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EFFECTS OF RADIATION ON BEARING CAGE MATERIALS
AND RETAINERS IN A LIQUID-HYDROGEN ENVIRONMENT

MASTER

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ABSTRACT

Four independent radiation-effects tests were conducted on bearing cages, bearing cage materials, and full-scale bearings in a liquid-hydrogen environment, with dose levels ranging from approximately 1×10^9 to 1×10^{11} ergs/gm(C). Seven roller-bearing retainers fabricated from TFE-Armalon, grade 405-L-116, and fourteen ball-bearing retainers (seven made of TFE-Armalon, grade 405-L-116, and seven made of FEP-Armalon, grade 510-L-128) were irradiated in liquid hydrogen to approximately 10^{11} ergs/gm(C) and were tested at room temperature. Degradation of tensile and flexural strength up to 75 and 95%, respectively, was obtained.

Four bearing cage materials, FEP-Teflon, FEP-Armalon, TFE-Armalon, and superpolymer SP-3, were irradiated to dose levels of 1×10^9 , 5×10^9 , and 3×10^{10} ergs/gm(C) in liquid hydrogen and were tested both at liquid-hydrogen and room temperatures with and without thermal cycling. An initial increase in strength properties for the first three materials at up to 1×10^9 ergs/gm(C) dose level was followed by a considerable decrease at the 3×10^{10} ergs/gm(C) dose level. The properties of the superpolymer were unaffected by test temperature or by radiation levels up to 3×10^{10} ergs/gm(C).

Four additional composite bearing cage materials, 90% superpolymer (SP) + 10% MoS₂, 70% SP + 20% bronze + 10% MoS₂, 70% SP + 30% bronze, and polybenzimidazole glass laminate (PBI) were irradiated to 5×10^9 ergs/gm(C) in liquid hydrogen and tested at room temperature. Compressive and tensile strengths were practically unaffected by this dose level; however, the flexural strength increased up to 24%, following the same pattern as the tensile properties of the Armalon materials.

The results of a test performed on two full-scale bearing retainers (FEP ball bearings and TFE roller bearings) in liquid hydrogen for 60-min duration at a dose level of approximately 1×10^9 ergs/gm(C) showed extensive damage to the ball bearings, whereas the roller bearings were in satisfactory condition.

INTRODUCTION

The space age, particularly the application of nuclear energy for rocket engine systems, has resulted in a number of materials applications under conditions rarely incurred in the past. These conditions include: (a) very low cryogenic temperatures, (b) high vacuum, and (c) high nuclear radiation. Friction and bearing-materials problems in this unusual environment are of particular interest to the NERVA Project*. In conjunction with this program, Aerojet-General has conducted several radiation-effects tests on bearing cages, bearing cage materials, and full-scale bearings to determine the useful radiation dose levels of these materials while submerged in liquid hydrogen. Part of this study is presented in this paper. Four independent radiation-effects tests were conducted at the General Dynamics Fort Worth Radiation Facilities; one on bearing cage retainers, two on bearing cage materials, and one on full-scale bearings.

* The Nuclear Engine for Rocket Vehicle Application Program (NERVA) is administered by the Space Nuclear Propulsion Office, a joint office of the U.S. Atomic Energy Commission and the National Aeronautics and Space Administration. Aerojet-General Corporation as prime contractor for the engine system and Westinghouse Electric Company as principal subcontractor responsible for the nuclear subsystem, are developing a nuclear propulsion system for deep space travel.

TEST DESCRIPTION

A. Bearing Cages

The radiation-effects test on the bearing cages consisted of irradiating three types of retainers in liquid hydrogen and subsequent testing at room temperature.

Twenty-one full-scale bearing retainers representing three types were included in this test. Seven parts of each type were submitted for testing. Two in each group were cut in half, and one half was used for control testing. The parts were made as follows:

1. Seven roller-bearing retainers were fabricated from TFE-Armalon, grade 405-L-116. This material consisted of several layers of No. 116 glass fabric (square weave, thread count of 57 warps and 59 fills) impregnated with polytetrafluoroethylene (TFE Teflon; E.I.DuPont product) and hot-pressed.

2. Seven ball-bearing retainers were fabricated from TFE-Armalon, grade 405-L-116 (same material as the roller bearings).

3. Seven ball-bearing retainers were made of FEP-Armalon, grade 510-L-128. This material consists of several layers of No. 128 glass fabric (square weave, thread count of 31 warps and 41 fills) impregnated with fluorinated ethylene propylene (FEP-Teflon, E.I.DuPont product) and hot-pressed. The irradiation test samples were exposed to approximately 10^{11} ergs/gm(C) gamma dose and to corresponding fast-neutron flux of 3×10^{16} nvt ($E > 1.0$ Mev) and thermal-neutron flux of 2×10^{16} , in a 200-hr liquid-hydrogen radiation run conducted at the General Dynamics Fort Worth Radiation Facilities. Postirradiation tests were made to determine the tensile strength (in the hoop direction; warp-circumferential; and fill-axial directions, relative to the retainer center line) and the flexural strength. A volumetric analysis was made to determine the glass and Teflon fractions. For comparison, nonirradiated control tests were performed for all three retainers.

B. Bearing Cage Materials

The first test on bearing cage materials consisted of irradiation and subsequent testing of approximately 250 tensile specimens made of the following materials: Teflon (FEP); Armalon FEP, grade 510-L-128; Armalon TFE, grade 405-L-116; and superpolymer SP-3 (Polypyromellitimide). These materials were irradiated to three different dose levels as shown below and were tested at both liquid-hydrogen and room temperatures with and without intermediate thermal cycling.

<u>Dose</u>	<u>Exposure</u>	
	<u>Gamma</u> <u>(ergs/gm(C))</u>	<u>Neutrons</u> <u>(n/cm²)</u>
High	2.7×10^{10}	5×10^{15}
Intermediate	5.4×10^9	7.8×10^{14}
Low	1.1×10^9	2.0×10^{10}

Remotely operated tensile test equipment (Figure 1) was used for irradiation testing. A more detailed description of this test equipment is presented in Reference 1.

The second test of bearing cage materials consisted of irradiation in liquid hydrogen to a dose level of 5×10^9 ergs/gr(C) and subsequent testing at room temperature of the following composite materials: superpolymer (SP) impregnated with 10% MoS₂; 70% superpolymer (SP) impregnated with 20% bronze and 10% MoS₂; 70% superpolymer (SP) impregnated with 30% bronze; and polybenzimidazole (PBI) glass laminate. Tension, compression, and flexure tests were performed on these materials.

C. Full-Scale Bearing Test

The bearing tester used for the nuclear-environment testing was designed to simulate the operating conditions of the bearings in the NERVA turbopump. Figure 2 shows a cross section of the bearing tester, which is

powered by a 50-hp motor that is integral with the tester shaft and is cooled with liquid hydrogen during operation. Axial and radial loads are applied to the rotating shaft through the use of pneumatic loaders, which are capable of producing up to a 4000-lb thrust load and a 2000-lb radial load, either independently or simultaneously. Gaseous hydrogen is used to pressurize these loaders. Sealing problems in the tester are minimized because all components of the tester, including motor, loaders, and test bearings, are within the tester housing.

Two cylindrical roller bearings are designed to carry the radial load. A sketch and the significant specifications of these bearings are shown in Figure 3.

The axial load is supported by a set of two tandem-mounted 50-mm ball bearings. A sketch and the significant specifications for this ball-bearing set are shown in Figure 4. The races and rolling elements of these ABEC-class bearings are modified 440C stainless steel.

TEST RESULTS

A. Bearing Cages

The results of the control and irradiated bearing cages on tensile strength, flexural strength, and volumetric changes are presented in Table I. Figure 5 shows graphically the average mechanical properties before and after radiation. These results indicate uniform losses in properties ranging from 67 to 94%. The ball-retainer materials impregnated with FEP-Teflon exhibited greater radiation damage, as shown by strength losses 10 to 20% greater than the losses for TFE-impregnated retainers.

Figures 6, 7, and 8 show the three types of retainers before and after irradiation. Surface degradation is noted in the form of unbonding, free-standing glass fibers, and localized delaminated surface layers. Somewhat less surface delamination was noted for the TFE ball retainers.

B. Bearing Cage Materials

Test results for the first bearing cage materials are discussed in detail in Reference 2.

Figures 9 and 10 are included to show typical changes in ultimate tensile strength and strain of these materials with test temperature and radiation level.

Irradiation of all materials (except SP-3) in LH_2 resulted in an initial increase in strength followed by an appreciable decrease at the higher radiation dosage. A general trend of significant strength degradation of Teflon and Armalon at 3×10^{10} ergs/gm(C) was apparent.

The radiation at liquid-hydrogen temperatures produced a marked decrease in elongation, particularly at the highest radiation dosage.

FEP Teflon showed extreme temperature sensitivity and brittleness at liquid-hydrogen temperatures. Radiation at liquid-hydrogen temperatures further decreases this property.

The results of the second test of bearing cage materials are presented in Table II. Average data on control and irradiated specimens for tensile, compressive, and flexural strength are included. The compressive strength for these materials was practically unaffected by the radiation dose level, 5×10^9 ergs/gr(C). Increases of up to 24% in flexural strength were observed for the composition of 70% SP and 30% bronze. Little degradation of tensile strength occurred.

C. Full-Scale Bearing Test

The results of the two 60-min tests of bearings operating in the nuclear environment of the 10 Mw ASTR reactor are shown in Table III. Tests were identical relative to test buildup, types of bearings, and test procedures.

The following parameters indicate the point of failure of the test bearings and test setup.

- Increase in drive-motor current to 100 amps.
- Rapid rise in bearing outer-race temperature.
- Loss of load pressure.
- Loss of LH_2 pressure.

The two tests satisfactorily completed the required 60 min of irradiated operation, but both showed ball-retainer-pocket failure during posttest evaluation. One of the tests completed the 10-min postirradiation run; the other failed after 6 min of its postirradiation test because of excessive friction (very high drive-motor current greater than 100 amps).

TECHNICAL DISCUSSION AND CONCLUSIONS:

A. Bearing Cages

Tensile and flexural specimens were cut from the retainers and were of subsize dimensions.

The differences in the mechanical properties between TFE- and FEP-reinforced Armalon retainers were partly reflected in, and supported by, the compositional changes due to irradiation. Analyses of these materials before and after irradiation indicated little, if any, change in composition in the TFE Armalon (405) as compared with the appreciable reduction noted for the Teflon fraction in the FEP Armalon (510).

The possibility exists, however, that some strength degradation may be caused by radiation effects attributable to changes in the glass composition, especially in view of the fact that the glass used (E glass) contains small amounts of boron oxide. No information is presently available that specifically relates the glass boron content to the radiation damage.

At this relatively high dose level for organic materials, the property degradations were high, as expected. The FEP-Teflon composition was more sensitive to radiation at this environment than the TFE-Teflon compositions.

B. Bearing Cage Material

The specimens for the first radiation-effects test on bearing cage materials were fabricated of 1/4-in. plates to the configuration shown in Figure 11 and were of standard size. After radiation, the specimens were tested as follows: (a) in LH_2 without warmup, (b) in LH_2 after warmup to room temperature with helium or air, (c) at room temperature after thermal cycling from LH_2 to room temperature back to LH_2 and air, (d) at room temperature after thermal cycling and annealing to 300°F, and (e) as received at room temperatures.

At low and intermediate dose levels, specimens failed within the gage length, whereas, at the high dose level, failure occurred at the tangency points. As can be seen in Figure 9, the properties of these materials, with the exception of the SP-3, are temperature sensitive. Subsequent irradiation of these materials to the low dose level hardly affected the properties; a small degradation was obtained at the intermediate dose level and considerable damage was observed at the high dose level (3×10^{10} ergs/gr(C)). The test-temperature effect showed that all materials were stronger at LH_2 temperature than at room temperature. Elongation for the Armalon at LH_2 temperature was higher than at room temperature, and all materials absorbed significantly more energy at failure when tested in LH_2 .

Annealing generally produced minor changes in the mechanical properties. Specimen design for the second radiation-effects test on bearing cage materials is shown in Figure 12.

Tensile-specimen failure occurred within the gage length. Typical fractures of the tensile, compression, and flexural test specimens are shown in Figures 11, 13, 14, and 15.

All materials were stronger at liquid-hydrogen test temperatures. The flexural strength was affected more by radiation at 5×10^9 ergs/gr(C) dose level.

Increase of the bronze content in the composite seems to increase the compressive strength with radiation. In view of the small number of test specimens for this test (three for each condition), statistical significance of the data cannot be determined.

C. Full-Scale Bearing

Incipient damage to the ball-bearing FEP-Armalon retainers in both full-scale bearing tests was noted to occur at nearly the same point in time and, within the measuring capabilities of the dosimetry, at the same integrated gamma dose, 6×10^8 and 10×10^8 ergs/gm(C). The incipient damage was indicated by an increase in total friction, as shown by drive-motor current. A nonnuclear test, duplicating the radiation test procedure, showed that drive-motor current remained nearly constant at low level for the entire 84 min of operation. There was no retainer damage during this test. Figure 16 shows a photograph of the damaged ball bearing from one of the tests. This bearing was loaded to a 2000-lb axial load at 24,000 rpm.

The cylindrical roller bearings, equipped with the TFE-Armalon retainers, performed well and did not fail in the cryogenic nuclear environment. It is likely that the roller bearing, because of its closely guided rolling action, is less demanding of the retainer than the heavily loaded thrust ball bearing whose rolling elements are subjected to both rolling and spinning action. Also, there is evidence from the previous cryogenic radiation tests that TFE Armalon is less sensitive to radiation degradation than FEP Armalon.

The mechanism of failure was probably Armalon embrittlement, especially at the ball pockets and other contacting surfaces. Repeated ball

impacts at very high sliding velocities are believed to have caused fragmentation at these surfaces, resulting in debris accumulation on the raceways. The normal ball rolling action was impeded by the debris, which resulted in ball skidding, differences in ball orbiting velocities, and repeated high retainer-ball-pocket loads. High retainer loads at very high sliding velocities resulted in ball pocket temperature rise, loss of retainer strength, pocket rupture, and failure.

CONCLUSIONS

A. Bearing Cages

1. The Armalon ball and roller retainers irradiated to 10^{11} ergs/gr(C) in liquid hydrogen exhibited considerable degradation in mechanical properties due to radiation.

2. The retainers fabricated with FEP Teflon as filler material were more sensitive to the radiation environment than the TFE-filled laminates.

B. Bearing Cage Materials

1. Irradiation of all materials (except SP-3) in LH_2 resulted in an initial increase in strength followed by an appreciable decrease at the higher radiation dosage. A general trend of significant strength degradation of Teflon and Armalon at 3×10^{10} ergs/gm(C) was apparent.

2. The radiation at liquid-hydrogen temperature produced a marked decrease in elongation after the highest radiation dosage.

3. FEP Teflon exhibited extreme temperature sensitivity and brittleness at liquid-hydrogen temperatures. Radiation at liquid-hydrogen temperatures still further decreased the elongation at failure.

4. SP-3 was relatively unaffected by the nuclear radiation and test temperature.

5. Three extremes of material response to the test environmental conditions were observed: (1) initial improvement in ultimate strength and elongation due to LH_2 exposure, with subsequent deterioration due to nuclear radiation as exhibited by the Armalons; (2) continuous degradation produced by the LH_2 radiation exposure, as exhibited by Teflon; and (3) no change due to liquid-hydrogen and radiation environments as exhibited by SP-3.

6. The tensile and compressive strengths of the bearing cage materials consisting of superpolymer (SP) composition with bronze and MoS_2 , as well as the polybenzimidazole (PBI) glass laminate, were practically unaffected by the 5×10^9 ergs/gr(C) dose level.

7. The flexural strength of these materials was more sensitive to radiation damage.

C. Full-Scale Bearing Test

1. Cylindrical roller bearing retainers made from polytetrafluoroethylene polymer (TFE) glass laminate satisfactorily withstood two 60-min radiation tests with an integrated gamma dose of 10^9 ergs/gm(C).

2. Ball-bearing retainers made from the fluorinated ethylene-propylene polymer (FEP) glass laminate completed the 60 min of irradiated operation in LH_2 in two separate tests. However, the severe ball-pocket damage sustained in each test demonstrated that this material degraded excessively at an integrated gamma dose of 10^9 ergs/gm(C).

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REFERENCES

1. W. Weleff, H. S. McQueen; "Remotely Operated Test Equipment for Materials Testing at Combined Cryogenic and Nuclear Radiation Environment" Transaction ANS - Remote Operation Technology, 1965.
2. C. E. Dixon, C. W. Funk; "Cryogenic Radiation Damage to Structural Polymers" Proceedings ANS, 1966.

TABLES

<u>No.</u>	<u>Title</u>
1	Bearing Retainers; Comparison of Mechanical Properties
2	Tension, Compression, and Flexural Strengths of Bearing Cage Materials
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FIGURES

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TABLE I
COMPARISON OF MECHANICAL PROPERTIES IN KSI

Bearing Retainers (10^{11} ergs/gr(C))

Material	Tensile Strength						Flexural Strength	
	Hoop Direction		Fill Direction		Warp Direction		Control	Irradiated
	Control	Irradiated	Control	Irradiated	Control	Irradiated		
TFE-405-L-116 Roller Retainer	-	6.6	-	3.46	3.7	0.7	7.66	1.44
TFE-405-L-116 Ball Retainers	-	4.0	-	3.12	5.9	1.1	8.31	2.36
FEP-510-L-128 Ball Retainers	12.6	1.7	15.5	5.1	7.1	0.4	13.02	1.28

VOLUMETRIC ANALYSIS

Material	Density		Volume % Glass		Volume % Teflon		Volume % Void	
	Control	Irradiated	Control	Irradiated	Control	Irradiated	Control	Irradiated
TFE-405-L-116 Roller Retainer	2.185	2.21	33.6	33.95	59.3	60.65	7.1	5.4
TFE-405-L-116 Ball Retainer	2.195	2.195	32.85	31.45	60.45	60.45	6.7	8.1
FEP-510-L-116 Ball Retainer	2.16	2.185	21.3	32.7	73.35	67.95	5.35	0

TABLE II
TENSION, COMPRESSION AND FLEXURAL STRENGTH OF BEARING CAGE MATERIALS

Dose 5×10^9 ergs/gr(C)

Material	Tensile Strength psi		Compressive Strength psi		Flexural Strength psi	
	Control	Irradiated	Control	Irradiated	Control	Irradiated
90% SP + 10% MoS ₂	7570	6800	24790	20600	12240	12400
70% SP + 20% Bronze + 10% MoS ₂	6210	6300	20600	20900	12100	12650
70% SP + 30% Bronze	8580	7290	29260	32400	12100	15090
PBI	33950	27880	-	-	63030	67600

TABLE III
NERVA BEARINGS RADIATION TEST RESULTS

BEARINGS: 50mm Duplex Ball Bearing Thrust Set
50mm Cylindrical Roller Bearing

SHAFT SPEED: 24,000 rpm LH₂ Coolant
LOAD: Thrust, 2000 lb
 Radial, 2000/500 lb

<u>PERFORMANCE</u>				<u>RADIATION EXPOSURE</u> ^{a)}			
<u>Test No.</u>	<u>60-Minute Radiation</u>	<u>10-Minute Post Radiation</u>	<u>Post Test Inspection</u>	<u>At First Change in Friction</u>		<u>At 60-Minutes</u>	
				Average Integrated Neutron Flux n/cm ²	Average Integrated Gamma Dose ergs/gm (C)	Average Integrated Neutron Flux n/cm ²	Average Integrated Gamma Dose ergs/gm (C)
				E 2.9 Mev		E 2.9 Mev	
ASTR-4A	Completed Satis- factorily	Completed: Drive Motor Current High at End	Thrust Set: One Retainer Pocket Ruptured Roller Brgs: Good	7×10^{13}	10×10^8	9×10^{13}	12×10^8
ASTR-5	Completed Satis- factorily	Failed at 6-Minutes	Thrust Set: Several Retainer Pockets Ruptured Roller Brgs: Good	7×10^{13}	6×10^8	8×10^{13}	7×10^8

A) Radiation exposure at bearing tester exterior surface near bearing compartment

REMOTELY OPERATED PULLING ASSEMBLY

FIGURE 1

BEARING TESTER

Figure 2

MATERIAL, RACES & ROLLERS	MODIFIED 440 C
BEARING INSIDE DIA	50 MM
BEARING OUTSIDE DIA	90 MM
BEARING WIDTH	20 MM
NUMBER OF ROLLERS	16
TYPE OF ROLLERS	CYLINDRICAL, CROWNED
ROLLER SIZE	0.382 IN. DIA x 0.459 IN.
DEPTH, OUTER RACE	20 %
BEARING CLEARANCE DIAMETRAL	0.0019 TO 0.0026 IN.
MATERIAL, CAGES	TFE ARMALON
TYPE OF CAGE	OUTER LAND RIDING

Roller Bearing

Figure 3

MATERIAL, RACES & BALLS	MOD 440 C
BEARING INSIDE DIA	50 MM
BEARING OUTSIDE DIA	90 MM
BEARING WIDTH (PER SET)	40 MM
NO. OF BALLS & SIZE (PER BRG)	16 x 7/16 IN. DIA
CONTACT ANGLE	29°
CURVATURE RACE, INNER	52% GOTHIC ARCH
CURVATURE RACE, OUTER	52% GOTHIC ARCH
BEARING CLEARANCE, AXIAL	0.006 IN. MAX
MATERIAL, CAGE	FEP ARMALON
CAGE TYPE	OUTER LAND RIDING

Thrust Bearing Set

Figure 4

FIGURE 5
AVERAGE MECHANICAL PROPERTIES OF CONTROL AND
IRRADIATED RETAINER SPECIMENS

a. UNIRRADIATED CONTROL

b. IRRADIATED TO 10^{10} ergs/gr (c)

ROLLER BEARING RETAINERS
TFE ARMALON, GRADE 405 - L - 116

FIGURE 6

a. UNIRRADIATED CONTROL

b. IRRADIATED TO 10^6 ergs/gr (c)

BALL BEARING RETAINERS
TFE ARMALON, GRADE 405 - L - 116

FIGURE 7

a. UNIRRADIATED CONTROL

b. IRRADIATED TO 10^{11} ergs/gr (c)

BALL BEARING RETAINERS
FEP ARMALON, GRADE 510 - L - 128

FIGURE 8

ULTIMATE STRESS VS TEST TEMPERATURE AND RADIATION

FIGURE 9

ULTIMATE STRAIN VS TEST TEMPERATURE AND RADIATION

FIGURE 10

TENSILE TEST SPECIMEN-ORGANIC

FIGURE 11

A. TENSILE SPECIMEN

B. FLEXURE SPECIMEN

C. COMPRESSION SPECIMEN

TENSILE, FLEXURAL AND COMPRESSION SPECIMEN
BEARING CAGE MATERIAL

FIGURE 12

Tensile Test
Figure 13

Compression Test

Figure 14

Flexural Test
Figure 15

Ball Bearings After Full Scale Bearing Test

Figure 16

Roller Bearings After Full Scale Bearing Test

Figure 17