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SNAP 8
CONTROL DRUM BEARING
DEVELOPMENT AND EVALUATION HISTORY

MASTER

AEC Research and Development Report

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By
P. H. HORTON

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ABSTRACT

Development and testing of the SNAP 8 Control Drum Bearings are traced from initial material selection through final design verification testing. Design of the self-aligning journal bearings relied on technology from previous SNAP 10 bearings, with material and dimension changes for operation under increased load, temperature, and life. The final design bearings, using a carbon-graphite against alumina bearing couple, successfully completed in excess of 78,000 total hours at test, with individual tests of 12,000-hr duration.

Figure 1. SNAP 8 Reactor Configuration

Figure 2. Control Drum Assembly

I. BACKGROUND

A series of small nuclear reactors, designated "Systems for Nuclear Auxiliary Power" (SNAP), have been under development at Atomics International (AI) for the past ten years.⁽¹⁾ The reactors are designed to provide long-term uninterrupted power for remote terrestrial and future space stations. Figure 1 illustrates the SNAP 8 reactor currently under development. It is based on technology gained from previous-generation SNAP 10A and SNAP 2 reactors, but designed for increased power and life requirements.

The reactor consists of a fueled core, through which a liquid metal coolant is circulated, and is surrounded by a beryllium metal reflector. Six control drums, Figure 2, are equally spaced around the reflector, and rotate to provide "windows" which regulate the escape of core fission neutrons and hence control the reactor power level. The mode of controlling compact reactors is to rotate the control drums in $1/2^\circ$ steps. After startup, and while controlling to a constant high temperature, the drums may dwell in a given position for several weeks. The important characteristic of materials used for these bearings is that they show a low starting friction coefficient after long-term dwell under load at high temperatures.

Each of the control drums is supported by a pair of self-aligning spherical bearings, Figure 3. Both bearings support the "radial" or positional weight of the drum, while the "thrust" or axial load of the drum is supported by the lower bearing. The bearings consist of an inner journal and an outer spherical bearing that provides for a redundant journal and allows for bearing misalignment due to thermal gradients. Bearing materials were chosen to provide a low-friction couple with the ability to undergo long dwell periods (up to 1000 hr) at temperature without self-welding.

As with the reactor system, the design and development of the control drum bearings have evolved through several generations. Individual bearing sets have been tested to 12,000 hr, while the total accumulated test time has been in excess of 75,000 hr. The SNAP 8 bearings were based heavily on information learned in the SNAP 10A and SNAP 2 programs, but new materials and configuration alterations were required to meet new temperature, load, and life environments.

Figure 3. S8DR Bearing Assembly

The final design has been proven in four 12,000-hr simulated life tests, and over 7,000 hr of operation in the "SNAP 8 Development Reactor" (S8DR) at the AEC's Santa Susana Field Laboratory. This report documents the material selection, development, and proof testing of the SNAP 8 bearings.

TABLE 1
SNAP 8 CONTROL DRUM BEARING DESIGN REQUIREMENTS

Environmental	
Temperature (°F)	
Maximum	1,150
Minimum	50
Pressure (torr)	
Space	10^{-13}
Ground test	10^{-5}
Neutron Dosage (nvt)	10^{20}
Gamma Dosage (carbon) (rad)	10^{11}
Life	
Ground Test (hr)	12,000
Space Operation (hr)	12,000
Launch (maximum)	
Shock (g)	35
Acceleration (g)	7
Sinusoidal Vibration (g)	19
Resonant Dwells (min)	5
Random Vibration (equivalent) (g)	21
Control Drum Weight (lb)	
Reflector Assembly	31
Allowable Drum Bearing Torque (shafts vertical, 1 g field) (in.-lb)	
System at 70°F	7.0
System at 1150°F	3.5
Bearing Clearance (nominal) (in.)	
Diametral (maximum)	0.012
Axial	0.002 to 0.010
Operational Life	
135° Oscillations, up to	210
Thermal Cycles (minimum)	200
Cooling, Heating Rate (°/min)	10 to 15

II. MATERIAL SELECTION

The design requirements of the SNAP 8 control drum bearings are listed as Table 1. An extensive program, from material selection to 12,000-hr proof tests on final design articles, was conducted to provide a reliable bearing capable of meeting the specifications. An extensive literature survey was conducted, to identify potential bearing couples for use in the reactor environment of high temperature, high radiation, and space vacuum, with intermittent operation over a 12,000-hr life. The list of couples supplemented other couples identified from SNAP 10A and SNAP 2 programs. As a result, some 120 material combinations were evaluated for friction and wear characteristics.^(2,3)

A. SLIDING-FRICTION TESTING

Five groups of materials were evaluated, and the results are shown in Figure 4. Couples are divided into metal vs metal, metal vs carbon, ceramic vs ceramic, metal vs ceramic, and ceramic vs carbon groups. Friction coefficients of the non-carbon groups were unacceptable, with numerous cases of seizing, gouging, and ploughing of the bearing surfaces. Friction of the metal vs carbon and ceramic vs carbon groups was acceptable, with the ceramic group being preferred. Application of a molybdenum disulfide (MoS_2) dry-film lubricant to the bearing surfaces greatly reduced the friction of the non-carbon groups, but not to the level of the carbon vs ceramic group. Of all couples tested, a combination of alumina and carbon-graphite provided the best friction couple, with coefficients as low as 0.2 for long-term testing at 10^{-7} torr and 1000°F . The alumina selected was a 99% pure coating, applied by a "detonation" gun process* on a metal substrate. The resulting coating, ~ 0.003 in. thick, had a porosity of $<1\%$. Studies also showed, Figure 5, friction to be a function of percent graphitization of the carbon, with a minimum occurring at $\sim 40\%$ graphitization.

B. BEARING DESIGN

The resulting bearing design, Figure 6, is a dual bearing, with a simple journal bearing within a spherical self-aligning bearing. While the inner journal is the primary rotational couple, the outer spherical couple allows for both

*Linde Division of Union Carbide.

Figure 4. Summary of Ultrahigh-Vacuum Sliding Friction Studies

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Figure 5. Sliding-Friction Characteristics of Carbon-Graphite Mixtures

7759 4701

Figure 6. SNAP 8 Development Control Drum Bearing

rotation and oscillation, to correct for misalignment. The shaft, ball, and socket are Inconel-750.* The shaft and ball OD's, and the socket ID are alumina coated. Carbon-graphite bushings are shrunk fit into the ball ID. This results in a journal couple of alumina against carbon-graphite, and a ball-to-socket couple of alumina against alumina. A MoS_2 dry-film lubricant is bonded to the ball OD to reduce friction and act as a cushion between the two alumina surfaces.

Inconel-750, a nickel-base alloy, was selected as the alumina substrate and bearing structural material, due to its high strength-to-weight ratio at 1150°F. Its coefficient of thermal expansion is also close to that of the beryllium reflector on which the bearings are mounted. Table 2 lists the properties of Inconel-750. The carbon-graphite and alumina have average thermal expansion coefficients of 2.6×10^{-6} and 3.9×10^{-6} in./in./°F, respectively, to 1500°F.

Due to the shrink fit of the carbon-graphite, and the alumina being a thin shell, both follow the expansion of the Inconel through the 1150°F operating temperature. Journal bearing diametral clearance varies from 0.0018 in. at ambient to 0.0025 in. at 1150°F. The design assures that the carbon-graphite bushings remain tight in the ball at temperatures below 1450°F.

*International Nickel Co.

TABLE 2
PROPERTIES OF INCONEL-750⁽⁴⁾

Composition (%)	
Nickel	70.0 min
Chromium	14.0 to 17.0
Iron	5.0 to 9.0
Titanium	2.25 to 2.75
Aluminum	0.4 to 1.0
Columbium	0.7 to 1.2
Manganese	1.0 max
Silicon, Sulfur, Copper, and Carbon	<0.5 each
Modulus of Elasticity (psi)	$\begin{cases} 31.0 \times 10^6 & (80^\circ\text{F}) \\ 23.0 \times 10^6 & (1200^\circ\text{F}) \end{cases}$
Mean Linear Thermal Expansion Coefficient (to 1200°F) (in./in./°F)	8.4×10^{-6}

III. S8DRM BEARINGS

The first SNAP 8 configuration bearing assemblies fabricated were designed for the S8DRM, a mockup reactor for non-nuclear testing. The bearings were subjected to simulated reactor tests, to study design compatibility during thermal cycling and intermittent operation at temperature. Additional sets were subjected to shock and vibration loads which would be encountered on launch of a space reactor.

A. THERMAL-FRICTION TESTING

Three tests were initiated to study alternate ball concepts, using: (1) the composite Inconel ball with alumina-coated OD and carbon-graphite bushings, (2) the same ball, with a sodium-silicate bonded MoS_2 dry-film lubricant on the ball OD to decrease friction and to act as a cushion between the ball and socket alumina surfaces, and (3) a solid carbon-graphite ball, in place of the composite Inconel ball. The tests were run under identical test conditions of 1150°F and 10^{-5} torr pressure, and were scheduled to run for 2,000 hr minimum. Starting friction-torques for the three tests are shown in Figure 7, and summarized in Table 3. For each data point recorded, bearing friction-torque was measured through three actuation sequences. Each actuation consisted of driving the bearing shaft 70°CCW and 35°CW at a rate of $\sim 5^\circ/\text{sec}$. Using a force ring transducer and a mechanical linkage, the resistance to rotation of the bearings was measured and recorded, as shown in Figure 8. Each spike represents the static friction, and the smooth back of the spike represents the dynamic friction.

The bearing test with the MoS_2 dry-film coated balls completed 1060 hr, and was terminated due to a vacuum system failure. The test with the solid carbon-graphite balls ran 2230 hr, and the test with the non-dry-filmed composite ball ran 5050 hr, prior to termination for examination of the bearing sets. No signs of any damage to bearing surfaces were visible, and carbon-graphite transfer films on the alumina-coated shaft surfaces indicated full contact and well distributed loading.

Two additional tests were initiated with the MoS_2 coated composite balls. The tests were conducted at 1150°F , one at 10^{-5} torr and one at 10^{-8} torr.

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Figure 7. S8DRM Short-Term Friction-Test Summary

TABLE 3
SUMMARY OF INITIAL BEARING 1150°F FRICTION DATA

Test	Maximum Torque (in.-lb)	Data Sequences *	Hours
Alumina-Coated Ball	1.5	370	5050
Alumina-Coated Ball with MoS ₂	2.0	225	1060
Solid Carbon-Graphite Ball	1.6	291	2230

*Bearing rotation cycles run

7759-4702

Figure 8. Bearing Friction-Torque Data Cycles

7759 4703

Figure 9. S8DRM 10^{-5} -torr 10,000-hr Friction-Test Data

Figure 10. S8DRM Bearing After Exposure to Air at 950°F

The low-vacuum test (10^{-5} torr) completed 10,095 hr at 1150°F, with a maximum starting friction-torque of 2.3 in.-lb. Figure 9 shows starting friction-torque as a function of test duration. The test was interrupted several times due to vacuum system malfunctions, and this is reflected in the periodic step changes in friction-torque. After ~5500 hr at test, a vacuum chamber failure occurred which exposed the bearings for 25 hr to 950°F and ambient pressure. Figure 10 illustrates the heavy oxidation of the carbon-graphite bushings and the MoS₂ dry-film. The pitted carbon-graphite and grayish ash present is in sharp contrast to the pre-test specimens of Figure 6. A small chip also occurred in the alumina-coated lip of the thrust ball. Close examination of the thrust bearing shaft revealed that all of the journal alumina coating had spalled off. As the ball-to-socket bearing couple continued to operate satisfactorily, there was no jump in friction to indicate seizure and failure of the bearing shaft.

The high-vacuum (10^{-8} torr) test completed 12,600 hr, with over 10,000 at 1150°F. Figure 11 illustrates the friction-torque history of the test. The increase in friction after 5,000 hr was due to an increase in thrust load, as a consequence of increasing the control drum weight from 26 to 31 lb. The test proceeded without incident, and post-test examination showed all bearing surfaces to be in excellent condition. As with the low-vacuum test, the shaft journals had an even carbon-graphite transfer film, indicative of low friction and wear. The MoS₂ coatings were well burnished, showing unrestricted oscillation of the balls within the bearing sockets.

B. BEARING THERMAL-TEST FIXTURES

Figure 12 shows a cutaway illustration of a high-vacuum bearing test chamber and a typical test bearing assembly. The upper and lower bearing test shafts were bolted together in a yoke with a built-in 2° offset, to provide bearing misalignment and force the balls to oscillate within the socket during bearing rotation. A 31-lb mass was connected, through a vacuum-tight bellows feedthrough, to the drum and simulated the 1-g axial control drum load. A 1/4-g radial load was simulated by the drum mass used to retain the bearing sockets. The bearing shafts were driven through a magnetic vacuum feedthrough, and a

7759-4704

Figure 11. S8DRM 10^{-8} -torr 10,000-hr Friction-Test Data

7658-0893B

Figure 12. Bearing Development Test Fixture

mechanical linkage and force transducer was used to measure the resistance to rotation of the simulated drum mass. The force required to restrain drum rotation was recorded on light-sensitive paper, using a recording oscillograph. A radiant heater within the vacuum chamber surrounded the drum mass and bearings, and was controlled by a cam-operated 2-kw silicon-controlled rectifier. Temperature was monitored with stainless steel sheathed miniature thermocouples embedded in the drum mass, adjacent to the two bearings.

To simulate both reactor space operation at 10^{-8} torr and preliminary ground test checkout of the reactor at 10^{-5} torr, two types of vacuum systems were used. The low-vacuum (10^{-5} torr) tests were conducted in the system shown in Figure 13. The systems used liquid nitrogen (LN_2) trapped oil diffusion pumps, in conjunction with mechanical roughing pumps. The cam-operated temperature controller, temperature recorder, and friction-torque recording oscillograph are also shown in the figure. Figure 14 shows a sorption-ion pumped vacuum system used for the 10^{-8} torr high-vacuum test. The system is "roughed down," using LN_2 -cooled sorption pumps. It is then sealed off, and electronically pumped to 10^{-8} torr or lower in a completely sealed system.

C. LAUNCH LOAD TESTING

Two bearing sets, using the solid carbon-graphite balls, were subjected to simulated launch load shock and vibration testing. Figure 15 shows the test fixture with a simulated drum mass, prior to testing. The load test levels are listed in Table 1. The first test resulted in fretting of the spherical OD of the balls, and the buildup of carbon-graphite debris in the ball-to-socket bearing cavity.

A second test was run after coating the alumina socket surfaces with the MoS_2 dry-film lubricant. The dry-film layer cushioned the hammering of the ball in the socket, and the test was completed to design loads without fretting or other damage. The bearings were then tested to twice the design load level without any damage. The post-test view of the lower ball is shown in Figure 16.

Figure 13. Low-Vacuum Bearing Test System

Figure 14. UHV Bearing Test System

Figure 15. Shock and Vibration Test Fixture

Figure 16. Solid Carbon-Graphite Ball After Vibration Testing

7568-551341

Figure 17. S8DR Bearing (Original design)

IV. S8DR BEARINGS

During development testing of the S8DRM bearings, the control drum design was modified, and resulted in a weight increase from 26 to 31 lb. At the same time, the reactor launch shock and vibration loads were substantially increased to the present levels listed in Table 1. It was necessary to redesign the radial bearing assembly to carry the increased torsional loads. The resulting S8DR bearing configuration is shown in Figure 17. The bearing shaft was increased in diameter, and the ball and socket enlarged to the size of the thrust bearing assembly. The S8DRM design used separate bearing shafts and drum mounting brackets, which required mating splines. The S8DR design was changed to a single shaft and bracket assembly, and a simplified shaft was used for development testing. While changing the configuration, the alumina vs carbon-graphite and MoS₂-coated alumina vs alumina bearing couples were retained. A series of performance tests were initiated, to study performance under simulated reactor conditions.

Two test plans were formulated, each stressing one phase of reactor operation. Thermal cycle tests were designed to study the effects of numerous thermal transients produced by reactor startup and shutdown cycles. Operational life tests were designed to study the effects of intermittent bearing rotation with long-term dwell periods at temperature. Three thermal cycle and two operational tests were initiated. All five tests were conducted at 10^{-5} torr in the liquid nitrogen cold trapped oil diffusion pumped systems described in Section III. All tests were run at 1150°F, with the exception of the second operational test which accumulated time both at 1150 and 1250°F.

A. THERMAL CYCLE TESTS

Thermal cycle tests were conducted according to the following test plan:

- 1) Friction-torque vs load test
- 2) 50 thermal cycles (450-1150°F) — friction-torque measured at 450 and 1150°F
- 3) Friction-torque vs load test
- 4) Repeat Items 2 and 3, to a total of 200 thermal cycles

a. Failed Alumina Coating
on Shaft

b. Shaft With Spalled Alumina

Figure 18. S8DR Bearing Set No. 1

5) 1000-hr dwell at 1150°F

6) 7500-hr operational test with bearing actuation sequence once daily.

Friction-torque measurements made were typical of those described for S8DRM bearings. The friction-torque vs load tests were sequences where thrust load was varied from 31.0 to 0 lb, to study the effect of drum mass on friction.

1. Test No. 1

Testing of Bearing Set No. 1 included the 200 thermal cycles, the 1000-hr dwell, and 600 hr of the operational test. Maximum friction-torque was 3.4 in.-lb, occurring at the conclusion of the 1000-hr dwell. Maximum torque during the thermal cycle phase was 1.4 in.-lb; during the 600-hr operational testing, it was 1.9 in.-lb. Following 600 hr of operational testing, a vacuum system malfunction occurred which resulted in shutdown of the test. The bearing set was removed for inspection, and the radial load shaft was found to be seized in the carbon-graphite insert bushing. Figure 18a illustrates the shaft, with the journal alumina broken off, still in the ball. Removal of the shaft, Figure 18b, showed almost complete loss of the coating. Examination of the thrust shaft and all other coated surfaces was made; all were in excellent condition, with no indication of cracking or chipping. Due to the redundant bearing, friction had remained satisfactory, with no indication of seizure during testing.

2. Test No. 2

Testing of Bearing Set No. 2 was terminated after 200 thermal cycles, the 1000-hr dwell, and 2500 hr of operational testing. This was done to inspect the bearings for possible alumina coating failures. Maximum friction-torque during testing was 5.1 in.-lb, which is in excess of the 3.5 in.-lb specification limit listed in Table 1. The maximum occurred following the 1000-hr dwell. Maximum torque during thermal cycling was 1.3 in.-lb, and 2.0 in.-lb during the operational test phase.

Upon termination of the test, no signs of cracking or other damage to the alumina coatings were visible.

7759 4705

Figure 19. S8DR 10,000-hr Operational Test Friction-Torque Data

3. Test No. 3

Bearing Set No. 3 was also terminated to inspect the bearings, following failure of Bearing Set No. 1. The 200 thermal cycles and 1000-hr dwell were completed, prior to bearing inspection. Maximum friction-torque following the dwell was 3.8 in.-lb, again greater than the specification limit; for the 200 thermal cycles, it was 1.8 in.-lb. Inspection of the bearing alumina surfaces revealed no signs of cracking or impending failure.

B. OPERATIONAL TESTS

Two operational life tests were conducted, one with the MoS₂ dry-film lubricant on the alumina surface of the ball OD's, and one without the MoS₂ dry film. The use or non-use of the MoS₂ dry film allowed for study of friction for nominal conditions and for most case conditions where all dry film had been lost.

1. Test No. 4

Testing of the MoS₂ dry film coated bearing set included 10,116 hr at 1150°F. Maximum friction-torque during the test at 1150°F was 2.8 in.-lb, occurring after ~7500 hr. Figure 19 shows friction as a function of test duration. Two short and a 1000-hr dwell period were included in the first 4000 hr of testing. Friction throughout the test was somewhat erratic, but averaged around 2.5 in.-lb over the last 6000 hr. Following the test, the bearings were closely examined, and no sign of alumina coating damage or failure was visible.

2. Test No. 5

The bearing test without the MoS₂ dry film on the alumina surface of the balls was conducted to study friction in the extreme case that all dry film was lost due to oxidation, sublimation, or poor adhesion. This resulted in a primary bearing couple of alumina vs carbon-graphite (ball-to-shaft) and alumina vs alumina (ball-to-socket). The test was conducted in two phases—the first 5000 hr at 1150°F, and the remainder of the test at 1250°F. Friction-torque during the 1150°F test remained at or below 2.0 in.-lb, and examination of the bearings showed little wear and no signs of alumina damage. During the 1250°F test phase, friction-torque reached 3.4 in.-lb through the first 2500 hr. Inspection of the bearings at that time revealed both shafts were seized in their

a. Thrust Bearing Shaft

b. Radial Bearing Shaft

Figure 20. Failed Alumina Coating on S8DR Bearing Shafts

respective balls. Again, due to rotation between the ball and socket couple, bearing operation had continued without significant increase in friction. Figure 20 shows both the thrust and radial shafts, following removal from the balls. Both have extensive loss of alumina, with all material in the bearing contact zone lost. Failure of these shafts resulted in a total of three separate cases of alumina coating loss. Only one case, the S8DRM test, could be attributed to massive oxidation. All further S8DR testing was suspended, and effort was directed towards isolating the mode of failure of the alumina.

TABLE 4
SNAP 8 CONTROL DRUM BEARING DEVELOPMENT TEST SUMMARY

Type of Test	Test Time and Temperature Summary	Operational Test Time (hr)	Dwell Test Time (hr)	Number of Thermal Cycles	Radial Load (lb)	Thrust ⁽⁴⁾ Load (lb)	Reactor ⁽⁵⁾ Startups and Shutdowns	Test Failure		Maximum Starting Torque (in.-lb)	
								(Yes)	(No)	(70°F)	(1150°F)
Operational Tests											
S8DRM-1 No. 1	12,560 hr at 10 ⁻⁹ torr, with 9600 hr at 1150°F	9,600	-	7	8.5	26 (1st 5000 hr) 31 (2nd 5000 hr)	800 (14.5)		X	3.60	1.80
S8DRM-1 No. 2	10,094 hr at 10 ⁻⁵ torr and 1150°F ⁽¹⁾	10,000	-	13	8.5	26 (1st 5000 hr) 31 (2nd 5000 hr)	132 (2.4)	X		3.70	2.25
S8DR No. 4	10,000 hr at 10 ⁻⁵ torr and 1150°F	8,300	1700	32	8.5	26 (1st 2840 hr) 31 (last 7160 hr)	1454 (26.5)		X	5.00	2.80
Thermal Cycle Tests											
S8DR No. 1	2928 hr at 10 ⁻⁵ torr and 1150°F ⁽²⁾	600	1000	210	8.5	31.0	3480 (62)	X		3.90	3.20
S8DR No. 2	3830 hr at 10 ⁻⁵ torr and 1150°F	2,500	1000	218	8.5	31.0	2218 (40.3)		X	5.80	3.10 ⁽¹⁰⁾ (5.1)
S8DR No. 3 ⁽⁸⁾	592 hr at 10 ⁻⁵ torr and 1150°F	-	1000	210	8.5	31.0	1048 (19)		X	3.70	1.60
Without-Dry-Film Tests											
S8DR No. 5	5000 hr at 10 ⁻⁵ torr and 1150°F	4,000	1000	17	8.5	36.0 (1st 850 hr) 31.0 (rest of test)	563 (10.2)		X	8.0 ⁽⁶⁾	2.50
S8DR No. 5	2500 hr at 10 ⁻⁵ torr and 1250°F ⁽³⁾	2,500	-	12	8.5	31.0	752 (13.7)	X		8.0 ⁽⁶⁾	3.40
S8DR Acceptance Tests ⁽⁸⁾											
	84 hr at 10 ⁻⁵ torr and 1150°F	-	-	7	8.5	31.0	260 (4.7)		X	3.65	0.90
S8DR Journal Bearing Test											
	1750 hr at 10 ⁻⁵ torr and 1150°F	2,130	1000	52	3.7	0	(7.3)		X	0.55 ⁽⁷⁾	0.75 ⁽⁷⁾

- NOTES:
- (1) Thrust shaft and thrust support shaft failure discovered at completion of 10,000-hour test.
 - (2) Test terminated after 600 hr of 5000-hr operational test due to air leak — discovery of failed radial shaft.
 - (3) Thrust shaft and radial shaft failure discovered at completion of 2500 hr at 1250°F.
 - (4) Thrust loads changed during test as indicated.
 - (5) Value in parentheses is equivalent system lifetimes, in terms of 55 maximum reactor startups and shutdowns.
 - (6) Maximum friction-torque allowable, due to force transducer limit — occurred during torque vs load (23 lb at 70°F) and torque vs temperature (450°F).
 - (7) Friction-torque not measured — value given is friction coefficient.
 - (8) Thermal Cycle Test No. 3 bearings are same as used in previously completed S8DR Acceptance Test (first article).
 - (9) S8DR Without-Dry-Film Test at 1250°F — bearings same as in Without-Dry-Film Test at 1150°F, except for new radial shaft due to nonbearing surface failure upon test disassembly after 5000 hr.
 - (10) First data point after completion of 1000-hr dwell. Torque immediately reduced to 2.6 in.-lb.

V. FAILURE ANALYSIS

None of the test failures were suspected, prior to visual examination of the bearing sets. No sharp increase, or even gradual increase, of friction-torque data occurred, in any of the three tests, to indicate a specific time of failure. Based on the design requirements of the SNAP 8 bearings (Table 1), the allowable maximum friction-torque is 3.5 in.-lb at 1150°F and 7.0 in.-lb at ambient. All friction-torque data remained within acceptable limits for the tests with alumina failures, except for the Without-Dry-Film Bearing Test, which exceeded 7.0 in.-lb at ambient. This illustrates that, even in cases of shaft seizure, the secondary ball and socket bearing couple maintained friction-torques below the maximum limits. A summary of all long-term SNAP 8 tests was compiled, Table 4, listing test parameters and results.

Failure of the S8DRM-1 bearing occurred between the 5000- and 10,000-hr Milestones (~5548 hr), with heavy oxidation of the carbon-graphite bushings on both test bearings. System vacuum was lost while bearings were at 900°F.

Failure of the S8DR radial shaft during thermal cycling (Test No. 1) was discovered when the test was shut down, after 2900 hr of testing, to repair a vacuum chamber leak. Oxidation of the bearing was extremely small. The test had completed 200 thermal cycles to 1150°F, a 1000-hr dwell at 1150°F, and 600 hr of a 5000-hr operational test at 1150°F.

The Without-Dry-Film S8DR bearing failure occurred during a 2500-hr, 1250°F operational test (100°F above design point), following a 5000-hr, 1150°F test. During the 1150°F test, the carbon-graphite bearings were heavily oxidized.

An analysis of all test parameters was made, to find similarities between tests which failed and to isolate possible failure modes. Referring to Table 5, it can be seen that, in the three cases of failure, failure occurred on shafts only; no ball or socket coating gave any indication of failure.

Many questions were raised, for which a complete analysis would be required to answer:

- 1) What conditions differed between the shaft-bushing and ball-socket couples?

TABLE 5
SUMMARY OF TEST BEARING FAILURES

Item	S8DRM-1 10^4 -hr Operational Test at 1150°F and 10^{-5} torr	S8DR Thermal Cycle Test No. 1 at 1150°F and 10^{-5} torr	S8DR Without-Dry-Film Operational Test No. 5 at 1250°F and 10^{-5} torr
System Vacuum (torr)	1×10^{-5}	1×10^{-5}	1×10^{-5}
Time of Pre-Failure Inspection (hr)	5548	-	5000
Time of Post-Failure Inspection (hr)	10,000	2928	7500
Dwell Test Time (hr)	-	1000	1000
Maximum Friction-Torque at 1150°F (in.-lb)	2.8	3.2	3.4 (1250°F)
Maximum Friction Torque at 70°F (in.-lb)	5.0	3.9	8.0 (Transducer limit)
Number of Reactor Startups and Shutdowns Simulated	132	3480	1315
Worst Vacuum Condition	25 hr at 950°F and 760-torr Air	1×10^{-5} torr at 1150°F	1×10^{-5} torr at 1250°F
Shaft Al_2O_3 Surface Condition	No checking - Heavy Oxidization	Checking of Radial Shaft	Checking of Thrust Face
P5N Graphite Bushing Condition	Extreme Oxidization	Good	Heavy Oxidization
Parts Which Failed	Thrust Shaft and Support Shaft	Radial Shaft	Radial Shaft and Thrust Shaft
Last Shaft-to-Bushing Measurement (in.)	Radial = 0.0026 Thrust - Not Recorded	Radial = 0.0018 Thrust = 0.0013	Radial = 0.0013 Thrust = 0.0014

Impregnated grade of carbon-graphite, produced by Pure Carbon Co.

- a) Bearing couple materials
- b) Loading and stress conditions
- c) Oxidation of carbon-graphite
- d) Impurities or impregnants in the carbon-graphite

2) Were clearances maintained at all times?

With these questions in mind, a multiphase investigation was started, covering metallurgical, chemical, and stress analyses of the alumina-coated Inconel-750 and the carbon-graphite. An industry-wide search for similar problems with other users of alumina coatings was also conducted.

Discussions with various material specialists provided generalized data on alumina and its properties. The alumina coating used is applied, using a Linde (Union Carbide) detonation gun process, where α -phase alumina powder is shot from a chamber through a gun-like barrel, using oxy-acetylene as the driving media. The powder is raised to the plastic state and hammered onto the surface to be plated, ~ 2 ft from the gun barrel. The alumina cools quickly in platelets as γ phase on the substrate, which is maintained below 400°F .

Experience with alumina has indicated that, if it is heated to $\sim 2200^\circ\text{F}$, it will return to the α phase. This phase change results in densification, from 3.6 gm/cc for γ phase to 3.9 gm/cc for α phase. In the presence of catalysts, such as fluorides, this phase transformation has occurred as low as 1600°F , still 450°F above the SNAP 8 operating temperature. The addition of high stresses in the alumina, due to the differential thermal expansion between the coating and the Inconel-750, could provide the necessary driving force to cause a phase change at as low as 1100 or 1200°F .

A. METALLURGICAL ANALYSIS

Some 65 alumina-coated bearing specimens were collected for metallurgical analysis. Those included the SNAP 8 drum bearings (Inconel-750 substrate), SNAP 8 actuator bearings (Hiperco-27* substrates), and SNAP 10A drum bearings (Ti - 6 Al - 4 V substrates), with exposures up to 1250°F and test periods

*Cobalt-Iron Alloy Produced by Westinghouse Electric Co.

7729-5-4

Figure 21. Test Environment –
Inconel Reaction Zone
(10,000 hr at 1150°F)

7872-1-5

a. Interface

7729-5-1

b. Test Environment

Figure 22. Alumina-Substrate
Test Reaction Zones
(10,000 hr at 1150°F)

up to 10,000 hr. Bearing couples were either alumina against carbon-graphite or alumina against alumina.

The three failures occurred on bearings tested at 1150 and 1250°F only. Failures were limited to the radial-load-bearing sections of the shafts (in contact with P5-N carbon-graphite) and the edges of the ball OD coatings (MoS_2 -coated, in contact with Al_2O_3). The additional specimens were analyzed to determine the extent of the failure possibilities to specimens with other than Inconel-750 coatings, and graphites other than P5-N.

All specimens were mounted and polished for metallographic examination. The SNAP 8 actuator bearing specimens (Hiperco-27 substrates) and the SNAP 10A and SNAP 2 control drum bearings (Ti - 6 Al - 4 V substrates) appeared unchanged and unaffected by testing. No distinction between pre-test and tested substrates was discernible. Examination of the SNAP 8 control drum bearings (Inconel-750 substrates) revealed the presence of two distinctive reaction zones on tested specimens: first, a reaction between the test environment and the exposed Inconel-750 substrates, and second, a reaction zone between the alumina coating and the Inconel-750 substrate. Neither of these reactions were present on untested specimens.

The reaction between the test environment and the Inconel-750 appeared in all specimens tested at 1150°F and 1×10^{-5} torr. It was found on shafts, balls, sockets, and thrust sleeves alike. Figure 21 exhibits a typical specimen and reaction zone.

The second reaction, occurring at the alumina and Inconel-750 interface, was restricted to shafts and thrust sleeves — those surfaces in contact with the P5-N carbon-graphite. The reaction at the alumina - Inconel-750 interface appeared less stable than the reaction between the test environment and the Inconel-750. In cases where the alumina coating spalled off the Inconel shafts, exposing the Inconel, the reaction with the test environment can be seen to cover and replace the reaction between the alumina and the Inconel-750. Figure 22 shows a typical reaction zone between the Al_2O_3 coating and the Inconel and a typical instance of the test environment reaction and interface reaction existing together.

7759-4706

a. Pre-Test

7759-4707

b. Post-Test
(10,000 hr at 1150°F)

Figure 23. Titanium Electron-Microprobe Analysis

Several specimens exhibiting the reaction zone at the coating and Inconel-750 interface were remounted for examination, using the electron-microprobe x-ray, and were analyzed to study concentrations of individual elements within the substrate, reaction zone, and coating. Traces were run for aluminum, carbon, chrome, iron, nickel, titanium, and tungsten. The concentration of all elements remained constant, except for titanium. While no gradient existed on untested Inconel-750 specimens, exposure at 1150°F for periods of 5000 to 10,000 hr resulted in a slight depletion of titanium, ~0.001 in. from the reaction zone (compared to the concentration in the Inconel-750 matrix), followed by a marked increase at the reaction zone. Figure 23 shows microprobe traces of an untested shaft with a constant titanium level, and a post-10,000 hr, 1150°F specimen exhibiting the gradient. The titanium depletion and the coating-Inconel reaction zone were found only on those specimens in contact with the P5-N carbon-graphite.

Of the shaft and thrust sleeve specimens examined, the indications were that the areas directly in contact with the P5-N carbon-graphite showed less adherence and less resistance to alumina spalling than adjacent areas not in contact with the graphite, and much less resistance to attack than specimens with no graphite contact (balls and sockets).

It was discovered that drawing requirements for heat treatment of the Inconel-750 test shaft differed from those of the other components (production shafts, balls, and sockets). Test shafts and thrust sleeves were given Heat Treatment A, and all other parts were given Heat Treatment B.

Heat Treatment A. AMS5667 (Service below 1100°F)

- 1) 24 hr at 1625°F — stress equalizing
- 2) 20 hr at 1300°F — aging

Heat Treatment B. AMS5668 (Service about 1100°F)

- 1) 4 hr at 2100°F — solution treatment
- 2) 24 hr at 1550°F — primary aging
- 3) 20 hr at 1300°F — secondary aging

As noted, Heat Treatment A differs from B, in that it is not recommended for service above 1100°F. For operation above 1100°F, solution and precipitation

TABLE 6
 α ALUMINA AS A FUNCTION OF BEARING COUPLE

Hours at 1150°F and 10 ⁻⁵ torr	α -Phase Alumina (%)	
	Against P5-N (Shafts and thrust sleeves)	Against Alumina (Balls and sockets)
Pre-Test	1.7/3.2*	1.1/2.3
10,000	9.8/15.7	1.6/3.2

*Data above slash: exposed alumina surface
 Data below slash: alumina surface against substrate

TABLE 7
 α ALUMINA AS A FUNCTION
 OF EXPOSURE TIME
 (Alumina against P5-N carbon-graphite)

Hours at 1150°F and 10 ⁻⁵ torr	α -Phase Alumina (%)
Pre-Test	1.7/3.2*
3,000	1.4/3.2
5,000	4.8/13.6
10,000	9.8/15.7

*Same as Table 6

treatments are the predominant mechanisms for maintaining adequate strength. The difference in heat treatment may have contributed to the susceptibility of the shaft failure; however, no parts treated with Method B were in contact with the carbon-graphite.

B. X-RAY DIFFRACTION ANALYSIS

Specimens duplicating those selected for metallurgical analysis were also subjected to x-ray diffraction analysis of the alumina coatings. The coatings were physically removed from the substrate materials, and x-ray diffraction patterns were obtained of both the bearing surface and the interface surface of the alumina. Again, a definite pattern of reaction was established. Table 6 shows the correlation between bearing couple (Al_2O_3 against Al_2O_3 , and Al_2O_3 against P5-N) and percent α -phase alumina, and Table 7 shows the correlation between hours at test and percent α phase of the alumina against P5-N couples. Transformation of the alumina from applied γ to α phase was found to occur, in varying degrees, in specimens in contact with the P5-N carbon-graphite for periods of 2500 hr or longer and temperatures above 1100°F. To a much smaller degree, α phase was detected in the balls and sockets (Al_2O_3 against Al_2O_3) under the same test conditions. All specimens with Hyperco-27 and Ti - 6 Al - 4 V substrates were tested below 1100°F, and showed no signs of α -phase increase in coated surfaces.

C. MATERIAL COMPATIBILITY TESTS

Spalling of the alumina was directly tied to contact with P5-N carbon-graphite, and indications were that the presence of the LiF impregnant in the graphite was responsible for the γ -to- α phase transformation and resulting failure.

A series of material compatibility tests were initiated to study coating materials to replace the alumina; included in the tests were a series of alumina-coated specimens of various substrates (Inconel-750, Inconel-600, and Ta - 10% W) against both P5-N carbon-graphite and P5 carbon-graphite (the identical graphite, without the LiF impregnant). Combinations tested are shown in the following list.

8148-3-1

a. 1350°F Against P5

8148-7-1

b. 1450°F Against P5

8148-4-1

c. 1350°F Against P5-N

8148-5-3

d. 1450°F Against P5-N

Figure 24. 2000-hr Alumina vs Carbon-Graphite Metallurgical Results

<u>Graphite</u>	<u>Coating</u>	<u>Substrate</u>
P5	Al_2O_3	Inconel-750
P5-N	Al_2O_3	Inconel-750
P5-N	Al_2O_3	Inconel-600
P5-N	Al_2O_3	Ta - 10% W
None	Al_2O_3	Inconel-750

The different substrates selected as possible replacement for the Inconel-750 were Inconel-600, a similar material, but without the titanium (to study the effect of the titanium peak at the coating interface), and Ta - 10% W, a material having a thermal expansion rate similar to alumina (to eliminate the stresses in the alumina due to the differential thermal expansion). P5 carbon-graphite was selected to determine the extent of the effect of the LiF impregnant in the graphite. The alumina-coated specimen without any contacting material was used as a control sample.

These specimens were tested at 1250, 1350, and 1450°F for 500, 1000, 2000, and 5000 hr, to accelerate the effects of temperature. Of the specimens tested, the alumina coating separated from the substrate in all cases where it was in contact with the LiF impregnated carbon-graphite. Inspection under 250X magnification revealed a definite change in the microstructure of all the alumina tested against P5-N. This is shown in Figure 24. These same specimens showed extensive γ -to- α transformation, while the alumina against P5 and the control sample showed no phase change, and no corresponding microstructure change.

D. SPECIAL TESTS

The redundant feature of the bearing presented the problem that neither the characteristics of the ball-to-socket, nor the ball-to-shaft bearing couple could be analyzed independently. This is illustrated by the fact that seizures of the ball-to-shaft couple were not reflected in higher friction-torque. Two special tests were set up to: (1) isolate the ball-to-shaft couple for study, and (2) to study the effect of alumina chips from the ball OD falling into the ball-to-socket cavity.

Figure 25. Journal Bearing Test Fixture

TABLE 8
FRICTION COEFFICIENTS FOR JOURNAL BEARING TEST

Event	Time (hr)	Maximum Friction Coefficient		
		S/N 001	S/N 002	S/N 003
Ambient		0.60	0.30	0.80
52 Thermal Cycles				
250°F		0.30	0.66	0.90
1150°F	614	0.30	0.35	0.60
1150°F, 1000-hr Dwell Test				
Pre-		0.38	0.30	0.58
Post-	1000	0.55	0.55	0.71
1150°F Operational Test	500	0.30	0.30	0.30
1250°F Operational Test	493	0.30	0.30	0.56
1250°F Air-Bleed Test	617	0.24	0.48*	-
Total Time at Test	3134			

*Exposed to directed air-bleed

1. Journal Bearing Test

The test fixture, Figure 25, was designed to test three journal bearing couples simultaneously, with visual observation of the bearings. The three bearings, two radial and one thrust, completed a series of tests at 1150 and 1250°F at a vacuum of 10^{-5} torr. The test was run to study bearing clearances, and the effect of temperature, thermal cycling, dwell periods, and excessive oxidation on friction levels. Table 8 gives a summary of the friction coefficients for the 3000-hr test. While friction coefficients rose, following the 1000-hr dwell test, they returned to pre-dwell levels and remained nearly constant throughout the remainder of the test. A final test was conducted with an air-bleed directed onto the P5-N carbon-graphite bushing of Bearing No. 2. Friction was compared to that of Bearing No. 1 (without direct oxidation). The friction increased steadily over the 600-hr test for the bearing exposed to the air-bleed, but no loss of bearing clearance resulted. Slight ash from oxidation of the carbon-graphite bushing was visible, but no signs of alumina cracking or chipping were evident.

2. Alumina Chip Test

A secondary problem associated with the Al_2O_3 failure was chipping of the alumina off the lips of the ball OD. This condition is shown in Figure 26. As previously stated, the ball OD was not in contact with carbon-graphite, and no increase in α phase occurred. The localized chipping was determined to be the result of high stress in the alumina along the lip. The main problem was the possibility of the alumina chips falling into the ball-to-socket or ball-to-shaft bearing cavities and binding either bearing couple.

A short-term test was set up, whereby known quantities of Al_2O_3 debris were purposely fed into the bearing cavities, to study the effect on bearing friction and possible seizure. Figure 27 shows the test ball, and the alumina particles which were placed above the ball and allowed to work their way into the bearing cavity. A prototype reflector assembly was used to load the bearings, while a series of thermal cycles were run. Drum rotation cycles were run at 1250°F, 800°F, and ambient, to study the effect of the alumina in the bearing assemblies. Maximum friction-torque at 1250°F was measured to be 1.0 in.-lb during a control cycle without alumina chips in the bearings, and

Figure 26. S8DR Ball With Chipped Alumina Edges

Figure 27. Alumina Chip Test

2.8 in.-lb with the chips. The specification limit of 3.5 in.-lb was well above both values. Disassembly and inspection of the bearings revealed chips within the cavity. Thus, the capability of the bearing to operate with acceptable friction levels and without damage, in the presence of the alumina chips, was demonstrated.

VI. MATERIAL EVALUATION TESTING

Based on information gathered from the alumina failure analysis, it was concluded that the best course of action was to replace the alumina-coated Inconel-750 ball with a solid, unimpregnated, P5 carbon-graphite ball. It had been determined that, on the existing bearing balls, the process of replacing the P5-N carbon-graphite bushings with P5 would overstress and probably fail the OD alumina coating. Replacement with a solid P5 graphite ball would eliminate the problem of chipped alumina (from the ball OD's), and would result in a P5 carbon-graphite versus alumina combination, which had already been proved to be a compatible and low-friction combination. Also, the alumina-coated shafts, thrust sleeves, and sockets would not need to be replaced.

To preclude any chance of a second failure without an alternate bearing couple, a series of materials were evaluated, and tests were run to select a backup bearing couple.

A. MATERIAL SELECTION

From the material evaluations previously conducted, and from a search of current literature, the following coatings were chosen for evaluation on Inconel-750 bearing shafts, for use with the existing composite ball (Al_2O_3 -coated Inconel-750 with P5-N carbon-graphite bushings) and Al_2O_3 -coated socket:

- 1) Cr_3C_2 flame-spray coating (LC-1)*
- 2) WC flame-spray coating (LW-5)*
- 3) TiC plasma-spray coating†
- 4) Al_2O_3 plasma-spray coating (Noroc)§
- 5) Haynes Alloy 90 hard facing**

Composition of each of the coatings is given in Table 9.

*Linde Division of Union Carbide

†Gianinini Corp.

§Norton Co.

**Haynes Stellite Division of Union Carbide

TABLE 9
COMPOSITION OF MATERIAL EVALUATION COATINGS
(wt %)

Cr_3C_2		WC		TiC		Al_2O_3		Haynes 90	
Cr_3C_2	93	WC	25	TiC	99+	Al_2O_3 (γ phase)	99+	Fe	65
		Ni	7	Cu	Trace			Cr	27
Co	7	Mixed W-Cr Carbides	68					C	3
								Si	1
								Mn (max.)	1
								Other	3

B. MATERIAL COMPATIBILITY TESTS

Test specimens, coated with the five candidate materials, were loaded to 80 psi in contact with the LiF-impregnated P5-N carbon-graphite, and subjected to up to 5000 hr static testings at 1250, 1350, and 1450°F. Specimens were removed after 500, 1000, 2000, and 5000 hr, and were metallographically examined for deterioration of the coating or the coating-substrate bond, and any interaction between the carbon-graphite and the test material.

1. Cr_3C_2 -Coated Specimens

A typical Cr_3C_2 -coated specimen is shown, Figure 28, after exposure for 500 hr at 1450°F. While the coating has remained intact, with a good coating-substrate bond, a thin layer of metallic deposit is evident on the carbon-graphite surface. A comparison of 1250, 1350, and 1450°F specimens, Figure 29, shows that the layer tends to increase as a function of temperature, and comparison with 500-hr specimens shows a direct function with time. Due to the presence of the layer, determined to be chrome rich, further examination of the 2000- and 5000-hr specimens was eliminated.

2. WC-Coated Specimens

Typical pre-test, and 1450°F, 500- and 1000-hr photomicrographs of WC specimens are shown in Figures 30 and 31. A thin, but well-defined, metallic film is present on the carbon-graphite surface. This condition also exists on the 1350°F specimen, but only a narrow diffusion zone is present on the 1250°F

b. Post-Test (1450°F)

Figure 28. Cr_3C_2 500-hr
Metallurgical Specimens

a. 1450°F Without Graphite 8085-4-1

b. 1450°F With P5-N 8083-5-2

c. 1350°F With P5-N 8084-9-2

d. 1250°F With P5-N 8084-2-3

Figure 29. Cr_3C_2 1000-hr Metallurgical Specimens

a. As-Coated

8050-1-1

b. Post-Test (1450°F)

8055-5-1

Figure 30. WC 500-hr Metallurgical Specimens

8085-5-1

a. 1450°F Without Graphite

8083-4-2

b. 1450°F With P5-N

8084-8-2

c. 1350°F With P5-N

8084-1-2

d. 1250°F With P5-N

Figure 31. WC 1000-hr Metallurgical Specimens

8050-3-3

a. As-Coated

8055-3-1

b. Post-Test (1450°F)

Figure 32. TiC 500-hr Metallurgical Specimens

specimen. Comparison with 500-hr specimens also shows the layer to be a function of time. In all cases, the chrome-rich layer is less than that present on the Cr_3C_2 specimens. Again, further investigation of the WC coating was eliminated, following examination of the 1000-hr specimens.

3. TiC-Coated Specimens

Pre-test and 1450°F specimens, exposed for 2000 and 5000 hr, are shown in Figures 32, 33, and 34. In contrast to the Cr_3C_2 - and WC-coated specimens, there was no transfer of material, and no formation of a film at the carbon-graphite and coating interface. The bond between the TiC coating and the Inconel-750 substrate was very good in all cases, and there was no sign of coating breakup. There was, however, a marked increase in the porosity of the coating from the pre-test condition. Table 10 shows a tabulation of porosity as a function of time and temperature. Values were estimated, using a 500X microscope and a measured grid.

TABLE 10
TiC COATING POROSITY ESTIMATES

Temperature (°F)	Exposure Time (hr)			
	"As-received"	500	1000	2000
1250	10.8	-	13.5	40.3
1350	10.8	-	24.8	30.5
1450	10.8	35.7	22.4	24.4
1450 (no graphite)	10.8	-	23.3	13.7

While no definite function of time and temperature is clear, it is apparent that porosity has increased due to exposure. It also appears that the porosity is influenced by the presence of the carbon-graphite. The Inconel-750 substrates show fine grain growth along the substrate-coating interfaces, and the presence of precipitates in the grain boundaries is evident.

8148-8-1

a. 1450°F Without Graphite

8148-6-2

b. 1450°F With P5-N

8148-2-1

c. 1350°F With P5-N

8148-1-4

d. 1250°F With P5-N

Figure 33. TiC 2000-hr Metallurgical Specimens

a. Edge Region

Marble's Etch

8269-2-1

b. Center Region

Marble's Etch

8269-2-2

Figure 34. TiC 5000-hr Metallurgical Specimens

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a. 1450°F Without Graphite

b. 1450°F Against P5-N

c. 1450°F Against P5-N

Figure 35. Plasma-Sprayed Alumina Metallurgical Specimens

Electron-microprobe scans of the substrate show the precipitates to be rich in Ti, Cr, and C, indicating Ti and Cr carbides were formed. In general, the TiC-coated specimens were in excellent condition, and were highly stable. The absence of any reaction or material transfer between the coating and either the carbon-graphite or substrate at 1450°F should ensure compatibility at the 1150°F S8DR nominal temperature.

4. Plasma-Sprayed Al₂O₃

Figure 35 shows the Al₂O₃ coating specimen after 1000 hr at 1450°F. The coating has completely separated from the Inconel substrate when in contact with the P5-N carbon-graphite. Severe breakup and deterioration of the coating is also typical of the 1350 and 1250°F specimens. The Al₂O₃ coating not in contact with the carbon-graphite was unaffected by testing. No consideration was given to further study of this Al₂O₃ against P5 carbon-graphite as a replacement of the Linde Al₂O₃, because of its greater porosity and general layered appearance.

5. Haynes Alloy 90

Concurrent sliding friction investigations of the alloy showed high friction material transfer to the carbon-graphite, and some cases of couple seizures. All consideration of the bearing couple was dropped, and metallurgical examination of the specimens was therefore eliminated.

C. SLIDING FRICTION TESTS

The bearing couples selected for evaluation as backup bearing materials were subjected to basic sliding friction tests at 1250°F and 10⁻⁷ torr. Specimens were evaluated on the basis of friction-coefficient wear, and the presence of any material transfer between surfaces. Tests were run under 40-psi loading for 1000 hr, or until failure. Table 11 summarizes the friction data from tests run on the candidate materials and the alumina against P5 carbon-graphite control specimens.

All of the Al₂O₃ vs carbon-graphite starting friction coefficients were below 0.5. Other couples exhibited friction below 0.5, but duplicates exceeded that value. Those included couples of carbon-graphite vs MoS₂, chrome, TiC, and WC. The Cr₃C₂ and Haynes Alloy 90 resulted in the highest friction, with

TABLE 11
FRICTION COEFFICIENTS OF MATERIAL EVALUATION TESTS
(1250°F and 10⁻⁶ torr)

Base	Coating	Rider	Hours	Maximum Friction Coefficient
Inconel-750	Al ₂ O ₃ (LA-2)	P5 Carbon-graphite	403	0.12
↓	Al ₂ O ₃ (LA-2)	P5 Carbon-graphite	1200	0.33
	Al ₂ O ₃ (Noroc)	P5-N Carbon-graphite	1010	0.28
	MoS ₂		72	0.15
Inconel-750	MoS ₂		616	0.62
WC	MoS ₂ (in-situ)		1487	0.25
Inconel-750	Chrome		192	0.32
K-162B*	None		898	0.35
Inconel-750	TiC		1018	0.42
↓	TiC		1068	0.62
	WC (LW-5)		1080	0.39
	WC (LW-5)		1005	1.05
	Cr ₃ C ₂ (LC-1)		1193	0.78
	Cr ₃ C ₂ (LC-1)		-	>2.0
	None		192	1.25
	Haynes 90		96	1.05
	Haynes 90		30	1.25
Inconel-750	Haynes 90	P5-N Carbon-graphite	329	>2.0

*TiC-Ni Cermet — Kennametal, Inc.

seizure of one couple each. The TiC against P5-N carbon-graphite (including one K-162B solid TiC specimen) resulted in friction coefficients between 0.35 and 0.62. While substantially greater than friction of Al₂O₃ against carbon-graphite, the TiC couples represent the best overall performance of any alternate group.

Post-test conditions of typical friction couples are shown in Figure 36. The Al₂O₃ against carbon-graphite are shown in Figures 36a, b, and c, and illustrate heavy film-transfer in two cases and light in the third. The impression on the third base resulted from contact during bake-out, and is not due to

a. Al_2O_3 vs P5 [403 hr, $\mu(\text{max.}) = 0.12$]

d. K-162B vs P5-N [1250 hr, $\mu(\text{max.}) = 0.41$]

g. Cr_3C_2 vs P5-N [Siezed at 1000°F, $\mu(800^\circ\text{F}) = 0.35$]

j. WC vs P5-N [1080 hr, $\mu(\text{max.}) = 0.39$]

b. Al_2O_3 vs P5 [1200 hr, $\mu(\text{max.}) = 0.33$]

e. TiC vs P5-N [1010 hr, $\mu(\text{max.}) = 0.42$]

h. Cr_3C_2 vs P5-N [1193 hr, $\mu(\text{max.}) = 0.78$]

c. Al_2O_3 vs P5-N [1010 hr, $\mu(\text{max.}) = 0.28$]

f. TiC vs P5-N [1068 hr, $\mu(\text{max.}) = 0.62$]

i. WC vs P5-N [994 hr, $\mu(\text{max.}) = 1.05$]

Figure 36. Sliding Friction Specimens (1250°F and 10^{-7} torr)

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any seizure during operation. The TiC specimens are shown in Figures 36e and f. Both have heavy carbon-graphite transfer, and show even full-width contact between the base and rider. The Cr_3C_2 specimens are shown in Figures 36g and h, and the WC specimens in Figures 36i and j. Both show evidence of galling and sticking. The test fixture is shown in Figure 37. The specimen base is rigidly held, and the carbon-graphite rider wiped across it by the oscillating mechanical drive. Friction force is measured by a force ring transducer, and recorded on light-sensitive paper in the same manner as the S8DR bearing data is recorded. The chamber is ion pumped, providing a contaminant-free test environment. Small, resistance heaters are inserted into tubes to provide heater replacement without breaking vacuum.

D. PROTOTYPE BEARING SHAFT TESTS

A series of six prototype bearing tests were initiated simultaneously with the friction tests and the material compatibility tests. The bearing tests utilized the composite Al_2O_3 -coated Inconel-750 ball with the P5-N carbon-graphite bushings and the Al_2O_3 -coated socket. Inconel-750 shafts were coated with WC, Cr_3C_2 , TiC, and Al_2O_3 (Noroc). Initially, two sets of Cr_3C_2 and WC, and one set TiC and Al_2O_3 bearings were set up. The material compatibility 500-hr tests showed the "Noroc" Al_2O_3 to fail in contact with the LiF-impregnated carbon-graphite in the same manner as the LA-2 type Al_2O_3 . Due to the promising results of the TiC-coated specimens, the Al_2O_3 prototype shaft test was replaced with a second TiC-coated shaft test. The bearing sets, tested in the same fixtures as the previous tests, were subjected to operations at 1250°F with periodic thermal cycling. Friction-torque was measured throughout the tests, and results are summarized in Table 12.

Excluding the Al_2O_3 -coated shaft test, which was eliminated for incompatibility, the Cr_3C_2 -coated shaft tests resulted in the most consistently low friction-torque, with the TiC- and WC-coated bearings second and third. Following testing, the bearings were disassembled, and inspected for wear and possible failure or damage. Inspection of the bearings revealed fully developed carbon-graphite transfer film on all the shafts, and no signs of chipping, cracking, or other signs of shaft damage. Figures 38a, b, and c show post-test condition of the TiC-, Cr_3C_2 -, and WC-coated shafts respectively.

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Figure 37. Sliding Friction Test Fixture

TABLE 12
 PROTOTYPE SHAFT FRICTION-TORQUE SUMMARY
 (1250°F and 10⁻⁵ torr)

Test	Maximum Friction-Torque (in.-lb)			Hours at 10 ⁻⁵ torr
	Thermal Cycles		Operational (1250° F)	
	450° F	1250° F		
TiC No. 1	4.1	2.7	2.7	2180
TiC No. 2	2.8	3.2	5.7	1260
Cr ₃ C ₂ No. 1	3.6	3.0	3.7	1465
Cr ₃ C ₂ No. 2	2.6	2.4	4.8	1415
WC No. 1	3.0	2.8	7.0	730
WC No. 2	2.6	1.6	3.7	1220
Al ₂ O ₃ (Noroc)	4.0	2.5	2.5	695

E. SUMMARY

Based on the results of the material compatibility, sliding friction, and prototype shaft tests, the following observations and conclusions were made:

- 1) The Cr₃C₂ and WC metallurgical specimens resulted in transfer of material between the coatings and the carbon-graphite, and the formation of a thin chrome-rich layer on the carbon-graphite surface. Under the same conditions, the TiC coating showed no signs of material transfer or deterioration of the coating, but did show some increase in porosity.
- 2) The TiC-coated sliding friction tests had the most consistently low friction coefficients, whereas one each of the WC- and Cr₃C₂-coated specimens exhibited a friction coefficient >1.0.
- 3) The prototype shaft tests showed the Cr₃C₂-coated bearings to have the lowest friction-torques, with the TiC and WC second and third.

a. TiC-Coated Shaft
(1260 hr)

b. Cr₃C₂-Coated Shaft
(1415 hr)

c. WC-Coated Shaft
(1220 hr)

Figure 38. Prototype Bearing Sets, Post-Test

The TiC-coated Inconel-750 was selected as the backup shaft, due primarily to the results of the material compatibility tests. While its higher friction is not desirable, it can be compensated for; but potential material incompatibility is totally unacceptable. The possibility of self-welding, due to the thin chrome layer at the carbon-graphite and coating interface, could jeopardize operation of the entire reactor system.

a. Reference Bearing — Al_2O_3 vs P5 Carbon-Graphite

b. Backup Bearing — TiC vs P5-N Carbon-Graphite

Figure 39. Modified Design S8DR Drum Bearing

VII. S8DR DESIGN VERIFICATION TESTS

The material evaluation tests confirmed the alumina and P5 carbon-graphite to be both a low-friction couple and metallurgically compatible under S8DR conditions. The tests also established the TiC and P5-N carbon-graphite to be the best overall alternate bearing couple. These couples were therefore chosen as the reference and backup material couples for the redesign of the S8DR bearing. Figures 39a and b illustrate these bearings. Both bearing sets are of the same configuration, except for the shaft coating and the ball designs. The reference bearing uses the solid P5 carbon-graphite ball, while the backup bearing retains the original S8DR composite ball (Inconel ball with alumina-coated OD and P5-N carbon-graphite bushings).

A. TEST DESCRIPTION

Table 13 shows a matrix of test conditions and parameters for the Design Verification Tests, planned to demonstrate the performance of these bearings under the expected SNAP 8 Developmental Reactor operational conditions.

Except for the vacuum and nominal temperature, all tests were conducted to the same plan. A condensed outline of the plan follows:

- 1) 30 thermal cycles between 450 and 1150°F (Test No. 3 at 1250°F, where plan shows 1150°F)
- 2) 500 hr at 1150°F
- 3) 500 hr at 1250°F
- 4) Continue at 1150°F to 5000 hr
- 5) 1000 hr at 1150°F, with 1 thermal cycle each 100 hr
- 6) 1000-hr dwell at 1150°F
- 7) Continue at 1150°F to 12,000 hr, with 1 thermal cycle each 100 hr.

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a. Test No. 1

Figure 40. S8DR Design Verification Friction History
 (Sheet 1 of 4)

TABLE 13
DESIGN VERIFICATION TEST PARAMETERS

Test No.*	Couples	Temperature (°F)	Vacuum (torr)	Time (hr)
1	Al ₂ O ₃ vs P5	1150	10 ⁻⁵	12,000
2	Al ₂ O ₃ vs P5	1150	10 ⁻⁵	12,000
3	Al ₂ O ₃ vs P5	1250	10 ⁻⁵	12,000
4	Al ₂ O ₃ vs P5	1150	10 ⁻⁸	12,000
5	TiC vs P5-N	1150	10 ⁻⁸	12,000

*Tests 1 to 4 (Reference Couple)
Test 5 (Backup Couple)

B. FRICTION DATA ANALYSIS

Starting and running friction-torques of the bearing sets were measured, and starting torque (as a function of test duration) is shown for each test in Figures 40a through d. A general consistency exists for the three 10⁻⁵ torr tests of the reference material. The torque level shows a gradual increase during the first 2000 to 4000 hr, after which a short period of stability is reached. A small decrease in friction then occurs, prior to the 1000-hr dwell. Following the dwell, the friction tends to again increase slightly. It is hypothesized that lubrication is initially enhanced by outgassing of the carbon-graphite; and, as the outgassing subsides, the friction increases until a carbon-graphite transfer-film is built up to a level where it, in turn, enhances the lubrication to decrease the friction. The same pattern, but with an accelerated increase in friction, is evident for the 10⁻⁸ torr bearing test. This could be accounted for by the lower system pressure, and hence the greater outgassing rate.

Approximately 7000 hr into the test, vacuum was partially lost on Test No. 4 (10⁻⁸ torr), with the pressure rising to 10⁻⁴ torr at 400°F. As a precaution, bearings were disassembled, and inspected for possible oxidation damage. No damage was found, the bearings were reassembled, and the test resumed, but with friction-torque falling to below 2.0 in.-lb (prior to inspection, it was averaging between 3.0 and 4.0 in.-lb). During assembly of the test fixture, prior to the initial testing, difficulties with obtaining free movement of the torque readout

b. Test No. 2

Figure 40. S8DR Design Verification Friction History
 (Sheet 2 of 4)

REFERENCE MATERIAL: Al_2O_3 vs P5 CARBON GRAPHITE
 SNAP 8 CONTROL DRUM BEARINGS DESIGN VERIFICATION TEST No. 3
 FRICTION AS A FUNCTION OF TIME AND TEMPERATURE
 1250°F AND 10^{-5} TORR
 31 lb AXIAL 8.5 lb RADIAL LOADS
 12 140 hr at 1250°F
 86 THERMAL CYCLES

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c. Test No. 3

Figure 40. S8DR Design Verification Friction History
 (Sheet 3 of 4)

d. Test No. 4

Figure 40. S8DR Design Verification Friction History
(Sheet 4 of 4)

linkage had required removal and reassembly of the fixture. It is possible that all restrictions were not eliminated, and that torque differences, before and following the midtest inspection, were due to linkage restrictions. This can not be proven, however, and the pre-inspection data are considered valid.

The friction torque profile of the backup bearing set, Figure 41, shows initial low friction, increasing to 4.0 in.-lb or greater, and stabilizing at that point. The test was terminated after 6000 hr, due to failure of the vacuum system. Inspection of bearings revealed cracks in the radial journal shaft TiC coating.

A summary of all test parameters and friction-torque data for the five tests are given in Table 14.

TABLE 14
DESIGN VERIFICATION TEST DATA SUMMARY

Event	Test No.				
	1	2	3	4	5
Bearing Couple					
Reference (P5 vs Al ₂ O ₃)	Ref.	Ref.	Ref.	Ref.	
Backup (P5-N vs TiC)					Backup
Nominal Test Temperature (°F)	1,150	1,150	1,250	1,150	1,150
Pressure (torr)	10 ⁻⁵	10 ⁻⁵	10 ⁻⁵	10 ⁻⁸	10 ⁻⁸
Maximum Friction-Torque (in.-lb)					
at 1150°F	3.8	3.7	-	4.5	5.5
1250°F	2.6	2.5	3.8	4.6	3.8
450°F	5.3	4.6	6.5	4.0	6.5
ambient	6.8	5.2	6.5	4.3	3.8
Friction-Torque (in.-lb)					
Pre-1000-hr dwell*	2.0	2.4	2.4	1.5	-
Post-1000-hr dwell	2.7	3.1	3.1	1.8	-
No. Thermal Cycles	86	85	86	86	33
Equivalent 270° Drum Cycles†	280	282	310	290	97
Total Hours at Vacuum	12,825	13,038	12,856	13,197	6,466
at 1150°F	11,436	11,417	-	11,443	5,387
1250°F	609	624	12,140	643	704

*Dwell conducted at 1150°F, except Test No. 3 (at 1250°F)

†270° represents a full in-and-out drum cycle

BACKUP MATERIAL: TiC vs P5N CARBON-GRAPHITE
 SNAP 8 CONTROL-DRUM BEARINGS DESIGN VERIFICATION TEST No. 5
 FRICTION AS A FUNCTION OF TIME AND TEMPERATURE
 1150°F AND 10⁻⁸ TORR
 31-lb AXIAL, 8.5-lb RADIAL LOADS
 5387 hr at 1150°F
 704 hr at 1250°F
 33 THERMAL CYCLES

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Figure 41. S8DR Design Verification Backup Test No. 5

C. POST-TEST ANALYSIS

Following completion of the design verification tests, each bearing set was disassembled, and inspected for wear and condition of the bearing components.

1. Reference Bearings

The post-test condition of a typical bearing set, Test No. 1, tested at 10^{-5} torr and 1150°F , is shown in Figure 42. A typical alumina-coated bearing shaft, Figure 43, shows the light, but well developed, carbon-graphite transfer film associated with even ball-to-shaft contact. All load-supporting alumina-coated surfaces were in excellent condition, with no signs of cracking or failure. Details of the carbon-graphite balls, Figure 44, show the OD surfaces to be lightly pitted from oxidation during the 12,000-hr testing. Weight loss of each carbon-graphite ball was measured, and compared to calculated curves of fully exposed and geometrically attenuated weight loss of carbon-graphite. Assuming all weight loss is due to oxidation, neglecting wear losses, is the worst case condition. Figure 45 shows the curves and test data points, with close agreement between the attenuated curve and data points for the 10^{-5} torr data. Data from the 10^{-8} torr test indicate excessive weight loss. Actual measurements show that bearing clearance did not increase significantly, and did not substantiate the weight loss data. In other words, weight loss was partially due to wear. Examination of the carbon-graphite balls did not show any signs of chipping or damage due to testing.

The post-test radial ball and shaft from Test No. 4 (the 10^{-8} torr test) are shown in Figure 46. The surface of the carbon-graphite ball is shiny and smooth, in contrast to the pitted surfaces of the balls from the 10^{-5} torr tests. This condition indicates considerably less oxidation than that from assuming all weight loss was due to oxidation. Areas of contact with the bearing socket are shown by the shiny rings around the ball. The shaft alumina coating had a well developed carbon-graphite transfer film, and was typical of all the alumina-coated surfaces. Examination of both shafts, the thrust sleeve, and the sockets showed all the alumina surfaces to be in excellent condition, with no signs of cracking or chipping.

Figure 42. Post-Test Condition of S8DR Design Verification Bearing Test No. 1 (Reference Bearing)

a. Radial Shaft

b. Thrust Shaft and Sleeve

Figure 43. Post-Test Bearing Shafts (Test No. 1)

a. Radial Bearing Assembly

b. Thrust Bearing Assembly

Figure 44. Post-Test Carbon-Graphite Balls, Showing Pitted Surfaces (Test No. 1)

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Figure 45. P5 Carbon-Graphite Oxidation Loss Rates

a. Radial Ball

b. Radial Shaft

Figure 46. Post-Test UHV Bearing Ball and Shaft

Figure 47. Post-Test Condition of S8DR Design Verification Bearing Test No. 5 (Backup Bearing)

2. Backup Bearings

Figure 47 shows the post-test condition of the backup bearing set (Test No. 5). Post-test condition of the thrust ball, Figure 48b, shows the contact zone between the ball and the thrust sleeve, and the burnished areas of the ball OD in contact with the socket. It appears in excellent condition. The thrust shaft and sleeve, Figure 49b, appear in good condition, with well-defined transfer films; however, close examination reveals three cracks in the TiC coating of the shaft. The largest, Figure 50, runs the full length of the coating. Line-to-line contact existed at post-test disassembly, and it is apparent the coating has sprung away from the substrate. Failure of the shaft coating, and the resulting seizure in the ball, did not cause failure of the bearing set, because of the redundant bearing assembly. Cause of the failure has not been identified, and further study is not contemplated, due to the excellent performance of the reference alumina against P5 carbon-graphite bearing couple.

a. Radial Bearing

b. Thrust Bearing

Figure 48. Test No. 5 Ball Details

a. Radial Shaft

b. Thrust Shaft

Figure 49. Test No. 5 Shaft Details

Figure 50. Details of Thrust Shaft Crack

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Figure 51. Summary of Bearing Material Development

	SNAP 10A	S8DRM*	S8DR	ZrH
SHAFT	TITANIUM ALLOY	INCONEL 750	INCONEL 750	Ta - 10 W
SHAFT COATING	Al_2O_3	Al_2O_3	Al_2O_3	Al_2O_3
BALL	SOLID T C-Ni CERMET	INCONEL 750 WITH GRAPHITE (P-5N) INSERT BUSHINGS	SOLID GRAPHITE (P-5)	SOLID GRAPHITE (P-5)
BALL COATING	BONDED MoS_2	Al_2O_3 + BONDED MoS_2	MoS_2 POWDER	MoS_2 POWDER
SOCKET	TITANIUM ALLOY	INCONEL 750	INCONEL 750	Ta - 10 W
SOCKET COATING	Al_2O_3	Al_2O_3	Al_2O_3	Al_2O_3

*INCLUDES ORIGINAL S8DR DESIGN

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Figure 52. Summary of Test History

	SNAP 10A TYPE SOLID CEMENTED CARBIDE BALL	S8DRM TYPE COMPOSITE BALL WITH GRAPHITE SLEEVES	S8DR TYPE SOLID GRAPHITE BALL	
TEST TEMPERATURE (°F)	≤ 700	≤ 1250	≤ 1250	≤ 1500
SETS TESTED	38	31	10	2
MAXIMUM HOUR ON ANY SET	10,005	12,560	12,000	12,000
TOTAL SET HOURS	97,700	79,376	100,000	12,500

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VIII. SUMMARY

The SNAP 8 Bearing Development Program culminated in the successful operation of the S8DR bearings through the 12,000-hr (minimum) design verification tests and the 7,000-hr S8DR reactor ground test. The four bearings sets under design verification testing, and the six bearing sets on the reactor, accumulated a total test time of over 100,000 hr. The bearings performed satisfactorily, and have proven the capability of meeting design objectives. Friction-torque peaks, while being slightly above specification limits, are well within the operating capability of the actuators under nominal conditions.

The SNAP 8 Bearing Development Program, and the alumina failure problems associated with it, points out the necessity of detailed material evaluation. The use of accelerated time-temperature material compatibility testing greatly reduced future potential incompatibilities between bearing couples. The techniques and technology have since been utilized in the current Advanced ZrH Reactor Program. The advanced reactor will require bearings which can successfully operate at 1350°F for up to 20,000 hr. Basic friction and material compatibility tests were conducted, prior to the initiation of a simulated life test on prototype bearings. The resulting couple, P5 carbon-graphite against alumina on a tantalum - 10% tungsten substrate, is shown in Figure 51. The current AI SNAP bearing development history is summarized in Figure 52.

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