINER SPECIFICATIONS AND COATINGS

Lead-alloy coating (87.5-percent Pb, 10-percent Sn, 2.5-percent Cu)
lead coating (99.9-percent Pb)

Bearing	Retainer substrate (c)	Locating surface	Coating	Coating thickness applied to retainer		Retainer clearance after plating			
						Inner race		Ball pocket	
				µm	in.	mm	in.	mm	in.
1	A	Inner race	Electro-plated lead	[a]50	0.002	0.81	0.032	0.31	0.012
3				50		.81	.032	.33	.013
9				50		.76	.030	.33	.013
4				50		1.42	.056	.33	.013
2			Ion-plated lead	[a].51	.00002	.81	.032	.43	.017
5				[b].51	.00002	.97	.038	.43	.017
6				10	.0004	1.40	.055	.76	.030
7				10		.97	.038	.64	.025
8				10		1.55	.061	.61	.024
10		Outer race		10.2		.56	.022	.58	.023
11				10.2		.64	.025	.61	.024
12	B			33.5	.0013	.53	.021	.56	.022
13	B			27.4	.0011	.69	.028	.51	.020
14	C			33.8	.0014	.76	.030	.53	.021
15	D			40.6	.0016	.71	.028	.56	.022
16	D			35.8	.0014	.71	.028	.53	.021
17	B		Electro-plated lead alloy	50.8	.002	.53	.021	.51	.020
20	B					.71	.028	.49	.020
18	D					.76	.030	.61	.024
19	D					.69	.028	.48	.019

[a]With a 0.51-µm- (0.00002-in.-) thick, ion-plated lead coating on the races.

[b]With a 50-µm- (0.002-in.-) thick, electroplated lead coating on the inner diameter of the retainer.

[c]Refer to material specifications in table I.

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TABLE III. - SUMMARY OF BEARING TEST RESULTS

Test bearings were deep-groove separable ball bearings; bore diameter, 40 mm; race and ball material, AISI 440C stainless steel; number of balls, 10; ball diameter, 9.53 mm (0.375 in.); grade 10 balls; inner- and outer-race curvature, 0.54; radial clearance, 0.0063 cm (0.0025 in.).

Bearing	Locating surface	Hours run at 30 000 rpm	Mode of failure	Weight change, percent				Sliding distance at locating race	
				Inner race	Outer race	Ball set	Retainer	Mm	M ft
1	Inner race	5.8	Coating wear	Not measured	Not measured	Not measured	Not measured	0.8	2.5
2		2.5	Coating wear	-0.02	-0.07	-0.02	-2.98	.4	1.2
3		14.9	Coating wear	-1.56	+.11	-1.07	-2.33	1.9	6.3
			Excessive power input						
4		3.3	Coating wear	-.02	+.01	(a)	-.60	.5	1.7
5		3.8	Coating wear						
			Excessive power input	+.01	(a)	+.02	-.21	.5	1.6
6	Located	1.8	Coating wear	+.03		+.05	-.87	.2	.8
7		1.9		(a)		+.01	-.25	.4	1.4
8		2.0		-.05		+.03	-2.39	.3	1.0
9		5.4		+.08		-.02	-1.51	.8	2.5
10	Outer race	3.5	Coating wear	+.04	+0.09	-0.06	-0.45	0.6	2.0
			Excessive power input						
11		4.7	Coating wear	(a)	(a)	(a)	-3.59	.8	2.5
12		2.1		+.02	+.02	-.01	-1.49	.4	1.2
13		3.1		(a)	+.01	(a)	-.85	.5	1.6
14		3.6		+.01	-.02	-.08	-2.63	.6	2.1
15	Located	2.7	Retainer fractured	(a)	-.03	+.03	-1.11	.3	.8
16		12.4	Coating wear	+.06	-.12	-.31	-4.14	1.9	6.3
			Excessive power input						
17		22.5	Coating wear	(a)	(a)	(a)	-2.65	3.3	10.7
18		12.2	Retainer fractured	+.07	-.43	-.06	-8.91	2.5	8.2
19		19.3	Coating wear	-.01	-.25	-.20	-2.71	3.5	11.3
20		15.2	Retainer cracked	-.03	-.01	-.03	-2.67	2.4	7.8

[a]Negligible.

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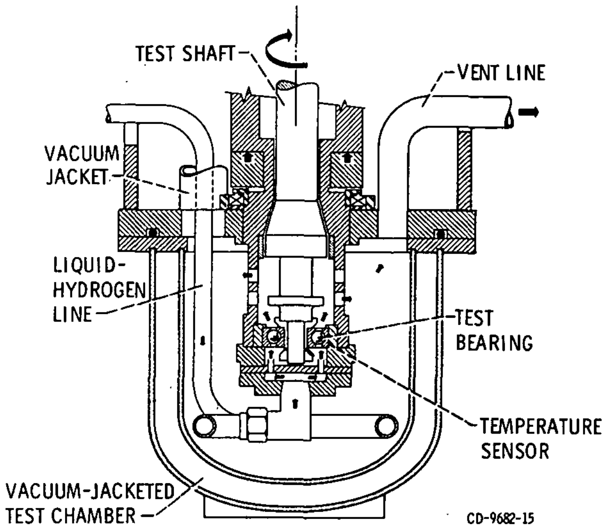

Figure 1. - Liquid-hydrogen bearing test apparatus.

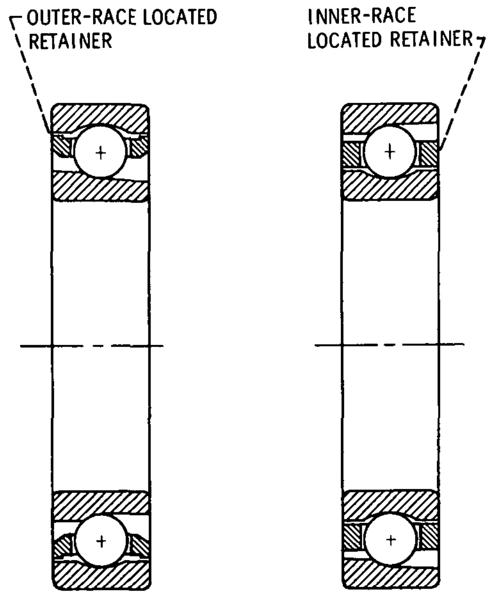

Figure 2. - Bearing and retainer design.

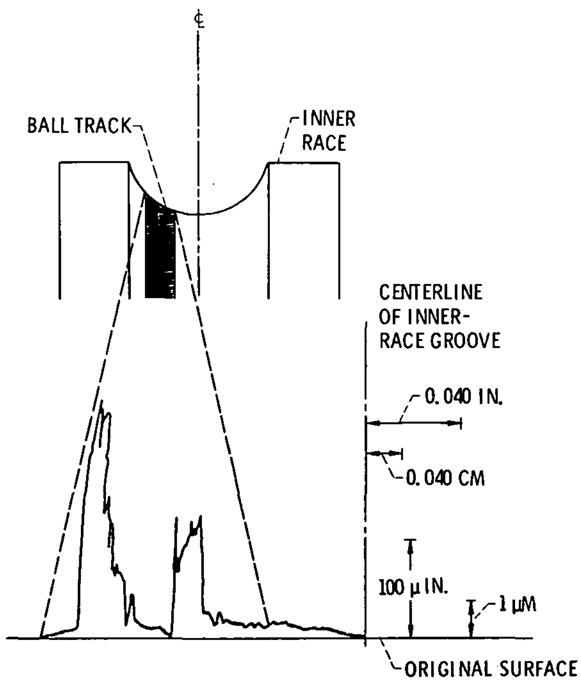

Figure 3. - Profile traces of inner-race ball track (normal to ball rolling direction) of bearing 4. Running time, 3.3 hours.

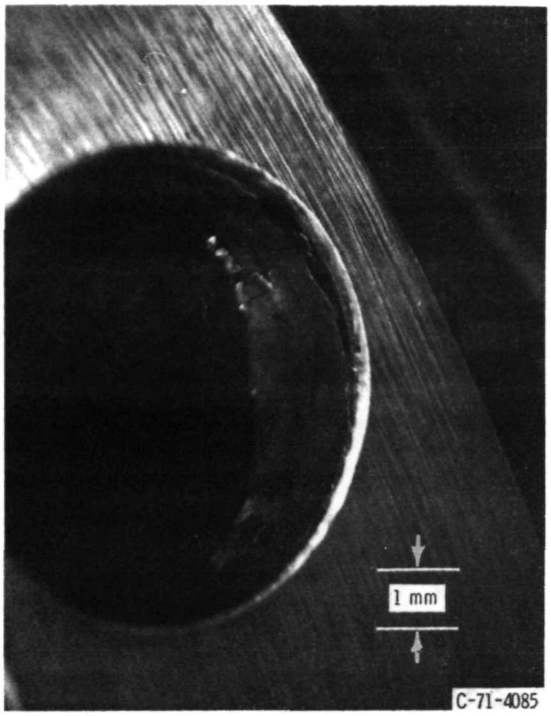

Figure 4. - Lead accumulation in retainer ball pocket of bearing 5.

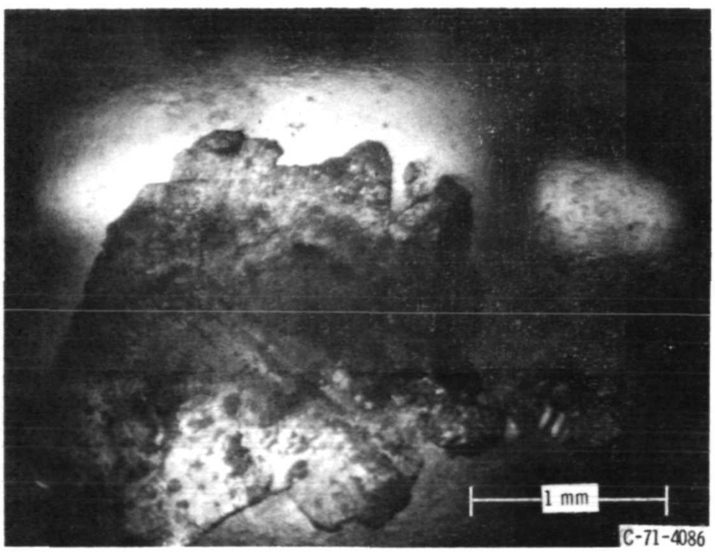

Figure 5. - Lead debris transferred to ball surface from retainer of bearing 8.

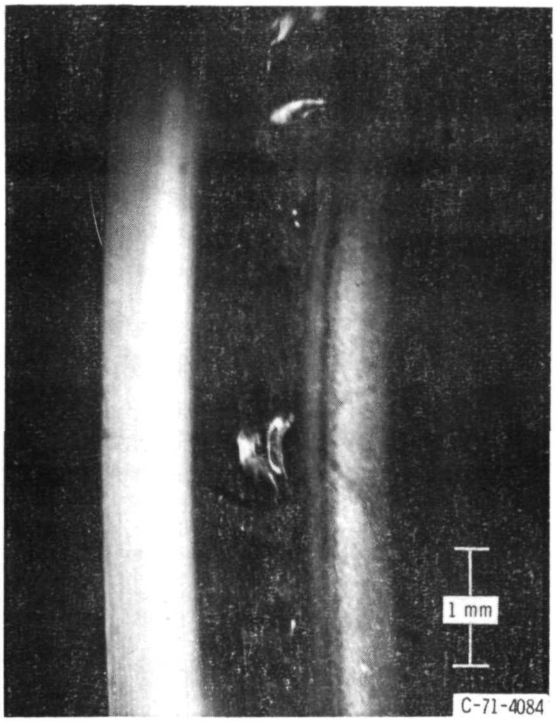

Figure 6(a). - Blistered lead transfer on inner race of bearing 6.

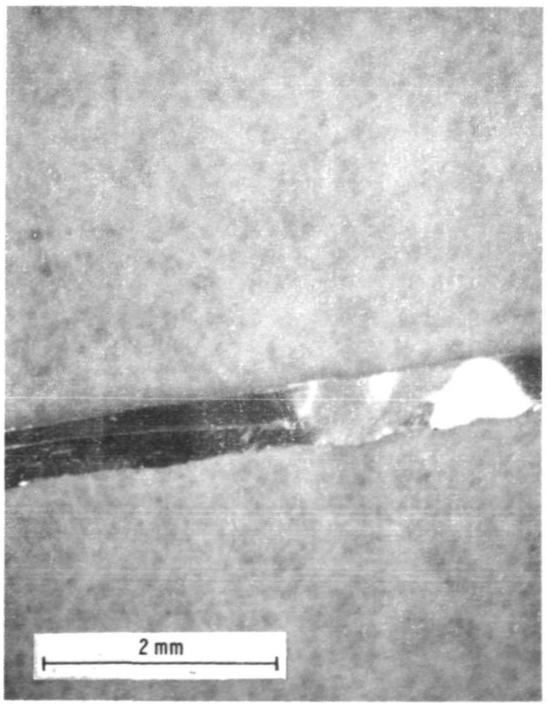

Figure 6(b). - Ribbon of lead transfer film removed from outer-race ball track of bearing 16 after 12.4 hours of run time.

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Figure 7. - Typical fracture of outer-race guided retainer (bearing 15).

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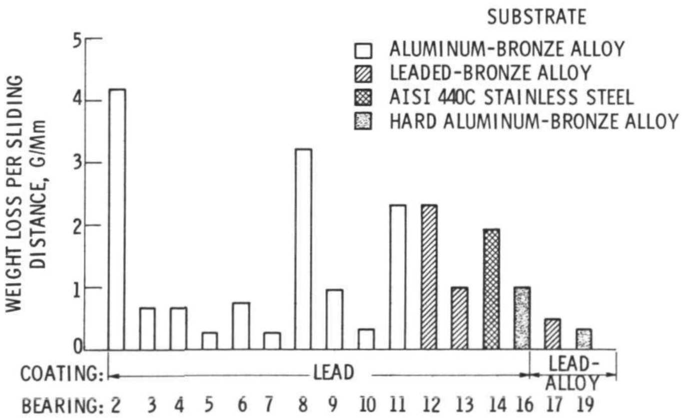

Figure 8. - Retainer weight loss per unit sliding distance for various coated retainer substrate materials. (Retainer rub velocities are 2340 m/min and 2650 m/min at the outer- and inner land, respectively.)