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FINAL REPORT
BEARING RETAINER MATERIALS DEVELOPMENT

NERVA Program Contract SNP-1

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NUCLEAR ROCKET OPERATIONS

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AEROJET-GENERAL CORPORATION
A SUBSIDIARY OF THE GENERAL TIRE & RUBBER COMPANY

RN-S-0534

FINAL REPORT
BEARING RETAINER MATERIALS DEVELOPMENT

P. Dessau

MASTER

C. W. Funk, Manager
Materials and Processes
Nuclear Rocket Operations

I. L. Odgers, Manager
Engineering Department
Nuclear Rocket Operations

R. V. Evleth, Manager
NERVA Program Office
Nuclear Rocket Operations

ABSTRACT

During the period January to June 1969, a series of 50-mm bearing tests were performed in liquid hydrogen with irradiated and unirradiated ball- and roller-bearing retainers fabricated from experimental materials. Several of these materials had been qualified by low- and high-speed wear tests, the results of which were reported in earlier reports (see References 1 and 2). Results of testing during the current period, in addition to the results of testing of five parts reported in Reference 2, indicated that the major objective of the program (i.e., to develop radiation-resistant retainer materials) has been successfully achieved.

Results of irradiation and bearing test performance are described. Several new, irradiated, reinforced polymers were tested. Of these, the PBI-glass material performed successfully in every respect, qualifying not only the material but an improved retainer configuration as well. The PBI-graphite roller retainers performed satisfactorily, also qualifying this material as a co-candidate for thrust-bearing-retainer application. Correlation between retainer wear rate and wear-test wear rate was demonstrated.

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ACKNOWLEDGEMENT

This program was conducted under the technical guidance of J. J. Lombardo, SMPO-C. The author acknowledges the concepts and guidance provided by C. W. Funk and J. B. Accinelli and extends his appreciation in particular to Mr. Accinelli for supervision of all bearing test runs.

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FIGURES (cont.)

I. INTRODUCTION

The selected NERVA turbopump concept incorporates liquid-hydrogen-cooled rolling element bearings as a means of shaft support. The possible bearing arrangements include roller bearings for radial load and ball bearings for axial load, or tandem ball bearings in a combined radial-axial application. Reliability estimates indicated that bearings contribute significantly to the turbopump failure rate. Of the bearing failure modes, retainer wear or rupture showed high probability of failure. Wear and rupture are obviously affected by the retainer material characteristics under the applicable environment of temperature, fluid, coolant flow-rate, rubbing velocity, retainer loads, radiation dose, and duration.

Development of bearings to adequate reliability levels under the intended environment was a part of the turbopump development program. Gamma radiation dose, in particular, resulted in retainer radiation-resistance requirements beyond the capability of state-of-the-art bearing technology. Current hydrogen-cooled bearings employ retainers machined from a laminated tube of Armalon (a fiberglass-reinforced Teflon cloth). This material exhibits a degradation of mechanical properties at the doses predicted for NERVA.

To acquire early performance-data applicable to future NERVA bearing size and configuration, a program was conducted using existing test equipment and bearings with the basic bearings incorporating new retainers fabricated from candidate radiation-resistant materials. Although the configuration of the test equipment limited testing to less-than-expected NERVA speed and DN values, the data are considered applicable to the selection of preferred materials with which to initiate NERVA turbopump bearing development.

The period covering calendar year 1968 and extending through the first half of 1969 was devoted to two major activities. The first was refinement of the 50-mm thrust-bearing retainer design to meet some of the apparent retainer operating problems noted and reported earlier (see Reference 2). This effort

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culminated in a slightly thicker part (with tapered sides to avoid restriction of coolant flow) as shown in Figure 1. Procurement of test parts was made to the requirements of Aerojet-General Drawing 1134747. Previous parts had been fabricated to the rectangular cross-section shown in Figure 2 (Aerojet-General Drawing 1118584). The roller-bearing retainer configuration shown in Figure 3 (Aerojet-General Drawing 1134704) was unchanged from previously used configurations.

The second major activity consisted of testing both irradiated and unirradiated retainers to establish capability of the new configuration and experimental material combination.

The test results show that the PBI-glass material is suitable for use in the NERVA turbopump environment. Exceptionally good test results were also obtained with graphite-fabric-reinforced PBI. No further developmental testing of these materials in this configuration appears necessary.

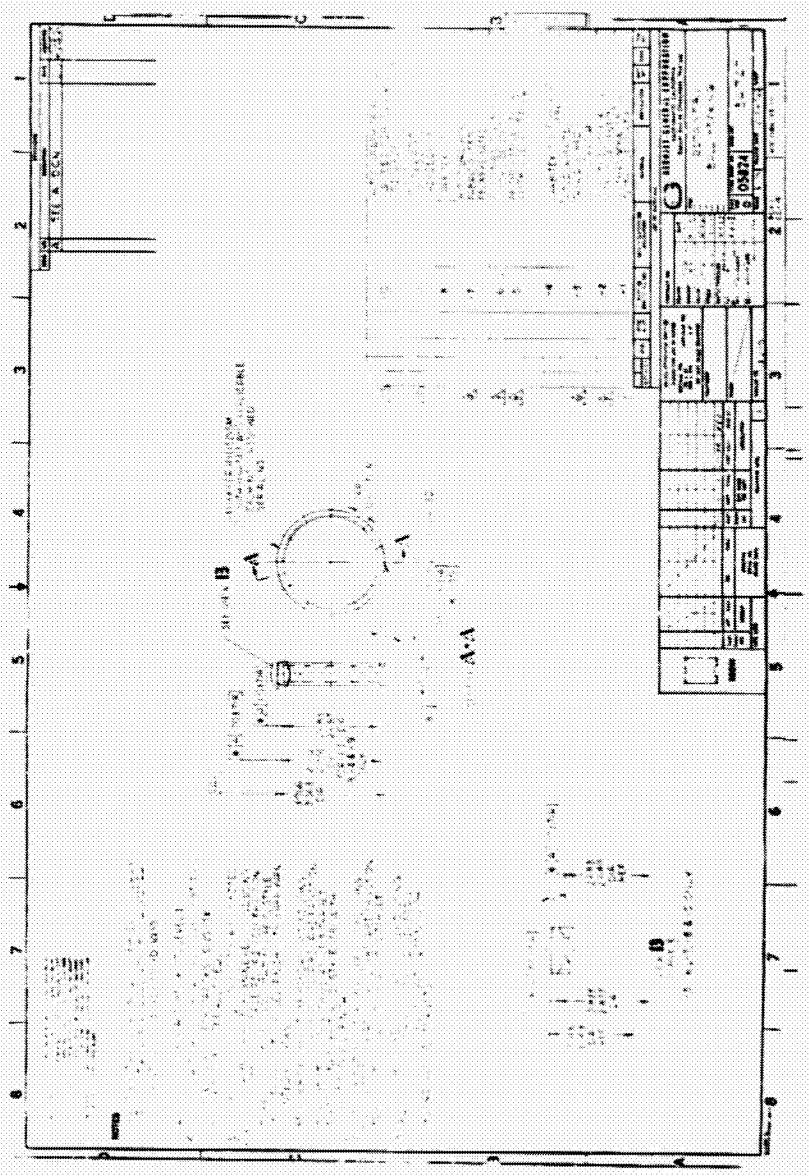

Figure 1 - AGC Drawing 1134747 - Ball-Bearing Retainer

Figure 2 - AGC Drawing 1118584 - Ball-Bearing Retainer

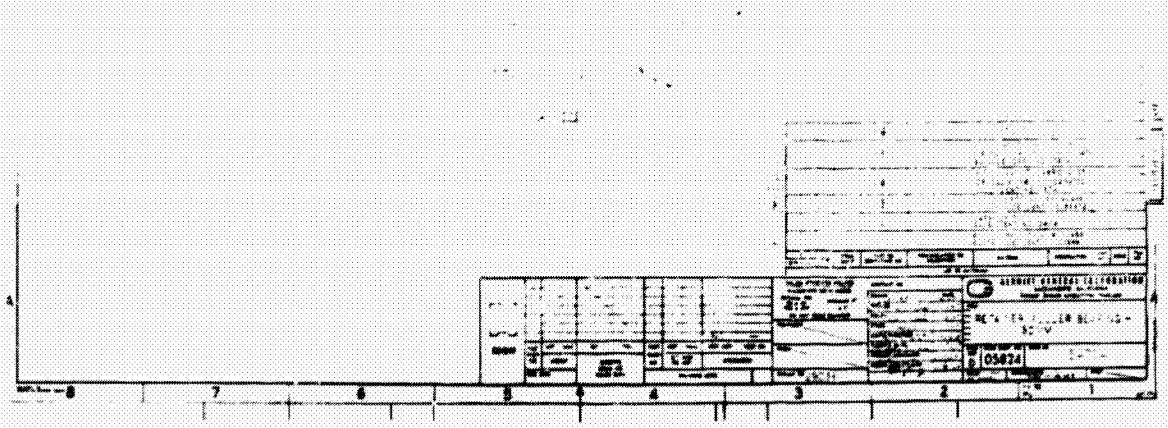

Figure 3 - AGC Drawing 1134704 - Bearing Retainer

II. CONCLUSIONS

1. Reinforced polymers of the PBI type are capable of operating satisfactorily in the required propellant-temperature-irradiation environment envisioned for the NERVA turbopump.

2. Satisfactory irradiation resistance was demonstrated by both the reinforced PBI and the PI materials.

3. Promising results were demonstrated for graphite-fabric-reinforced polymers, in accordance with the low liquid hydrogen wear rate previously demonstrated with these materials.

III. RECOMMENDATIONS

1. Additional bearing testing is required to establish the reliability growth of the reinforced PBI and PI materials systems and to improve confidence in their use for DN operation to 1.8 million.

2. Correlation of test performance and retainer quality is required.

3. Evaluation of graphite-reinforced polymers with and without Molykote solid-film lubricant may eliminate dependence upon MoS_2.

IV. TECHNICAL DISCUSSION

A. MECHANICAL PROPERTIES

1. Hoop Test Results (GTR-20A)

Test hoops ordered with each procurement of experimental 50-mm bearing retainers were tested both before and after irradiation. For such reinforced polymer materials as PI and PBI, gamma dose levels to 4.2×10^{11} ergs/gm (C) were experienced, slightly higher than the highest dose level to which materials of this class had been exposed in previous tests (3.2×10^{11} ergs/gm (C) in GTR-19: see Reference 2). Graphite-reinforced polymers and such graphite products as AGCarb-101 and Carbitex were exposed to fast-neutron flux levels to 2.9×10^{17} n/cm^2. These test items, as well as 50-mm bearing retainers, wear, and flexure specimens were irradiated in liquid nitrogen and subsequently tested at room temperature. Results of irradiated hoop-tension tests are shown in Table 1. With only a single exception, the irradiation level on the average, had a slight strengthening effect. However, insufficient data exist to determine if observed changes were significant. PBI-glass, fabricated by San Rafael Plastics Company (SRP), was the only material which exhibited lower strength after irradiation as a result of one of two hoops failing at a hoop stress of 41.2 ksi, the other at 61.0 ksi. In the absence of more data, the post-irradiated hoop strength may be attributable to normal variance in properties with composite materials of this type.

2. Flexure Test Results (GTR-20A)

Irradiated bearing-retainer materials results are shown in Table 2. The data show the polymers PI and PBI to be approaching a region of significant irradiation strengthening, when exposed to gamma dose levels in excess of 10^{11} ergs/gm (C), beyond which degradation might be expected.

TABLE 1

COMPARISON OF HOOP TENSION PROPERTIES-BEARING MATERIALS

	Procured With	Control Hoop Strength ksi	Irradiated hoop Strength ksi	Volumentric Analysis Results*							Specific** Hoop Strength, ksi
				wt % Reinf.	wt % Matrix	vol % Reinf.	vol % Matrix	vol % Void	Sp. Gravity Actual	Sp. Gravity Theor.	
AGCarb 101 (SRP)	Test Sample	2.932	Defective Part	-	-	-	-	-	1.29	-	2.932
Epoxy/Graph. (SRP)	Test Sample	7.5	7.9	46.7	53.3	35.0	28.5	36.5	1.14	1.87	22.6
PI/Glass (SRP)	Ball Retainer P/N 1134747	14.0	14.8	83.1	16.9	52.0	19.5	28.5	1.56	2.31	28.5
PI/Glass (BR-2)	Ball Retainer P/N 1134747	7.6	9.3	53.2	46.8	33.0	55.0	12.0	1.56	1.96	28.2
PI/Glass (BR-3)	Ball Retainer P/N 1134747	2.9	5.2 Avg of 3	69.2	30.8	50.0	41.0	9.0	1.82	2.15	10.4
PI/Graph (SRP)	Ball Retainer P/N 1134747	4.8	5.1	85.4	14.6	50.0	10.0	40.0	0.88	1.47	10.2
PBI/Glass (SRP)	Ball Retainer P/N 1134747	61.3	51.0 Avg of 2	78.9	21.1	51.0	26.0	23.0	1.64	2.25	100.0
PBI/Glass (Narmco-2)	Ball Retainer P/N 1134747	34.6	38.8 Avg of 2	66.6	33.4	33.0	31.0	36.0	1.23	2.11	117.0
Carbitex 700 (Carborundum Co.)	Ball Retainer P/N 1134747	6.5 Avg of 3	-	-	-	-	-	-	1.411	-	6.5
PBI/Glass (SRP)	Roller Retainer P/N 1134704	37.6 Avg of 2	-	30.8	69.2	17.5	73.3	9.1	1.41	1.70	215.0
PBI/Graph (SRP)	Roller Retainer P/N 1134704	15.4 Avg of 2	-	33.1	66.9	26.2	58.6	15.2	1.18	1.39	58.8

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*Unirradiated

**Irradiated Hoop Strength, where applicable, divided by vol % reinforcement.

TABLE 2

FLEXURE TEST RESULTS - CONTROL AND IRRADIATED

	Control			Irradiated - GTR - 20A					
				Low Dose			High Dose		
				4.8×10^{10} ergs/gm (C)			2.6×10^{11} ergs/gm (C)		
Material	Flex Str. ksi	Flex Mod. $\times 10^{-6}$	Hardness Rockwell	Flex Str. ksi	Flex Mod. $\times 10^{-6}$	Hardness Rockwell	Flex Str. ksi	Flex Mod. $\times 10^{-6}$	Hardness Rockwell
PBI (pure)	28.18	0.937		31.91	0.949		33.96	0.942	
	27.96	0.964		25.04	0.938		35.11	0.942	
	29.47	0.980	F 92.7	23.96	0.930	F 90	40.66	0.941	F 90
				4.8×10^{10} ergs/gm (C)			4.2×10^{11} ergs/gm (C)		
PBI-Glass	63.89	2.994		64.82	3.092		62.82	2.852	
	64.51	3.117	F 82	62.48	3.067	F 93	60.49	2.617	F 91
				No Low Dose			2.5×10^{17} n/cm^2 2.6×10^{11} ergs/gm (C)		
PBI-Graphite	18.80	1.351					21.69	1.355	
	20.61	1.340					19.39	1.328	
	18.01	1.303	M 88				22.00	1 329	M 89.5
				4.7×10^{10} ergs/gm (C)			2.6×10^{11} ergs/gm (C)		
PI (pure)	13.46	0.523		13.02	0.548		16.47	0.634	
	13.32	0.544		13.25	0.525		17.62	0.623	
	12.82	0.539	M 85	14.45	0.570	M 87	16.06	0.607	M 92
				4.8×10^{10} ergs/gm (C)			4.2×10^{11} ergs/gm (C)		
PI-Glass	33.08	2.740		24.19	2.028		22.42	2.277	
	28.64	2.690		26.82	2.445		21.56	2.430	
	33.27	3.040	M 34	25.42	2.383	M 38	23.06	2.419	M 33
				4.3×10^{15} n/cm^2 4.8×10^{10} ergs/gm (C)			2.5×10^{17} n/cm^2 2.6×10^{11} ergs/gm (C)		
PI-Graphite	24.53	1.480							
	23.60	1.540							
	22.08	1.430	M 30	23..	1.389	M 26	23.79	1.473	
							26.11	1.682	M 46
				5×10^{17} nvt (GTR 21)			2.5×10^{17} n/cm^2		
Carbitex 700	9.07	1.220		9.45	1.55		11.80	1.930	
	10.37	1.480		9.43	1.56		11.41	1.872	
	9.16	1.370	R 91	11.09	1.83	NA	10.67	1.976	R 93
				4.3×10^{15} n/cm^2 4.8×10^{10} ergs/gm (C)			3×10^{17} n/cm^2 4.2×10^{11} ergs/gm (C)		
AGCarb-101	10.77	1.354		11.52	1.308		11.23	1.710	
	12.44	1.409	R 83	10.94	1.289		10.36	1.336	
				10.46	1.433	R 87	13.29	1.655	R 93

As shown in Figures 4 and 5, degradation was not observed in GTR-20A and the damage threshold appears to be at an unrealistically high dose, compared with bearing-retainer dose levels expected at the NERVA turbopump.

An anomaly was observed in tests of glass-reinforced PI. Because of excessive specimen thickness, this material failed in a mixed tension-shear mode during control tests, attaining an average strength of approximately 31 ksi.

Irradiation apparently strengthened the reinforcement sufficiently to cause failure at the fiber-matrix bond in horizontal shear at a characteristically lower stress of approximately 25 ksi. This failure mode resulted in the absence of outer fiber breaks and was manifested by delamination in the neutral axis area and buckling at the compression side of the specimens. In view of the upward flexural strength trend in both the pure PI and graphite-reinforced PI (as shown in Figure 4), the observed trend in glass-reinforced PI was not attributed to irradiation degradation.

Both graphite materials, Carbitex and AGCarb-101, exhibited strengthening, as would be expected at these relatively low-neutron dose levels (see Figures 6 and 7).

Analysis of the data presented in Table 2 resulted in calculations of means and variances, where possible, and comparisons of control and irradiated properties to determine whether observed differences were statistically significant. Both t and F tests were performed to determine the significance of differences at the 97.5% confidence level. As shown in Table 3, most differences observed and indicated in Figures 4 through 7 were not statistically significant. Exceptions were as follows:

1. Flexure strength increase of pure PBI at the high γ dose level.

2. Flexure strength and modulus increases of pure PI at the high γ dose level.

3. Flexure strength and modulus increases of Carbitex 713 at the high fast-neutron dose levels.

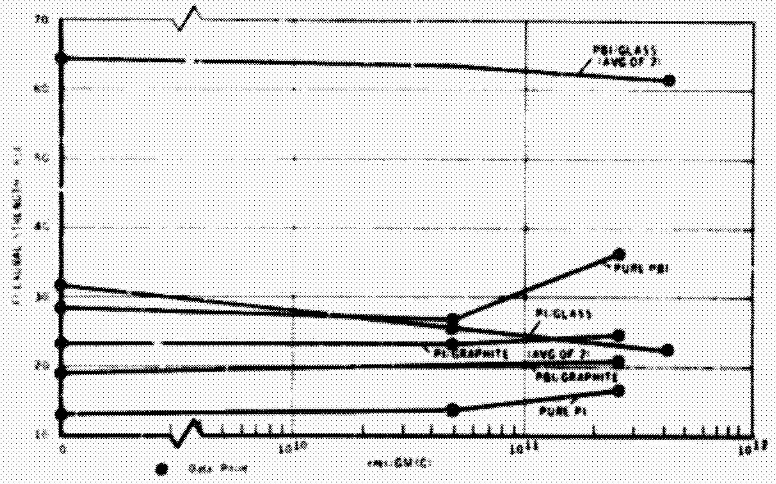

Figure 4 - Effect of Gamma Radiation on Flexure Strength of Retainer Materials (Average of Three Except Where Noted)

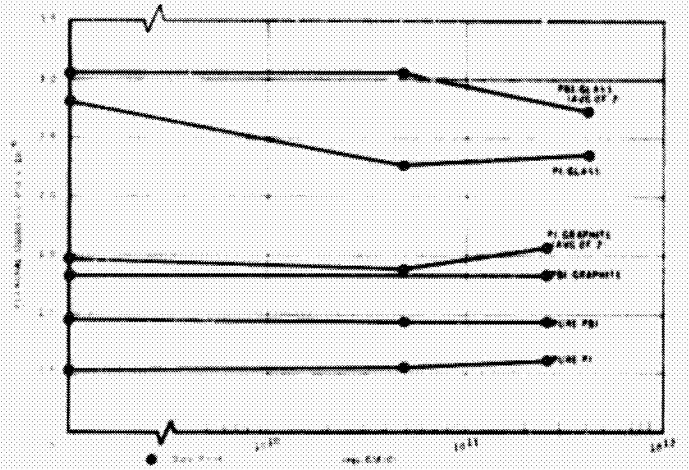

Figure 5 - Effect of Fast-Neutron Fluence on Flexure Strength of Graphite Bearing-Retainer Materials (Average of Three)

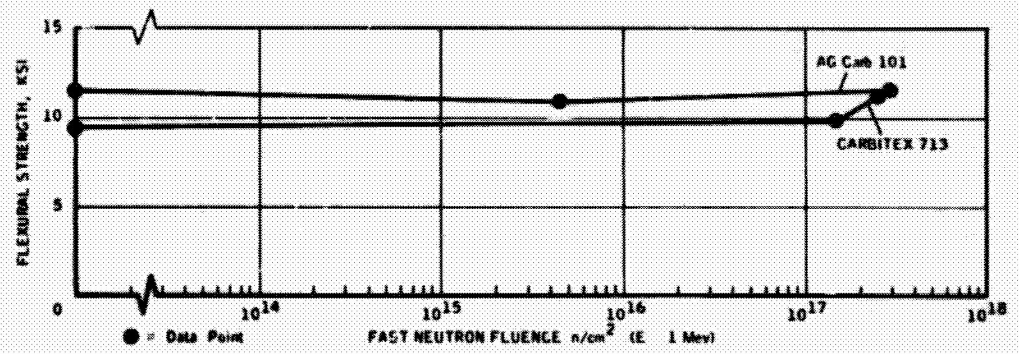

Figure 6 - Effect of Fast-Neutron Fluence on Flexural Modulus of Graphite Bearing-Retainer Materials (Average of Three)

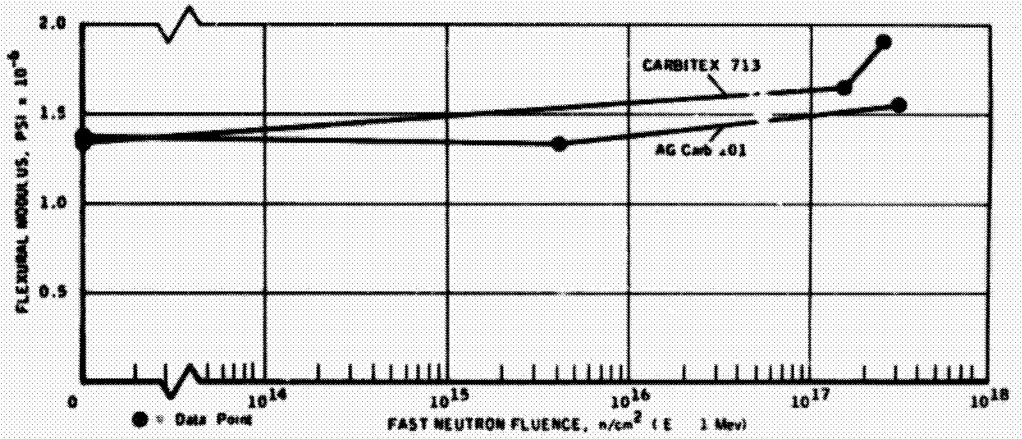

Figure 7 - Effect of Gamma Radiation on Flexure Modulus of Bearing-Retainer Materials (Average of Three Except Where Noted)

TABLE 3

STATISTICAL SIGNIFICANCE OF GTR-20A FLEXURE TEST DATA

		Control		Low Dose		Significance of Results (C & Lo Dose)		High Dose		Significance of Result (C & Hi D)		Remarks
		$\bar{x}$	s	$\bar{x}$	s	Variance $F_{0.975}$	Means $t_{0.975}$	$\bar{x}$	s	Variance $F_{0.975}$	Means $t_{0.975}$	
				[illegible] x 10^{10} ergs/gm (C)				2.6 x 10^{11} ergs/gm (C)				
[illegible]	Flex Str.	[illegible]	[illegible]	[illegible]	[illegible]	No	No	36.57	1.6	No	Yes	Significant radiation effect on strength high dose.
	Flex Mod.	[illegible]	[illegible]	[illegible]	[illegible]	No	No	[illegible]	Negl.	No	No	
	Hardness	[illegible]	[illegible]	[illegible]	[illegible]	No	No	[illegible]	[illegible]	No	No	
				[illegible] ergs/gm (C)				4.1 x 10^{11} ergs/gm (C)				
[illegible]	Flex Str.	[illegible]	[illegible]	[illegible]	[illegible]	No	No	[illegible]	[illegible]	No	No	
	Flex Mod.	[illegible]	[illegible]	[illegible]	[illegible]	No	No	2.71	[illegible]	No	No	Significant difference in hardness could be caused by porosity.
	Hardness	[illegible]	[illegible]	[illegible]	[illegible]	No	Yes	[illegible]	[illegible]	No	No	
								[illegible] x 10^{11} ergs/gm (C) [illegible] x 10^{17} nvt				
[illegible]	Flex Str.	[illegible]	[illegible]					[illegible]	[illegible]	No	No	
	Flex Mod.	[illegible]	[illegible]					[illegible]	[illegible]	No	No	
	Hardness	[illegible]	[illegible]					[illegible]	[illegible]	No	Yes	Significant difference in hardness.
				[illegible] x 10^{10} ergs/gm (C)				[illegible] x 10^{11} ergs/gm (C)				
[illegible]	Flex Str.	[illegible]	[illegible]	[illegible]	[illegible]	No	No	[illegible]	[illegible]	No	Yes	Significant strength effect.
	Flex Mod.	[illegible]	[illegible]	[illegible]	[illegible]	No	No	[illegible]	[illegible]	No	Yes	Significant modulus effect.
	Hardness	[illegible]	[illegible]	[illegible]	[illegible]	No	No	[illegible]	[illegible]	No	Yes	Significant hardness effect.
				[illegible] ergs/gm (C)				[illegible] x 10^{11} ergs/gm (C)				
[illegible]	Flex Str.	[illegible]	[illegible]	[illegible]	[illegible]	Not Applicable		[illegible]	[illegible]	Not Applicable		State of stress changed due to improperly designed specimen, tensile strengthening effect by shear failure after irrad.
	Flex Mod.	[illegible]	[illegible]	[illegible]	[illegible]	See Remarks		[illegible]	[illegible]	See Remarks		
	Hardness	[illegible]	[illegible]	[illegible]	[illegible]	Yes	No	[illegible]	[illegible]	No	No	
				[illegible] ergs/gm (C) [illegible] nvt				[illegible] x 10^{11} ergs/gm (C) [illegible] x 10^{17} nvt				
[illegible]	Flex Str.	[illegible]	[illegible]	[illegible]	---	*	*	[illegible]	---	**	**	*Low dose - one specimen, only.
	Flex Mod.	[illegible]	[illegible]	[illegible]	---	*	*	[illegible]	---	**	**	**High dose - two specimens, only.
	Hardness	[illegible]	[illegible]	[illegible]	[illegible]	No	No	[illegible]	[illegible]	No	Yes	
				[illegible] [illegible] nvt				[illegible] x 10^{11} ergs/gm (C) [illegible] x 10^{17} nvt				Low dose - GTR-21, See Reference 2.
[illegible]	Flex Str.	[illegible]		[illegible]	[illegible]	No	No	[illegible]	[illegible]	No	Yes	
	Flex Mod.	[illegible]		[illegible]	[illegible]	No	No	[illegible]	[illegible]	No	Yes	
	Hardness	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	Yes	
				[illegible] ergs/gm (C) [illegible] nvt				[illegible] ergs/gm (C) [illegible] nvt				
[illegible]	Flex Str.	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	No	*Control: Two specimens only. Comparison of dose effect (High and low dose)
	Flex Mod.	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	No	
	Hardness	[illegible]		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	No	Yes	

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B. SUBSCALE RETAINER TESTS (50 mm)

1. Continuation of Test of an Irradiated S-Glass-Reinforced PBI Retainer, P/N 1118584, S/N 1

a. Objective

This part was retested as a result of the successful 3-hr test described in Reference 2. The test objective was to test for 6 hr or to failure.

b. Procurement and Fabrication

The procurement and fabrication details are outlined in Appendix A. In general, the parts were made by mandrel wrapping and impregnation of resin, followed by elevated temperature curing. The large amount of volatiles expelled by the resin during cure generally resulted in a porous product containing up to 25% voids, by volume. The configuration of the final-machined part was identical to Armalon retainers successfully used in the technology program. The parts nominally had a 3-in. OD, and were 0.09-in. thick, 0.68-in. wide and contained 12 equally spaced 0.53-in.-diameter ball pockets.

c. Test Results

Two parts were tested. The results of the first test with S/N 2 is described in Reference 2. The second part, S/N 1, was irradiated prior to testing and the result of the first 3-hr test also is described in Reference 2 and summarized below.

The part was irradiated in liquid nitrogen to a total gamma dose of 5.9×10^{10} ergs/gm (C) and a fast-neutron dose of 1.13×10^{17} nvt ($E > 1$ mev). The gamma dose level represented a substantial excess over the level expected during actual service in the NERVA engine. An additional increment of conservatism was imparted to the subsequent test results because gamma-dose absorption and mechanical degradation are expected in actual service to occur in parallel rather than in series, as occurred in this test.

Prior to placement in the test bearing, the part was cleaned in methanol and wiped to remove excess radioactive contamination. Subsequent handling was performed under closely controlled conditions. The appearance of the part following irradiation but prior to testing is shown in Figure 8.

The part was lubricated with brush and spray applications of Molykote 321 and placed in a new ball bearing. Testing was conducted at 24,000 rpm with a 1200-lb axial load. Liquid-hydrogen flow rate was approximately 20 to 30 gpm at a pressure of 205 psig.

The tester ran smoothly at amperages varying from 30 to 40. As the test progressed, amperage declined to the 28 to 32 range. After operating satisfactorily for 3 hr, the test was terminated. Disassembly of the tester revealed that bearing components were in excellent condition (see Figures 9 and 10). Having successfully endured the minimum 3-hr testing duration required to qualify the material, a second 3-hr test was scheduled in an attempt to establish time for failure.

Although the bearing was disassembled to facilitate inspection, weighing, and photography, no additional lubricant was added. Pretest preparation of the bearing components consisted of removal of dirt and contaminants by blowing with compressed gaseous nitrogen.

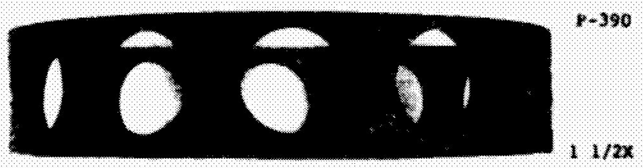

Figure 8 - Postirradiation, Pretest Appearance of Glass-Reinforced PBI Retainer

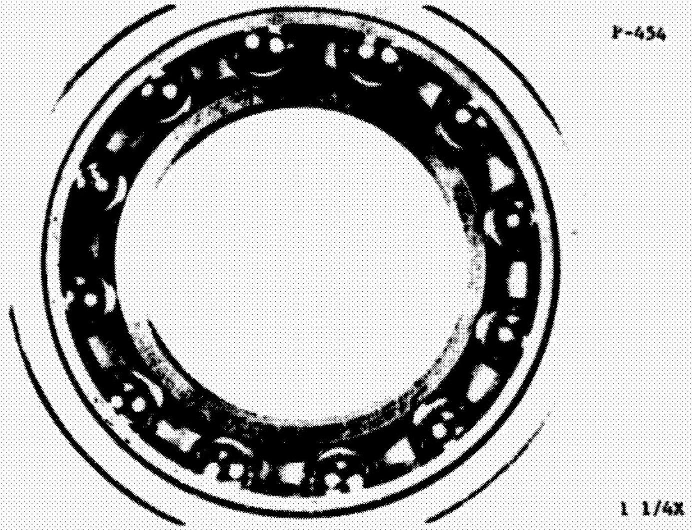

Figure 9 - Posttest Appearance of PBI-Glass Retainer in its Bearing With Portion of Inner Race Removed Showing Excellent Condition of Components After 3-hr Testing

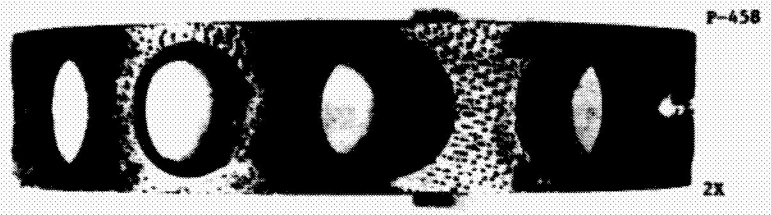

Figure 10 - Posttest Appearance of PBI-Glass Retainer After 3-hr Testing Showing Lack of Wear on OD and Good Condition of Ball Pockets

The second test was conducted with the same parameters as the first. However, the speed during test was 26,400 rpm instead of the required 24,000 rpm*. Liquid-hydrogen flow rate, pressure, and axial load, however, remained the same.

The tester ran smoothly at amperages varying from 35 to 45 for the scheduled 3 hr. Disassembly of the tester again revealed that the retainer was in excellent condition (see Figures 11 and 12).

Evidence of insignificant wear was provided by the retainer weight changes listed in Table 4. The weight increase following the last test was difficult to explain; however, a close examination of bearing components revealed extremely fine, embedded metal particles in the retainer material. The source of these particles was, in all likelihood, the edges of the outer race cracks, shown in Figure 13. These cracks, assumed to be caused by fatigue, extended around the entire thrust side of the outer race. The total test time of 6 hr complies with the B_{10} life of this bearing when loaded to 1200 lb and running in oil, supporting the hypothetical equivalence between oil-lubricated bearings running in air and nonlubricated bearings running in liquid hydrogen.

TABLE 4

WEIGHT CHANGE, PBI-S-GLASS RETAINER, S/N 1

Condition	Weight, gm	Change, gm	Cause
As Received	6.2295	-	-
Postirradiated	6.2168	-0.0127	Techniques and Balance Differences
Post Run No. 1 (3 hr)	6.3057	+0.0889	Wt. of Molykote
Post Run No. 2 (6 hr)	6.3917	+0.0860	Metal Debris

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*It was discovered during posttest calibration that a Brown recorder had malfunctioned prior to the test.

Figure 11 - Appearance of PBI-Glass Retainer 6-hr Testing with Conditions Essentially Unchanged From Those Shown in Figure 10

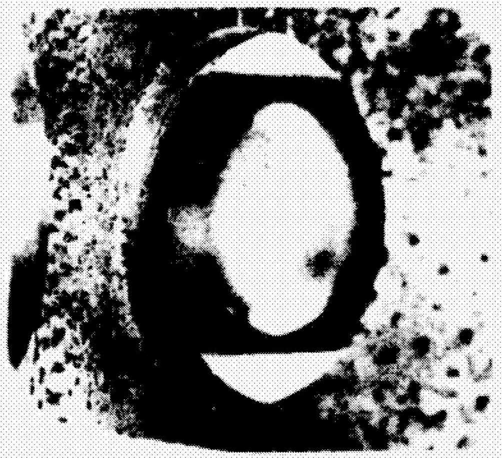

Figure 12 - Appearance of Ball Pocket After 6-hr Testing Showing Barely Visible Evidence of Wear on ID Edge

Figure 13 - Appearance of Fatigue Cracks in Thrust Side of Outer Race Track After 6-hr Testing

2. Test of PBI-Graphite Roller-Bearing Retainer, P/N 1134704-4, S/N 880008

a. Objective

The PBI-graphite-fabric composite was developed as a backup material for the turbopump bearing retainer. It was introduced in response to several early tests of parts with S-glass reinforcement which were noted to generate excessive amounts of abrasive glass particles. The lower strength of the graphite fabric, as compared with S-glass, was offset by its better lubricity, thermal conductivity, and satisfactory liquid-hydrogen wear rate (see Reference 2).

b. Procurement and Fabrication

The fabrication procedure, as reported by the vendor, was as follows:

The material used for the part was Union Carbide WCA graphite fabric-impregnated with Imidite 4824 resin purchased as a prepreg from the Whittaker Corporation.

Strips, 5-in. wide and 120-in. long, were cut and wrapped on a released mandrel in a wrap lathe to a diameter of 3.3 in. under 3-lb tension and 250-lb force on a 3-in. diameter cylindrical steel roller.

The cylinder thus produced was cured at temperatures to 700°F followed by final machining, using single-point carbide and diamond drills.

The final configuration was identical to the Armalon roller retainers successfully used in the technology program (see Figure 3). It generally consisted of a 3-in. OD cylinder approximately 0.73-in. wide and 0.16 in. thick containing 16 equally spaced 0.48-in. by 0.40-in rectangular roller pockets.

c. Test Results

Prior to placement in the test bearing, the retainer was coated with brush and spray applications of Molykote 321. Testing was conducted at 24,000 rpm with a 2,300-lb radial load. The liquid-hydrogen flow rate was approximately 20 to 30 gpm at a pressure of 205 psig.

Following approximately 1.5 hr of smooth operation, perturbations in tester motor amperage were noted. No other abnormalities in the recorded parameters were noted with the exception of higher-than-usual gaseous hydrogen vent pressure. The test was ended after 1.8 hr, because of a fire, caused by shorting of tester motor terminals.

Subsequent examination of tester components indicated that the short was caused by roller-end wear debris from the motor roller-bearing, downstream from the bearing containing the experimental retainer. The heavy end-wear was associated with inadequate coolant flow caused by liquid-hydrogen leakage into the vent cavity, which, in turn, resulted in the abnormally high vent pressure noted above. The experimental retainer was in good condition (see Figure 14).

After the tester motor and motor roller-bearing were replaced, the loader roller bearing was reinstalled without additional application of lubricant.

In the second test phase, the tester was operated successfully for 2.2 hr at the same operating parameters used during the first phase. Although vent pressure was again higher than normal, it apparently was not caused by liquid-hydrogen leakage but, rather, by gaseous-hydrogen leakage as indicated by higher-than-normal cascade pressure consumption. Following the test, all components were again inspected. No end wear was noted on the motor roller-bearing rollers and the experimental PBI-graphite retainer was in good condition.

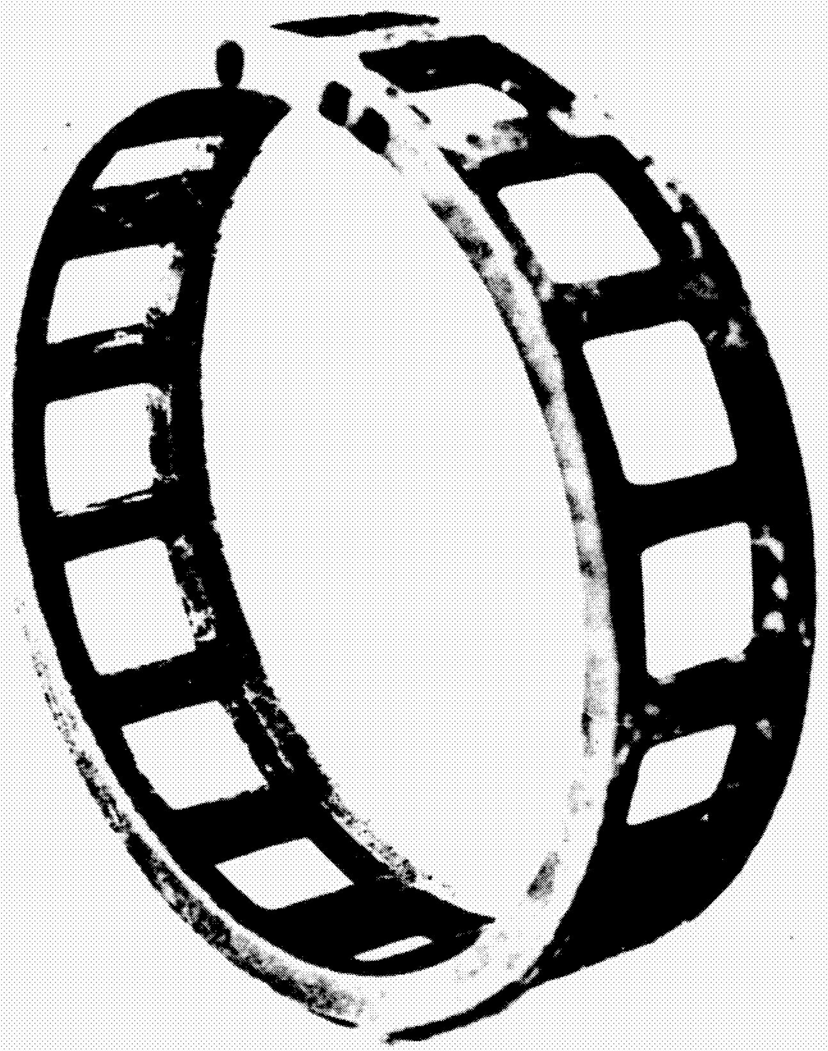

Figure 14 - Appearance of PBI-Graphite Roller Retainer After 1.8-hr Operation

A final test phase was needed to complete the targeted 6-hr run duration. The same bearings were operated as in the second phase of the test and parameters were unchanged. Again, as for the second test phase, no additional lubricant was applied to the test retainer.

The final test phase was satisfactorily completed after 2 hr with the experimental PBI-graphite retainer sustaining a total duration of 6 hr. The retainer and rolling elements completed the test in good condition with the only visual evidence of testing being a normal amount of discoloration in the rolling contact zones of both the inner and outer bearing races. Appearance of the retainer and rolling elements is shown in Figures 15 and 16, respectively. Weight change of the experimental retainer, recorded after each of the three test phases, indicated negligible, if any, retainer wear (see Table 5).

Visual and nondestructive, fluorescent penetrant inspection of the inner and outer bearing races failed to reveal any evidence of fatigue cracking or other form of degradation.

TABLE 5

WEIGHT CHANGE, PBI-GRAPHITE ROLLER RETAINER

S/N 880008

Condition	Weight, gm	Change, gm	Cause
Pretest	10.5043	---	---
Posttest			
Phase I	10.3192	-0.1851	Loss of molykote
Phase II	10.3247	+0.0055	Negligible
Phase III	10.3158	-0.0089	Negligible

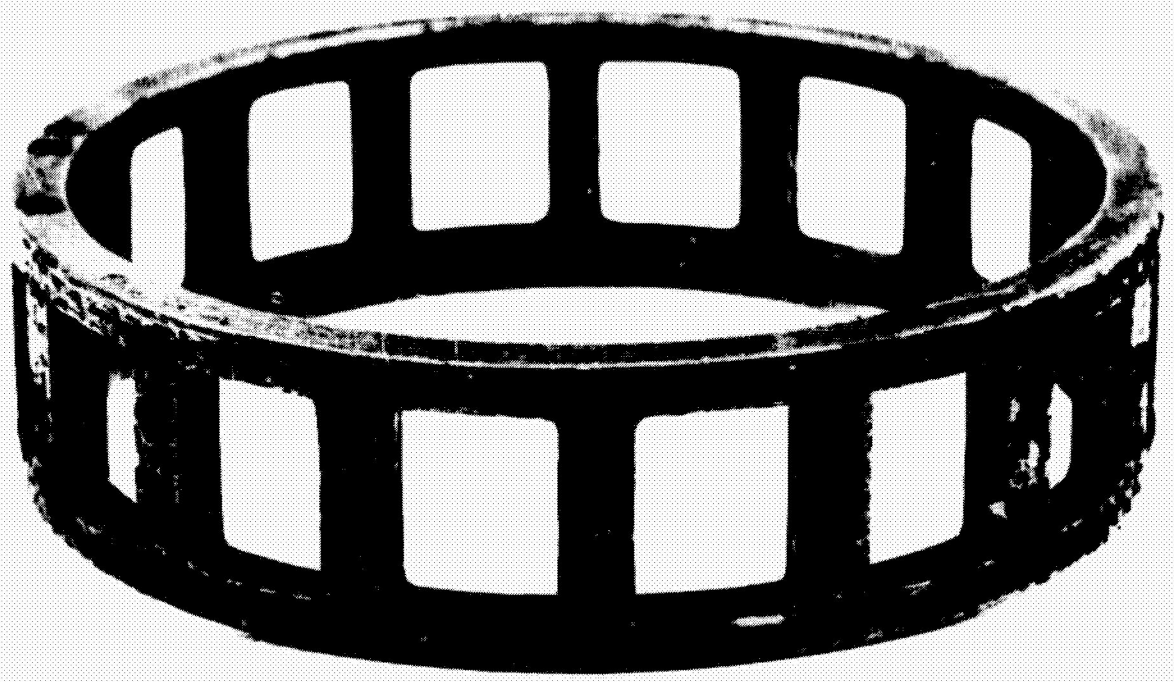

Figure 15 - Posttest Appearance of PBI-Graphite Roller-Retainer After 6-hr Operation

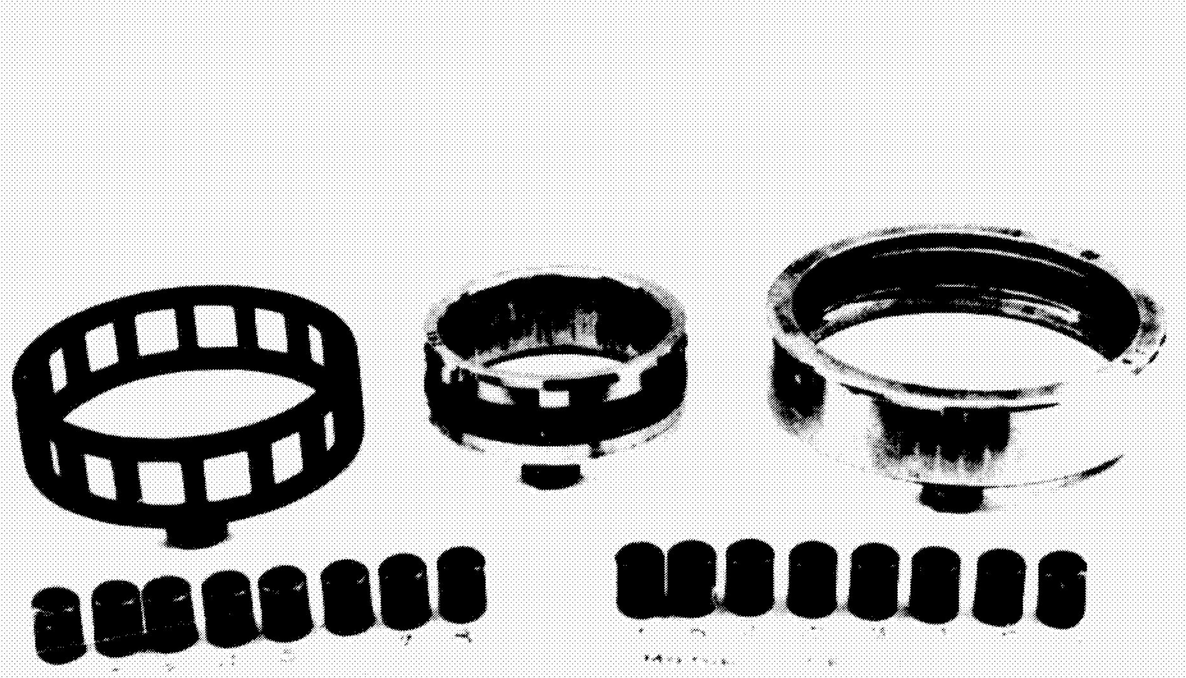

Figure 16 - Posttest Appearance of Roller-Bearing Components After 6-hr Operation

3. Test of PBI-Graphite Roller-Bearing Retainer, P/N 1134704-4, S/N 880009

a. Objective

The second in a series of roller-bearing retainer tests was performed on the companion part to roller retainer S/N 880008. The bearing tester contained Armalon ball-bearing and motor roller-bearing retainers and the S/N 880009 PBI-graphite loader roller-bearing retainer.

To expedite the testing and to reduce costs, it was planned to proceed to the 6-hr test limit, or to failure, without intervening tester disassembly and component inspection. Consequently, this second, experimental roller-bearing retainer was tested for 7 hr and 40 min with only one tester build-up and required only two runs.

b. Procurement and Fabrication

The procurement and fabrication history of this part was identical to that described earlier for S/N 880008.

c. Test Results

Prior to placement in the test bearing, the retainer was cleaned by removing machining debris and loose material with a trichloroethylene-dampened cloth. The retainer was coated with brush and spray applications of Molykote 321 solid-film lubricant.

The test was conducted at 24,000 rpm, following a 3-min run-in at 12,000 rpm. The roller bearing containing the test retainer was radially loaded to 2,300 lb. Liquid-hydrogen flow rate was maintained at 20 to 30 gpm at a pressure of 205 psig. The tester ran smoothly at these conditions for 3 hr and 53 min at which time gaseous-hydrogen pressure needed for loader actuation was exhausted and the test terminated.

Following replenishment of liquid-hydrogen and gaseous-hydrogen actuation pressure, the test was resumed, without an intervening disassembly. Again, tester operation was smooth and uneventful with motor amperage recorded at 26 to 29 amp. Good performance of carbon seal prevented a high gaseous-hydrogen loss rate and enabled the accumulation of an additional 13,600 sec of testing. Pressure, load, flow-rate, and temperature parameters were normal and similar to those observed in the previous run. The test was discontinued after 7 hr and 40 min of testing.

Upon disassembly of the tester, all bearing components were found to be in satisfactory condition. The only evidence of wear on the experimental retainer was burnished areas on the retainer OD and in the roller pockets (see Figure 17). Retainer weight, measured before and after testing, indicated only a small weight change attributable to a loss of Molykote (see Table 6). The rollers and races were characteristically discolored from heat generated in the contact area, but cracking or roller end-wear was not noted (see Figure 18). The 7 hr and 40 min run caused some Armalon pocket wear in both the motor roller and thrust-bearing retainers, however.

Posttest radiographic inspection of the S/N 880009 retainer, as well as the retainer tested previously (S/N 880008), revealed no visible signs of degradation (e.g., delaminations or cracks). Therefore, both parts were scheduled for further testing in an attempt to establish material endurance limits.

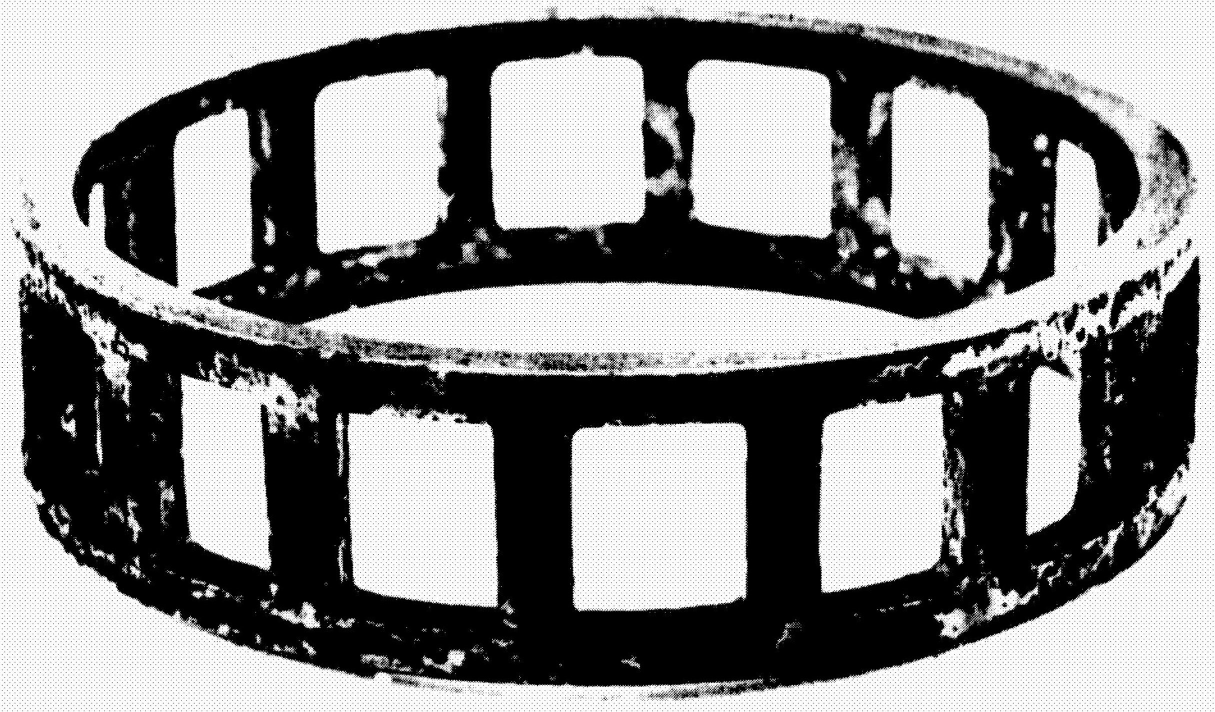

Figure 17 - Posttest Appearance of PBI-Graphite Roller-Bearing Retainer S/N 880009 After 7 hr, 40 min Operation

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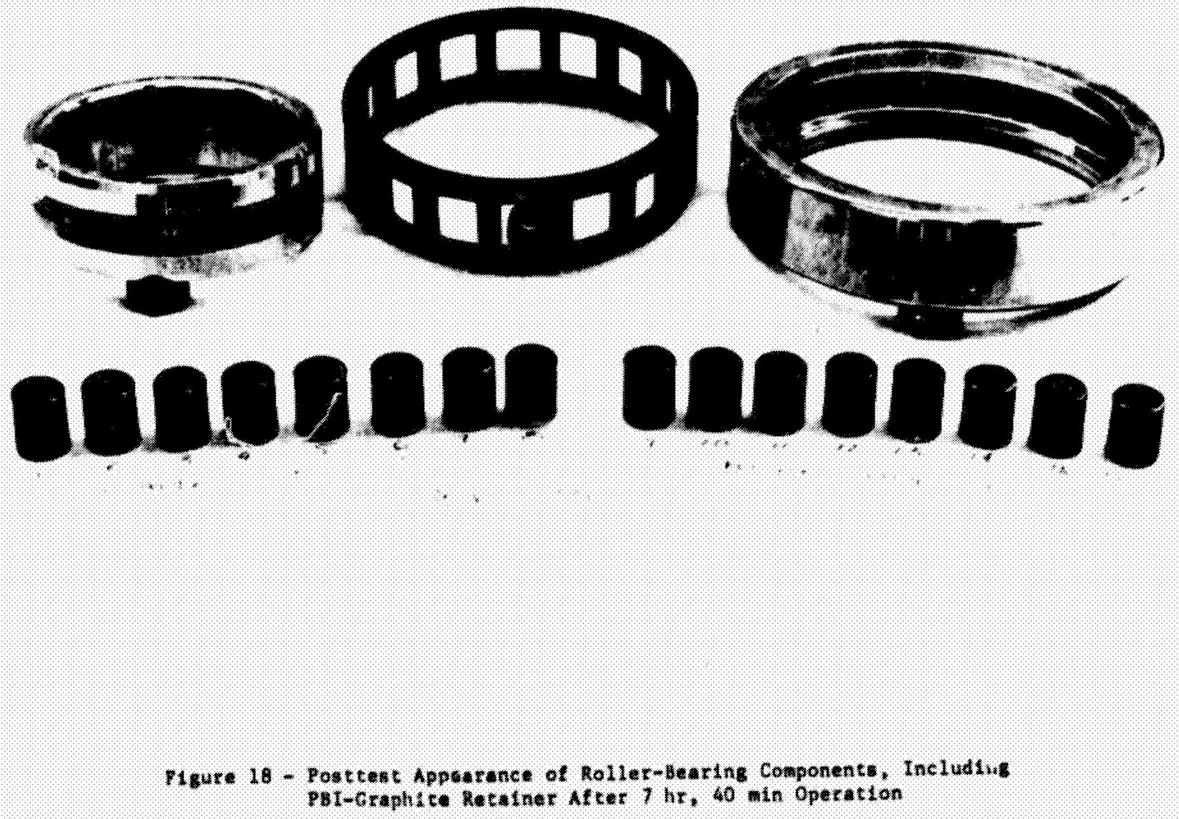

Figure 18 - Posttest Appearance of Roller-Bearing Components, Including PBI-Graphite Retainer After 7 hr, 40 min Operation

TABLE 6

WEIGHT CHANGE, PBI-GRAPHITE ROLLER RETAINER S/N 880009

Condition	Weight, gm	Change, gm	Cause
Pretest	9.8637	-	-
After Application of Molykote	10.1665	+0.3028	MoS_2
Posttest	10.0409	-0.1256	Loss of Molykote (41.5% of lubricant was transferred or lost)

NOTE: Roller weight loss varied from 0.1 to 1.4 mg.

4. Test of a PBI-Glass Thrust-Bearing Retainer Irradiated to 4.8 x 10^{10} ergs/gm (C) in LN_2 (GTR-20A), P/N 1134747-5B, S/N 880027

a. Objective

This test was the first to utilize an improved thrust-bearing retainer design, P/N 1134747, (see Figure 1). This configuration was necessitated by several problems noted in tests of the earlier configuration, P/N 1118584 (see Figure 2), wherein it was noted that ball-retainer contact was concentrated at the retainer ID resulting in both point and line loading and excessive wear. Measurement of reinforced PI and PBI thermal expansion indicated that these materials had greatly reduced coefficients of thermal expansion in the -423°F to room temperature range, as compared with those of the reinforced fluorocarbon materials which served as models for the P/N 1118584 configuration. Consequently, the new configuration had a smaller ID (2.685 as compared with 2.875-in.), enabling positive ball-to-retainer-pocket contact and, theoretically, preventing the high rate of edge wear noted earlier.

In addition to its improved design, the test retainer was one of two parts which had been irradiated in liquid nitrogen to a total gamma dose of 4.8 x 10^{10} ergs/gm (C).

b. Procurement and Fabrication

The test retainer was fabricated to the requirements of Drawing P/N 1134747-5B and serialized S/N 880027. It was one of six parts fabricated by mandrel-wrapping a PBI-impregnated S-glass fabric prepreg, followed by a gradually increasing elevated-temperature curing cycle. The resultant cylindrical pieces were machined to the required configuration, inspected, and radiographically examined for wrinkles or kinks in the glass-fabric reinforcement. Four hoop-tension test specimens were machined and delivered in addition to the six retainers. Results of the hoop-tension tests, volumetric analyses, and detailed fabrication sequence are shown in Appendix B. Radiographic inspection indicated the retainers to be in good condition with no evidence of delaminations or cracking noted.

c. Test Plan

Four of the six parts of the type used in this test were first submitted to irradiation in the General Dynamics/Ft. Worth GTR reactor. Retainers S/N 880027 and 880028 were irradiated to 4.8 x 10^{10} ergs/gm (C) in liquid nitrogen and subsequently returned to Aerojet-General. S/N 880027 was randomly selected for bearing testing and, following removal of excess dust and loose material, was lubricated by brush applications of Molykote 321. The two PBI-graphite roller bearing retainers discussed above were used for roller-bearing separators in this test as a means of accumulating additional operating time with these parts. However, additional lubricant was not applied prior to testing. PBI-graphite roller retainer S/N 880008 was placed in the roller bearing downstream of the ball bearing (motor roller). PBI-graphite roller retainer S/N 880009 was placed in the roller bearing upstream of the ball bearing (loader roller). The motor roller-bearing, in addition to utilizing an experimental retainer with an accumulated operating time of 6 hr, was instrumented with micro-thermocouples to record heat generated at the outer-race roller guide because of roller end-wear (see Figure 28). It was planned to reduce liquid-hydrogen flow rate from 25 gpm to determine the lower-threshold flow rate required to cause roller end wear.

d. *Test Results*

The test was performed at the same parameters as used previously. After the tester was started, speed was adjusted to 12,000 rpm and held for a 3-min run-in period. At the end of this period, axial and radial loads were adjusted to 1,200 and 2,300 lb., respectively. Following bearing-load application, speed was brought to 24,000 rpm and the time count started. Liquid-hydrogen flow rate was held in the 20 to 30 gpm range and pressure at 205 psi.

In the first test segment, the tester was operated for 1 hr and 44 min. Earlier-than-usual shutdown was necessitated by excessive loss of gaseous-hydrogen actuation pressure past improperly functioning carbon seals. However, just prior to shutdown, the flow rate was gradually reduced to determine the effect of lower pressure-drop across the bearing on roller end-wear. An analysis of the effect of flow rate on bearing temperatures and end wear is beyond the scope of this report. However, it may be stated that slight heat effects were indicated by the instrumentation when the flow rate was reduced to 20 and 15 gpm and violent thermal effects at a flow rate of 10 gpm were recorded. The results of these tests were also indicated by a permanent increase in motor current from 38 to the 40 to 42 amp range following the flow-rate tests.

The second test segment was performed after actuation pressure and liquid-hydrogen coolant had been replenished. The tester operated uneventfully for 3 hr and 21 min, increasing the accumulated test time to 5 hr and 4 min. Evidence of permanent bearing damage was reflected in higher motor current of 45 to 55 amp, observed throughout the second test segment. The actuation-pressure leakage rate was erratic but reduced, accounting for the longer run time.

The third test segment, again performed after replenishment of actuation-gas pressure and coolant but without intervening tester disassembly, was needed to complete the minimum target run time of 6 hr. The tester operated more smoothly than during the second test segment, as indicated by reduced motor current of 41 to 42 amp. A reduced actuation-pressure leakage rate enabled the accumulation of an additional 2 hr and 39 min of testing. However, prior to test termination, another flow-rate-effect experiment was made with flow reduced to 5 gpm. Following very violent heating indications from the motor-roller-bearing thermocouples, motor current increased to the "kill" level of 100 amp and the test was ended. Total run times on the three experimental bearing retainers were:

1. PBI-glass irradiated ball retainer S/N 880027 - 7 hr, 45 min.
2. PBI-graphite roller retainer S/N 880009, loader roller - 15 hr, 27 min.
3. PBI-graphite roller retainer, S/N 880008, motor roller - 13 hr, 48 min.

e. Posttest Inspection

(1) Thrust Bearing, S/N 867A:

The condition of the components of this bearing, including the S/N 880027 irradiated ball retainer, is shown in Figure 19. Although generally in good condition, the rolling elements of the bearing

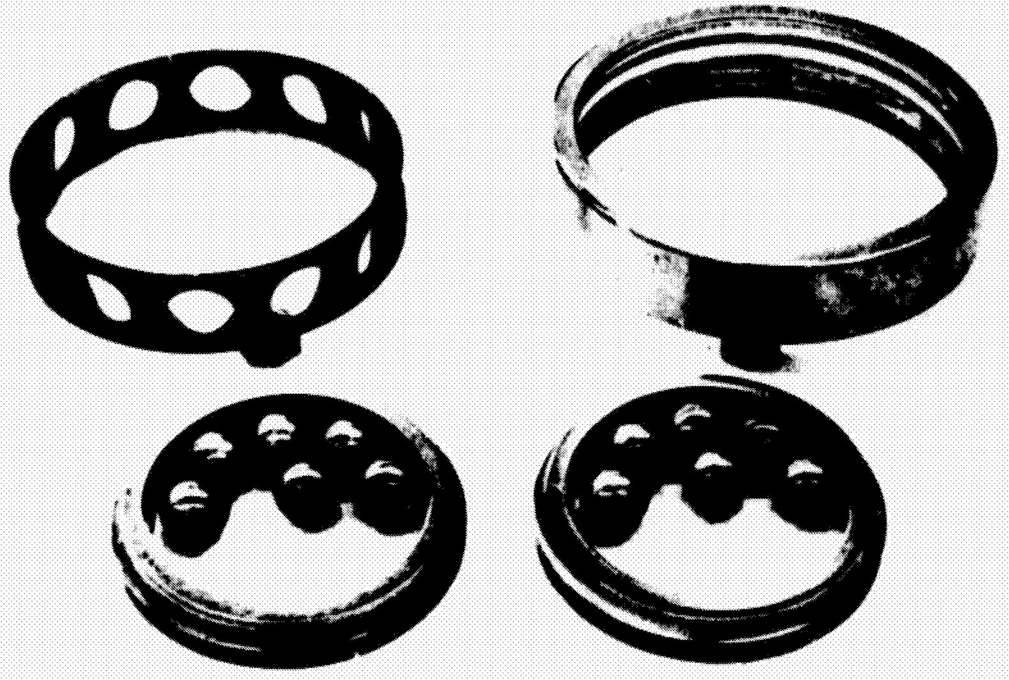

Figure 19 - Appearance of Thrust-Bearing Components, Including Irradiated PBI-Glass Retainer S/N 880027, After 7.75 hr Operation

(i.e., the balls, the outer race, and the loaded half of the inner race) had lost their pretest finish and had a finely frosted surface condition (see Figure 20). Closer examination revealed small dents and gouges in several balls and in the outer race track. The cause of the surface degradation (i.e., abrasive debris from the ball retainer) was evident from examination of the retainer. As shown in Figures 21 and 22, each ball pocket contained wear scars at both driven and trailing walls, resulting in the generation of considerable debris. Table 7 shows that a total of more than 0.69 gm of material (solid lubricant and retainer material) was lost during the test.

TABLE 7

WEIGHT CHANGE, THREE EXPERIMENTAL BEARING RETAINERS (BUILD-UP 31)

Part Description	Condition	Weight, gm	Change, gm	Cause
1. Ball Retainer S/N 880027	Pretest	11.7252	-	-
	After Application of Molykote	12.0776	+0.3524	MoS_2
	Posttest	11.3809	-0.6967	Loss of MoS_2 plus wear
2. Roller Retainer S/N 880008	Pretest	10.3158	-	-
(Motor Roller Bearing)	Posttest	9.9114	-0.4044	Wear
3. Roller Retainer S/N 880009	Pretest	10.0409	-	-
(Loader Roller Bearing)	Posttest	10.0792	+0.0383	Carbon seal debris pick-up

Wear scars extended across the entire thickness of the part, resulting in large contact areas and probably considerable heat generation. Since neither wear nor weight loss was noted in the test of the first irradiated PBI-glass ball-retainer (GTR-21), it was assumed that the cause of both the wear and wear effects described above were associated

Figure 20 - Frosted Surface Condition of Balls Caused by Abrasive Glass Debris from Retainer

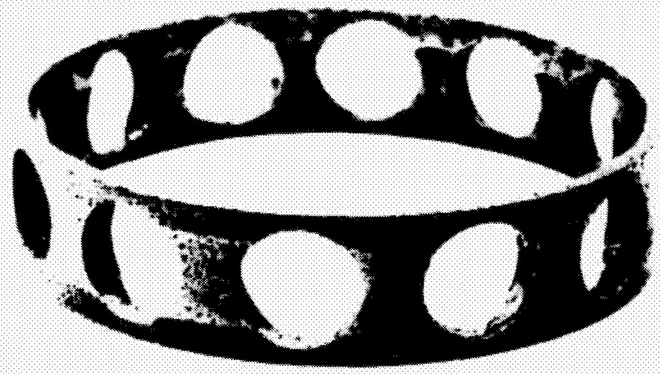

Figure 21 - Posttest Appearance of Irradiated PBI-Glass Ball-Retainer After 7.75 hr Testing, Showing Outer-Surface Wear and Ball-Pocket Scars

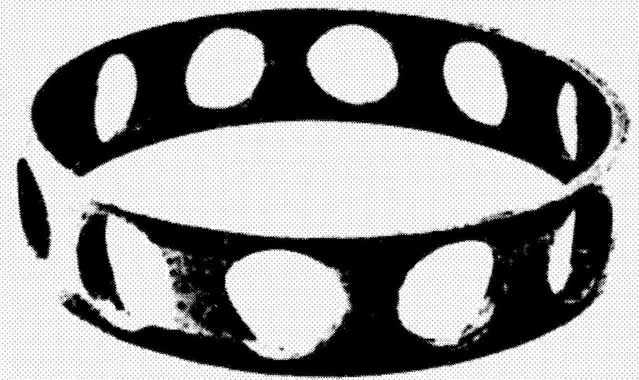

Figure 22 - Posttest Appearance of Irradiated PBI-Glass Ball-Retainer After 7.75 hr Testing, Showing Inner-Surface and Ball-Pocket Scars

with the short, lower-than-usual flow rate which may have affected ball-pocket heat transfer characteristics, resulting in excessive debris formation. Subsequent testing of a companion part (S/N 880028) shed more light on the results of this test as further flow-rate experimentation was not planned.

A comparison was made between the retainer wear-rate (in terms of volume lost per unit of distance) and the PBI-glass unlubricated, 8500 ft/min wear rate determined in the liquid hydrogen wear tester (see Reference 1)). Assuming that 0.60 of the 0.69 gm weight loss was attributable to retainer wear (with the remainder being lost MoS_2) the wear rate per pocket was determined to have been 0.27×10^{-7} cc/m. This compares favorably with the experimentally determined wear rate of 1.88×10^{-7} cc/m where the material is under an initial Hertz stress of 1,600 psi without MoS_2 lubrication. Wear-test results given in Reference 1 are, therefore, conservative estimates of the material's wear characteristics in liquid hydrogen.

(2) Loader Roller Bearing, S/N 1110

The loader roller bearing components were in excellent condition, considering the extensive test time (see Figure 23). Since this bearing is the furthest upstream in the cooling sequence, the lowered coolant flow-rate had no effect. The good condition of the rollers is typified by the parts shown in Figures 24 through 26. The experimental PBI-graphite retainer sustained the test in excellent condition (see Figure 27). Its appearance remained essentially unchanged from its first 7.75-hr test run and no evidence of wear was noted, as shown by the results in Table 7.

(3) Motor Roller Bearing, S/N 1103

The motor roller bearing is more sensitive to coolant flow rate to the extent that its operating temperature

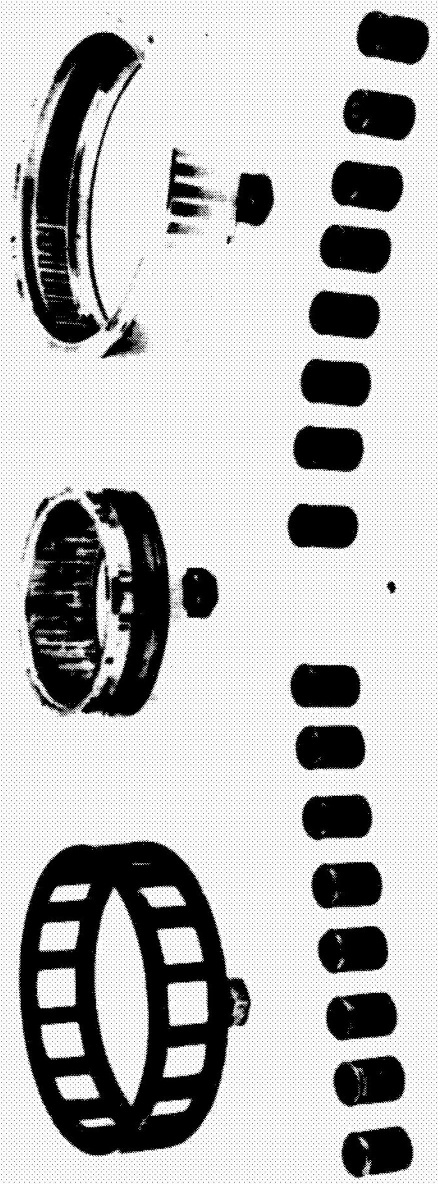

Figure 23 - Posttest Appearance of Loader Roller-Bearing, Including Experimental PBI-Graphite Retainer After More Than 15 hr Testing

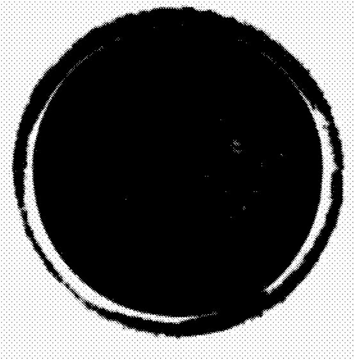

Figure 24 - Posttest Appearance of Loader Roller-Bearing Roller, Upstream End, Showing Absence of End Wear

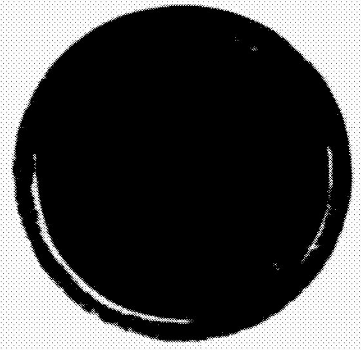

Figure 25 - Posttest Appearance of Load Roller-Bearing Roller, Downstream End, Showing Absence of End Wear

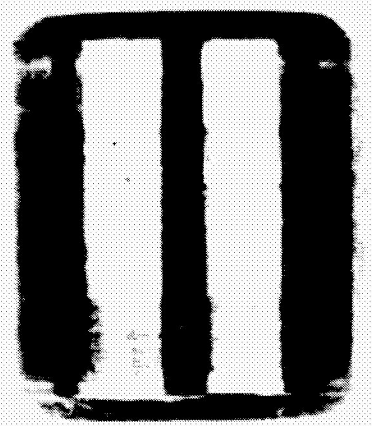

Figure 26 - Posttest Appearance of Loader Roller-Bearing Roller, Side View, Showing Absence of Wear and Heat Effects

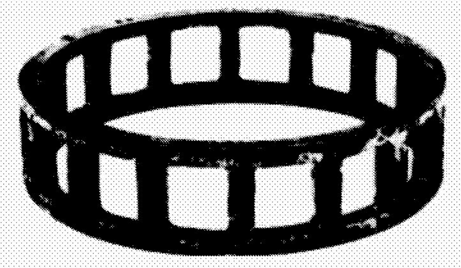

Figure 27 - Posttest Appearance of PBI-Graphite Loader Roller-Bearing Retainer Showing Light Pocket-Wear Scars

was adversely affected. Operating within the motor armature and furthest from the coolant inlet, the bearing operating-temperature may be several degrees higher than that of the loader roller bearing. Consequently, reducing coolant flow through this bearing had drastic effects upon its components, as the thermocouple instrumentation described above predicted. The appearance of the bearing components is shown in Figure 28. Immediately evident is the end wear exhibited by each roller on both ends: the downstream end, for example, was worn by approximately 0.01 in. (see Figures 29 and 30) while upstream (loader) end-wear was approximately 0.002 in. (see Figure 31). The roller ends, as well as the race lands against which the rollers bear, were chattered, exhibiting the extreme effects of cold welding and tearing. The resultant metal debris caused denting of both races and rollers and also appeared to have removed the normal blue layer of FeN developed during the test. The roughened roller surfaces greatly affected the retainer operation and accounts for the somewhat high weight loss of 0.4 gm shown in Table 7. It should be recalled that during its initial 6-hr test run, the weight loss of this retainer was negligible.

Appearance of the experimental PBI-graphite retainer is shown in Figures 32 and 33. Indentations on the retainer OD caused by the outer race support lands are evident in Figure 32. The wear caused by roller sideloads are evident as elliptical marks on the retainer side-rings (see Figure 33). Heavier-than-usual wear was manifested by wear scars in the separator bars (see Figure 33): these are hour-glass shaped because of a lack of line-to-line contact with the roller. Generally, all retainer degradation was directly attributable to flow-rate-caused bearing anomalies.

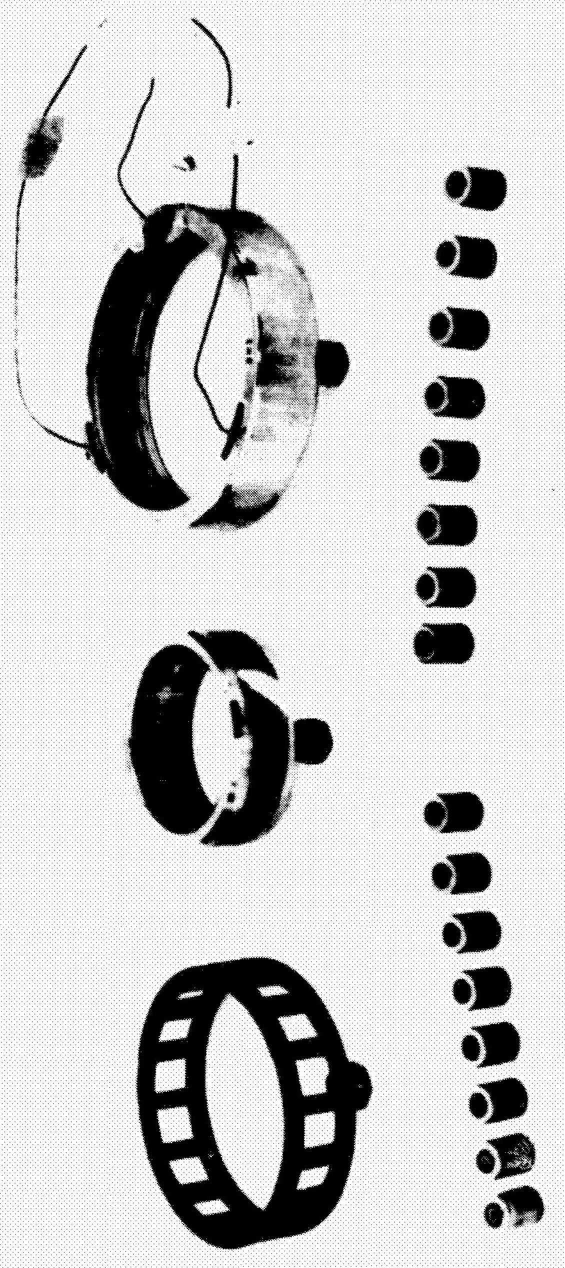

Figure 28 - Posttest Appearance of Motor Roller-Bearing Components, Showing Roller End Wear from Reduced-Coolant-Flow Rate Experiments

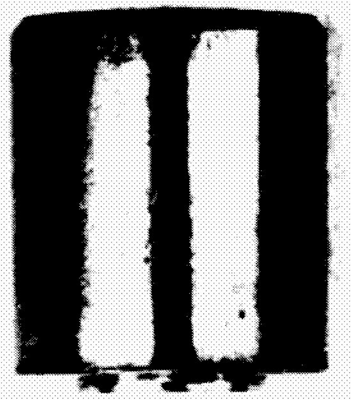

Figure 29 - Side View of End Wear Sustained by Motor Roller-Bearing Roller, Downstream Face

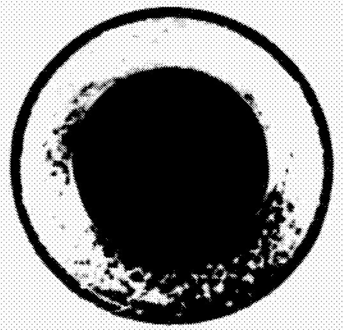

Figure 30 - Appearance of Motor-Roller End-Wear Surface Showing Effects of Cold Welding and Tearing on Downstream Roller Face

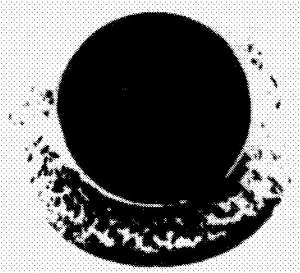

Figure 31 - Less-Severe End-Wear Appearance of Motor Roller-Bearing Roller Upstream Face

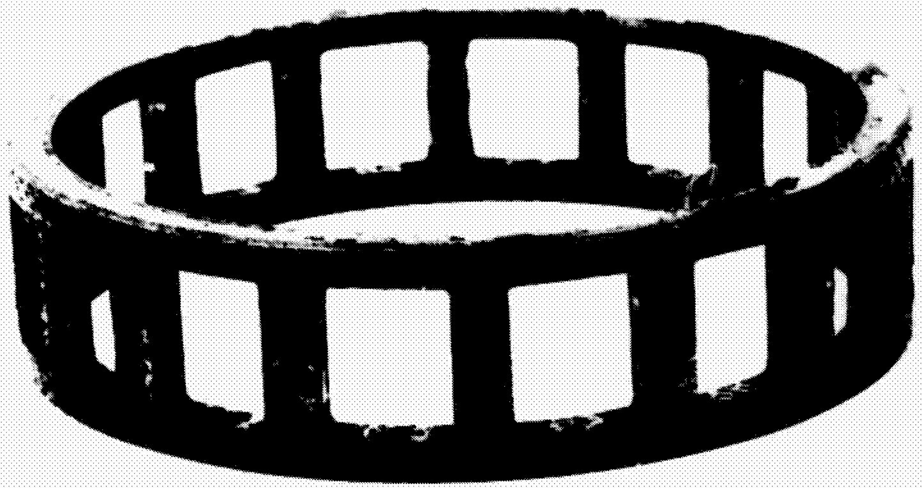

Figure 32 - Posttest Appearance of Experimental PBI-Graphite Motor Roller-Retainer S/N 880008 with More Than 13.5 hr of Accumulated Testing, Showing Generally Satisfactory Condition and Light Pocket Scars

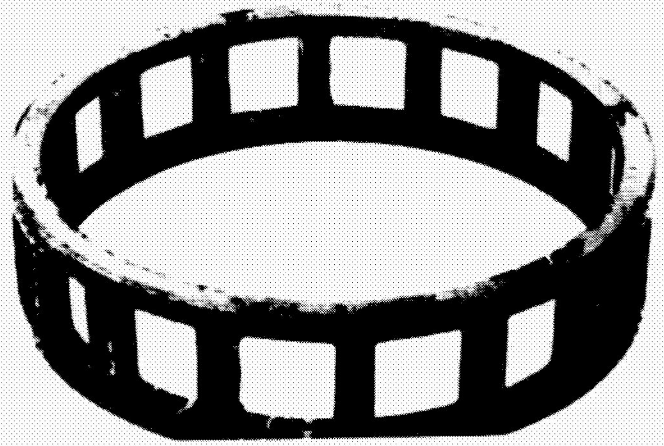

Figure 33 - Posttest Appearance of Experimental PBI-Graphite Motor-Roller Retainer S/N 880008, Showing Inner-Surface and Pocket Scars

5. Test of a Second PBI-Glass Thrust-Bearing Retainer Irradiated to 4.8 x 10^{10} ergs/gm(C) in LN_2 (GTR-20A), P/N 1134747-5B, S/N 880028

a. Objective

This test immediately followed testing of S/N 880027, and was needed to verify the successful operation of the new ball-retainer design and to provide additional confidence in the integrity of irradiated PBI-glass. To avoid any test perturbations which might influence the results, flow-rate experiments were not planned.

b. Procurement and Fabrication

The test retainer was fabricated to the requirements of Drawing P/N 1134747-5B (see Figure 1), and serialized S/N 880028. Essentially a twin to S/N 880027, it was machined from the same cylinder and underwent the same processing steps described above.

c. Test Plan

The part was irradiated in the General Dynamics/Ft. Worth GTR reactor (GTR-20A) by immersing it in a liquid-nitrogen dewar and then exposing the part to fast neutrons and gamma radiation. The total gamma dose was tentatively reported to have been 4.8 x 10^{10} ergs/gm (C). Preparation for testing consisted only of removal of loose material and lubrication by brush applications of Molykote 321. The appearance of the test part before and following Molykote application is shown in Figures 34 through 37. One of the two roller bearings used in this test (S/N 1110) incorporated graphite-reinforced PBI roller-retainer S/N 880009 used in three earlier tests. This part was reinstalled in the loader-roller location upstream of the test ball-bearing. Lubricant was not added beyond the remainder of the coating applied for its first test. The downstream roller-bearing (i.e., the motor roller) contained a conventional Armalon retainer.

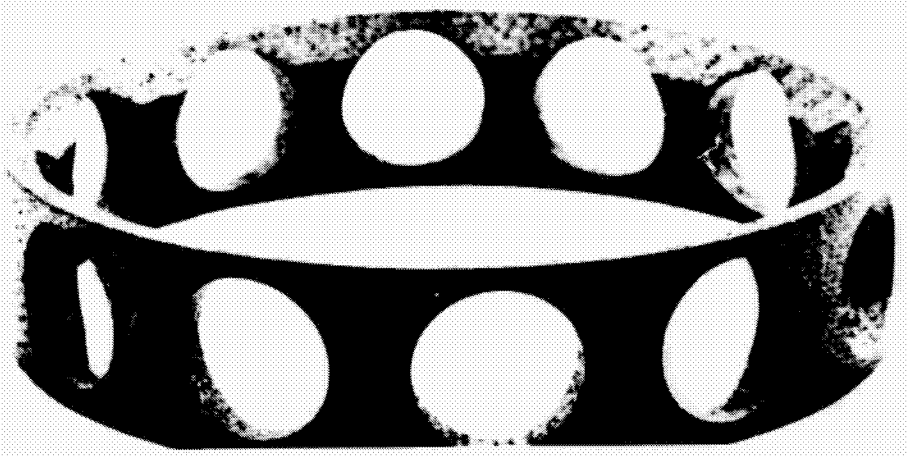

Figure 34 - Pretest Appearance of Irradiated PBI-Glass Ball Retainer S/N 880028, Outside Surface

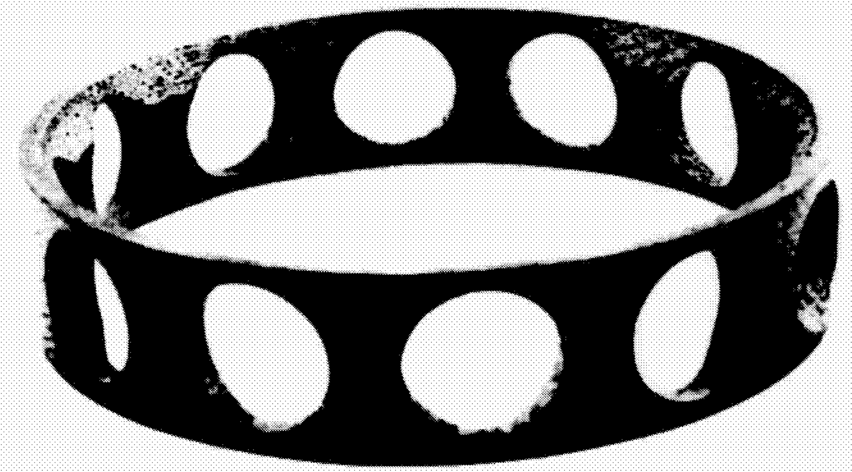

Figure 35 - Pretest Appearance of Irradiated PBI-Glass Ball Retainer S/N 880028, Inside Surface (Note Porous Nature of Laminate)

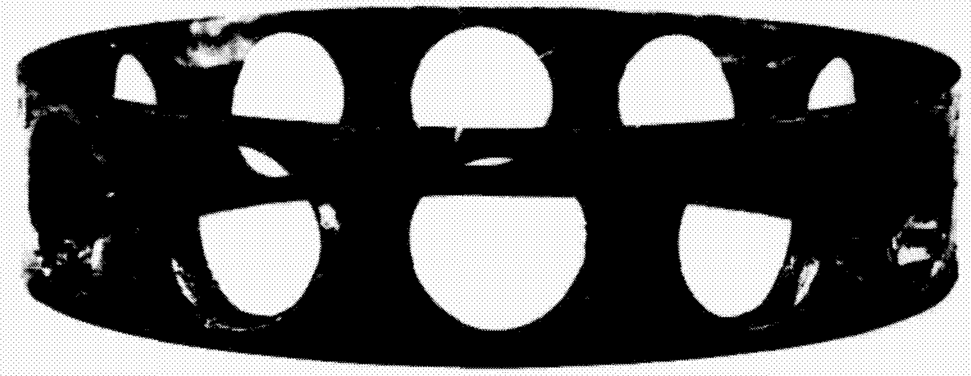

Figure 36 - Pretest Appearance of Irradiated PBI-Glass Ball Retainer S/N 880028, After Application of MoS_2, Outside Surface

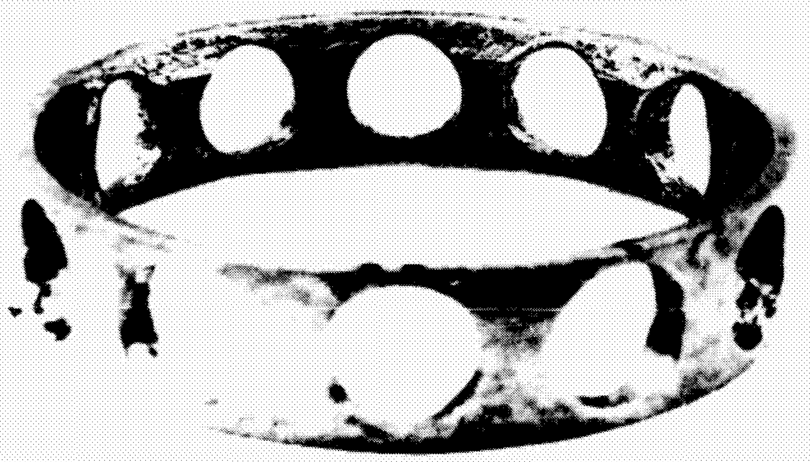

Figure 37 - Pretest Appearance of Irradiated PBI-Glass Ball Retainer S/N 880028, After Application of MoS_2, Inside Surface

d. Test Results

The test of this part was conducted in three segments with no intervening disassembly and with an objective of accumulating at least six hr of test time. The test was performed at the same parameters as used previously. After the tester was started, speed was adjusted to 12,000 rpm and held for a 3 min run-in period. At the end of the run-in period, axial and radial loads were adjusted to 1,200 and 2,300 lb, respectively. Following bearing-load application, speed was brought to 24,000 rpm and the time count started. The liquid-hydrogen flow rate was held in the 20 to 30 gpm at a pressure of 205 psi.

During the first test segment, the tester was operated for 1 hr and 47 min. Shutdown was necessitated by rapid use of bearing-load actuation gas pressure but the instrumentation indicated a smooth run with tester amperage fluctuating between 34 and 37 amp.

The second test segment was performed after actuation pressure and liquid-hydrogen coolant had been replenished. The tester operated uneventfully for 2 hr and 30 min, increasing accumulated test time to 4 hr and 17 min. The smoothness of the test was reflected mainly by the narrow motor-current range of 36 to 38 amp throughout the test segment.

The third test segment, again performed after replenishment of actuation-gas pressure and coolant, was needed to complete the minimum target run-time of 6 hr. Tester operation was smoother and quieter than earlier test segments with motor current remaining at the very low 30 to 31 amp level. A reduced actuation-pressure leakage rate during the final test segment (as in the previous test) enabled the accumulation of an additional 3 hr and 17 min of testing.

Total run times on the two experimental bearing retainers of interest were:

1. PBI-glass irradiated ball retainer S/N 880028 - 7 hr, 35 min.

2. PBI-graphite roller retainer S/N 880009, loader roller - 23 hr, 2 min.

There were no occurrences during the test which would indicate anything other than successful bearing operation.

e. Posttest Inspection

(1) Thrust Bearing, S/N 866B

The excellent condition of the components of this bearing, including the irradiated ball retainer, is shown in Figures 38 through 40. Inspection revealed that the magnitude and severity of debris-caused damage was greatly reduced in this test, compared with that of the S/N 880027 retainer test, indicating the importance of maintaining adequate coolant flow-rate and low interfacial temperature. The surface finish of the rolling elements of the bearing was intact with only isolated pits and dents evident. The PBI-glass retainer wear scars at the driving and trailing pocket walls had rubbed through the lubricant coating at the ID portion of the pocket wall. However, the scars did not extend across the entire retainer thickness and wear was considered light. Weight-change data indicated a loss of over more than 0.5 gm was sustained (see Table 8). Since wear was light, it was assumed that most of the weight loss represented loss of the excessively heavy Molykote coating.

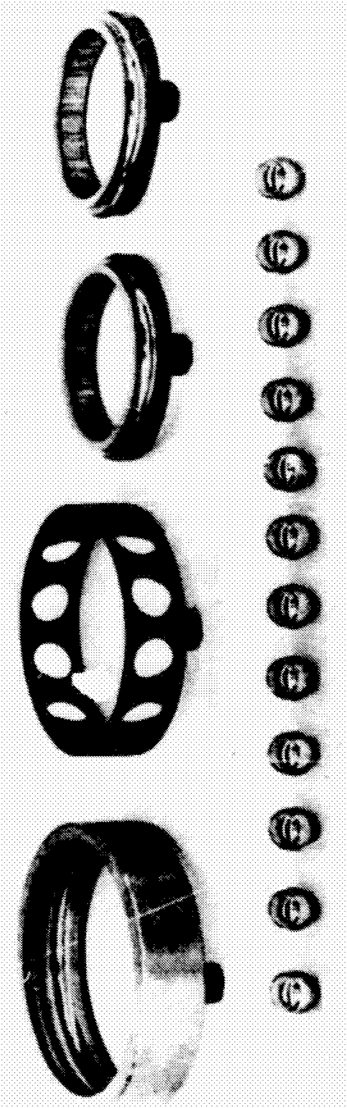

Figure 38 - Posttest Appearance of Thrust-Bearing Components, Including Satisfactory Condition of Irradiated PBI-Glass Retainer S/N 880028

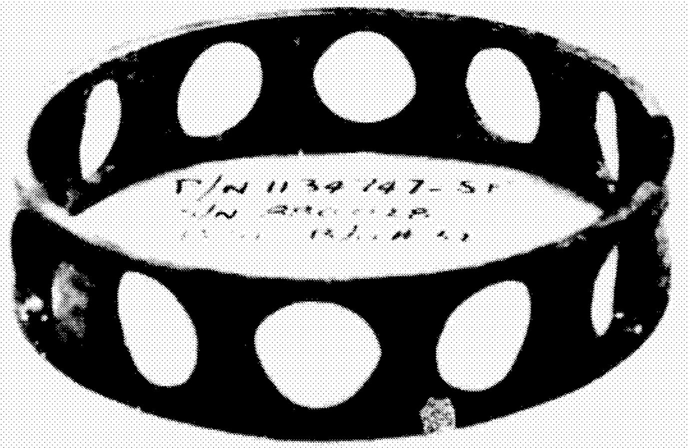

Figure 39 - Posttest Appearance of Irradiated PBI-Glass Ball Retainer, Showing Inside Surface and Ball-Pocket Scars

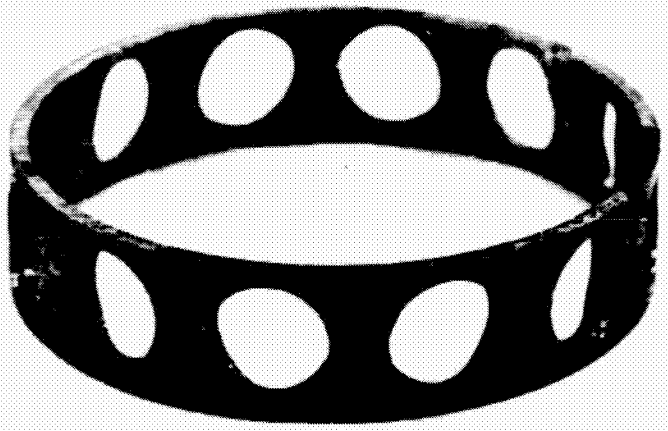

Figure 40 - Posttest Appearance of Irradiated PBI-Glass Ball Retainer, Showing Outside Surface and Ball-Pocket Scars

TABLE 8

WEIGHT CHANGE, TWO EXPERIMENTAL BEARING RETAINERS (BUILD-UP 32)

Part Description	Condition	Weight, gm	Change, gm	Cause
1. Ball Retainer S/N 880028	Pretest	11.7187	-	-
	After Molykote Application	12.7946	+1.0759	MoS_2
	Posttest	12.1611	-0.6335	Loss of MoS_2, slight wear
2. Roller Retainer S/N 880009	Pretest	10.0792	-	-
(Loader Roller Bearing)	Posttest	10.0667	-0.0125	Negligible

(2) Loader Roller Bearing, S/N 1110

The loader roller-bearing components were, again, in excellent condition after more than 23 hr of testing (see Figure 41). Examination of races and rollers failed to reveal any evidence of significant wear and no signs whatsoever of end wear (see Figures 42 and 43). The PBI-graphite retainer was in good condition with partial roller wear scars in the roller pocket-driven walls (see Figures 44 and 45). These scars, as well as the wear marks on the retainer OD, were essentially unchanged from their appearance following both previous tests of this bearing, as reflected by the negligible weight changes recorded in Table 9.

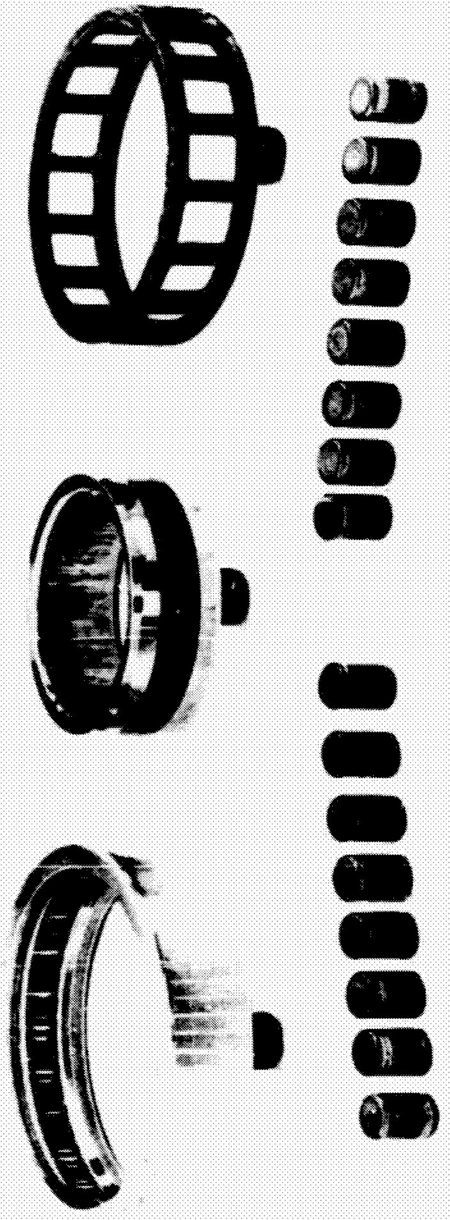

Figure 41 - Satisfactory Posttest Appearance of Loader Roller-Bearing Components

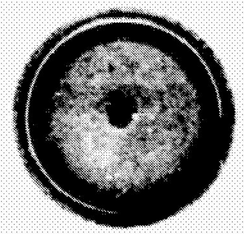

Figure 42 - Posttest Appearance of Upstream Face of Loader Roller-Bearing Roller

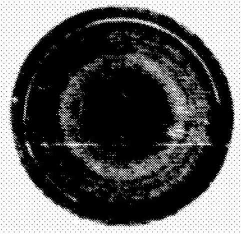

Figure 43 - Posttest Appearance of Downstream Face of Loader Roller-Bearing Roller

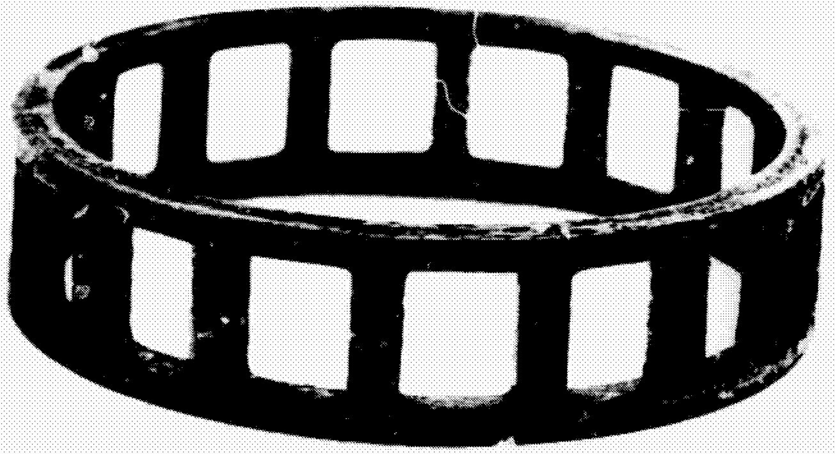

Figure 44 - Excellent Appearance of Loader Roller-Bearing Retainer S/N 880009 After More Than 23 hr of Testing, Outside Surface

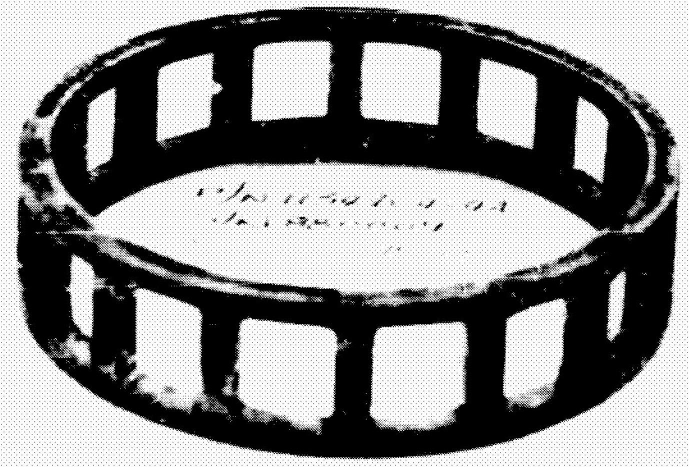

Figure 45 - Posttest Appearance of Inside Surface of Loader Roller-Bearing Retainer After Testing

TABLE 9

SUMMARY OF WEIGHT LOSS RECORD OF PBI-GRAPHITE ROLLER RETAINER S/N 880009 (BEARING S/N 1110)

Build Up No.	Total Run Time, sec	Posttest Weight, gm
30	27,600	10.0409
31	55,543	10.0792
32	82,837 (23 hr, 2 min)	10.0667

6. Test of a PI-Glass Thrust-Bearing Retainer Irradiated to 4.8×10^{10} ergs/gm (C) in LN_2 (GTR-20A), P/N 1134747-6 NC, S/N 880003

a. Objective

This test was performed: (1) to evaluate the effect of the gamma radiation dose on a glass-reinforced polyimide, as opposed to the polybenzimidazole; (2) to evaluate the new ball-retainer design as fabricated by a different vendor; and (3) to provide justification for the new ball-retainer design in view of the fact that two PI-glass retainers of the old design had failed in less than 3 hr (see Reference 2). Additional test objectives were the testing of an unirradiated glass-reinforced-PBI roller bearing retainer (S/N 880005) and further testing of the S/N 880008 PBI-graphite roller-bearing retainer which already had been tested 13.8 hr.

b. Procurement and Fabrication

The principal test part, a glass-fabric-reinforced-PI system, was fabricated to the requirements of Drawing P/N 1134747-6 NC and serialized S/N 880003. It was one of three parts fabricated by mandrel wrapping a PI-2501-impregnated S-glass fabric prepreg, followed by a gradually increasing elevated temperature curing cycle. The resultant cylinder was machined to the required configuration and visually inspected for discontinuities and wrinkles or kinks in the glass reinforcement. Two hoop-tension test specimens were machined and delivered with the three retainers. Results of the hoop tests both before and after irradiation, as well as volumetric analysis results, are shown in Appendix C. However, no detailed fabrication and processing information was obtained from the vendor who considered this information as being proprietary.

c. Test Plan

The part was radiographically inspected and found to be structurally sound. It was submitted to the General Dynamics/Ft. Worth GTR reactor as part of the GTR-20 irradiation experiment. Retainers S/N 880002 and 880003 were irradiated to 4.8×10^{10} ergs/gm (C) gamma dose and 4.3×10^{15} nvt fast neutron irradiation in liquid nitrogen and subsequently returned to Aerojet-General. S/N 880003 was selected for bearing testing and, following removal of loosely adhering material, the part was lubricated with brush applications of Molykote 321. The appearance of the part prior to testing is shown in Figure 46.

Similar lubricant application was performed on the loader roller-bearing PBI-glass retainer S/N 880005 (see Figure 47). The roller-retainer appearance before Molykote application, showing the degree of porosity commonly obtained with highly volatile aromatic polymers, is shown in Figure 48.

No additional solid-film lubricant was applied to the previously tested and coated PBI-graphite motor roller-bearing retainer S/N 880008.

d. Test Results

The test of S/N 880003 required three segments with two intervening disassemblies and with the objective of accumulating at least 6 hr of testing. The test was performed at the conventional bearing test parameters used throughout 50-mm bearing testing.

After the tester was started, speed was adjusted to 12,000 rpm and held for a 3-min run-in period. At the end of this period, axial and radial loads were adjusted to 1,200 and 2,300 lb, respectively, and the flow rate was set at 20 to 30 gpm. When speed was increased to 24,000 rpm,

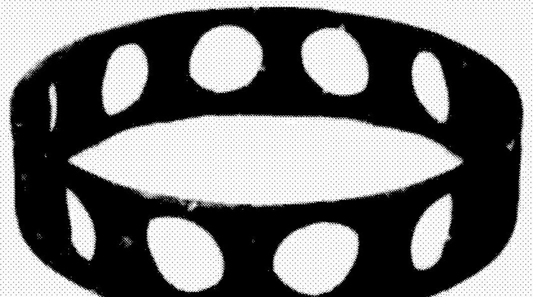

Figure 46 - Pretest Appearance of Irradiated PI-Glass Ball Retainer S/N 880003

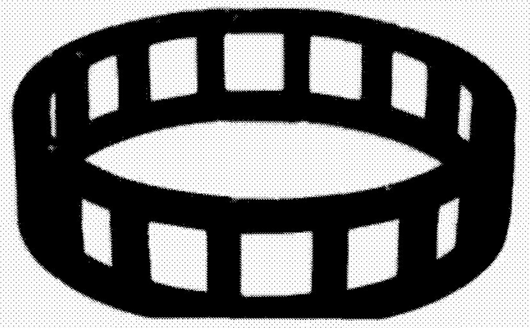

Figure 47 - Posttest Appearance of Experimental PBI-Glass Roller-Bearing Retainer S/N 880005

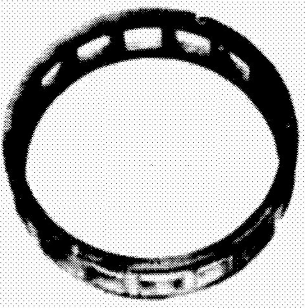

Figure 48 - Pretest End View of PBI-Glass Roller-Retainer, Showing Type and Distribution of Porosity

motor current increased to 45 to 55 amp range, compared with the usual 25 to 35 amp observed in earlier tests. Tester noise appeared to be louder than usual with harsh overtones coincident with higher amperage spikes. After approximately 1700 sec, tester amperage increased erratically to the 70 to 100 amp range and the test was terminated 43 sec later. When an attempt to restart the tester failed, the tester was then disassembled.

The load roller-bearing and ball-bearing retainers were found to be in good condition as shown in Figures 49 through 52. Rough and noisy bearing performance, and test termination, were found to have been caused by heavy end-wear in the motor roller-bearing (see Figures 53 and 54) culminating in the rollers skidding and turning 90° from their original positions. Excessive skidding and turning resulted in outer-race land chipping and complete destruction of the PBI-graphite retainer (see Figures 55 and 56).

Investigations of the factors which may have caused such heavy end-wear were made both after this and the following test and were primarily aimed at determining whether restricted coolant flow-rate may have caused the observed roller-bearing performance. It was found that coolant flow-rate was, in fact, considerably lower than had been indicated by instrumentation in both this and the next test. While the cause and discussion of this anomaly is beyond the scope of this report, it must be borne in mind that the severity of this and the following test was far greater than normal and, no doubt, affected both loader roller-bearing and ball-bearing retainer weight changes (See Table 10).

Final test time of the PBI-graphite roller retainer S/N 880008 was 14.3 hr.

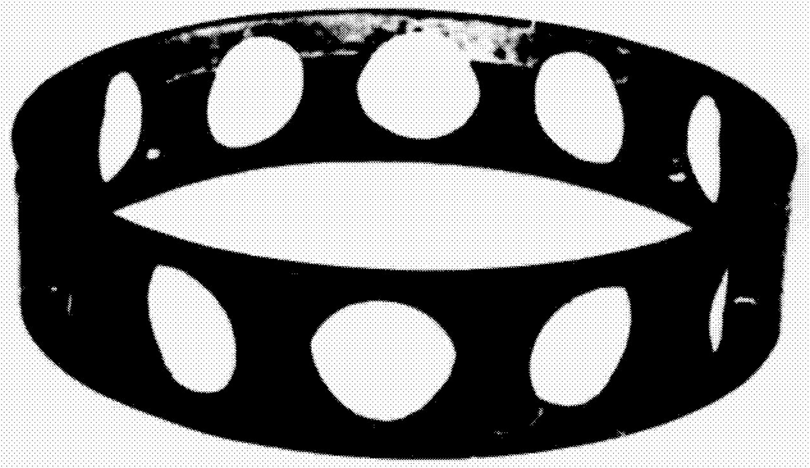

Figure 49 - Appearance of Irradiated PBI-Glass Ball Retainer S/N 880003 After Initial 1743 sec Test (No Evidence of Degradation or Incipient Failure was Noted)

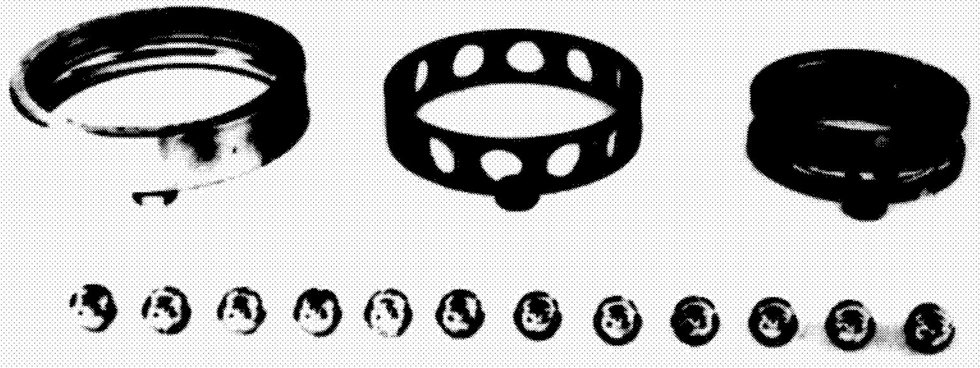

Figure 50 - Satisfactory Appearance of Ball-Bearing Components After First Test Segment

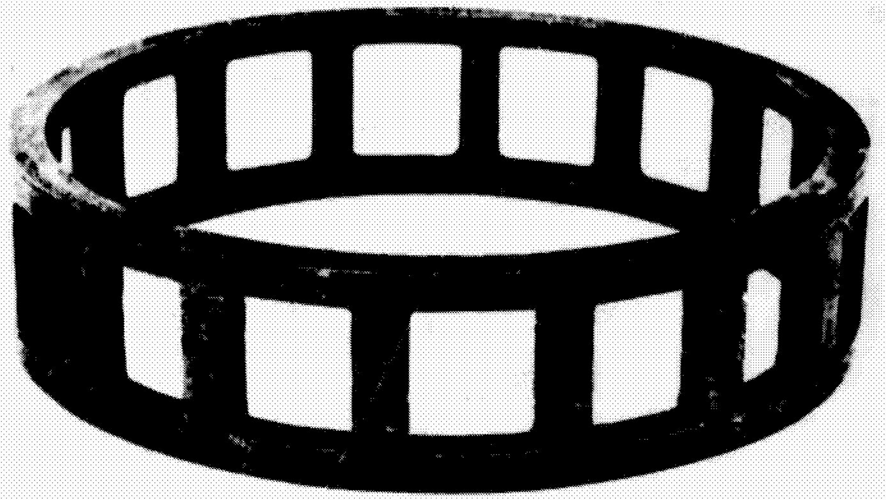

Figure 51 - Satisfactory Appearance of Experimental Roller Retainer S/N 880005 After First Test Segment

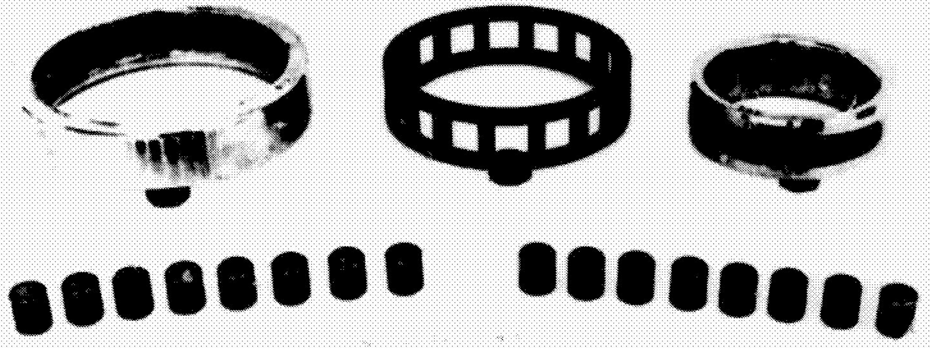

Figure 52 - Satisfactory Appearance of Loader Roller-Bearing Components, Including Experimental PBI-Glass Retainer, After First Test Segment

Figure 53 - Posttest Appearance of Motor Roller-Bearing Rollers Showing Effects of Extreme End-Wear and Bearing Failure, Upstream Faces

Figure 54 - Posttest Appearance of Motor Roller-Bearing Roller Downstream Faces

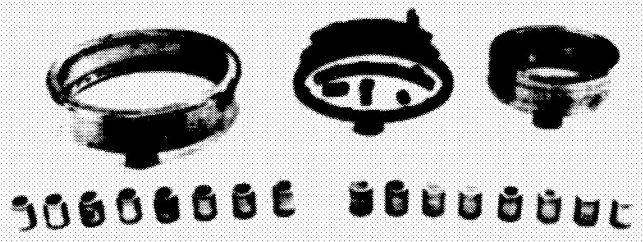

Figure 55 - Posttest Appearance of Motor Roller-Bearing Components Including Destroyed PBI-Graphite Retainer S/N 880008

Figure 56 - Posttest Appearance of PBI-Graphite Roller Retainer S/N 880008, Destroyed by Extreme End-Wear and Roller Skewing

TABLE 10

WEIGHT CHANGE, TWO EXPERIMENTAL BEARING RETAINERS (BUILD-UP 33)

Part Description	Condition	Weight, gm	Change, gm	Cause
1. Ball Retainer S/N 880003 PI-Glass	Pretest	14.0265	-	-
	After Molykote application	14.1668	+0.1403	M_oS_2
	Posttest 1st Segment (29 min)	14.0011	-0.1657	Loss of M_oS_2; Slight Wear
	Posttest 2nd Segment (2 hr 5 min)	13.9870	-0.0141	Negligible
	Posttest 3rd Segment (8 min)	Failed		Unknown
2. Roller Retainer S/N 880005 PBI-Glass	Pretest	12.0390	-	-
	After Molykote	12.2068	+0.1678	M_oS_2
	Posttest, 1st Segment	12.1842	-0.0226	Loss of M_oS_2
	Posttest, 2nd Segment	12.0636	-0.1206	Slight Wear
	Posttest, 3rd Segment	Not Used		

The second test segment was performed following motor roller-bearing replacement and tester reassembly. Both the loader roller-bearing and ball-bearing were reassembled without further processing. The new motor roller-bearing contained a conventional Armalon retainer which was spray-and brush-lubricated with Molykote 321 prior to assembly.

Following tester starting and operation at 12,000 rpm, and during its subsequent operation at 24,000 rpm, it soon became apparent that tester operation was similar to that observed during the first test segment. With bearing loads adjusted to 1,200 and 2,300 lb, and the coolant flow rate at 25 to 30 gpm pressurized to 205 psig, tester motor current was 45 to 55 amp. Occasional excursions were observed to the 60 to 70 amp range coincident with increased tester sound level. The tester operated in this manner for 2 hr and 5 min at which time motor current increased in several short stages to 100 amp. The test was terminated 35 sec later.

Since the previous attempts to correct rough tester operation had not succeeded, the tester was again disassembled for detailed investigation of all components. Heavy end-wear was again noted in the motor roller-bearing (see Figure 57). In addition, some end wear was also incurred by the load roller-bearing with the resultant debris flowing through the ball bearing (see Figures 58 and 59). The PBI-glass loader roller-bearing retainer, however, was in good condition (see Figure 60) as were the ball bearing components (see Figure 61). Evidence of metallic debris embedded in the ball retainer was noted and the debris from the loader roller may have been the cause of the slightly frosted surface condition noted in the inner and outer race track areas. The retainer pockets contained light scars from ball contact and burnished areas were developed on the OD at the outer-race support areas. In general, the retainer was in satisfactory condition and warranted further testing (see Figure 62).

In the detailed tester component investigation which followed, it was determined that a condition had existed in the previous two test segments analogous to coolant leakage between the tester and the flow meter. This discovery indicated that flow through the test bearing was significantly lower than registered by instrumentation, resulting in roller-bearing end wear and an excessively high motor-current requirement. The high current resulted in abnormal heat input to the already inadequately cooled motor roller-bearing. The combination of a low flow-rate and high motor-current

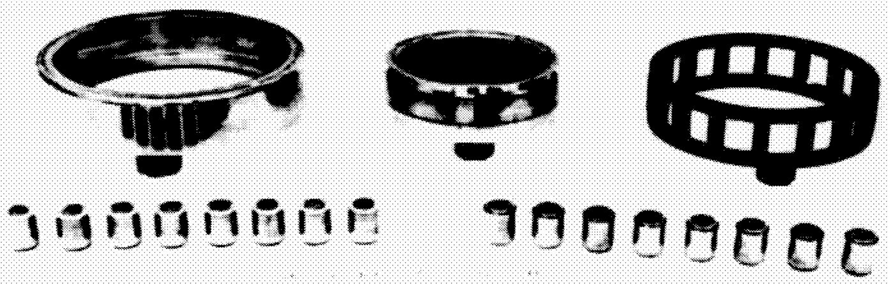

Figure 57 - Posttest (Second Segment) Appearance of Motor Roller-Bearing Components Showing Heavy End-Wear on Roller Downstream Faces (Left Side)

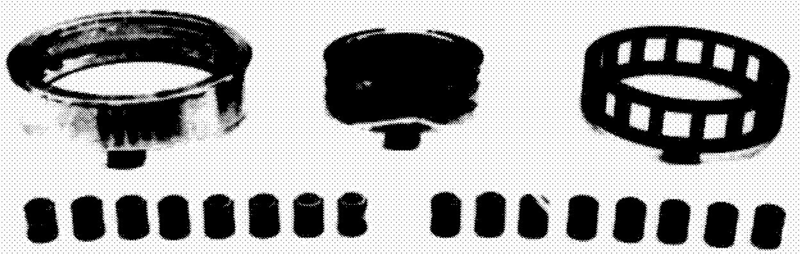

Figure 58 - Posttest (Second Segment) Appearance of Loader Roller-Bearing Components Including Experimental PBI-Glass Retainer S/N 880005

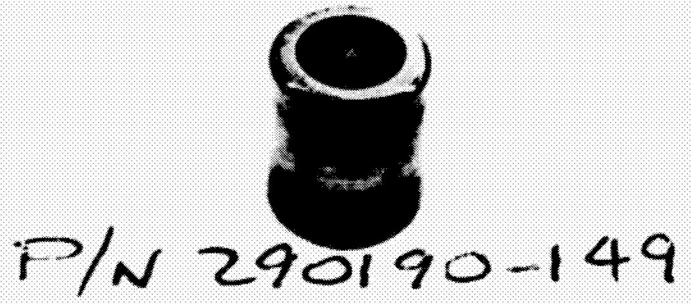

Figure 59 - Posttest (Second Segment) Appearance of Loader Roller-Bearing Roller End-Wear, Indicative of Abnormally Low Coolant Flow-Rate During Testing

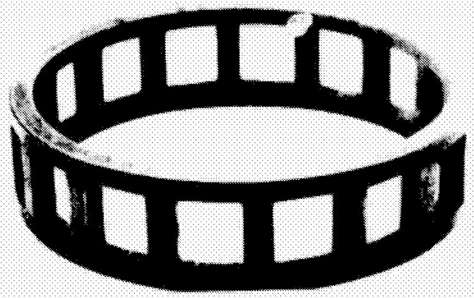

Figure 60 - Satisfactory Appearance of Loader Roller-Bearing Retainer S/N 880005 After Second Test Segment

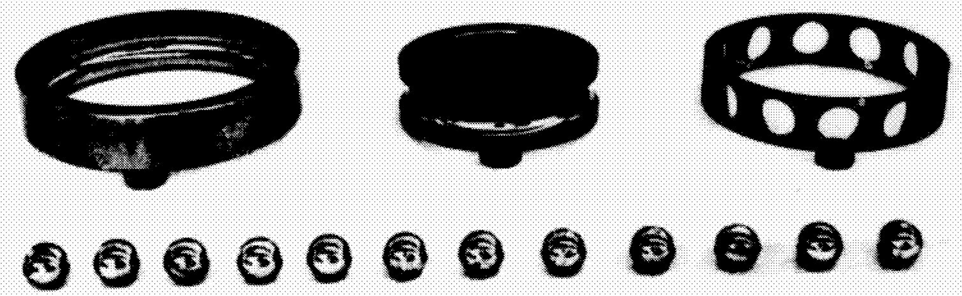

Figure 61 - Satisfactory Appearance of Ball-Bearing Components, Including Irradiated PI-Glass Ball Retainer S/N 880003, After Second Test Segment

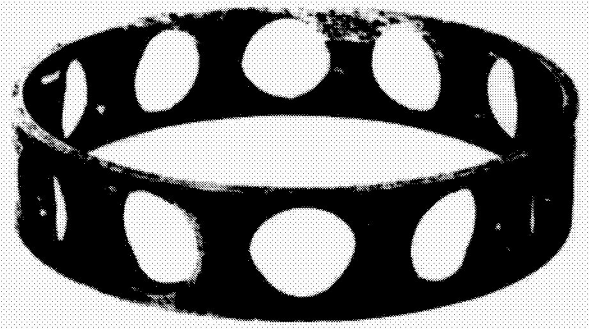

Figure 62 - Posttest (Second Segment) Appearance of Irradiated PI-Glass Ball Retainer S/N 880003 Showing Very-Light Burnishing on Outer Diameter and Light Pocket Scars

led to a mutually reinforcing degradation cycle, resulting in the extensive bearing damage described earlier.

To avoid repetition of this test condition, tester components used in previous successful tests were scheduled for employment in the third test segment. In addition, the PBI-glass loader roller-bearing retainer was replaced by a conventional Armalon retainer and the experimental PI-glass ball retainer was placed in a new bearing. Additional lubricant was not applied to the PI-glass retainer.

The tester was operated satisfactorily at the low run-in speed of 12,000 rpm for approximately 3 min. However, it was noted that tester current was again high (i.e., approximately 35 to 40 amp). Upon applying bearing loads and increasing tester speed to 24,000 rpm, tester current and sound level became noticeably harsh. The tester operated in this manner for 510 sec with tester current fluctuating between 40 amd 80 amp. An excursion to 100 amp accompanied by a noticeable drop in tester speed (approximately 1000 rpm), resulted in tester shutdown.

Inspection of tester components and bearings indicated that the cause of the noisy and erratic test was failure of the experimental PI-glass retainer. No evidence of roller-bearing end wear was observed and the two roller-bearing Armalon retainers were in good condition, as were all other roller-bearing components (see Figures 63 and 64).

The ball-bearing retainer failure was caused by delamination and loss of two ball-separation sections (see Figures 65 through 67). These sections, once loose, nevertheless were held in place by their ball contour and, therefore, were probably the cause of severe vibration and rough bearing operations, explaining both the abnormal tester noise and high operating current. The rapidity of the failure indicated damage was incurred during the previous test segments and that incipient failure after the first or

second test segment was probably attributable to the earlier tester anomalies described above.

Evidence that excessive wear, <u>per se</u>, was not the cause of failure is shown in Appendix C. The calculations were made to compare the retainer volumetric wear-rate with the volumetric wear-rate developed by PI-glass in the liquid-hydrogen wear test. As shown, the retainer wear rate was 66% of the wear-test wear rate, indicating that other factors (e.g., overheating or mechanical shock during the first two test segments) may have influenced the performance of the part.

Final test time for the PI-glass retainer was 2 hr and 42 min. Further tests will be required to evaluate the PI-glass material.

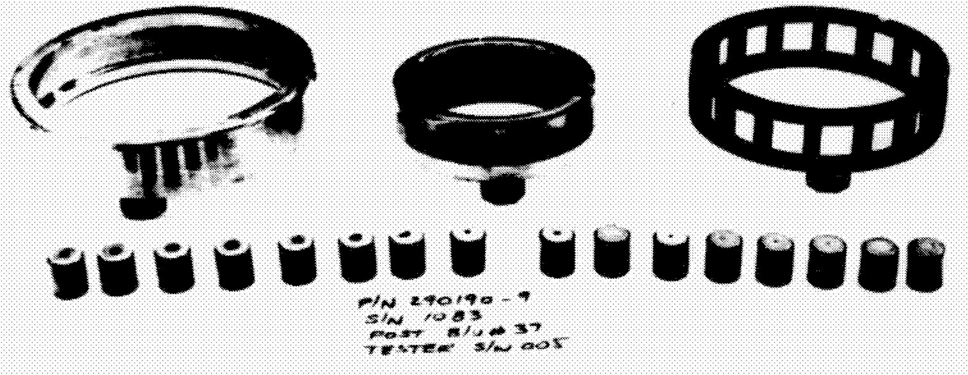

Figure 63 - Posttest (Third Segment) Appearance of Motor Roller-Bearing Components with No Evidence of End-Wear or Other Damage

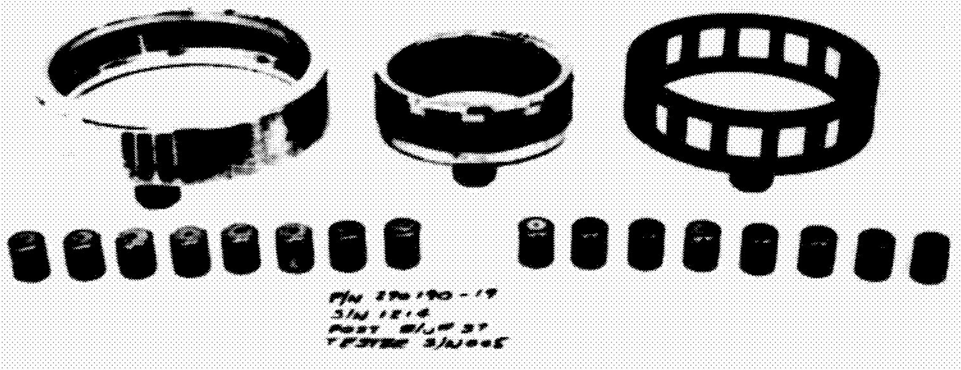

Figure 64 - Posttest Appearance of Loader Roller Bearing Showing Satisfactory Condition of All Components

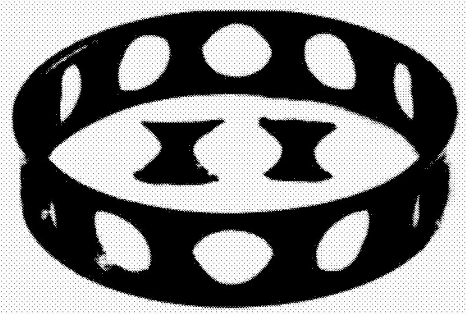

Figure 65 - Posttest Appearance of Irradiated PI-Glass Ball-Bearing Retainer S/N 880003 Showing Nature of Failure (Delamination of Ball Separator)

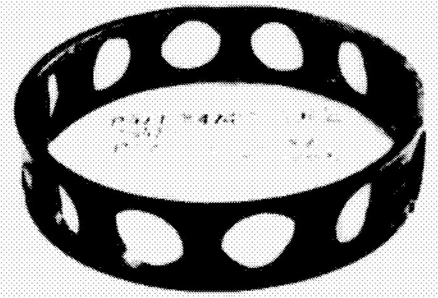

Figure 66 - Posttest Appearance of Irradiated PI-Glass Ball-Bearing Retainer S/N 880003 Showing One Delaminated Area and Adjacent Separator Section About to Fail

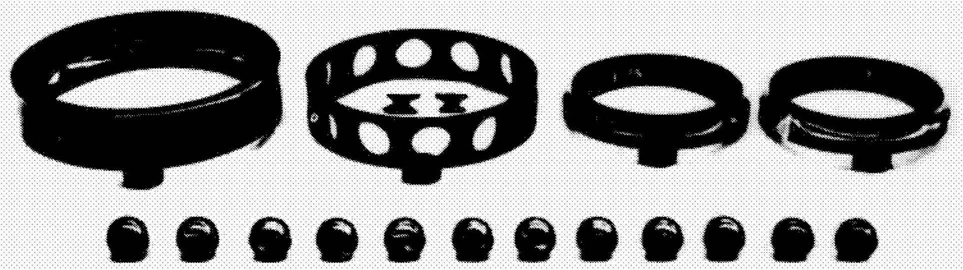

Figure 67 - Posttest Appearance of Ball-Bearing Components Including Irradiated PI-Glass Ball Retainer S/N 880003 with Ball Separator Sections Which Failed During Testing

REFERENCES

1. Aerojet-General Report RN-S-0408, First Progress Report; Bearing Retainer Materials Development, February 1968.
2. Aerojet-General Report, Second Progress Report; Bearing Retainer Materials Development, May 1968.

APPENDIX A

PROCUREMENT AND FABRICATION OF S-GLASS REINFORCED PBI 50-MM BALL BEARING RETAINERS

1. P.O. 204370-0914 issued 10/24/66.
2. Vendor, Narmco R&D Division of Whittaker Corporation, San Diego
3. P/N 1118584-1 N/C
4. S/N 1 and 2
5. Materials used:
   a. Heat-cleaned 1581 S-glass fabric
   b. PBI (polybenzimidazole) resin, 30% by weight, minimum
6. Approximate fabrication sequence:
   a. Straight cut approximately 4-in. wide and 44-in. long.
   b. Material wrapped on a released and primed mandrel in a wrap lathe and wrapped to a 3.3-in. diameter under approximately 30-lb tension and 250-lb force on a 3-in. cylindrical steel roller.
   c. The cylinder shrink-taped and the tape heavily perforated and cured as follows:

      Start cure at 75°F. Slowly increase in temperature (25°F/10 min) to 450°F and hold at 450°F for 120 min. Slowly increase temperature (25°F/10 min) to 550°F and hold at 550°F for 120 min. Slowly increase temperature (25°F/10 min) to 700°F and hold at 700°F for 4 hr. Slow cool to room temperature.
   d. After cure, the parts were sectioned from the cylinder and machined.

APPENDIX B

PROCUREMENT, FABRICATION AND TEST RESULTS OF S-GLASS REINFORCED PBI 50-MM BALL BEARING RETAINERS

1. P.O. 101973 issued 5/8/68.
2. Vendor: Narmco R&D Division of Whittaker Corporation, San Diego, Calif.
3. P/N 1134747-5B
4. S/N 880025 through 880030.
5. Materials Used:
   - a. Heat-cleaned 1581 S-glass fabric
   - b. 1850 Imidite PBI (Polybenzimidazole) resin, 30% by weight, minimum.
   - c. 6-in. long steel mandrel.
6. Approximate fabrication sequence:
   - a. Cut the 1850/1581 Imidite prepreg to 3-in. wide, 220-in. long (two required).
   - b. Preheat mandrel to 300°F. Wrap prepreg on mandrel with maximum tension (approximately 20 lb). Squeegee each ply to insure compaction.
   - c. Apply barrier cloth and overwrap with glass roving at 20 to 25 lb tension.
   - d. Cure in stainless steel box under gaseous nitrogen pressure at a flow rate of 8 cubic ft per hour.
   - e. Cure:

     Increase from room temperature to 450°F at 60°F/hr and hold at 450°F for 2 hr.

     From 450°F, increase temperature to 700°F at 170°F/hr and hold at 700°F for 3 hr.
   - f. Postcure:

     Hold at 800°F for 16 hr. Cool under a gaseous nitrogen pressure purge of 8 cubic ft per hr.
   - g. Remove barrier cloth and machine
   - h. Cut ends to clean and inspect for wrinkles.
   - i. Determine the following characteristics:

% Resin Content:	34.1% weight percent
Specific Gravity:	1.42

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APPENDIX B

7. Hoop test results from tests performed by Aerojet-General:

		w/o	w/o	v/o	v/o	v/o	Sp. Grav.		Hoop Strength,
	Material	Glass	Resin	Glass	Resin	Void	Actual	Theor.	Ksi
Control	PBI/Glass	66.6	33.4	33	31	36	1.23	2.11	34.59
Irradiated (GTR-20A)	PBI/Glass	-	-	-	-	-	-	-	41.8 & 35.8

APPENDIX C

PROCUREMENT, FABRICATION AND TEST RESULTS OF S-GLASS REINFORCED PI 50-mm BALL BEARING RETAINERS

1. P.O. 275842 issued 1/26/68
2. Vendor: Brunswick Corporation, Defense Products Division,
   Marion, Virginia
3. P/N 1134747-6 NC
4. S/N 880001 through 880003
5. Materials used:
   a. Heat-cleaned (112) 181 S-Glass fabric.
   b. DuPont laminating resin PI-2501, 30% by weight, minimum.
6. The following characteristics were determined in tests performed by Aerojet-General

		w/o	w/o	v/o	v/o	v/o	Sp. Grav.		Hoop Strength,
	Material	Glass	Resin	Glass	Resin	Void	Actual	Theor	Ksi
Control	PI-Glass	53.2	46.8	33	55	12	1.56	1.96	7.59
Irradiated (GTR-20A)	PI-Glass	-	-	-	-	-	-	-	9.30

Wear Rate: PI-Glass Ball Retainer - S/N 880003

1. Time in test (not counting test segment causing failure): 154 min
2. Surface Speed: 8500 ft/min
3. Wear Distance: 1,309,000 ft
   or 403,000 meters
4. Weight Loss (adjusted for some loss of M_oS_2): 0.1565 gm
5. Weight loss per pocket: 0.013 gm
6. Volume loss per pocket: 0.0084 cc
   (density 1.56 gm/cc. See Above)
7. Retainer Volumetric Wear Rate: 2.08×10^{-8} cc/m
8. PI-glass wear rate from wear test (Reference 2): 3.14×10^{-8} cc/m

   (Retainer wear rate is 66% of wear-test wear rate.)