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ZIRCONIUM HYDRIDE REACTOR CONTROL REFLECTOR SYSTEMS SUMMARY REPORT

AEC Research and Development Report

Atomics International Division
Rockwell International

P.O. Box 309
Canoga Park, California 91304

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ZIRCONIUM HYDRIDE REACTOR CONTROL REFLECTOR SYSTEMS SUMMARY REPORT

P. H. HORTON
AND
W. J. KURZEKA

CONTRIBUTOR:
R. T. THEXTON

Atomics International Division
Rockwell International
P O Box 309
Canoga Park, California 91304

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ABSTRACT

The beryllium reflector control system development for SNAP reactors is documented, from the initial SNAP 10A System through the current 5-kwe Thermoelectric System. Described are the various reflector concepts used in these systems for shadow-shielded and 4π-shielded nuclear systems. The development of the key components, such as the actuators, bearings, and drive mechanisms for these systems, is also traced from the SNAP 10A concept through to the current system. Developmental test results are outlined, showing the performance capability improvements made throughout the life of the SNAP programs.

Component development was highly successful, as proven by a number of reactor systems tests, including the launch and operations of the SNAP 10A flight.

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I. INTRODUCTION

Since 1957 a series of small compact nuclear reactors designated "Systems for Nuclear Auxiliary Power" (SNAP) have been under development at Atomics International (AI). These reactors have been designed to provide long-term uninterrupted power for space and remote terrestrial applications. Several generations of reactors: SNAP 10, SNAP 2, SNAP 4, SNAP 8, the Advanced ZrH Reactor, the Space Power Facility Test (SPF), and the 5-kwe Thermoelectric Reactor Systems have undergone design, development, testing, and operation to varying degrees. Technical developments of each generation have been utilized in succeeding generations, with the basic reactor concept modified for power and life requirements.

The reactors consist of a U-ZrH_x fueled core, through which a liquid metal coolant is circulated, surrounded by a beryllium moderator and reflector assembly. The reactor is controlled by closing "windows" in the reflector assembly to regulate the neutron leakage and consequently maintaining the desired core and coolant temperatures.

The SNAP 10A, 2, 4, 8, SPF, and Advanced ZrH reactors have movable reflector segments which are rotatable half cylinders parallel to the core centerline. The SNAP 10B and 5-kwe thermoelectric reactors have movable segments which slide vertically parallel to the core centerline.

The reflector control assemblies of both types of reactors consist of fixed reflector segments, movable control reflectors, drive motors and gears, position sensors and limit switches on control drums, support structures, and a variety of components necessary for startup and long-term uninterrupted reactor operation and control.

A. REFLECTOR SYSTEM FUNCTION

The SNAP reactor design is based on a small cylindrical core packed with uranium - zirconium hydride fuel elements. A liquid metal coolant is circulated through the spaces between the fuel elements within the core and removes the heat of reaction. The coolant is then passed through either direct or indirect radiating thermoelectric modules or through a mercury-Rankine cycle evaporator. Control and moderation of the core is provided by an external beryllium reflector assembly.

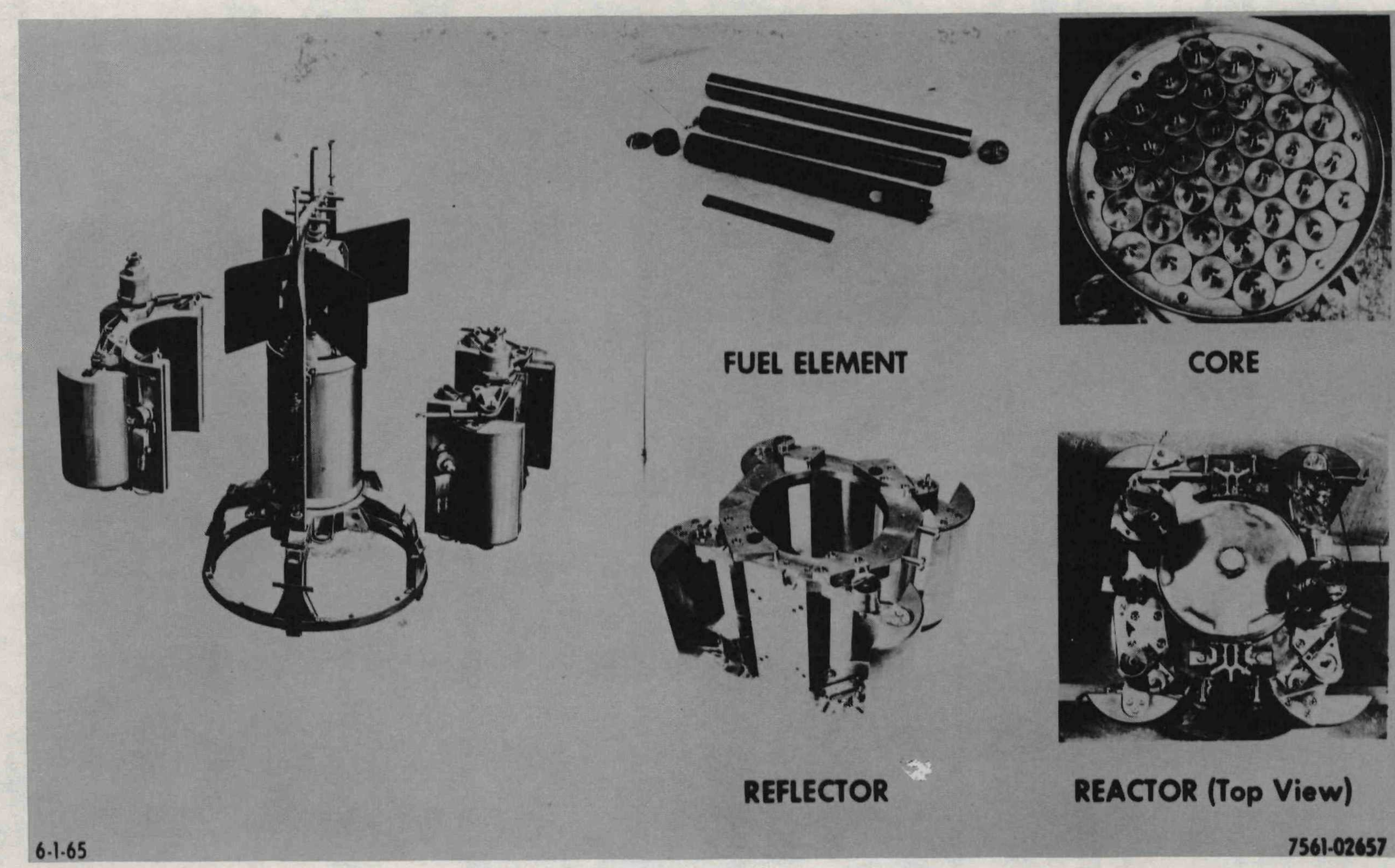

Figure 1. SNAP Reactor Design

The reactivity of the reactor determines its potential life. Sufficient reactivity must be built into the system to ensure that, as the fuel is consumed, the power level can be maintained for a given design life. The basic function of the reactor reflector assembly is to reflect the neutrons generated in the reactor core back into the core in sufficient numbers to maintain the nuclear reaction. The movable reflectors of the SNAP reactors serve three functions. Prior to startup they must prevent spurious startup during assembly and normal handling. Second, they must insert sufficient reactivity into the core to make the reactor go critical and sustain the nuclear reaction. Third, they must maintain the desired power level as the fuel is consumed.

Designers of the SNAP reactors calculate control drum size based on the required reactivity. However, upon assembly, reactor criticality tests are conducted to determine how much insertion of the drums (rotation toward the core to increase reactivity) is required for specific power levels. To achieve design reactivity levels, shims or thin plates of beryllium are added to the control drums as required. The essence of reactor control is simply to close "windows" in the spaces between the fixed reflector segments as required to maintain required reactivity levels.

Means of shutting the reactor down during ground test or in orbit are provided. Three methods are available on ground: (1) removal of reactivity by reversing the normal step control motor, (2) "scramming" the normal control elements using a trip and spring device or by a rapid mode of operation of the normal control motor, and (3) an ultimate scram that rapidly moves both the fixed and movable beryllium away from the core. In orbit it was possible to shut the reactor down by stepping the normal control outward and/or by energizing a spring-loaded reflector ejection system.

B. BASIC SYSTEM REQUIREMENTS

The SNAP reactors have been designed to provide power for a variety of missions which determine specific power levels and configurations.

Figure 1 illustrates the basic SNAP reactor concept and design. The nuclear core is a cylindrical can containing a close-packed arrangement of small diameter elements containing uranium - zirconium hydride fuel. The

TABLE 1

PERFORMANCE AND ENVIRONMENTAL PARAMETERS OF SNAP REACTOR SYSTEMS

Parameter	Reactor System						
	SNAP 10A	SNAP 2	SNAP 8			Advanced ZrH Reactor	5-kwe-TE
			S8ER	S8DRM	S8DR		
Configuration							
Number of Control Drums (Material)	4 (beryllium)	4 (beryllium)	6 (anodized beryllium)	6 (anodized beryllium)	6 (anodized beryllium)	10 BeO, Ta-10W poison backed	2, sliding (anodized beryllium)
Shielding (rating)	shadow (instrument)	shadow (instrument)	-	shadow (instrument)	shadow (instrument)	shadow (man-rated)	shadow (instrument)
Performance							
Life, Design	1 yr	1 yr	3,000 hr	10,000 hr	12,000 hr	20,000 hr	5 yr
Thermal (kwt)	40	100	600	-	600 to 1000	600	110
Electrical (kwe)	0.500	3.0			Function of Mission	Function of Mission	5.0
Operating Temperature NaK outlet (°F)	1025	1150	1300		1300	1300	1200
Thermal Cycles	10	--	--	10	50	50	50
Environment							
Pressure (torr-space)	10^{-6}	10^{-8}		10^{-5}	10^{-5}	10^{-12}	10^{-8}
(torr-ground test)	10^{-2}	10^{-5}	1.0 atm He	10^{-5}	10^{-5}	10^{-5}	10^{-5}
Radiation							
(nvt)	7.0×10^{18}	1.5×10^{19}			1×10^{20}	18.7×10^{20}	1×10^{19}
(gamma)	1.5×10^{10}	3.5×10^{10}			1×10^{11}		5×10^{11}
Launch							
Vibration							
Sinusoidal (g)	7.5	7.5			19 (maximum)	6.0	
Random (equivalent g)					21	2.0	
Acceleration (g)	9.4	9.4			7.0	6.0	16.25
Shock (g)	20.0	20.0			35.0	20.0	

core is surrounded by a beryllium reflector assembly. The reflector consists of fixed segments and movable rotating half cylindrical control drums. Rotation of the control drums is accomplished by stepper type actuator motors through a reduction gear mechanism. Drum position sensors, limit switches, and other instrumentation are added to control and monitor reactor operation.

Performance characteristics of the SNAP reactors are tailored to specific missions. Table 1 lists the performance characteristics and environmental conditions for the various reactor types and specific reactor systems.

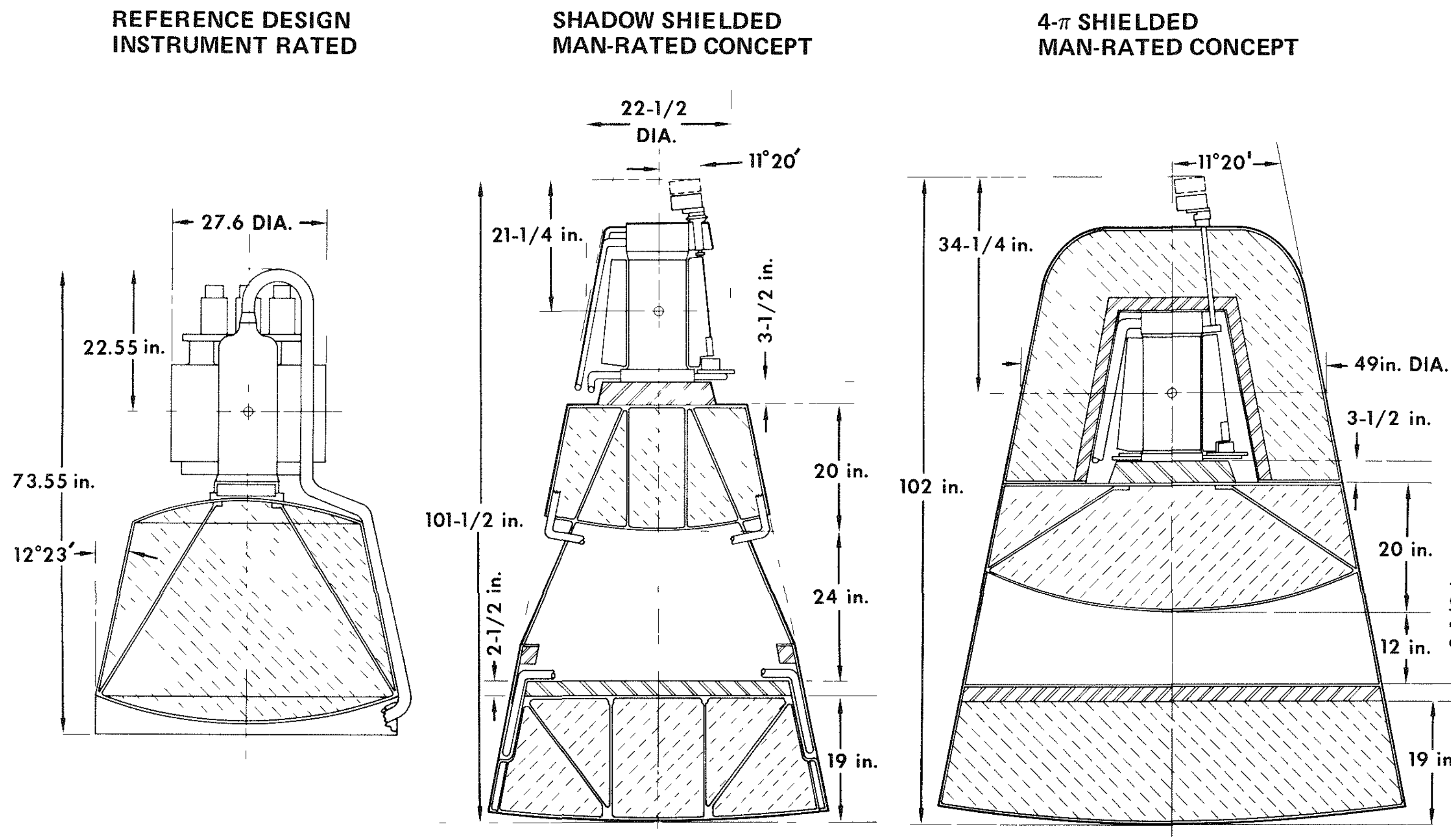

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Figure 2. SNAP Reactor and Shield Configurations

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II. SNAP REFLECTOR SYSTEM HISTORY

Proposed missions for SNAP reactors have required from 500 watts to 60 kilowatts electric power and have included both unmanned (instrumented) and manned space station applications. The required power level, the life of the mission, and the application resulted in two basic configurations, the shadow-shielded reactor and the 4-π shielded reactor.[1] Both place specific restraints on the design and provide certain unique design problems. The shadow shield concepts are further divided into instrument and man-rated concepts. Figure 2 illustrates the three different basic designs. The basic differences are the amount of radiation shielding required and its configuration.

The shadow shield concept places the reactor system at the apex of a cone and separates the payload from the reactor by a shield in the shape of a conical section. All instruments or personnel must stay within the cone or be subjected to the direct reactor radiation. The reactor and all components must be inside the cone also or neutrons will be scattered around the shield into the protected zone. As minimizing shield weight is a prime object, the reactor configuration is as closely packed as practical.

On a manned shadow shield system, all approaches must be made to the space station from within the cone angle, and experiments located outside the cone are subjected to reactor radiation.

A. REACTORS

The initial design of the SNAP reactor was conceived to provide long-term power for instrument-carrying missions. The first of these was the 500-watt electric SNAP 10A reactor.[2]

1. SNAP 10A

a. Description and Features

Figure 3 shows the basic SNAP 10A flight reflector control-drum-drive system.

The major components are the two reflector halves, each consisting of a fixed reflector, a coarse control drum, a fine control drum and its drive motor, drum position sensors and limit switches, and all necessary electrical cables.

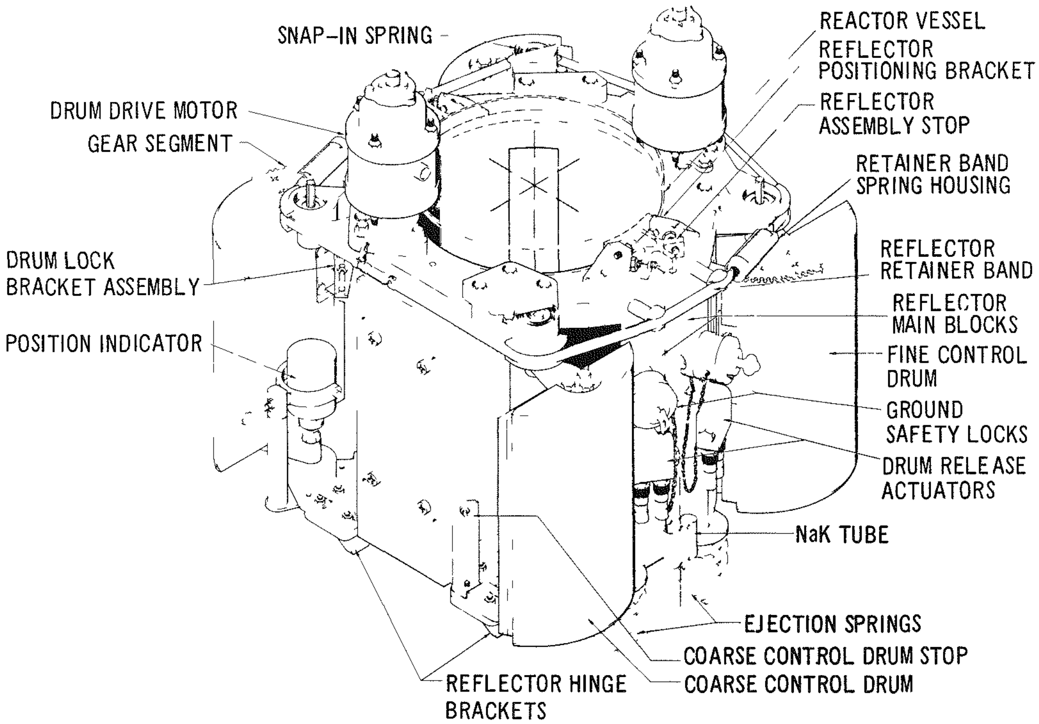

Figure 3. SNAP 10A Control and Reflector Assembly

In addition, the reflector halves are held together by a retaining band and are spring loaded for separation at the end of the reactor operating life. For ground testing and checkout an emergency scram or shutdown device is also required.

(1) Reflectors, Control Drum, and Shims

The neutron moderator and reflector assembly surrounding the SNAP 10A core consists of two halves fabricated principally of beryllium metal. Each half consists of a structural skeleton with a fixed beryllium segment and two rotatable half cylinder segments for control. Each reflector drum rotates on a pair of self-aligning bearings. The upper bearing is a radial bearing and the lower bearing is a radial-thrust bearing. The basic rotation couple is provided by a journal-sleeve bearing, and the self-aligning feature is attained with a ball and socket configuration.

One drum on each reflector half is designated as a coarse drum which is snapped to the full-in position by torsion springs on reactor startup and remains in that position. The second control drum is designated as a fine control drum and is rotated toward the core by a stepper-motor actuator through a gear train. The drum is positioned by a closed loop control system which is activated by a specified decrease in the reactor coolant temperature. Each control drum consists of a semi-cylindrical sector of beryllium with a series of beryllium plates or "shims" attached to the flat face of the control drum to accurately provide the necessary amount of moderation established during assembly criticality tests.

(2) Control-Drum Drive

The fine control-drum-drive system consists of (1) the stepper-motor actuator, (2) the reduction gear assembly, (3) the control drum, (4) the support bearings, and (5) the instrumentation required to maintain and record the required drum position.[3,4]

The stepper-motor actuators provide a stepping sequence of 7.2° per actuation. They are discussed in depth in Reference 5. The actuator is connected to the control drum through a 13.67:1 gear ratio single-stage spur gear set. Following a development program which studied self-welding of the teeth, transmission friction, and related manufacturing problems, a reference design was selected. The pinion gear was fabricated from Haynes Stellite 6B and the main gear was fabricated of a titanium alloy (Ti-6Al-4V) with a copper insert in the area of pinion contact during launch loading. The teeth were coated with Alpha Molykote-X-15, dry-film lubricant to ensure low friction and prevent self-welding. The large drive gear is mounted directly on the control drum and the upper control drum bearing is mounted in the actuator housing. A flexible coupling is therefore not required as the misalignment is minimized.

The coarse control drive includes a redundant squib-operated device which when energized will pull a pin from a hole in the drum. The released drum is then rotated full-in by a wound-up torsion spring on the bearing shaft.

(3) End-of-Life Shutdown

The end-of-life (EOL) shutdown of the SNAP 10A reactor is accomplished by releasing the spring loaded band surrounding the upper reflector assembly.[6] The reflector halves are mounted on ejection springs in such a manner that upon release of the reflector retaining band, the springs cause the reflector halves to swing out, and at 15° out the reflector halves are completely ejected from the reactor core assembly. Release of the reflector retaining band can be initiated by two methods. An electrically actuated band release device (EABRD) is incorporated into the retaining band which, upon a command signal, will actuate a heater in a fusible link and cause separation of the link and consequently the reflector band. In addition, the band is sized to melt during reentry and thus initiate the spring ejection sequence in the event that the electrical system does not operate.

(4) Ground Test Scram Device

A ground test kit (GTK) was designed to replace the flight test coarse and fine reflector control-drum drives with special drive units for ground testing of the SNAP 10A reactor. The test kit replaced the control-drum drives and provided fine reversible control, sensed position accurately, and scrammed the drums upon manual command or automatically as a function of selected operating parameters. The test kit is also required for fuel loading, reflector shimming, NaK coolant loading, and special physics tests.

The ground test kit system block diagram is shown in Figure 4. The "joy stick" switch, controller, power supply, and instrumentation are mounted within the reactor control console area. One ground test kit is mounted directly onto each of the four reactor reflector control drum shafts.

The controller is an electromechanical pulse sequencer which provides direct current pulses to each of the eight coil sets of each GTK stepper motor. A motor within the controller continuously drives a shaft with four sequencing cams at a speed of 300 rpm. Each cam operates a switch. The "joy stick" selects output sequences to drive the GTK in either direction as demanded. Each controller is capable of driving four ground test kits. Normal operation from the reactor console is to drive one kit in or out at a time, but it can be commanded to drive all four drums out simultaneously.

The GTK consists of six major parts: (1) a stepper motor, (2) a worm gear transmission, (3) a clutch mechanism, (4) a scram and snubber mechanism, (5) a position sensor, and (6) shafting with support items. A sectioned isometric view of the GTK is shown in Figure 5.

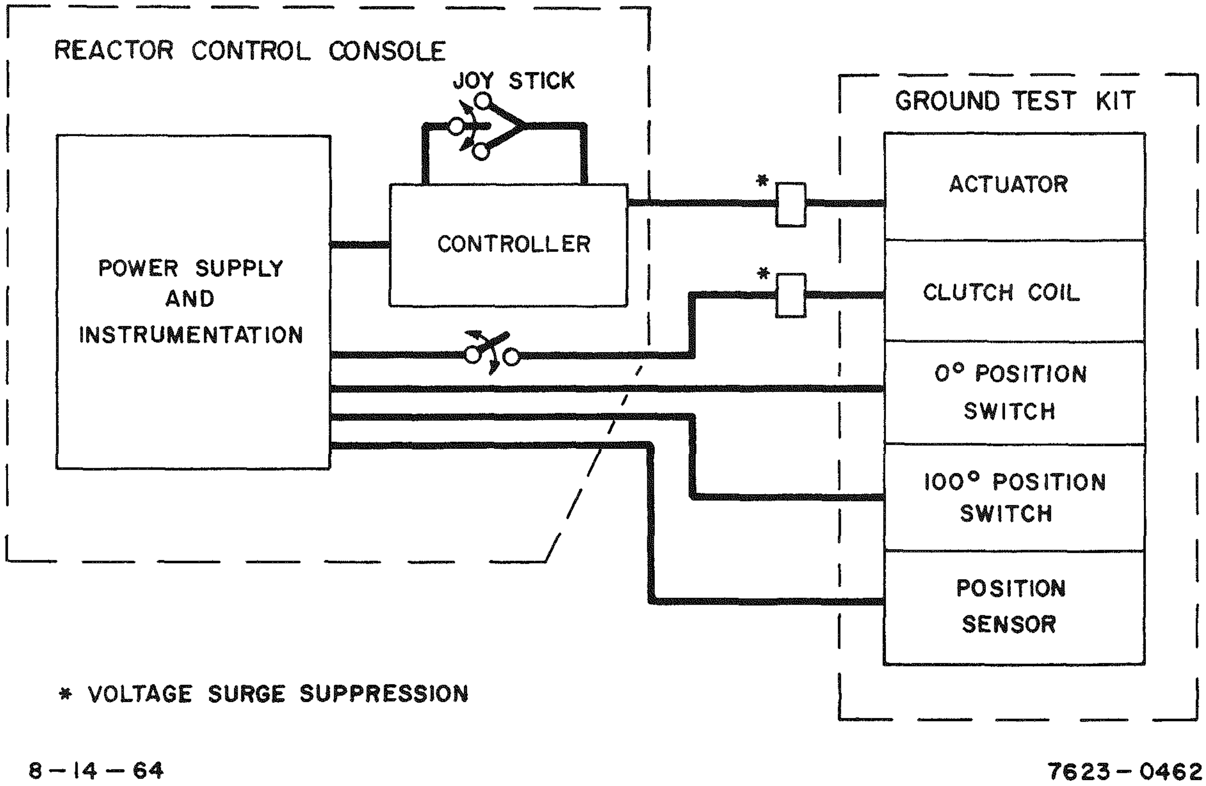

Figure 4. Ground Test Kit Control Diagram

The motor is a direct-current, stepping, reluctance-type machine. The armature has 50 poles and the field structure has a pitch of 48 poles. The poles of the field structure are energized by eight coil sets. As the program controller selectively energizes the field coils sequentially, new poles align causing rotation in discrete steps. Each discrete step is 1.8° which is sequenced by the controller in sets of four steps for 7.2° rotation of the motor shaft.

The worm-to-worm wheel has a 80:1 transmission ratio. The worm gears have a 2° 26' lead angle and the profile of the worm and worm wheels are cylindrical. Both gears are coated with a dry film. The design is such that the worm wheel is self-locking to the worm and will move only when the worm is driven.

The clutch coil, which is stationary, produces a magnetic field when energized. This magnetic flux is carried through the rotor which is keyed to the gear shaft. The magnetic flux attracts and holds the clutch armature which is connected by a bellows to the kit output shaft. The clutch rotor and armature

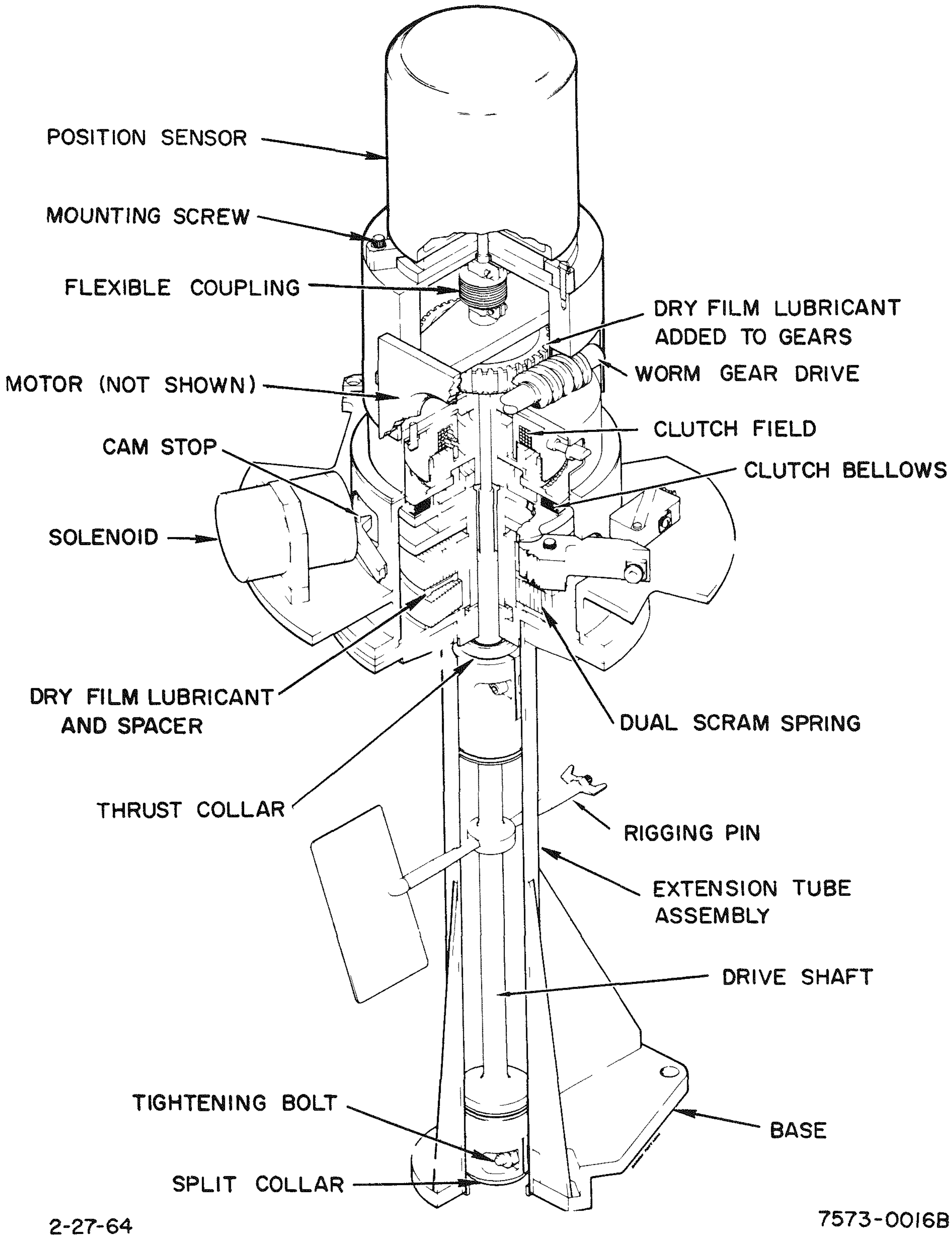

Figure 5. Ground Test Kit – Final Design

contact faces are serrated which provides for greater transmission torque as well as providing a throw-out force for disengagement when deenergized if the scram springs have energy stored.

A pair of clock-type scram springs store energy when wound up with the output shaft. When the clutch is disengaged, the power springs drive the output shaft out to 105° from the full-in drum position. The snubbing mechanism consists of cams that are attached to the kit output shaft and spring-loaded cam followers that cushion the scram momentum from 105 to 135° out. A rigid stop is fixed at 135°. A rebound stop located at 100° prevents the drum from reinserting after scram. This rebound stop is held out with a solenoid during normal drive operation.

A position sensor head is mounted atop the kit. This head encloses two independent sensors. One is a potentiometer type and one is a selsyn type. The position sensor shaft is coupled to the kit output shaft by the inner shaft of a coaxial shaft pair. The gear drive and clutch shafting are on the outer shaft of the coaxial pair.

The long shafting and support from the reflector to the kit mechanism provides clearance for other reactor hardware. The extension shaft also is designed to act as a spring during scram impacts. The extension drive shaft has two flexible bellows elements to accommodate misalignment. A rigging pin is provided for assembly and disassembly to minimize end loading of the kit mechanism.

b. Development and Operational Tests

To demonstrate performance of SNAP 10A, a total of eight prototype and qualification systems were built and tested; three of these were devoted to purely structural tests, three were prototype thermal-vacuum performance tests, and two were final complete system qualification tests.[7] The latter two systems consisted of a nonnuclear unit, SNAP 10 Flight System Mockup 4 (S10FSM-4) (the reactor core was replaced by an electrical heater, but in all other respects the system was identical to the flight units), SNAP 10 Flight System (S10FS-3), identical to the flight units. These two systems were subjected to the complete spectrum of tests including initial performance record measurements, full qualification-level shock and vibration, transient startup tests, and long-term endurance testing in a simulated space environment. Test results from these two qualification systems, especially S10FS-3 which completed a totally successful continuous 10,000 hour endurance test, have been used extensively throughout this report to analyze flight system performance. The final test was SNAPSHOT which was launched into a 700-mile orbit and operated successfully for 43 days before being shut down.

(1) System Tests

(a) SNAP 10 Developmental Reactor Mockup (S10DRM) Tests

The prototype thermal-vacuum test reactors were designated as SNAP 10 Development Reactor Mockups. The reactors were subjected to pre-launch checkouts, simulated shock and vibration loads, and nonnuclear thermal-vacuum operation tests. Control systems were operated under simulated reactor startup and flight conditions. Information gained was used to upgrade final flight system designs.

(b) SNAP 10 Flight System 3 (S10FS-3) Nuclear Ground Test

The S10FS-3 reactor system operated for more than 10,000 hours at full power in a demonstration of the SNAP 10 long-term reliability. The test was initiated on January 22, 1965 and continued in operation until the test was concluded on March 15, 1966.[8]

The coarse drum snap-in springs in S10FS-3 were replaced with the ground test drive and scram kit. The coarse drums were therefore driven into the full-in position rather than being snapped in. A normal startup procedure was then followed with the fine control drums being stepped in at a rate of 0.5°/150 sec. Initial closure of the temperature switch, terminating continuous drum stepping, occurred with an NaK outlet temperature of 1054°F. The switch reopened following a temperature drop to 1032°F at which time two additional drum steps were made. The two-step sequence became typical during active control operation and was attributed to slower than expected response of the temperature switch.

After 72 hours of active control, the controller was deenergized and the reactor operated on a static control mode. About one year later, the control system was reactivated to step the drums in and raise the power level. Despite the year-long dwell, the reflector drive system functioned properly and exhibited no signs of self-welding or sticking of any component.

During steady-state operation, the reflector temperatures stabilized at 620°F, the actuator stepper motors at 530°F, and the position sensors at 370°F. The test chamber caused significant neutron back scatter and resulted in an integrated dose of over 1.5×10^{19} nvt fast neutrons and 1.5×10^{10} R gamma. The drum limit switches performed satisfactorily, but the position sensors experienced slightly more drift than anticipated although they functioned within acceptable levels.

At the conclusion of the test, shutdown was accomplished by driving the fine control drums out. The drive system operated satisfactorily throughout the entire test. Following shutdown the electrically actuated band release device (EABRD) was energized and the reflector retaining band released as required. The reflector assemblies were not spring loaded for the test and were not separated.

(c) SNAP 10 Flight System 4 (S10FS-4), SNAPSHOT

The SNAP 10FS-4 nuclear reactor and its direct conversion thermoelectric system were launched into earth orbit on April 3, 1965, to become the world's first space nuclear power system.[9] The system operated for 43 days at its rated power (500 to 600 watts electric) prior to being shutdown. Figure 6 shows the assembled system prior to launch.

Following establishment of a 700-mile, 3800-year life orbit the reactor was given a startup command. The drum lock squibs were fired, the coarse control drums snapped in, and an active control period was initiated which lasted 154 hours. During this period, the actuators, control drive mechanism, and all sensors and switches functioned properly. The reflector control drum temperature stabilized at approximately 620°F once steady-state operation was attained.

Following 43 days of operation, a signal from the Agena vehicle initiated reactor shutdown. The reflector halves were ejected on command, shutting down the system. Telemetry data indicated all systems functioned properly and

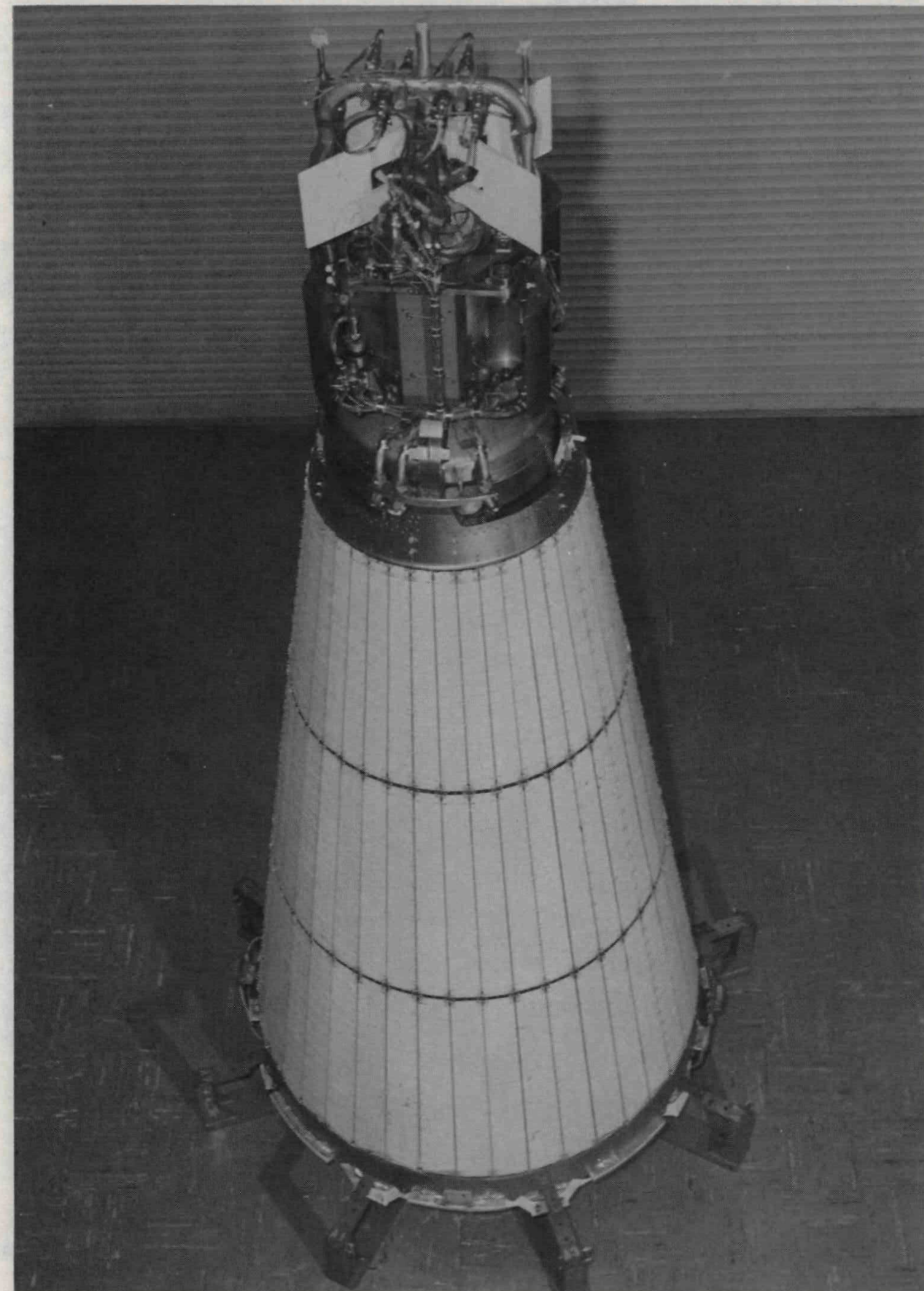

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Figure 6. S10FS-4 Reactor System

no signs of self-welding due to ultra high space vacuum were encountered. The reflector control system operated satisfactorily throughout the test.

(2) Components and Subsystems

Each component in the reflector and control-drum-drive assembly went through development and qualification testing. Components were subjected to thermal-vacuum endurance tests and simulated launch shock and vibration loads.

Design development and qualification of the actuator stepper motors are discussed in detail in AI-AEC-13080.[5] Final design actuators received life performance tests at 800°F or above, and 10^{-6} torr air in excess of 10,000 hours. Additional units were subjected to radiation environment operational tests, and full shock and vibration launch qualification.

The control drum support bearings and their development history are discussed in AI-AEC-13079.[10] The final design bearings, titanium shafts and sockets coated with Al_2O_3 and lubricated with MoS_2 dry-film lubricant against solid titanium carbide (with nickel binder) balls, underwent thermal vacuum testing in excess of 2500 hours, and simulated launch shock and vibration load testing with satisfactory performance.

The manufacturability of gears for SNAP 10A was investigated using materials that appeared to offer favorable low self-welding or adhesion characteristics. Manufacture of gears of titanium, nitrided titanium, and Haynes Alloy 90 was successful, and titanium was selected for S10A gears. Later materials friction tests showed that the self-welding properties of titanium are as satisfactory as those of other materials, thus supporting the titanium selection. Also, titanium has weight and low nuclear scatter cross section advantages. Attempts were made to manufacture pinions of Stellite 6B, plasma-sprayed aluminum oxide on Inconel X, plasma-sprayed titanium carbide on Inconel X, vapor-deposited aluminum oxide on titanium, and sintered nickel plus carbon. The Stellite 6B pinions and the sintered nickel-carbon pinions were manufactured satisfactorily. The nickel-carbon pinion, however, fractured during the initial startup portion of an operational test at 10^{-5} torr and elevated temperature. Attempts to manufacture the pinions using plasma-sprayed coating were totally unsuccessful in maintaining accuracy or adherence

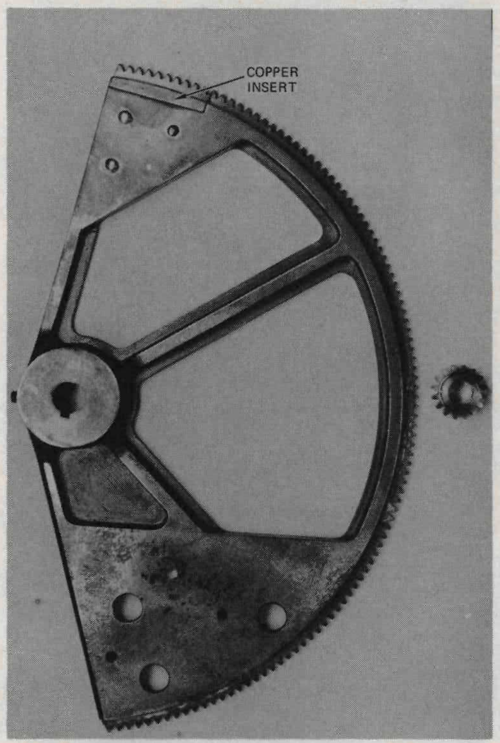

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Figure 7. S10A Drum-Drive Gear Set

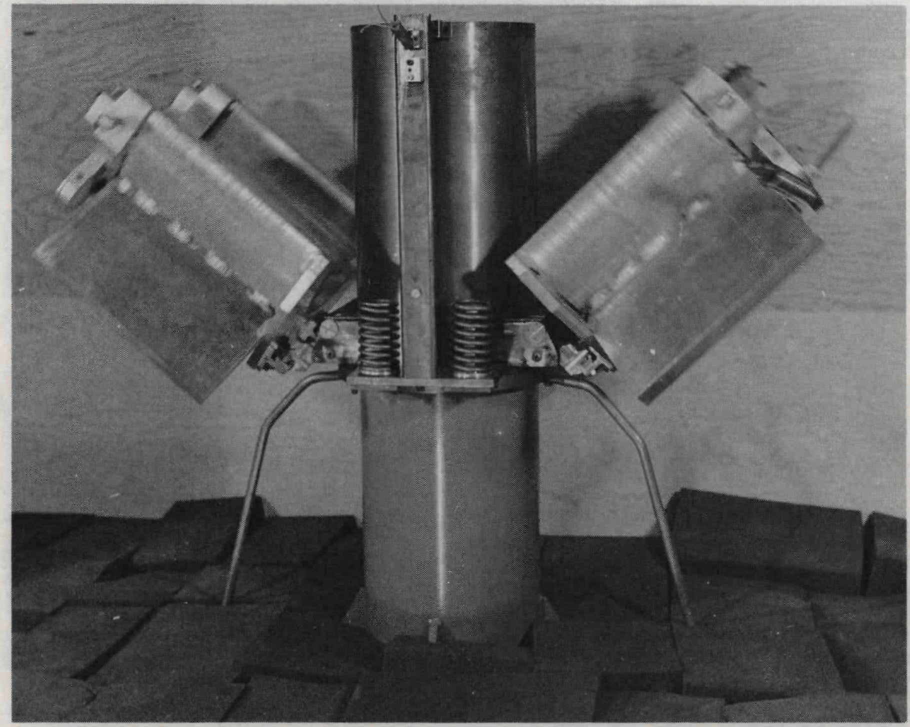

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Figure 8. Reflector Halves During Ejection

of coating. Of these special materials, Stellite 6B was the only successful pinion manufactured. Friction tests of material samples of Stellite 6B plus dry-film lubricant against metal showed promise and this material selection was followed. Figure 7 shows the reference design gear set. The pinion is made of Haynes Stellite 6B and the gear is made of titanium (Ti-6Al, 4V), with a soft copper insert in the area of pinion contact during launch conditions.

Two performance tests were run on the final gear design. The first operated 430 hours at 800°F and 10^{-5} torr. The second consisted of gear operation before and after a 90-day dwell at 700°F and 10^{-9} torr. Both tests were successful and no signs of wear or self-welding were encountered.

A mass mockup of the reactor core and reflector halves was built for feasibility testing of the End of Life separation system.[11] Figure 8 illustrates initial tests conducted showing the reflectors being ejected after the reflector retaining band was released.

Dynamics of the integrated scram test kit system were evaluated through a series of tests:[6] A number of developmental tests, eight acceptance tests, and two qualification tests were performed with system dynamics monitored. The test fixture utilized simulated reflector control drums and prototype drum bearings. Tests were performed at laboratory ambient conditions and at 10^{-3} torr vacuum. A series of system torques were measured as listed below.

1) Stepper Motor-Transmission Mechanical Drag Torque - These torques were taken by driving the deenergized motor with a torque meter with the clutch disengaged. Acceptable values ranged from 6 to 15 in.-oz.

2) System Mechanical Drag Torque - These torques were taken by driving the deenergized motor with a torque meter with the clutch engaged. Acceptable values ranged from 46 to 63 in.-oz. to drive to the full-in drum position. Typical data are shown in Figure 9.

3) Spring Torque - These torques were measured by driving the output shaft with a torque meter with the clutch disengaged. Acceptable values ranged from 15 to 19 in.-lb. Typical data are shown in Figure 10.

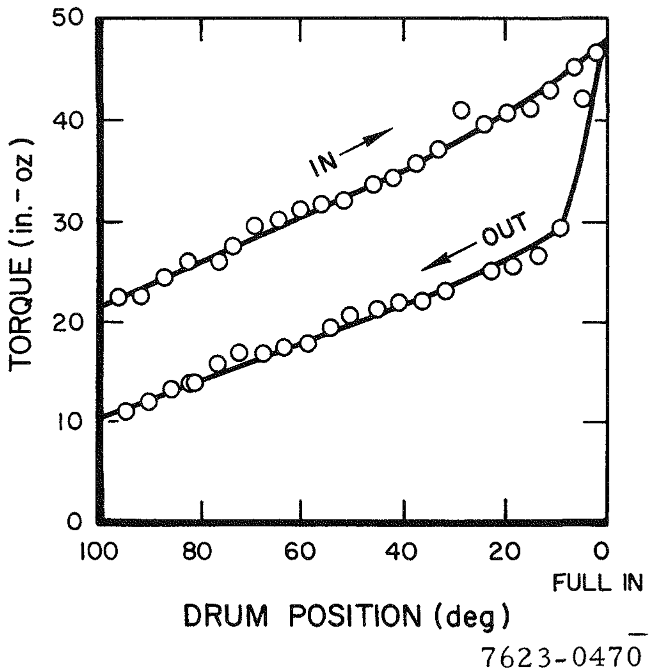

Figure 9. SNAP 10A Scram Kit Mechanical Drag Torque

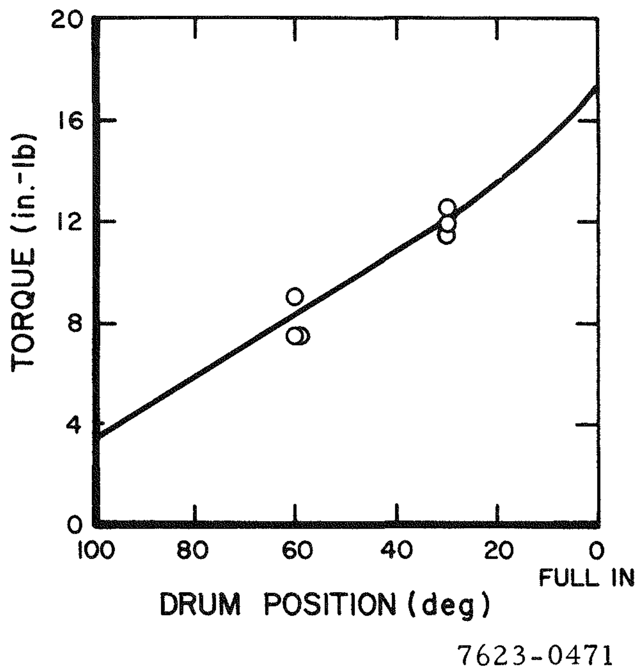

Figure 10. SNAP 10A Scram Spring Torque

4) System Stall Torque - These torques were taken by electrically driving the stepper motor with the clutch engaged and measuring an externally imposed output load at stall. These values ranged from 27 to 41 in. -lb with stepper motor current set at 1.7 amp.

Comparison of the stepper-motor transmission mechanical drag torques to typical values served to isolate any drag problems. Evaluation of the spring torques and the system stall torques would indicate that the system-required torque was comparable to available torque. Average ratios of available torque to required torque were 33:18 or 183%. This indicates the available torque had about 83% safety margin over required torque.

Scram dynamics showed consistent reproducibility of scram from 0° full-in to 100° out within less than the maximum allowable 300 msec. Scrams through angles less than 100° were also well within the required maximum time. The effect of ambient pressure upon scram time showed that scrams in vacuum were about 5 msec faster. This was probably caused by windage effect. Thirty-one (31) scrams each on eight GTK acceptance tests concluded the test program, resulting in over 2650 scram attempts with no failures on the final design GTK.

A description and development history of components that are not part of the drive train is given in a section on miscellaneous components later in this report.

2. SNAP 2

The SNAP 2 Control Drum Drive Assembly is shown in Figure 11.

a. Description and Features

As with the SNAP 10A reactor system, the SNAP 2 utilizes a four-drum control drive assembly.[3] Two drums are spring-loaded coarse control drums and two are stepper-motor-driven fine control drums. The reflector assembly is separated into two halves which are mounted on springs for end-of-life separation, and held together by a steel band during operational life.

The SNAP 2 reactor system was basically a SNAP 10A system upgraded from 500 watts electrical to 3 kwe power output. The SNAP 2 reactor was to be used with the mercury-Rankine cycle turbogenerator in place of the thermoelectric modules of SNAP 10A.

The control-drum support bearings configuration was unchanged from SNAP 10, but a material change was incorporated based on continuing test programs. The reference bearing couple was upgraded to use a composite ball with P5-N carbon-graphite inserts while retaining the Al_2O_3 coated titanium shaft and socket assembly.

b. Development and Operational Tests

(1) SNAP 2 Developmental Reactor Mockup (S2DRM) System Test

The SNAP 2 Development Reactor Mockup No. 1 (S2DRM-1) test program was designed to demonstrate the ability of the complete reactor system and shield to meet system requirements at the qualification test levels, to gain sufficient operating time to establish system endurance confidence, and to improve the quality of marginal components through development.[12] The test sequence was designed to simulate the nonnuclear conditions of the SNAP 2 reactor system from final assembly through launch and 90 days operation in earth orbit.

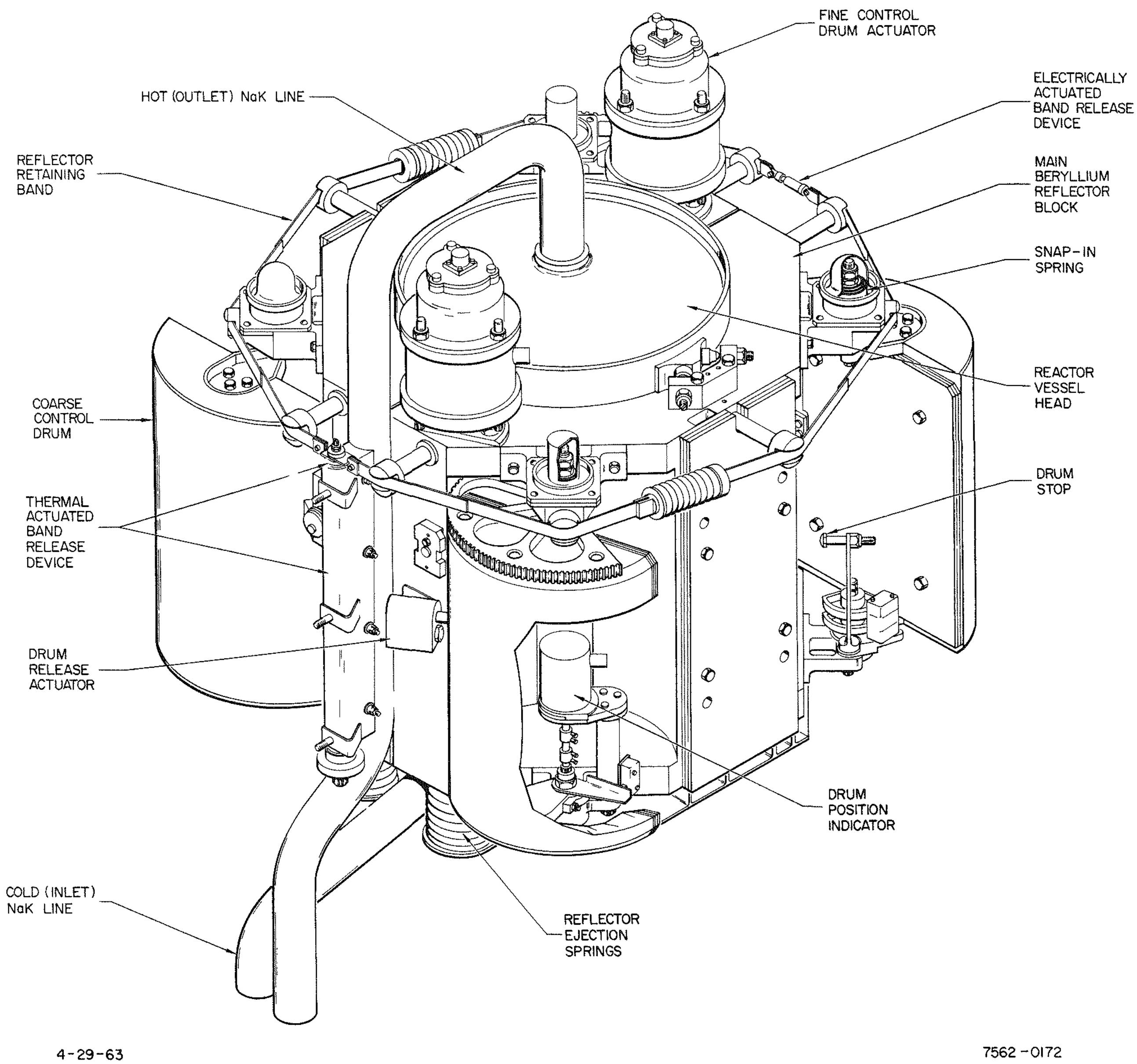

Figure 11. SNAP 2 Reactor Control-Drum-Drive System

The S2DRM-1 reactor system consisted of a reactor vessel with the top head, grid plates, dummy fuel elements, internal reflectors, the reflector assembly, the shield assembly, and the reactor inlet and outlet NaK lines. Support structures were required for vibration and thermal vacuum tests. The radiator-condenser heat simulator and the reactor heat simulator became part of these structures. The heat simulator was designed to heat NaK and to pump it through the reactor vessel and coolant lines. Flow was opposite that of the flight system to maintain the outlet NaK temperature above the inlet temperature—the condition existing during reactor operation.

The S2DRM-1 system tests consisted of (1) reflector thermal-vacuum tests; (2) launch simulation vibration and shock tests; (3) NaK loading tests; and (4) simulated operational tests. In the reflector thermal-vacuum test, the S2DRM-1 reflector assembly was attached to a test reactor vessel and placed in a small vacuum chamber. Electrical heating units in the reactor vessel simulated the thermal input to the reflector assembly. The temperature actuated band release device (TABRD) was attached to a simulated NaK outlet line containing a heating element. SNAP 10A stepper motors were used to drive the control drums during operation. The vacuum test chamber was capable of maintaining a pressure in the 10^{-6} torr range throughout testing.

One acceptance level and two simulated hot-critical thermal-vacuum tests were conducted during December 1964. The test included operation of the control drums at room temperature and operating temperature (1200°F). The assembly was also thermally cycled from room temperature to 1200°F at about 6°F/min simultaneously with drum operation, three times per test sequence. The reflector assembly thermal transients achieved during the tests were comparable to these observed for SNAP 10A reactor tests. There was no indication of degradation or malfunction of the reflector assembly during any test phase.

The complete S2DRM-1 reactor system, consisting of the reactor vessel and internals, the reflector assembly, the NaK inlet and outlet lines, and the shield, were mounted to a vibration test fixture and subjected to loads simulating launch and placement into orbit. The reactor vessel and NaK lines were filled with distilled water to simulate the damping effects of NaK. Figure 12 shows the test setup.

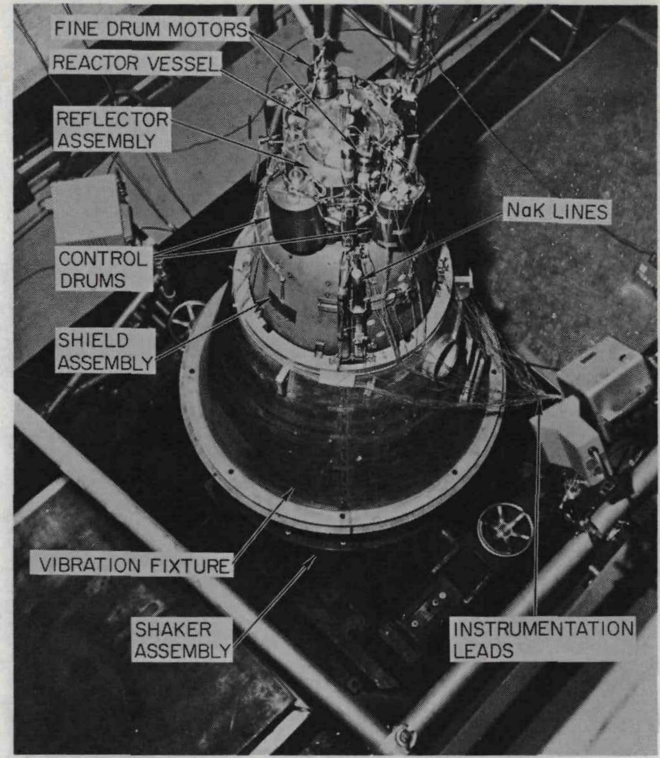

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Figure 12. S2DRM-1 Reactor System Vibration Test

The reactor system was subjected to vibration inputs along the X (longitudinal) and Y and Z (lateral) axes. A single sinusoidal sweep was conducted in each axis from low to high frequencies at a constant octave sweep rate in 45 min. Vibration inputs were measured by accelerometers at the lower mounting bracket. The input levels are given in Table 2.

A preliminary low level (less than 1 g) survey was conducted to map resonant frequencies prior to the specified vibration test. The reactor and shield response was limited to the above levels by an accelerometer on the reactor top head.

Two shocks in each axis were also conducted in the form of a half sine wave of 8 msec duration. The input levels of 5.5 g (X axis) and 1.5 g (Y and Z axes) were measured at the shield mounting ring.

The maximum transmissibilities for the reactor-reflector structure were determined and are shown in Table 3.

TABLE 2

S2DRM VIBRATION INPUTS

Axis	Frequency (Hz)	Load
X	5 to 12	1/2 in. ± 10% (double amplitude)
	24 to 400	3.5g ± 7%
	400 to 2000	7.5g ± 5%
Y and Z	5 to 10	1/2 in. ± 10% (double amplitude)
	10 to 250	2.5g ± 7%
	400 to 2000	7.5g ± 5%

TABLE 3

S2DRM Vibration Response

	Input Axis	Input Frequency (Hz)	Maximum Transmissibility
Reactor vessel top head vs input at shield mounting brackets	X-X	240	8
	Y-Y	50	12
	Z-Z	70	21
Reactor vessel top head vs reflector support ring	X-X	240	2.7
	Y-Y	50	2.6
	Z-Z	70	2.3
Reflector support ring vs input at shield mounting brackets	X-X	250	3
	Y-Y	50	4.6
	Z-Z	70	9
Reflector top vs input at shield mounting bracket	X-X	70	10
	Y-Y	70	12.5
	Z-Z	70	20.0

Control drum response was similar to the reactor-reflector structure in the Y and Z axes, and 1/2 the natural frequency and transmissibility in the X-X axis. A performance test of mechanical, electrical, and operational items was made prior to and following each vibration and shock test. No failures occurred. The S2DRM-1 demonstrated its ability to withstand launch shock and vibration loads without any detectable failure or degradation.

The S2DRM-1 system, without the reflector assembly, was installed in a vacuum system and loaded with NaK. No problems were encountered. The reflector assembly was then added to the system to complete the full S2DRM-1 assembly. NaK flow during thermal-vacuum testing was reversed to obtain NaK outlet temperature above the inlet temperature consistent with an operating reactor. The radiator-condenser heat simulator was added to the system. This test setup is shown in Figure 13.

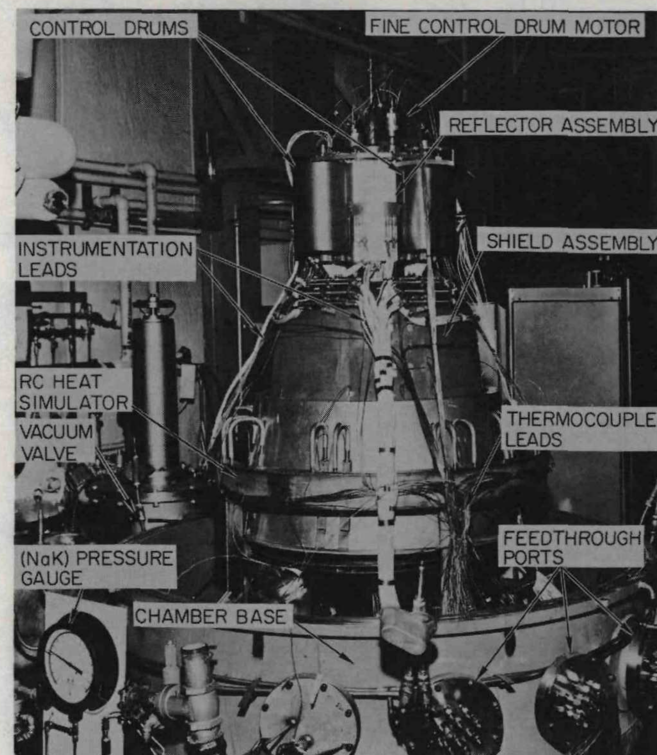

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Figure 13. S2DRM-1 Thermal Vacuum Test

The vacuum system consisted of the large test chamber with eight instrumentation ports and two 16 -in. oil diffusion pumps. The diffusion pumps were valved off for ultra-high vacuum operation to eliminate oil back-streaming. The ultra high vacuum system utilized a titanium depositing getter pump and two 1000 liter/sec ion pumps.

The outlet NaK was stabilized at 1170°F and the inlet at 1080°F instead of with the required 200°F ΔT due to NaK pressurization and flow problems. Subsequent problems resulted in failure of three NaK heaters after approximately 20 days operation with the NaK system above 1000°F and chamber pressure in the low 10^{-7} torr range. As a precaution against NaK line failures and leakage, the test was terminated.

A post-test performance evaluation and inspection of the components was conducted to study the effects of combined S2DRM-1 testing. No significant movement of the reflectors and components occurred. The torque measurements indicated no degradation of coarse control-drum bearings or snap-in springs. No problems were encountered with operation of either fine control drum. The drums position sensors showed no signs of failure or degradation and drum position switches operated satisfactorily throughout testing.

The drum release actuators survived launch simulation. All squibs (Type M130) fired and all actuators released the control drums upon startup command. The snubber had expanded and locked inside the striker, as expected.

The S2DRM-1 reflector assembly performed without incident throughout the full vibration and thermal-vacuum test sequence.

(2) Components and Subsystems

The reflector control system components were basically SNAP 10A components with modifications to guarantee operation under the increased life and temperature requirements of SNAP 2. Tests on individual components were limited and were conducted in conjunction with SNAP 10A component tests. The S2DRM-1 test was the principal component proof test.

2. SNAP 8 Developmental Reactor Mockup (S8DRM)

The S8DRM reflector system is shown in Figure 14.

a. Description and Features

The S8DRM reflector assembly is based on a six-control-drum concept instead of the four-drum concept of SNAP 10A and 2.[13] Three of the drums are spring driven to snap in to the full-in position during reactor startup. The remaining three control drums are motor driven using the variable reluctance

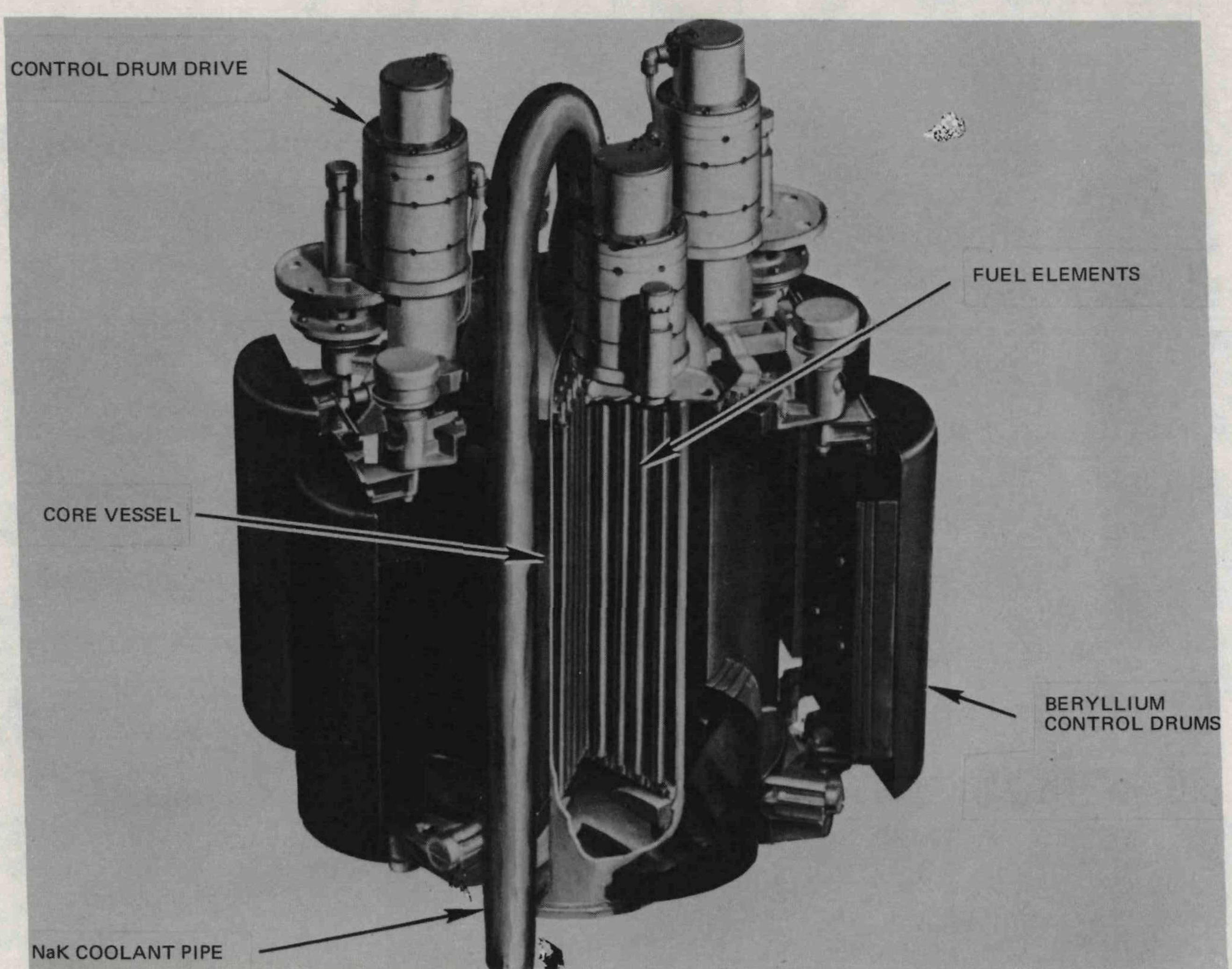

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Figure 14. S8DRM Reflector Control System

stepper motor developed for SNAP 10. The spring-driven and motor-driven drums are alternated and the reflector assembly is split into two halves, spring loaded, and held together by a retaining band similar to those on SNAP 10 and 2.

The S8DRM-1 was designed as a flight prototype system without live fuel elements and was used to (1) qualify the design for flight applications, (2) test fabrication techniques, (3) demonstrate the ability of the SNAP 8 system to operate in a simulated space environment for up to 10,000 hours following simulated launch conditions.

(1) Reflector and Control Drums

The S8DRM reflector assembly consists of two halves, fabricated of beryllium and mounted on an Inconel plate supported from the core vessel. This support plate holds both the fixed reflector segments and the lower bearing housings.[14] Each reflector half contains three movable drums that provide a nominal 3-in.-thick beryllium cylinder when the drums are in their full-in position. The fixed reflector portions were designed to support the reflector retaining band. The support structure incorporates the shutdown pivot joint and is spring loaded for end of life (EOL) separation.

The beryllium was hot pressed, stress relieved, final machined, and anodized to provide a constant emissivity surface of 0.7 or better. The drums were designed with a 0.060-in. clearance between the rotating and fixed reflectors. Each drum is provided with the capability of accepting varying thickness shims on the flat side to allow precise fixing of the neutron reflectance during criticality tests.

(2) Control-Drum Drive

Each control drum is mounted on a pair of spherical self-aligning bearings similar to those of SNAP 10 and 2. The reference bearing couple of S8DRM consists of an Al_2O_3 against P5-N carbon graphite journal couple, and an Al_2O_3 against MoS_2 dry-film-coated Al_2O_3 self-aligning socket assembly. In all cases, the Al_2O_3 substrate material is Inconel-750.

The spring-driven drums use an Inconel-750 torsion spring pre-torqued to 16-in-lb. and captured in an Inconel housing. Upon startup command, a squib-fired, drum-release actuator, similar to that of SNAP 10, is fired, the locking pin is released, and the drum snaps to the full-in position. A snubber spring and latch are incorporated in the design to stop the drum at its full-in position and lock it in place.

The motor-driven control drums use the variable-reluctance type of stepping motor developed for SNAP 10 and 2. The motor is based on a four coil design operating on 28 vdc. Sequential energizing of the four coils results in a 1.8° step. The control mode is based on a 4 pulse, 7.2° step sequence. A sequence consists of energizing the first coil, releasing the brake by energizing it, and energizing the other three motor windings in sequence. The brake is then relocked prior to deenergizing the 4th motor winding.

The motor drives the control drums through a 13.8-1 gear ratio resulting in a 0.52° step of the control drum for each 7.2° step actuator sequence. The large drive gear is driven by the actuator motor pinion and is supported off the actuator housing. The gear is fabricated of Inconel-750 and the support bearing shaft is Al_2O_3 coated and rides in a P5-N bushing press-fitted in the actuator end bell. The gear is coupled to the control-drum-drive shaft through a flexible coupling to compensate for misalignment. The gear teeth are coated with MoS_2 dry-film lubricant to prevent self-welding and provide low friction operation.

(3) End-of-Life Shutdown

The basic end-of-life shutdown mode is through separation of a metal band which holds the reflector halves together, and ejection of the two reflector halves. The band, made of 0.036-in-thick 0.625 in. -wide, Type 316 stainless steel is spring loaded in 2 places to compensate for normal thermal expansion during operation and is mounted on ceramic standoffs to prevent self-welding prior to EOL separation. A T-bolt fixture is included in the band to adjust the spring load for proper tension for launch load survival without overstressing the expansion compensation springs or the EOL actuation devices. Each reflector half is pre-loaded on two 360-lb force springs which will cause each reflector half to swing out 15° to the pivot disengaging point and be ejected. The springs are fabricated from Rene 41 and are designed to survive creep under a 1000°F, radiation environment for 10,000 hours. The reflector retaining band can be separated by three separate techniques as with the SNAP 10A system.

(4) Ground Test Scram Kit

The ground test scram mechanism designed for SNAP 8 differed from that of SNAP 10 in that it is a "plug-in" unit which retains the actuator motor for normal in and out of rotation of the control drum, and provides only a torsion spring drive to scram the drum "out" in the event of an emergency.[3] The mechanism is shown in Figure 15 and consists of the scram spring, a clutch and brake assembly to hold the spring in its cocked position, a drive shaft assembly which attaches to the control drum gear, and a snubber to absorb the drum momentum and stop it following scramming.[15] In addition, there are several position switches for diagnostic purposes.

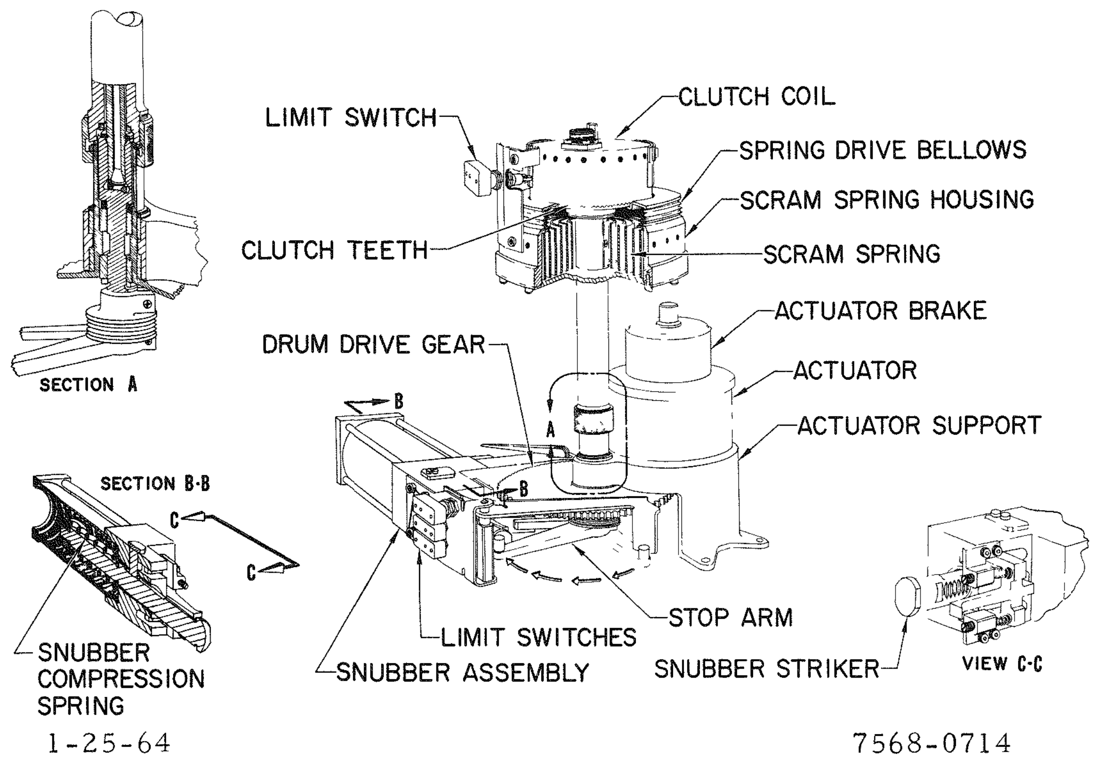

Figure 15. SNAP 8 Reflector Drive System Scram Kit

The scram spring and its release clutch operate through double concentric shafts. The outer tube of the double shaft is attached to the lower half of the clutch, and extends downward to attach to the gear. The inner shaft is attached to the upper half of the clutch, and extends down to attach to the drum through a flexible coupling. The lower portion of the clutch assembly contains the clock-type scram spring. The outside end of the spring is connected to the spring housing. The inside end of the spring is attached to the inner shaft. Prior to operation, the spring is prewound by the actuator and the energy locked in by energizing the clutch solenoid and closing the clutch.

Under normal operation, the entire clutch assembly is locked together and functions or rotates as a single unit. The energy for scramming the drum is locked in and does not impose any drag on the drum except for a small inertia effect. The normal drive path from the actuator is through the rotor pinion, through the large diameter drive gear, up through the outer tube, through the clutch housings, and down to the drum through the inner shaft.

To scram the drum, the current to the actuator brake and the current to the clutch solenoid are interrupted simultaneously. The actuator brake locks the rotor upon loss of power, and the clutch disengages upon loss of power. Locking the actuator also locks the pinion and gear, the outer tube, and the lower housing of the clutch, all of which are directly coupled to the motor and brake shaft. With the clutch disengaged, the scram spring drives the inner shaft causing the control drum to rotate away from the core, thereby shutting down the reactor.

After the drum reaches the full-out (180°) position, it engages a spring-loaded snubber shaft which absorbs its rotational energy. The energy of the scrammed drum is absorbed by a spring in the snubber assembly. After completing its travel, the spring is prevented from returning by the action of a spring-loaded ratchet. The ratchet engages the one-way teeth of the integral ratch of the snubber shaft.

Before restarting the reactor, the scram spring is rewound by the actuator. With clutch deenergized and open, the actuator is driven in the proper direction to step the drum out; but because the drum cannot rotate outward any further due to the fact it is being held by the snubber, only the outer shaft and the spring housing can rotate, thus rewinding the spring. When the spring is fully wound, a microswitch mounted on the spring housing is depressed by a cam on the clutch housing. The clutch is then energized and closed again, holding the torque of the spring. The drum may then be rotated inward. After the control drum is out of the snubber zone, a ratchet dog trips the snubber ratchet which releases the compressed snubber spring. The release of this spring is, in turn, damped by the snubber release damping spring.

Three limit switches are mounted on a bracket attached to the snubber assembly. One of the switches indicates when the control drum nears the full-in position. The other two switches indicate when the drum is in the full-out (180°) position and when the drum is beyond the full-out position in the snubber zone.

This drive mechanism is failsafe because a power failure interrupting the motor brake power and the clutch power will automatically result in drum scram. Also, in the event of burnout of the clutch coil, this mechanism will automatically scram the control drum, and in the event of burnout of the brake coil the drum can still be scrammed.

The basic specifications of the drive-scram mechanism are given in Table 4. The drive system of the final design for the scram mechanism is kinematically similar to the proof-of-principle scram drive. It has some design improvements which were derived from the testing of the proof-of-principle drive system. After extensive environmental testing it was found that the ratchet teeth and pawl of the snubber assembly were considerably worn due to the vacuum and temperature environment. The ratchet teeth and pawl were therefore coated with a high temperature, cobalt-base, wear-resisting material. This hardface coating can be applied by shielded arcwelding, is machinable, and is relatively ductile.

The maximum stress of the scram drive motor spring was reduced from 40,000 to 20,000 psi. This change was made in order to reduce the rate of spring relaxation during long-term (S8DS) operation. The clearance between the spring coils was also increased in order to reduce the friction caused by the relative motion of adjacent coils during scramming. During bench testing of the development scram drive it was noticed that, when the spring is fully wound, the tangential force of the outer spring coil tends to force the coils to shift eccentrically to one side. This "bunching" of the coils caused them to make contact and increased the friction torque of the scram drive. A centering blade was therefore added to the outer coil of the scram spring. This is a proven method of preventing the spring coils from making contact.

TABLE 4

CONTROL-DRUM-DRIVE SYSTEM SCRAM MECHANISM CHARACTERISTICS

Scram time	23° in < 0.5 sec
Scram velocity at maximum temperature	6.55 rad/sec
Scram acceleration at maximum temperature	19.5 rad/sec^2
Drum rotation range	0 to 135°
Snubber travel	26° drum rotation
Snubber deceleration (maximum) 1100°F	-153 rad/sec^2
Scram clutch data	
Holding torque	45 in. -lb
Voltage	28 dc
Amperage	1.5 (at 1000°F)
Scram spring data	
Material	René-41
Initial torque at operating temperature	19.0 in. -lb
Spring rate at operating temperature	0.1 lb/°
Maximum spring stress	20,200 psi
Calculated operating temperature	775°F
Friction torque	
Drum bushings only	2.5 in. -lb
Total drive system	6.0 in. -lb maximum
Control drum weight	26 lb
Bearing materials	
Bushings	Carbon graphite (Purebon P5N)
Shaft journal	Al_2O_3 coating on Inconel-X
Shaft materials	Inconel-X
Snubber spring material	René 41

The most critical components of the scram drive system are the scram spring and the release clutch. As mentioned earlier, the scram drive is designed to permit easy removal from the drum-drive control system. To permit this design feature, it was necessary to lengthen the scram shafts in order to locate the scram drive unit above the control drum actuator. Due to the increased distance from the reactor core vessel, the operating temperatures of the scram spring and release clutch were reduced from 1000 to 650°F.

The proof-of-principle scram drive clutch utilized slip rings for power connections. These connections were found to be unreliable due to the large variation in contact resistance which occurred between the brushes and the slip rings. The scram drive clutch now uses a flexible cable loop which is terminated with a high-temperature connector.

The S8DS upper control drum shaft was stress analyzed to see whether the shaft would yield in torsion if the snubber spring should break. It was found that the torsional yield of the shaft would be exceeded under this kind of failure. As a safety precaution, the snubber arm of the scram drive was therefore redesigned to absorb additional strain energy under impact. As a result of this change, the S8DS control drum shaft can absorb a scram from the drum full-in position against a stationary snubber shaft without damage.

b. System and Component Development Tests

The S8DRM-1 test program was designed to proof test the SNAP 8 reactor control system under nonnuclear conditions.[14] A block diagram of the planned test schedule is shown in Figure 16. The reactor assembly is shown in the vacuum chamber prior to performance testing in Figure 17.

The assembly test consisted of assembling the reactor and reflector system in the proper sequence, noting, and correcting improper fits or problems.

The performance record test checked critical dimensions and the operation of the S8DRM-1 system at ambient conditions. Hundreds of data points on the mechanical and electrical performance of control, safety, and diagnostic components were monitored. This procedure was used to check the assembly after each major test to assess the effect of that test and to define the condition of the assembly prior to the next test in the sequence.

The system met almost all the performance record requirements; but wiring harness, controller, and spring drive deficiencies were noted. The harness showed inadequate insulation at the connector pins and poor weld connections to the connector pins. A transistor in the controller failed and the design was

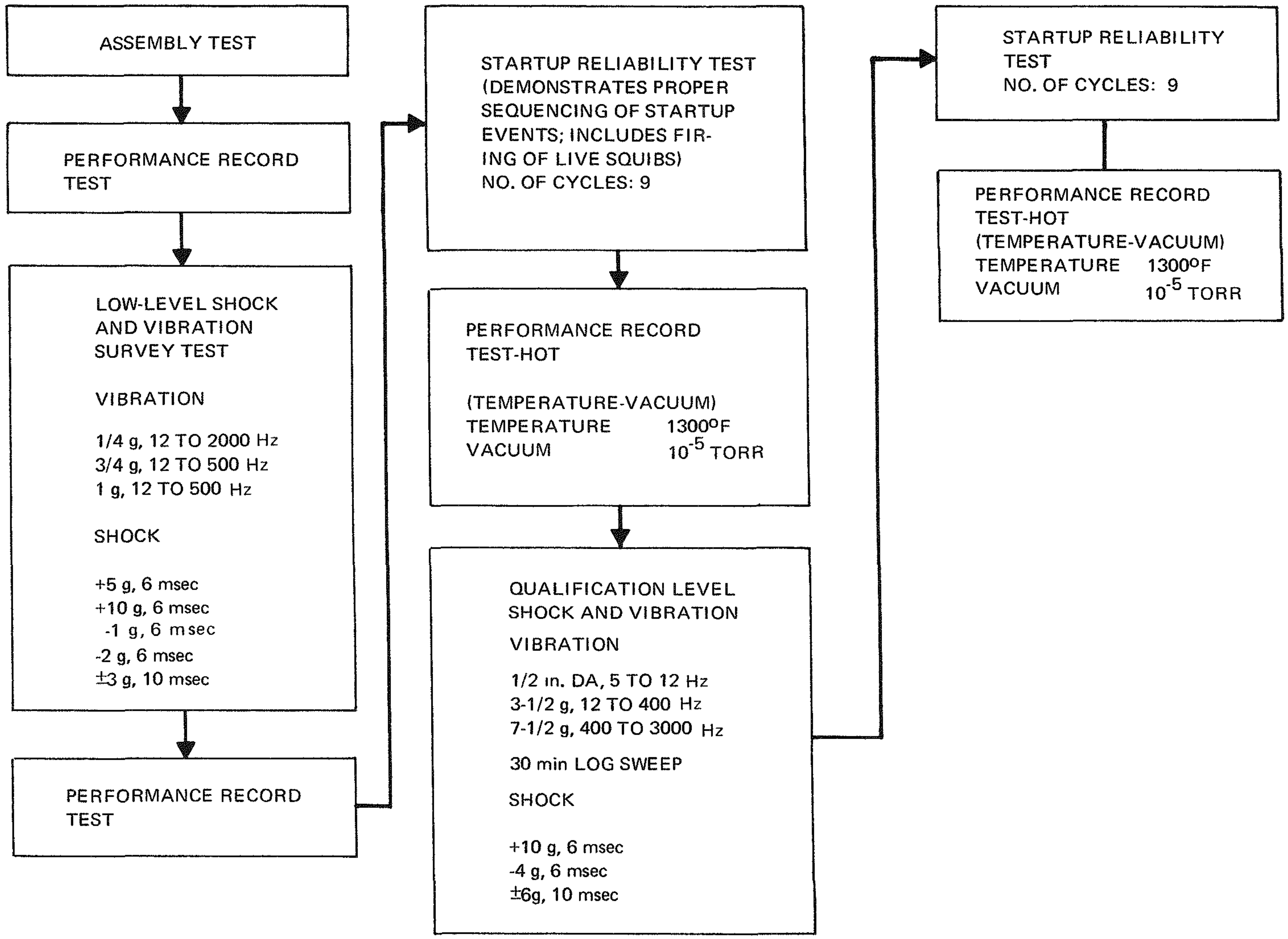

Figure 16. S8DRM-1 Nonnuclear Test Sequence

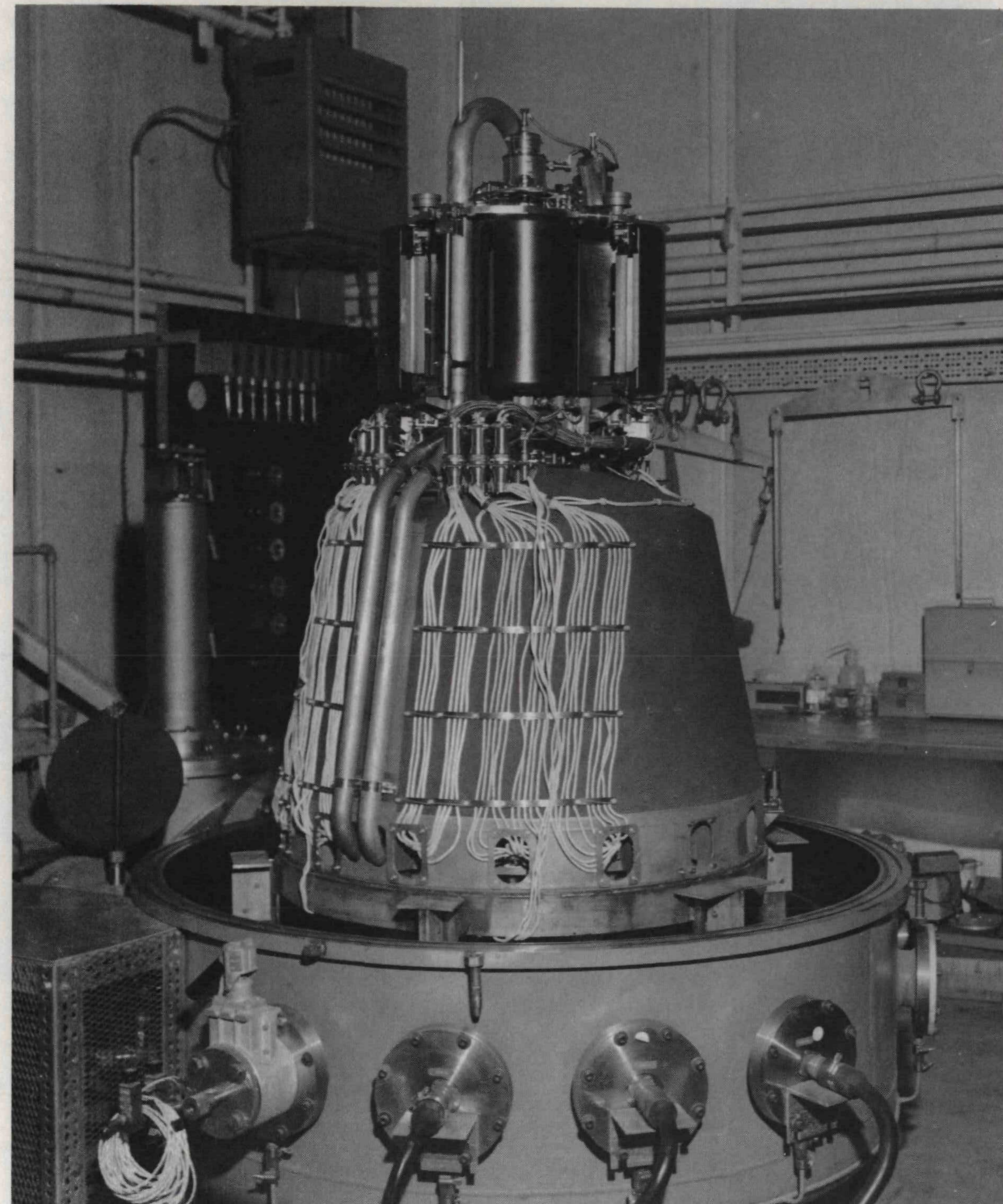

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Figure 17. S8DRM-1 Thermal-Vacuum Test Assembly

improved. Also, improper phase-excitation of actuator coils necessitated controller modification. The springs for the snap-in drums did not meet the requirements but were used in the testing to prevent a delay in the program. All other performance record requirements were met.

Initial low level shock and vibration surveys were conducted to determine resonant frequencies and attenuation factors. Surveys were made at 0.25 g (12 to 2000 Hz), and at 1 g (12 to 500 Hz) in all three axes sweeping at a constant octave rate. A series of half-sine-wave shocks were also run using inputs of 10 g maximum in the longitudinal axis and 3 g maximum in the lateral axis. Responses to the 1 g vibration inputs are shown in Table 5 for reflector assembly components.

TABLE 5

S8DRM-1 VIBRATION CHARACTERISTICS

Part	Response to 1-g Input		Expected* Maximum Response		Allowable g	
	X	Y(Z)	X	Y(Z)	X	Y(Z)
V Band Clamp	4.5	6.5	16	16	95	18
Control Drum Drive Bracket	4	13	14	33	100	100
Scram Pivot Bracket	4.5	6.5	16	16	23	100
Reflector Support Bracket	4.5	6.5	16	16	100	100
Bearing Housing	7	8.75	24.5	22		100
Reflector Support Structure	4	13	14	33	100	100
Reentry Band	14.5	47	51	117		

*At full launch loads extrapolated from 1 g input.

As a result of testing, several wire harness clamps failed and a new clamp was designed. Also, the ground safety keylock interlocks loosened and snapped into a test position.

Following vibration testing, the reactor assembly was placed in a thermal - vacuum chamber, dehumidified overnight, and given a Performance Record Test. All performance was met except that one drum stopped stepping at 90° from full-in. The small clearance in the bearing had packed with dry-film lubricant during vibration and had bound up. It was loosened for further testing and larger clearances were incorporated in a new bearing design. Finally, the reactor was disassembled, and weld areas were dye-penetrant or helium-leak checked as before with satisfactory results.

A series of nine startup reliability tests were conducted firing the lockout squibs each time and operating the control system through a simulated reactor startup. At the end of every three firings of the lockout squibs, a Standard Performance Record Test was conducted. Measurements of the shock imparted to components during squib firing were recorded. All sequences simulated a successful startup of the reactor although malfunctions of some components were noted.

A Hot Performance Record test was conducted to run the reflector control at operating temperatures in a vacuum prior to launch level shock and vibration testing and to determine assembly thermal gradients. A core heater was used to simulate nuclear heating, and it raised the system temperature at a rate of 100°F/min to an average core temperature of 1120°F in a chamber at 2×10^{-5} torr pressure. An orbital startup sequence was conducted, without squib firing, and component temperatures stabilized as noted in Table 6. The test sequence was completed without incident.

The entire system (reactor and neutron shield) was subjected to a shock and vibration launch test for purposes of determining component amplification factors, verifying component design related to shock and vibration characteristics, testing the adequacy of design of integrated components under a shock and vibration environment, and determining the ability of the integrated system to withstand this test environment. The information was utilized in the design

TABLE 6

S8DRM-1 COMPONENT TEMPERATURES AT STEADY STATE*

Component	Temperature (°F)
Reflector Support Structure	478
Reflector (fixed)	560
Control Drum (in full-out position)	399
Drum Bearings	469
Actuator	429
Ejection Springs	598
Position Sensor	444

*Drums in the full-out position

of subsequent SNAP 8 components and systems. Table 7 lists the shock and vibration test levels. No major component or structural member of the reflector assembly failed, however, three limit switches broke and two drive bellows failed. Following the launch vibration tests, a final startup reliability test was conducted.

Development testing of reflector components was a continuous effort and included upgrading of some SNAP 10A and 2 components as well as redesign of other components.

The S8DRM utilized an upgraded SNAP 10 actuator motor[5] and control-drum support bearings of configuration similar to SNAP 10, but of higher temperature materials developed in a continuous study of bearing material and friction properties.[10] Testing at 1000°F proved the Al_2O_3 against P5-N carbon-graphite and Al_2O_3 against MoS_2 dry-film-coated Al_2O_3 bearing couples to be satisfactory, but indicated a required coating substrate upgrading to Inconel-750.

The ground test scram mechanism (reference to Figure 15) underwent preliminary bench testing and demonstrated the feasibility of the basic design following some 140 scrams over 135 hours.

TABLE 7

S8DRM-1 LAUNCH VIBRATION AND SHOCK INPUTS

Vibration Test		
Direction	Magnitude	Frequency (Hz)
Longitudinal (X) Axis	0.5 g	12 to 700
Longitudinal (X) Axis	1.0 g	12 to 700
Lateral (Y and Z) Axes	0.5 g	12 to 700
Lateral (Y and Z) Axes	1.0 g	12 to 700
Longitudinal (X) Axis	1/2-in. double amplitude	5 to 12
	3.5 g	12 to 400
	7.5 g	400 to 3000
Lateral (Y and Z Axes)	1/2-in. double amplitude	5 to 10
	2.5 g	10 to 250
	5.0 g	250 to 400
	7.5 g	400 to 3000
Shock Test		
Axis	Magnitude (g, half sine wave)	Duration (msec)
Longitudinal (+X)	10	6
Longitudinal (-X)	4	6
Lateral (Y and Z), (±g)	6	10

Performance tests were conducted at 800°F and 10^{-5} torr and successfully met design requirements for 23° rotation within 0.5 sec and 105° rotation within 1 sec. During 115 scrams over a 640-hour period, scrams to a full 105° varied between 0.34 and 0.37 sec, well under requirements. Proof-of-life tests were conducted to several hours and 500 scrams minimum.

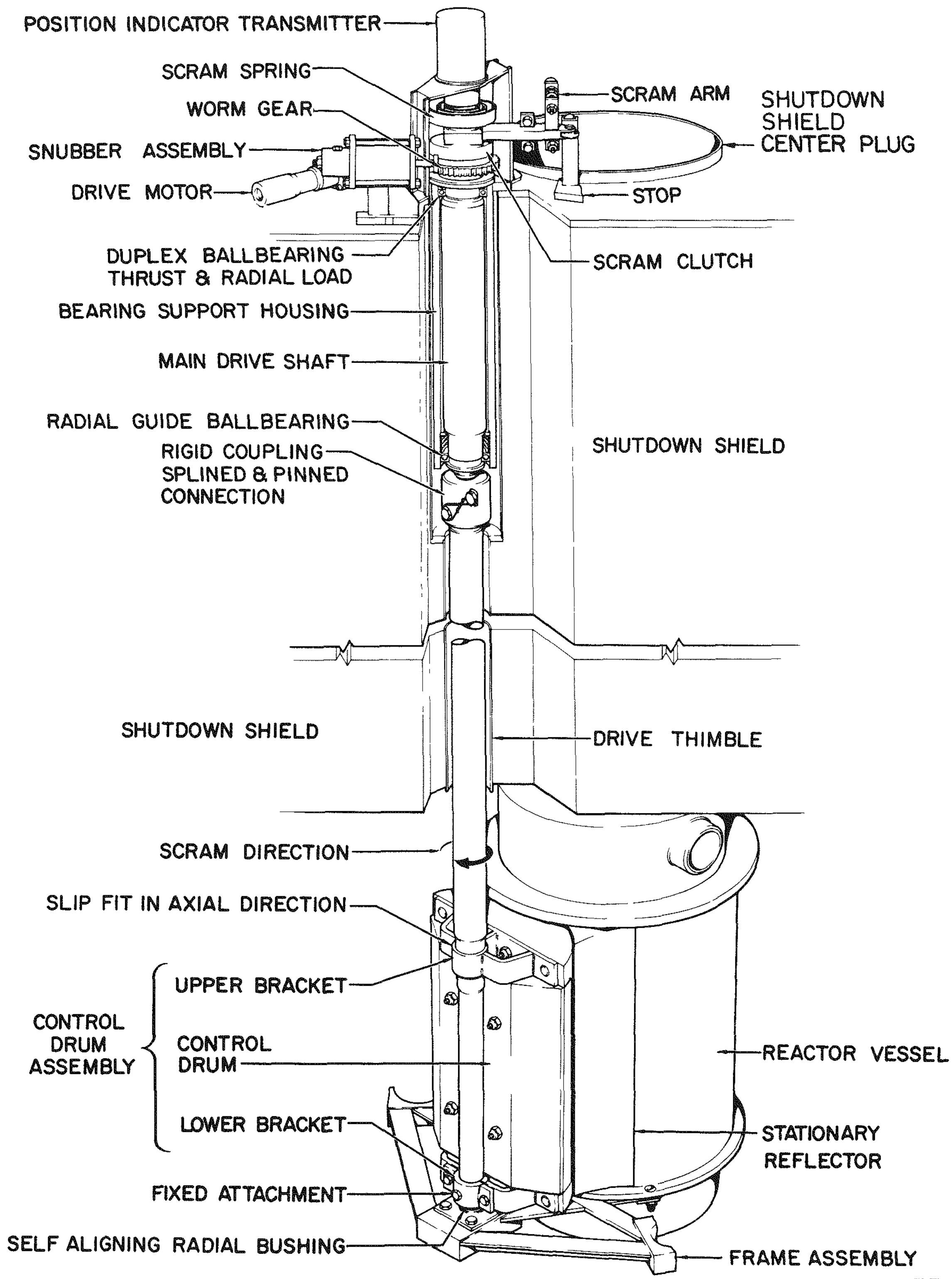

Figure 18. S8ER Control-Drum Support and Drive

4. SNAP 8 Experimental Reactor (S8ER) Nuclear Test

The S8ER was the initial SNAP 8 nuclear test. It had fixed beryllium and rotating drums of beryllium similar to the S8DRM-1, but the drive, scram, and snubbing system was designed specifically for the S8ER test. It operated for 12,000 hours at 1300°F NaK outlet temperature. Operation at both 400 and 600 kwt verified the SNAP 8 reference core and reflector design.[16-18]

The core, which was 14 in. high and 9 in. in diameter, consisted of 211 fuel-moderator elements arranged on 0.570-in. centers in a triangular array.

Six rotating beryllium drums, arranged around the core vessel, served as control and safety elements. Stationary beryllium cusps filled the space between adjacent movable drums. Each drum could be individually driven by a reversible a-c motor. Figure 18 shows a typical control-drum support and drive arrangement. Scram action was initiated by disengaging an electromagnetic clutch, permitting the scram spring to rapidly rotate the drum to the out position. Position-indicating transmitters, located on top of the control-drum drive shafts, transmitted drum position signals for control room readout. The S8ER core was located below ground in a shielded containment vessel. The reactor core assembly was suspended from a shutdown shield. The 4-ft-thick shutdown shield, containing high-density borated concrete, lead, and insulation, was air cooled. A compartment above the shutdown shield contained primary coolant piping, control-drum drive and position indicating equipment, and instrumentation. Above this was the 4-1/2-ft-thick ordinary concrete operating shield. The containment vessel dome, which projected above the reactor room floor level, was concrete filled. To retard corrosion of the beryllium reflectors, the helium atmosphere in the containment vessel was recirculated through NaK bubblers to remove oxygen and moisture. Water cooling coils encircled the 3/4-in. -thick carbon steel containment vessel. The control drum was prototypical; however, the control-drum-drive system was designed especially for the ground test operation. The test operated satisfactorily and demonstrated the feasibility and reliability of the rotating control-drum control system.

5. SNAP 8 Developmental Reactor (S8DR)[16-18]

The SNAP 8 Development Reactor (S8DR) was designed to verify the ability of the SNAP 8 reactor system to operate for 12,000 hours at its designed power level of 600 kwt. The S8DR reactor was a complete flight system with the addition of ground test scram devices to allow repeated startup and shutdown tests, and for emergency scramming of control drums under ground test conditions.

a. Description and Features

The S8DR reflector assembly is shown in Figure 19. The design was initiated in 1964 and incorporated several modifications based on S8ER and S8DRM experience. The basic reflector assembly consisted of two identical halves as did previous SNAP 10A, 2, and S8DRM reactor systems, however the S8DR reactor utilized six control drums each individually driven by a stepper motor.[18] This was different from previous reactors which used a combination of snap-in coarse control drums for initial startup and stepper-motor-driven drums for fine control. The S8DR reactor retained the reflector halves concept for end-of-life separation and had add-on scram kits for ground test shutdown and scram.

The reflector assembly was designed as two identical halves providing a nominal reflector thickness of 3 in. surrounding the reactor core with the

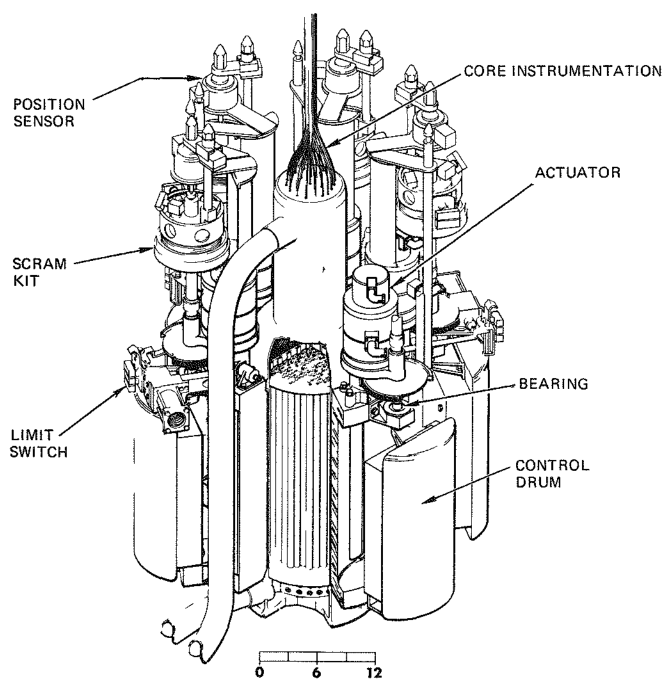

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Figure 19. S8DR Reactor Reflector Assembly

the control drums full-in. The fixed reflector structure and the rotating control drums were both of beryllium metal anodized to provide a minimum emissivity of 0.7 for improved heat dissipation and to prevent oxidation of the beryllium metal. The reflector halves retain the spring-load pivot mount technique of previous reactors and the spring-loaded retaining band for end-of-life separation. These features were not installed on the assembly during the nuclear ground test, however.

The S8DR control-drum-drive system incorporated two major changes from S8DRM design. The snap-in mechanisms and the coarse control drums were eliminated and all drums were motor driven. Reactor startup is accomplished by stepping each drum in sequentially. At the same time, the mass of the control drums was increased from a nominal 31 to 36 lb. This resulted in driving torque requirements above those of the S8DRM actuators and required a redesigned actuator with increased power output.[19] The resulting drive system provided an actuator stepping rate of 3.6° per 2 sequence step which was reduced through a redesigned 13.8:1 ratio gear to 0.26° per sequence control drum step.

The increased control-drum weight also resulted in a configuration change in the control-drum support bearings to carry the additional load. Figure 20 shows the redesigned bearings. At the time of the redesign, the Al_2O_3 against P5-N carbon-graphite journal and Al_2O_3 against MoS_2-coated Al_2O_3 self-aligning bearing couples were also retained. Subsequent bearing tests resulted in several instances of Al_2O_3 shaft coating failures. Following a detailed failure analysis and additional testing, the composite bearing ball (P5N carbon-graphite bushings shrunk-fit into the Al_2O_3 Inconel-750 ball) was replaced by a solid P5 carbon-graphite ball in the final design.[20]

The drum position sensors were also redesigned to increase reliability and survive the increased operating temperature of SNAP 8.

The S8DR reactor is designed as a ground test system and EOL shutdown is based on either (1) driving the control drums to the full-out positions with the actuator stepper motors, or (2) scramming the drums with the add-on scram mechanisms.[21] No reflector separation mechanism was incorporated

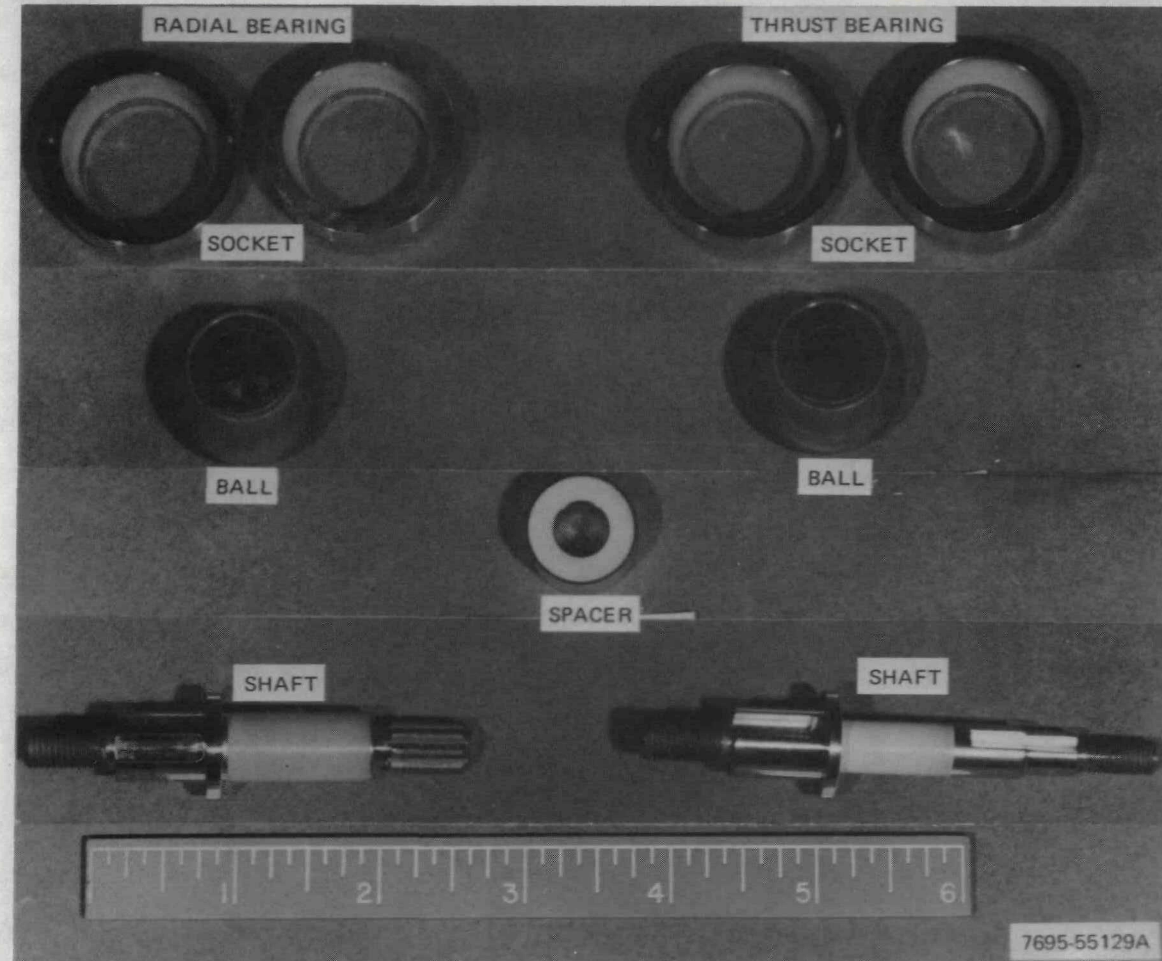

Figure 20. S8DR Redesigned Control-Drum Bearings

on the reactor system. The S8DR ground test scram kit is unchanged from the S8DRM design and is attached to the reduction gear shaft as shown in Figure 19.

b. Development and Operational Tests

Three half S8DR reflector and control assemblies were fabricated using flight configuration hardware, but also using ground test control-drum scram mechanisms. Each reflector assembly was given an assembly test, a performance record test and an ambient operational test checkout. This consisted of a complete electrical and mechanical checkout including drive-torque measurements, scram times, drum step size, limit switch and position sensor operation, and complete startup and shutdown operational sequences.

Two S8DR reactor reflector halves were assembled, and subjected to qualification (thermal-vacuum) testing. The full reflector assembly was installed in a large thermal-vacuum chamber with an electrical core heater to simulate nuclear heating. During a 50-hour test at 10^{-6} torr, the reflector system underwent numerous startup, shutdown, and scram test cycles. The only problems encountered resulted from controller malfunctions during attempts to rewind the scram springs.

Following mating of the reflector assembly to the core, final operational checkouts were conducted, the vacuum vessel sealed, and the projected 12,000 hour nuclear testing was initiated in January 1969. Five automatic startup tests were conducted with no reflector control system problems. Following these tests, the reactor completed 1000 hours at 600 kwt (1300°F outlet temperature), 430 hours at 1.0 Mwt (1150°F outlet, and approximately 5600 additional hours at 600 kwt prior to shutdown. Several control-drum scram operations were performed satisfactorily during test. During steady-state operation, nominal control-drum temperatures stabilized at approximately 600°F.

The 12,000-hour test was terminated after approximately 7000 hours due to excessive fuel element cladding ruptures. Following shutdown, the reactor was transported to the AI Hot Cell Laboratories and disassembled for examiation.(23)

During post-test inspection of the S8DR in the AI hot cells, the control-drum drive components were inspected for any signs of degradation, wear, and self-welding of moving parts.(23) All components were in good condition. Bearings and gears showed no signs of self-welding and all components were found to be in satisfactory working order.

The S8DR reflector assembly components also underwent developmental and qualification testing in addition to acceptance testing of complete half-reflector assemblies.

The redesigned S8DR actuator motors underwent detailed proof testing of AI-developed coil assemblies. Three actuator assemblies completed approximately 20,000 hours each of thermal-vacuum operational testing including

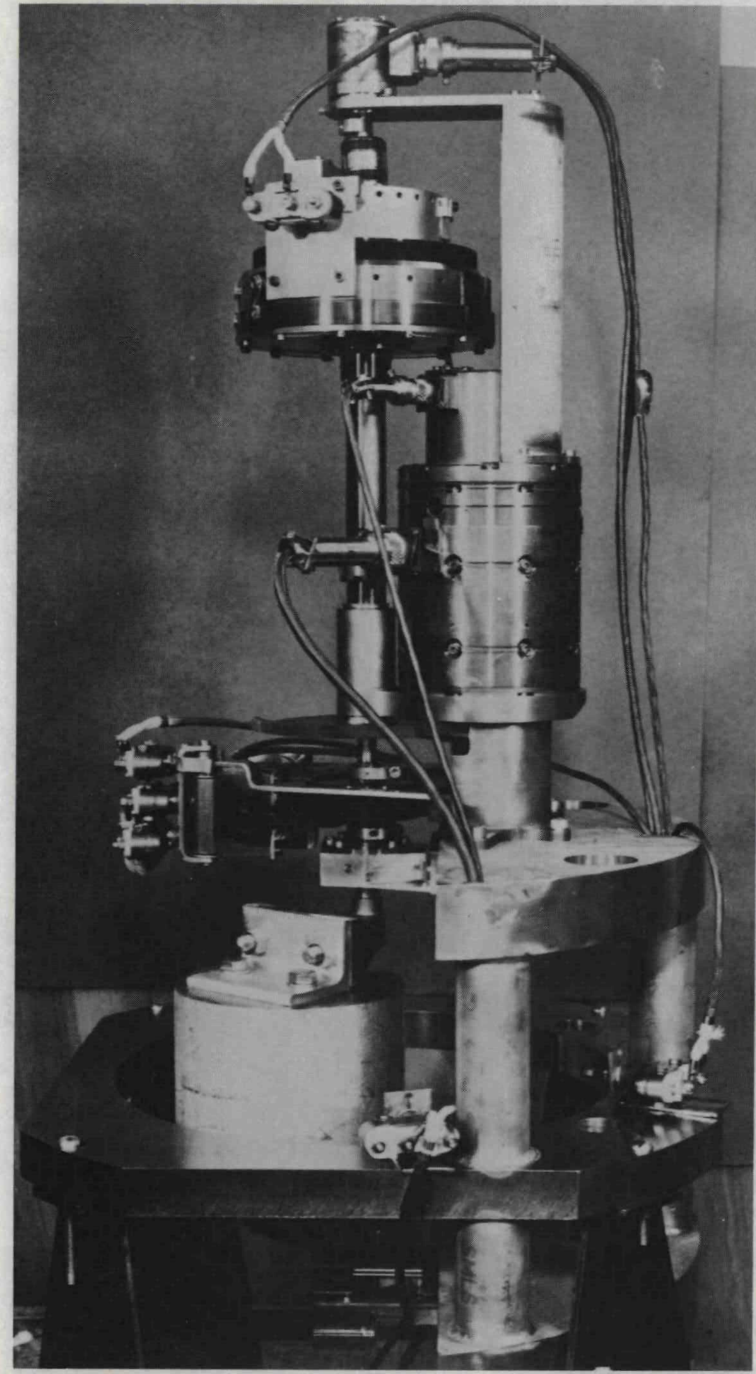

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Figure 21. S8DR Scram Kit Test Assembly

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repeated dwell tests, thermal cycling, and multiple life operational testing. The actuator design was proven to be highly reliable.[5]

The control drum support bearings accumulated in excess of 100,000 hours of thermal vacuum development testing with four individual sets completing 12,000 hours each at 1150°F and 10^{-5} torr or lower. This was following the discovery of Al_2O_3 shaft coating failures and the subsequent replacement of the composite ball with the solid P5 carbon-graphite ball.[10]

Three S8DR scram mechanisms and actuators were subjected to combined performance and endurance tests at 10^{-5} torr with scram clutches operating at or above 850°F. Table 8 summarizes the test history. Figure 21 shows test assembly S/N 001 at the end of life-testing. The three tests demonstrated the ability of the scram mechanism to function repeated after long hours of thermal-vacuum soak. Several minor failures occurred with the carbon-graphite guide bushings of the S/N 001 snubber cracking, and bearing clearance problems with the full-in limit switch shaft. In all cases, however, the problems did not significantly effect performance and were corrected with minor changes.

TABLE 8

S8DR SCRAM MECHANISM TEST HISTORY

Item	Assembly Number		
	001	002	003
Test Duration (hr)	13,102	15,508	9,912
Pressure (torr)	1×10^{-5}	1×10^{-5}	1×10^{-5}
Clutch Temperature (°F)	850	850	950
Thermal Cycles	200	201	204
Number of Scrams	1,389	1,200	1,448

6. Space Power Facility Test (SPF)

The conceptual design of the SPF reactor and reflector assembly is shown in Figure 22. The design was based on a planned 300-kwt, 1200°F reactor for the NASA Space Power Facility (SPF) at Plum Brook.[24]

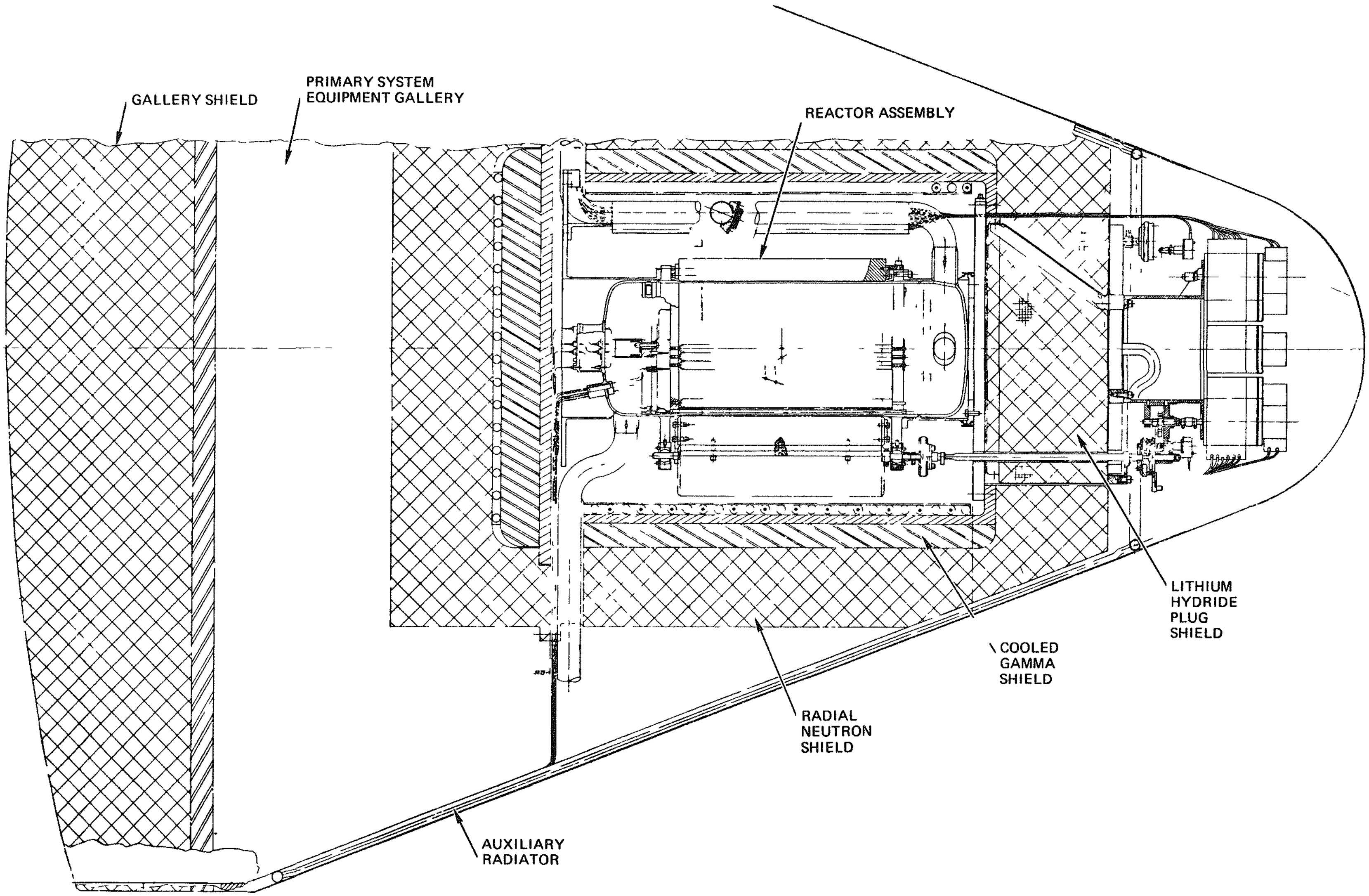

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Figure 22. SPF Reactor-Shield Installation

The reactor design is based upon the experience gained in previous reactor tests conducted in the ZrH Reactor Development Program. The heat produced in the core is removed by circulating NaK coolant. Reactivity control to achieve a reactor lifetime of 5 years is provided by 8 beryllium void-backed control drum.

Eight independent drive trains, Figure 23, with beryllium reflectors were employed to control the reactor. Each drive train consisted of an actuator-brake, gear reduction, flexible coupling, self-aligning bearings, and reflector drum. A cam and pin device was also incorporated into the design to positively lock out the drums during launch shock and vibration. Maximum use was made of S8DR-type components in the drive train. Thermal expansion mismatches were accommodated by the use of ball and socket bearings, and bellows flex couplings. The "full drums out" envelope of the reactor was 26 in. in diameter.

The conceptual design of the reactor was completed and the program terminated prior to initiation of hardware fabrication and system checkout.

7. Advanced Zirconium Hydride (ZrH) Reactor

The advanced reactor design requirements included operation at 600 kwt with a NaK outlet temperature of 1300°F for a minimum of 20,000 hours.[25] The design was compatible with thermoelectric, mercury-Rankine, Brayton, or organic-Rankine cycle power-conversion systems and was capable of operation in either a shadow shielded or 4 π shielded configuration, e.g., shielded in all directions. Figure 24 shows an overall view of the advanced ZrH reactor.

(a) Description and Features

The Reference ZrH reactor had 10 control drums and utilized the basic SNAP concept of a cylindrical core surrounded by a series of rotating control reflectors, however two major changes were incorporated in the design.

The control drums for previous systems were void backed or simple sections of cylinders. In this fully shielded design a very large void would be needed to negate the reflection and scatter of neutrons from the shield. A large void would increase the size and weight of the assembly. Therefore, this reactor design incorporated poison or absorber backed drums which instead of allowing all excess core neutrons to escape, captured most of them

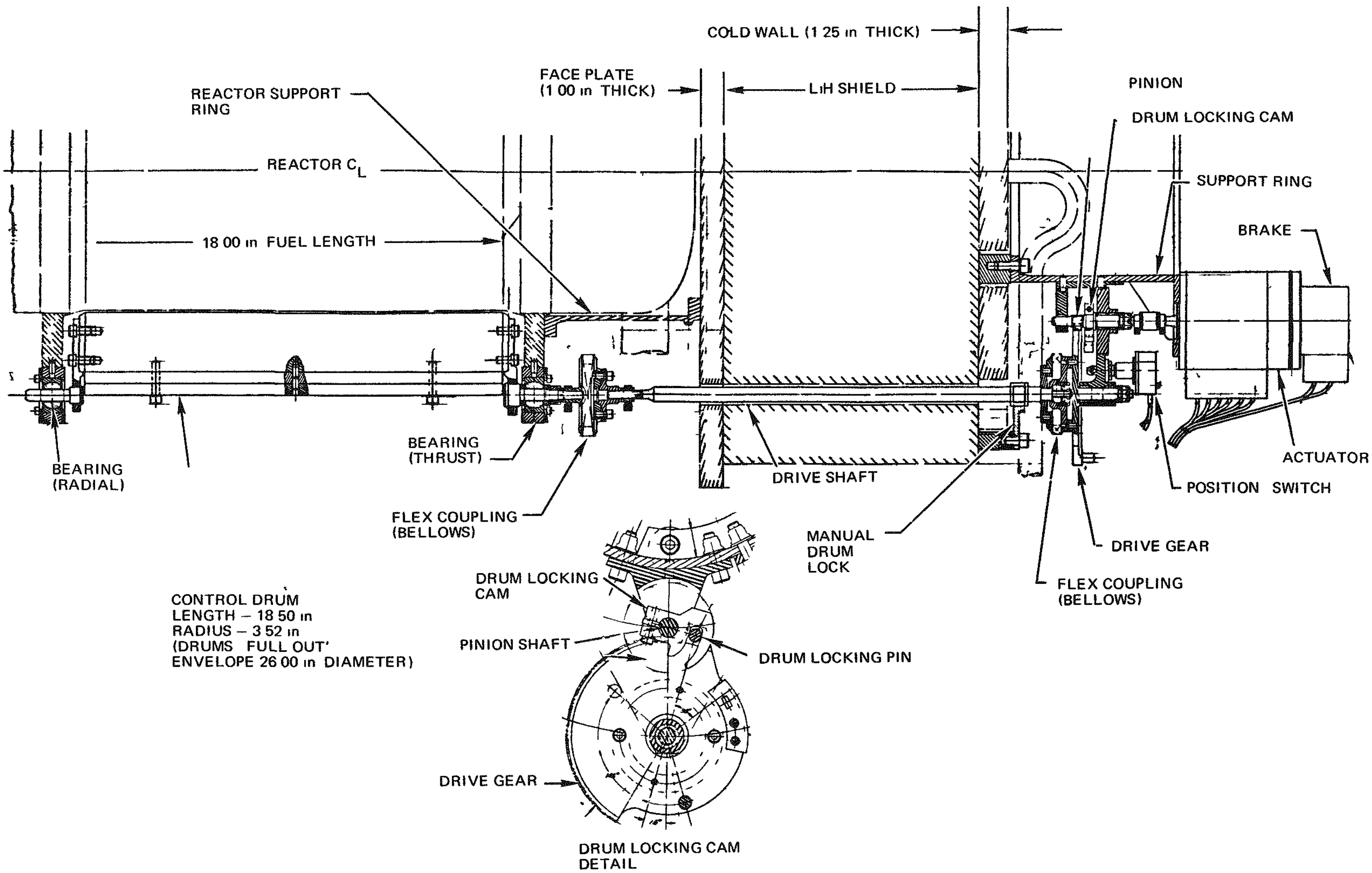

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Figure 23. SPF Reflector Control and Drive System

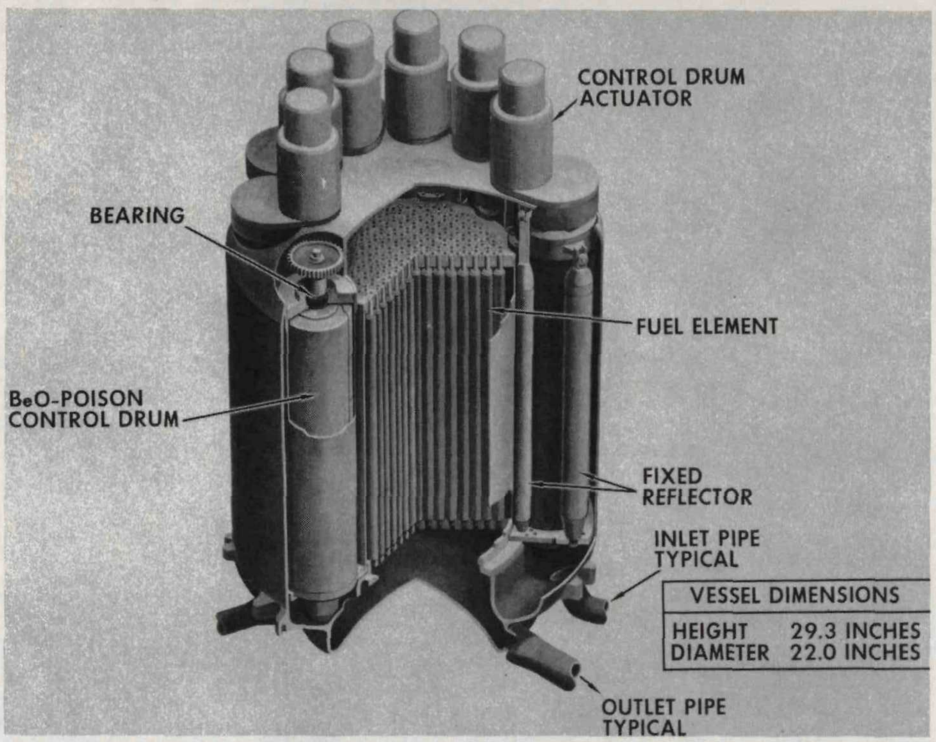

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Figure 24. Reference ZrH Reactor Reflector Assembly

in the poison material. Due to the increased control-drum operating temperature, 1900°F vs the 1150°F SNAP 8 temperature, beryllium oxide replaced beryllium metal as the control drum moderator material. Beryllium oxide, a ceramic, is not a suitable structural material and therefore required additional structure.

A detailed study was conducted to determine the best absorber material and how to integrate the BeO, the poison, and the structural material into the optimum reflector design. The study narrowed the selection to two combinations: the first used a tantalum-10% tungsten alloy as the absorber and structural member, and the second used a 60 wt % mixture of europium oxide in nickel as the absorber and either a tungsten carbide or columbium alloy as the strongback. Due to the extra complication of three components and the sublimation of nickel from the Eu_2O_3-Ni material, Ta-10W was chosen as the absorber material. The BeO reflector was segmented longitudinally due to thermal expansion differences between BeO and Ta-10W. The individual BeO segments were held in place on the Ta-10W strongback by guide pins and

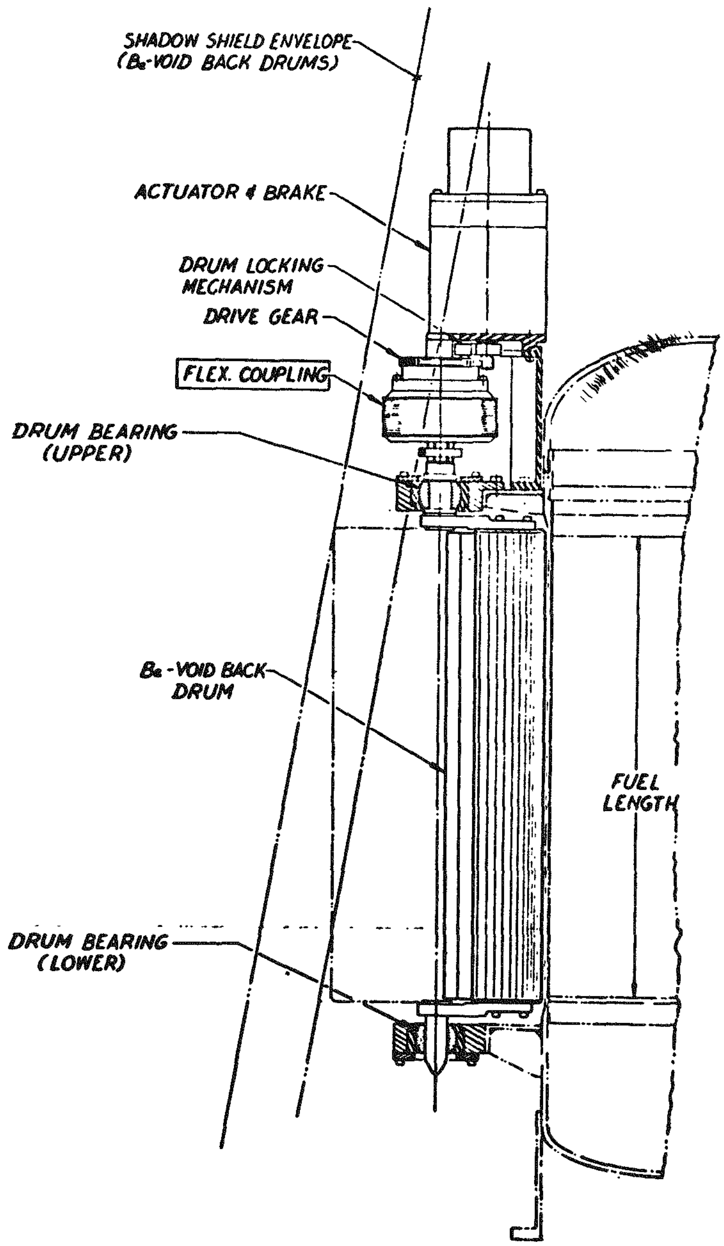

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Figure 25. Control Drive with Shadow Shield

tension straps. Then a thin cladding was placed around the BeO to prevent particles that might erode during launch vibration from falling into and jamming the drum support bearings or gears.

The second major difference from previous SNAP reactors (see Figure 24), was that the ZrH control drums were fully enclosed within wells. Due to nuclear heating, control-drum temperatures were calculated to be as high as 1900°F with the absorber section facing the core. To cool the control drums, the inlet NaK flowed up around the control drum well before entering the reactor core. The main problems as a result of the fully enclosed control drum were oxidation due to high O_2 partial pressure, and assembly of the lower support bearings which were at the bottom of a 4-in.-diameter, 28-in.-deep well. The evolution of O_2 from the BeO under irradiation and the poor conductance path between the BeO and space caused the relatively high O_2 partial pressure inside the cladding.

The ZrH reactor was designed for a variety of missions and included shadow-shielded and 4 π shielded concepts. Figures 25 and 26 show the control-drum drive system required for the two concepts. The main difference is that in the shadow-shielded concept the drive motor can be mounted directly to the reactor vessel while in the 4 π shield concept, a self-aligning drive shaft must be provided and the drive motor placed outside the shield to prevent overheating.

The actuator stepper motor is essentially an upgraded SNAP 8 motor to handle the increased torque loads.[26] The control-drum support bearings, Figure 27, are spherical self-aligning bearings similar in configuration to SNAP 8.[26] The bearing couples of Al_2O_3 vs solid P5 carbon graphite balls were retained, but the coated shaft and socket substrate was changed to Ta-10W. The Ta-10W has greater strength at the 1500°F operating temperature and has a thermal expansion coefficient close to that of P5 and Al_2O_3. A unique added feature is a tapered lip on the bearing sockets that provides positive self-alignment between the Ta-10W socket and Type 316 stainless-steel housing and dry well. This feature compensates for the clearance that results from the difference in the socket and housing thermal expansion. The lower bearing socket, which provides radial support is spring-loaded in the housing and held

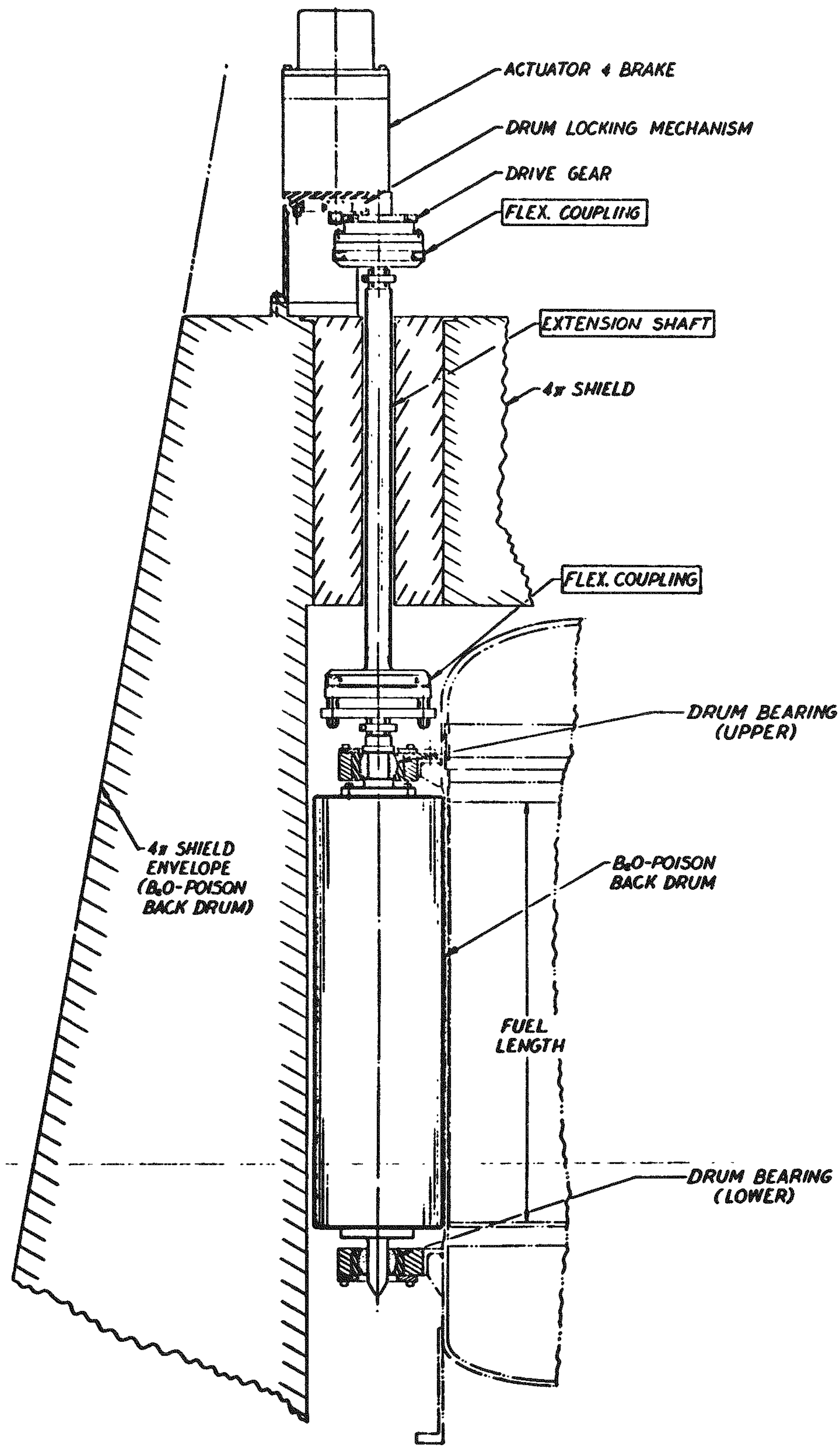

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Figure 26. Control Drive with 4π Shield

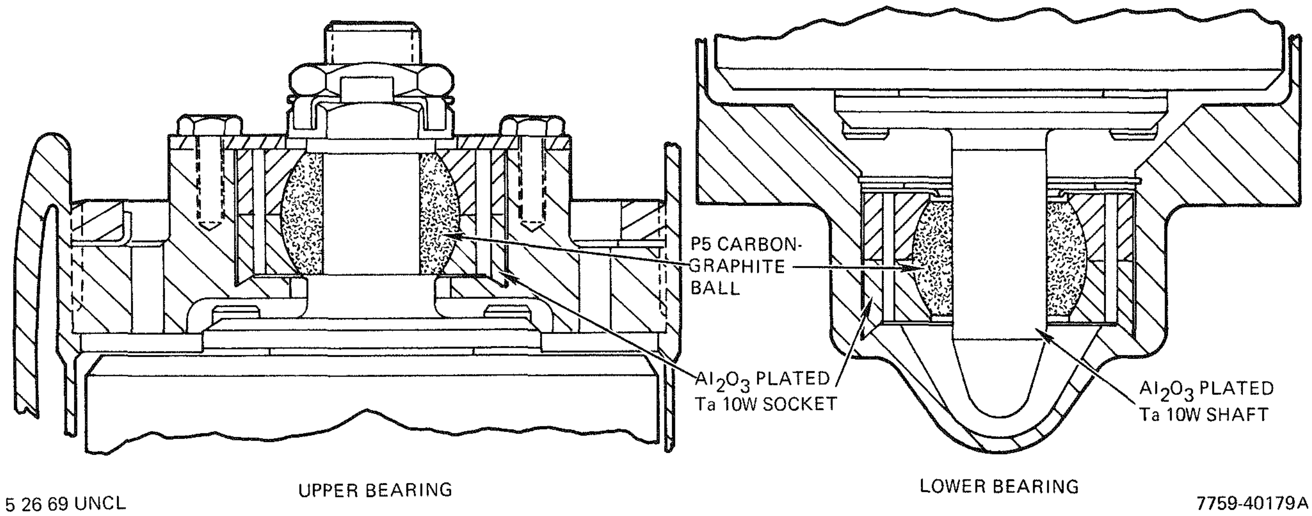

Figure 27. Control-Drum Bearings Design

in place by a snap ring. The upper housing assembly is threaded and screws into the dry well cavity. On assembly, the lower bearing is locked into the dry well and the upper housing is screwed into place with the control drum hanging from the pre-assembled upper bearing and drive shaft.

On both the shadow-shielded and 4 π - shielded concepts the actuator drives the control drum through a 6:1 gear ratio and a flexible bellows type coupling to prevent binding due to angular and coaxial misalignment. In the shadow-shield design, Figure 25, the coupling is mounted directly to the control-drum-drive shaft and to the lower end of the main drive gear. The coupling was designed to withstand launch shock and vibration loads by pre-loading. The flexible coupling for the 4 π shield design, Figure 26, consists of a bellows coupling at each end of a long drive shaft. The bellows coupling at the upper end of the drive shaft is connected to the lower end of the main drive gear and is designed to provide angular misalignment only. This is accomplished by mounting the bellows on a spherical bearing that allows for angular movement but prevents axial movement. This feature was necessary to prevent either bellows from carrying the drive shaft weight during launch vibration loading. The lower bellows allows for both axial and angular misalignment.

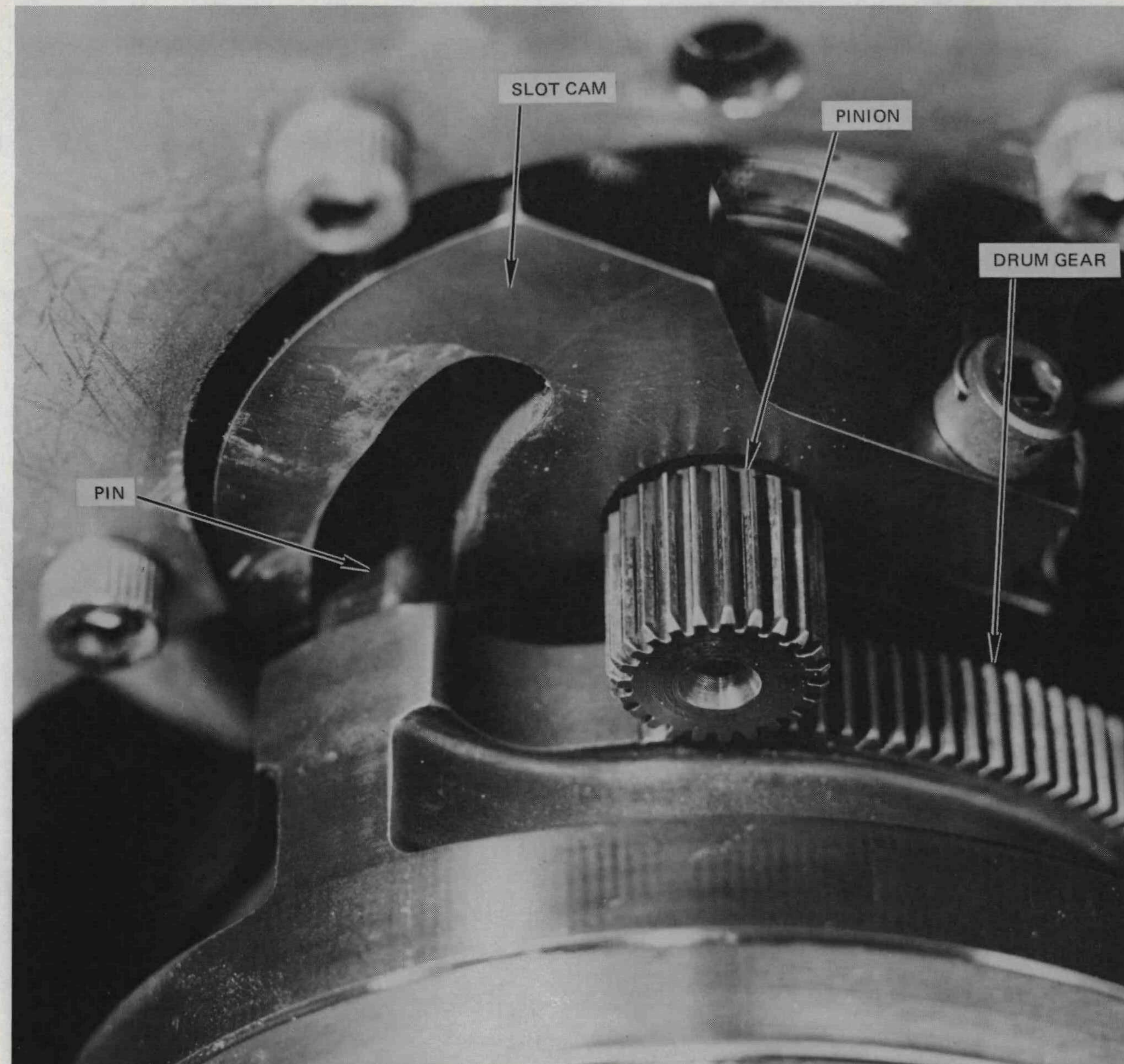

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Figure 28. Drum Launch Mechanism

To facilitate assembly of the drive shaft and mating with the control-drum shaft, a keyed fork and yoke coupling was designed. This allows the drive shaft to be lowered into the blind hole and provides positive alignment and orientation with the control drum. The actuator and drive gear housing with the suspended drive shaft is then bolted to the top of the shield.

Design requirements for the reactor stipulated a positive drum lock for launch, but excluded all electrically or explosively actuated types as used on SNAP 10 and 2. The resulting lock utilizes a mechanical cam and slot device and is shown in Figure 28.

The cam and slot device is attached to, and rotates with the actuator pinion gear. During the last 8° of rotation to the poison-in position, the cam engages a mating pin which is integral with the drive gear and simultaneously the gear disengages from the actuator pinion. The cam and pin rotate the gear to the full poison-in position when the cam and pin are fully locked. Launch vibration drum response torque is then transmitted directly as radial loading to the drum-drive gear and bearing. The device is simple and provides a positive lock without the added complexity of an electrically actuated squib and its control. The lock also works equally well on both the shadow and 4 π shielded concepts.

The reactor does not have a separate scram system, but uses rapid driving out of all ten control drums to shut down in the event of an emergency.

(b) Development Tests

The reference ZrH reactor program was reoriented before a complete reactor assembly was fabricated. However, the 4 π control drum and drive system was fully fabricated, assembled, and subjected to launch vibration and thermal-vacuum proof testing.

Initial control drum testing concentrated on BeO moderator block fabrication studies and development of techniques for attaching the BeO to the Ta-10W drum structural or strong back member. Figure 29 shows the test setup for vibration testing of the BeO reflector retaining band. The BeO block was stress relieved at 1500°F, and thermally cycled four times to 1300°F at a pressure of 10^{-5} torr to simulate prelaunch thermal tests of a reactor. It was mounted

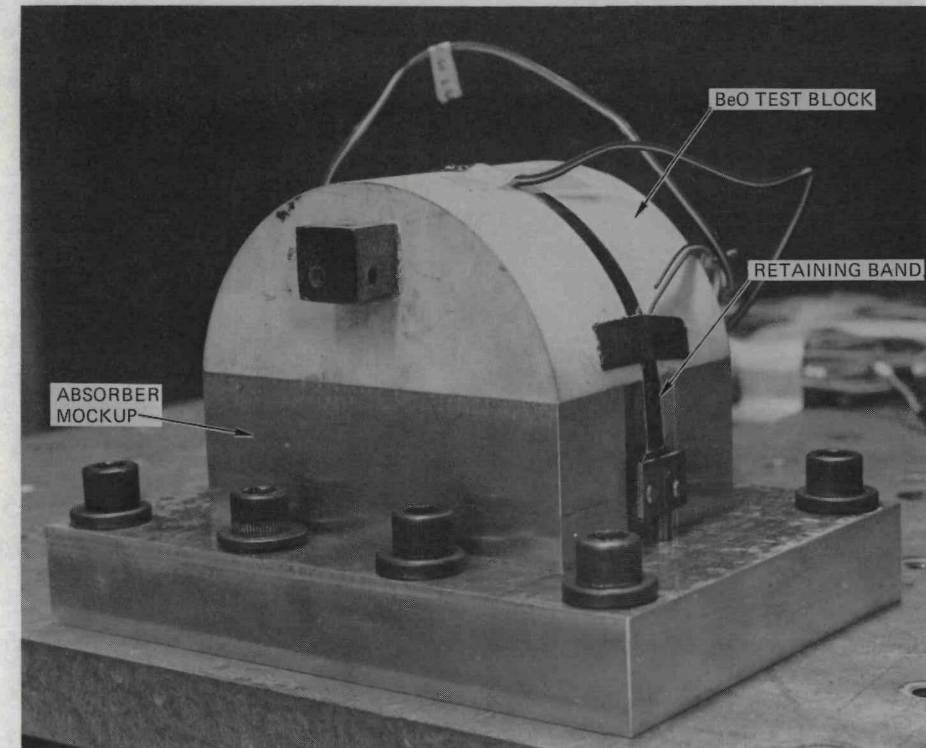

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Figure 29. BeO Reflector Block and Tension Band Vibration Test Setup

on the aluminum fixture with a Ta-10W retaining band tensioned to the calculated pre-load necessary to withstand launch loading. Strain gages on the band recorded less than 1500-psi stresses during 20 g shocks in all axes. The fixture was then subjected to random vibration testing duplicating profiles expected on Saturn V launches (see Table 1). A resonant frequency search was conducted at a 2-g input level, and an 85-min, 22-g dwell was run at the 200-Hz resonant frequency. No damage was observed to the BeO block and the band tension was measured to be unchanged from the pre-test value. The test established the reliability of the basic BeO block mounting technique.

Following satisfactory testing of the BeO block mounting scheme, a prototype control drum was fabricated of Ta-10W.[27] Figure 30 shows the drum during assembly prior to installation of the Ta-10W cladding. Each of the 6 BeO blocks are mounted on two pins and banded to the Ta-10W absorber. During assembly, one end of each band is riveted to the strongback; the band is then

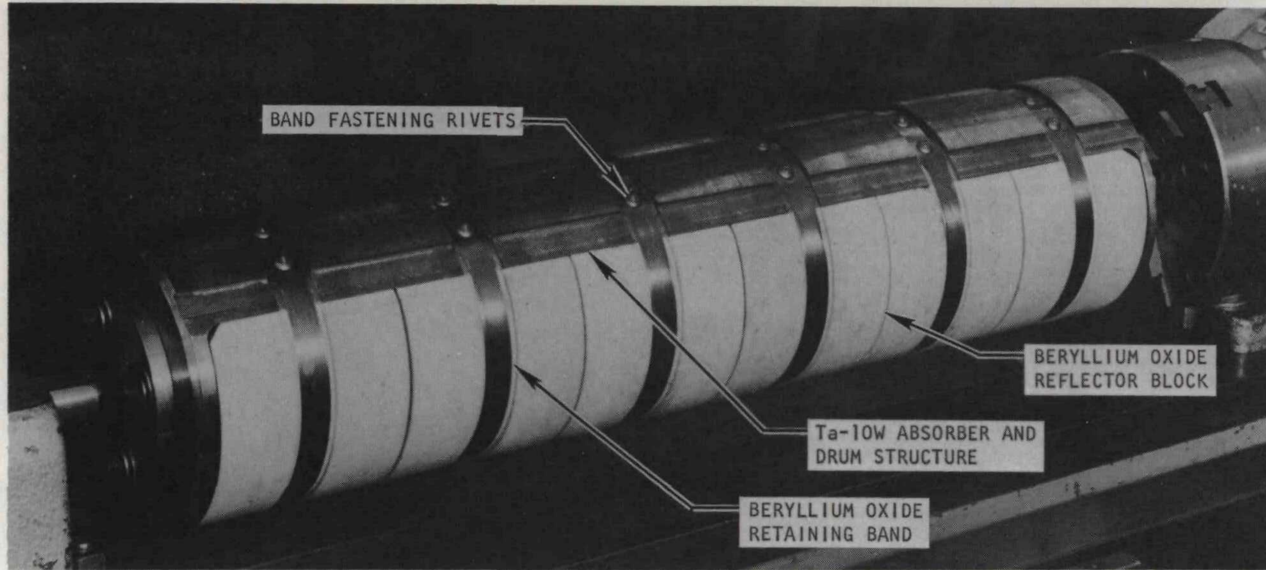

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Figure 30. Prototype Drum No. 1 Prior to Cladding Installation

pulled around the BeO block with the proper pre-tension load. Holes are drilled through the band and absorber, and the band is riveted to the absorber. A development study was conducted to determine the precise style and size rivet required to secure the retaining bands and the cladding material.

The drum assembly was placed in a thermal-vacuum test fixture and supported in flight configuration with a set of prototype support bearings. Figure 31 shows the complete control drum prior to thermal cycle testing to 1300°F and back to 400°F or less in a vacuum of approximately 10^{-5} torr. Post-thermal-cycle visual examination showed no signs of damage to the drum; however, it was slightly discolored. There was no audible sign of loose parts in the drum when it was shaken manually. Measurements of drum-shaft alignment indicated no warping of the drum as a result of thermal cycling.

The drum was assembled and instrumented in a vibration fixture as shown in Figure 32. A bellows was used in the assembly to simulate the bellows-type coupling in the drive train. Nylon cord was tied around the drum in four places to prevent the cladding from being damaged in case cladding rivets become loose. The drum was subjected to a 1 g sinusoidal sweep from 10 to 2000 Hz in each of three directions. The 1 g input was applied at the control accelerometers on the bearing housing shown in the figure. Natural frequencies

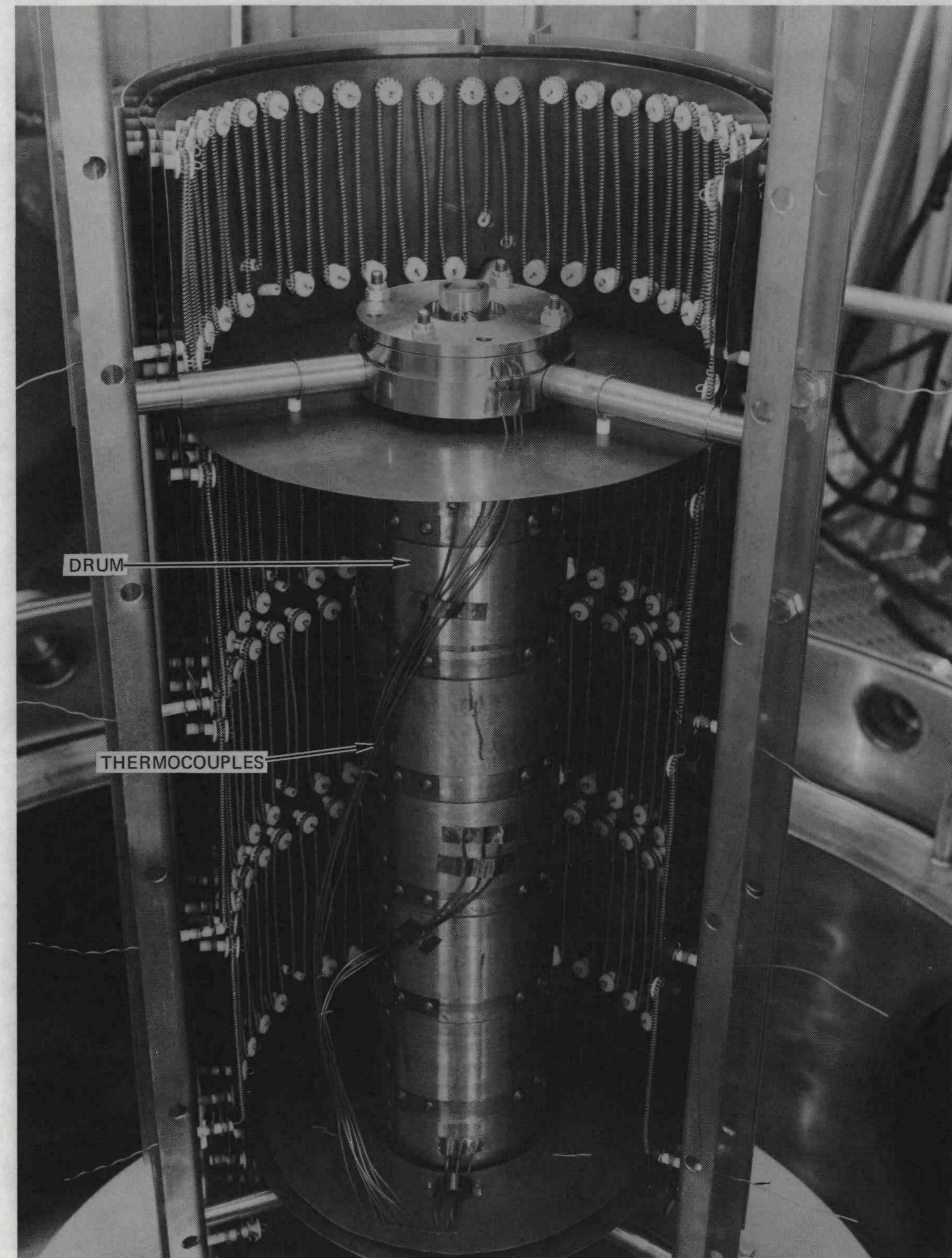

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Figure 31. Development Drum No. 1 in Thermal-Vacuum Fixture

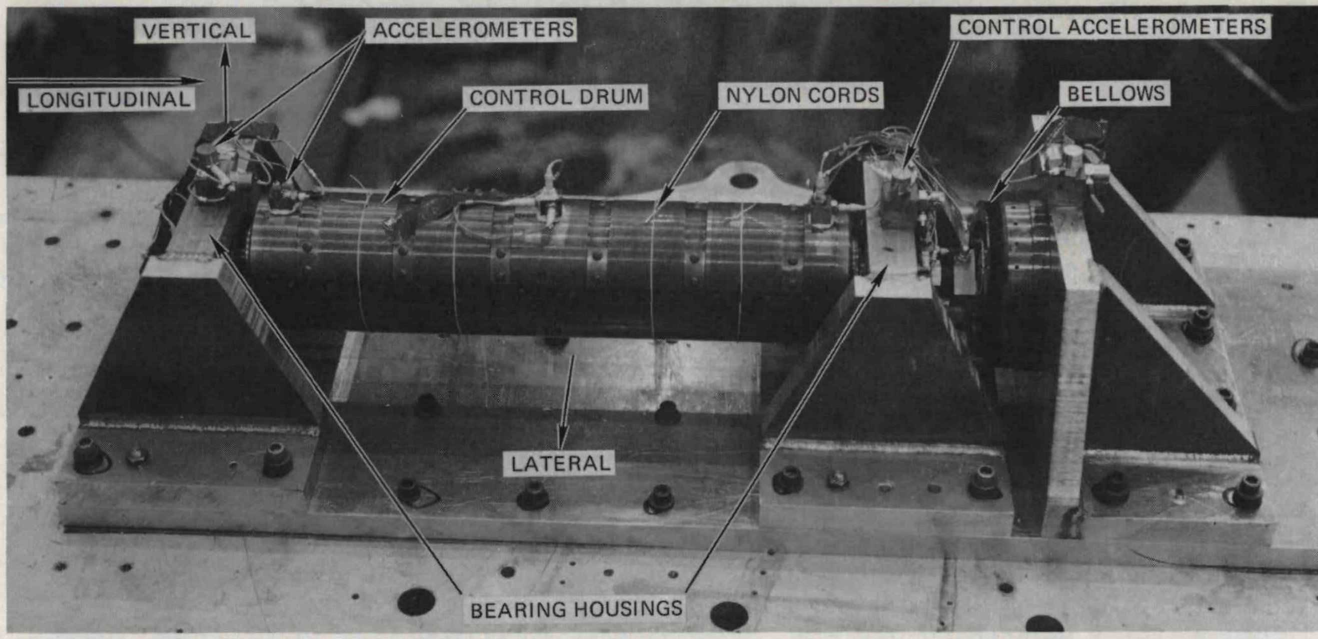

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Figure 32. Drum Assembled in Vibration Fixture

of the drum and its transmissibilities as determined by this test are given in Table 9. These data are necessary in determining drum design loads.

TABLE 9

REFERENCE ZrH DRUM NATURAL FREQUENCIES AND TRANSMISSIBILITIES

Axis	Natural Frequency (Hz)	Transmissibility
Vertical	85	4
Lateral	48	8
Longitudinal	60	3.3

Next the drum was subjected to a 3-min random vibration test from 20 to 2000 Hz in each of the three axes. The acceleration spectral density for the input to the control-bearing housing was taken from design specifications. Table 10 shows the calculated peak acceleration g-response of the drum at the drum peak-response frequencies. The maximum load on the drum during random vibration was therefore 5.13 g along the vertical axis.

TABLE 10

CALCULATED LOADS ON DRUM DURING RANDOM VIBRATION

Location of Accelerometer	Frequency at Peak Responses, (Hz)	Peak Acceleration, (g)	Frequency at Peak Responses, (Hz)	Peak Acceleration, (g)	Frequency at Peak Responses, (Hz)	Peak Acceleration (g)
End of drum near control	73	1.79	56	2.66	75	0.80
accelerometer	400	3.83	280	2.7	No third peak	
Middle of	90	3.6	52	2.33	70	0.91
drum	300	2.5	No second peak		No third peak	
End of drum opposite control	90	3.42	56	2.25	70	0.81
accelerometer	300	5.13	260	2.33	120	1.84

Post-vibration examination of the drum showed no visual damage or loosening of cladding rivets. Measurements of shaft alignment indicated no significant warping or bowing of the drum. The drum bearings appeared undamaged. The drum weighed 80 lb, and the center of gravity of the drum was located 0.706 in. from the shaft centerline, corresponding closely with the calculated value of 0.704 in. Manual shaking of the drum gave no audible sign of any loose parts inside the drum.

The drum was next used in some criticality experiments during which the drum cladding was removed. Upon removal of the cladding it was found that one of the BeO blocks had cracked as shown in Figure 33. The small cracked pieces of the BeO block were wedged tightly in place and the critical experiments were continued.

After completion of the criticality tests, the drum was examined to determine the cause of the BeO fracture. The main cause of the fracture is attributed to the BeO-block-locating dowel pin being frozen in the absorber and protruding 0.066 in. farther into the absorber than normal. The pin was designed to be a free fit in the absorber as well as in the BeO. There was a possibility of interference between the slight step in the bottom of the hole in the BeO and the bevel on top of the pin.

It was also found that the band rivets had not completely filled the holes in the band thus permitting possible loss of band tension. A sufficient loss of tension could have permitted impacting between the bottom of the BeO and the pin

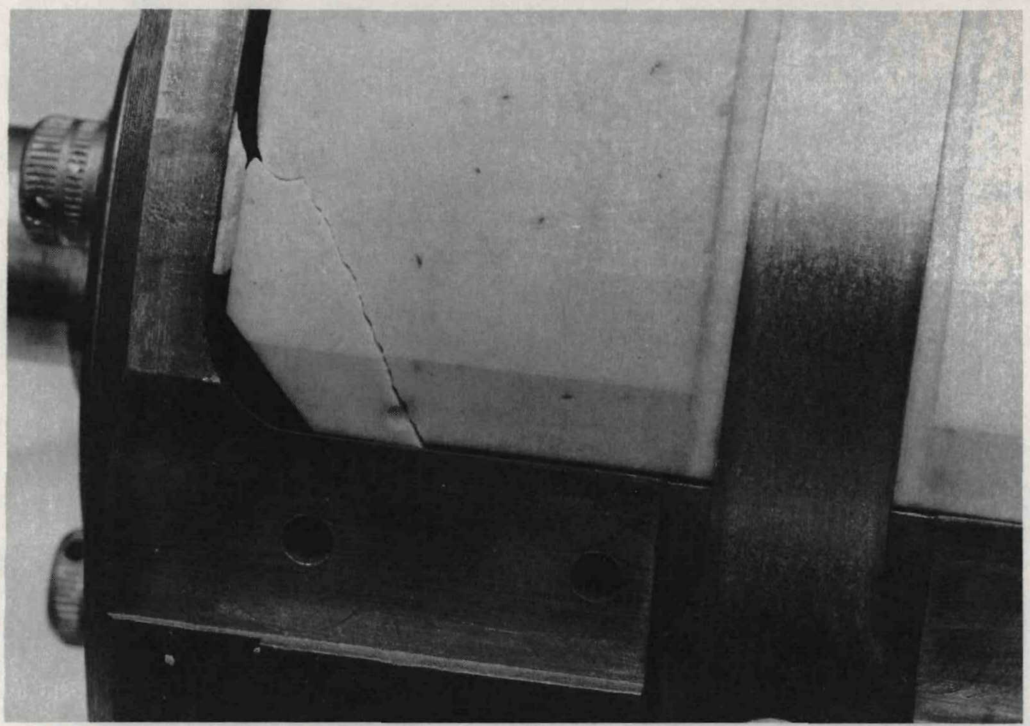

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Figure 33. Cracked BeO Block

during vibration, fracturing the block. The other five blocks appeared undamaged. The dowel pins and band rivets were redesigned to prevent a recurrence of BeO fracture.

A prototype drive system was fabricated for testing and design evaluation.[28] The test drive system consisted of the rebuilt development drum and support bearings, the 4 π drive shaft and bellows couplings, and a mechanical mockup of the actuator with the launch cam lock and the drive gear.

The test program included 10 thermal cycles to simulate the pre-launch system nonnuclear tests, a sinusoidal sweep vibration test to determine the natural frequencies of components, and a random noise vibration test to simulate acceptance levels of anticipated launch loading. Total system torque and backlash measurements were taken at times during these test conditions to verify system operation within design limits.

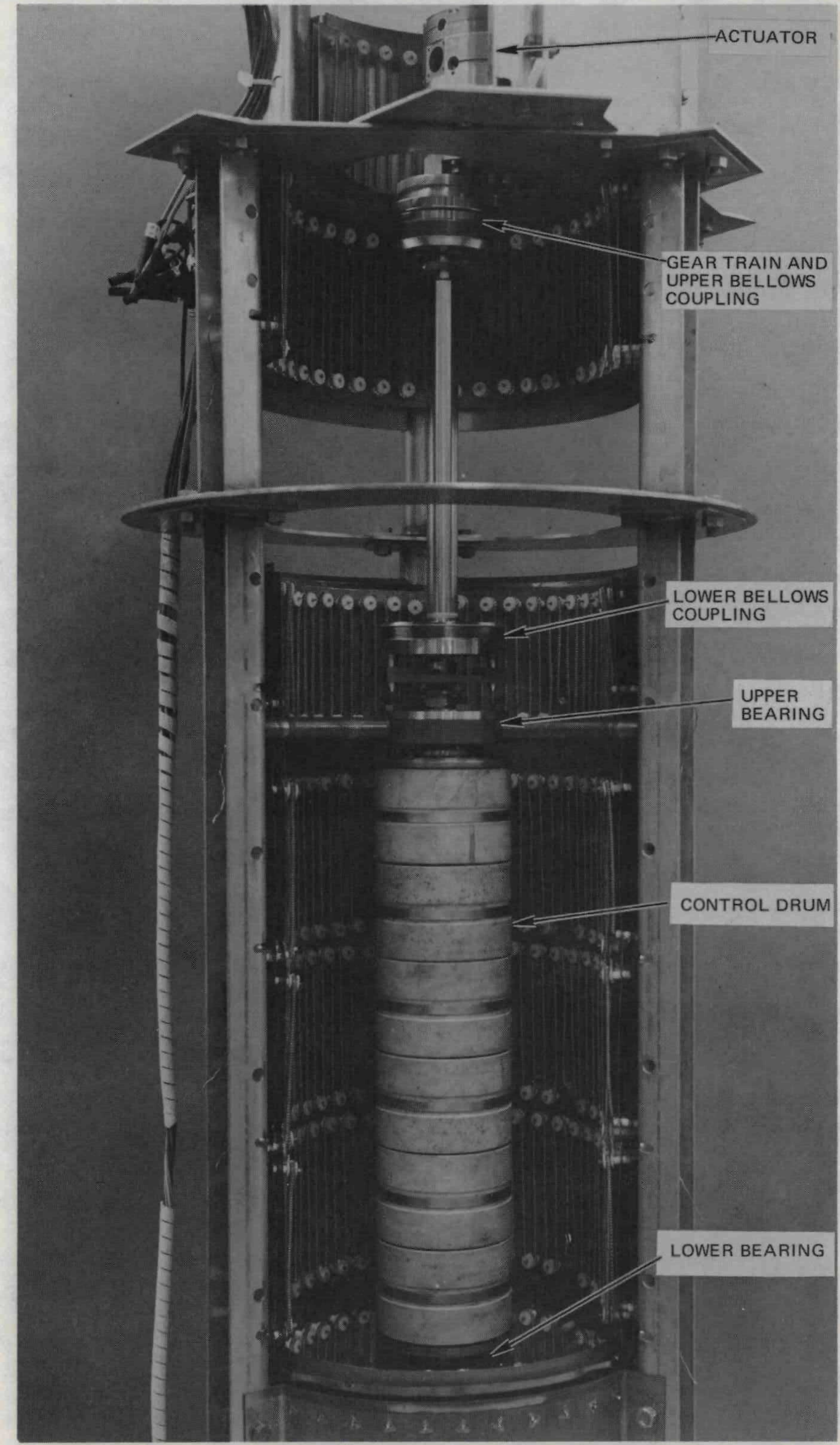

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Figure 34. Drum Drive Train

A long-term nonnuclear (greater than 10,000 hours) thermal-vacuum test was also planned to simulate reactor operation in space; however, the program was terminated prior to starting the test.

The control drum and drive train were assembled in the thermal-vacuum test fixture as shown in Figure 34. Ten thermal cycles were conducted between 400°F and a control-drum temperature of 1350°F at a pressure of 10^{-5} torr. Temperature was stabilized at 1350°F for 2 hours minimum during each thermal cycling total of 63 hours for the various components at the following temperatures:

Actuator	- 900°F
Gear Train and Upper Bellows	- 900°F
Upper Bearing	- 1275°F
Control Drum Midpoint Absorber	- 1350°F
Lower Bearing	- 1350°F

A SNAP 8 actuator was attached to the upper shaft of the prototype mockup actuator through a rotary torque transducer. The torque required to rotate the control drum was measured in air prior to thermal cycle testing, and under vacuum at ambient and at operating temperature. Maximum torque in ambient air was 5.6 in.-lb and in vacuum was 9.75 in.-lb while at temperature was less than 5.6 in-lb. Torque was generally highest during operation of the cam lock mechanism, the first 8° of drum rotation. In all cases, however, torque was below specification limits (10.6 in. -lb). This development drum weighed 81 lb with an unbalanced moment of 60 in. -lb or more than the final reference design of 62.5 lb with an unbalanced moment of only 34 in. -lb. The lower moment should result in a margin of safety of about 50%.

During testing, the cam stuck and prevented the actuator from driving to gear engagement. Disassembly showed the MoS_2 dry-film lubrication on the cam surface was worn through due to repeated cycling. During actual operation, however, such repeated cycling would not occur.

Following the 10 thermal cycles, the drive train and control drum were reassembled on the vibration fixture of Figure 35. The drum was positioned to induce the maximum torsional loading during vibration.[29] A sinusoidal resonant search and random vibration test were conducted on the full assembly.

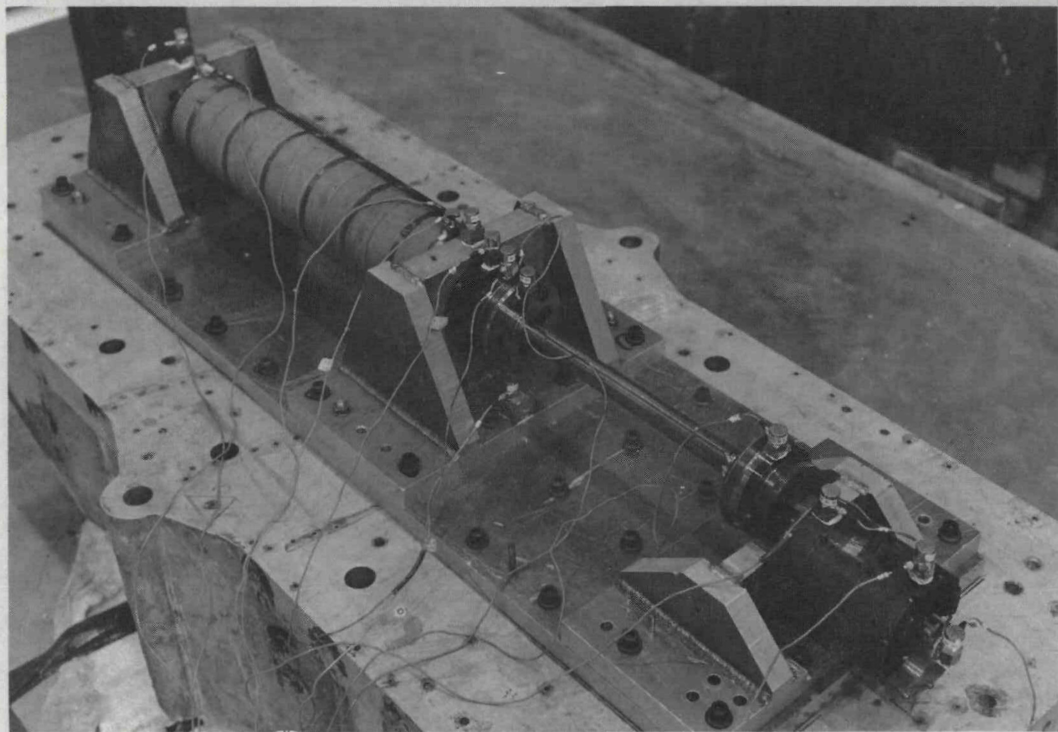

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Figure 35. Drum Drive System Vibration Test Setup

A spurious signal during the sinusoidal search resulted in a 50 to 90 g shock and deformed the upper bellows coupling. The coupling survived subsequent random vibration testing without further damage and did not degrade rotational freedom of the drive train. The cam locking device successfully prevented the drum from rotating during vibration and worked freely following the test.

The thermal cycle and vibration tests demonstrated the successfulness of the drive train and control drum design.

B. REFLECTOR MATERIALS STUDIES

In the S8DR reflector design, the prime concern was protection of the beryllium from oxidation from the inert gas impurities. The S8DR required some oxidation protection but also needed high emissivity to reject heat. The refractory materials on the Advanced ZrH control drums required oxidation protection even at very low oxygen partial pressures plus high emissivity to reject the heat generated in the drum.

1. Beryllium Coating for S8ER and S8DR

In the design and analysis stages of the S8ER effort, it was calculated that the beryllium-fixed reflectors and control drums would reach 1300°F during reactor operation at full power. Since the test was designed to operate for 3000 hours in an inert atmosphere with less than 2% oxygen, an investigation of potential beryllium problems was made. Preliminary investigation indicated that the beryllium could suffer catastrophic oxidation under these conditions.[30] Figure 36 shows a typical beryllium control drum after 300 hours at 1300°F in an argon-purged environment. Similar tests on small beryllium coupons (with less than 1% oxygen) in nitrogen resulted in massive oxidation and partial disintegration of the coupons. It was concluded that the lifetime of bare beryllium at 1380°F in 200 ppm oxygen would be above 1600 hours. Since the operational goal of the S8ER was 3000 hours, efforts were initiated at AI and the Armour Research Foundation to develop oxidation-inhibiting coatings for beryllium.

Three basic types of protective coatings were evaluated and adapted to standard coating techniques used for refractory metals.[31] An evaluation was then made of these and other commercially available coatings.

Ceramic coatings were applied to beryllium by flame-spraying and direct enameling, and enameling over other base coats was attempted. Most flame-sprayed coatings were too porous to provide oxidation resistance, but a barium-titanate coating was satisfactory and was used to coat a series of test coupons. The coating appeared uniform and adherent, but spalled off the beryllium after 90 hours at 1400°F in air.

All attempted coating with glass-type enamels resulted in failure to produce uniform coatings, and duplex coatings spalled when cooled following firings of the coatings.

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Figure 36. Post-Exposure Appearance of Be Control Drum at 1300°F for 300 Hours in Argon

Diffusion coatings were studied with chromium, titanium, and silicone or combinations of the three using the pack cementation process. Process parameters such as atmosphere, temperature, and pack design were varied and resulted in promising chromized and titanized coatings. However, test coupons of coated beryllium began to blister and oxidize after 110 hours at 1400°F. Further development of the chromized coating showed improved life.

Various nickel-chrome, titanium-copper, titanium-nickel, and titanium-beryllium base brazing alloys were applied to beryllium by slurry-coating and furnace-firing techniques. All failed by separation from the beryllium during post-firing cooldown. A duplex silver-nickel coating was developed, however, which wetted the beryllium surface and resulted in good adherence. Test coupons of beryllium coated in this manner were exposed to 1400°F air for 400 hours before the start of oxidation.

Various commercial and proprietary coatings were evaluated for oxidation at 1400°F by Armour. Plasma-arc-applied alumina, zirconia, beryllia, and calcium-zirconate coatings all resulted in poor oxidation resistance. The most promising coating was an anodizing coating produced by Brush Beryllium Corporation on a proprietary basis.

a. Development of Anodized Beryllium

Development of anodized beryllium coating at this stage was an experimental laboratory process at Brush Beryllium Company.[32] All samples tested were small solid cubes or cylinders. The beryllium control elements were large irregular shapes which contained through-stepped and blind holes. In order to upgrade this laboratory procedure into a reliable production, three apparent problem areas remained to be solved. These were process control limits, anodizing of the electrode contact area, and of the internal surfaces of the holes.

The original test samples had been processed under rigid laboratory control which would be difficult or impossible to maintain during production processing. Brush Beryllium Company conducted thorough process parameter studies during which the variation of voltage, current density, process time, and electrolyte concentration and purity were evaluated and checked by oxidation testing of samples. The final process control requirements were well within the capability of the facility.

Original test samples were anodized using pinpoint electrodes which were moved during the process. These contact areas were the points of failure on the test samples. Various techniques were investigated to eliminate these failure points. The final solution was the development of a portable anodizing method which allowed coating of the contact areas after completing the tank anodizing process. This consisted basically of using an electrode with an attached cotton swab.

Coating of holes was accomplished by placing the cathode into the center of the hole. Blind holes presented greater difficulty, but additional effort produced proper electrode design and placement to achieve satisfactory coatings.

Two side benefits were achieved from the anodized coating. First, the coating provides a barrier against the diffusion between stainless steel and beryllium. Other investigations have shown that beryllium diffusion may seriously affect the structural capacity of stainless steel in direct contact with beryllium. No such diffusion was observed with the anodized specimens. Anodizing the beryllium also significantly increases the surface emittance and increases dissipation of heat from the control drum and reflector segments. An additional margin of safety is thus achieved by reduction of the beryllium temperature.

b. Coating Verification Tests

A series of long-term (10,000 hour) performance tests were conducted to measure anodized beryllium test specimens for oxidation resistance and emissivity stability.[33]

Ten specimens representative of anodized reflector segments were tested for 5000 hours at 1300°F in helium with 100 ppm oxygen and a dew point of -40°F. Oxidation was found to be minor and restricted to corners, edges, and locations in contact with electrodes during the anodizing process. The anodized coating was judged to be adequate protection against oxidation for the projected reflector lifetime based on onset of massive oxidation.

Emittance of these coupons was measured at the end of the test at 800 and 1100°F (Table 11) and agreed with emittance test data showing a general decrease in emittance with time from the pretest values of 0.80.

TABLE 11

POST-TEST EMITTANCE OF ANODIZED BERYLLIUM

Coupons	Exposure Time (hr)	Emittance	
		at 800°F	at 1100°F
5	3169	0.51	0.52
5	5709	0.53	0.54

A second test series was conducted to study emittance of anodized beryllium as a function of time at 1150°F and 10^{-7} torr. Periodically, the test was interrupted and emittance checked. As shown in Table 12, the emittance of the anodized coatings appeared to degrade during the initial 1000 hours and then stabilize between 0.55 and 0.70. Calculations indicated that an emittance of 0.8 was required to maintain reflector temperatures below 1300°F and that an emittance of 0.5 would result in reflector temperatures as high as 1400°F. Based on Figure 37, this would provide marginal life expectancy for 10,000-hour ground tests in a 100-ppm oxygen environment.

TABLE 12

LONG-TERM EMITTANCE DATA AT 800°F

Coupons	Coating	Emittance at 800°F			
		Original	1000 hr	2000 hr	5000 hr
10	Anodized	0.76 to 0.87		0.55 to 0.68	0.55 to 0.68
5	Anodized	0.76 to 0.87	0.52 to 0.50	0.53 to 0.68	
3	Bare	0.15 to 0.23		0.12 to 0.13	

Two other emittance coatings were under investigation and that work was accelerated in an attempt to replace the anodized beryllium coating. The coatings were (1) a plasma-sprayed, 3-phase graded chrome oxide used on S10A reflector shims, but at 700°F, and (2) an AI-90 coating of aluminum-phosphate,

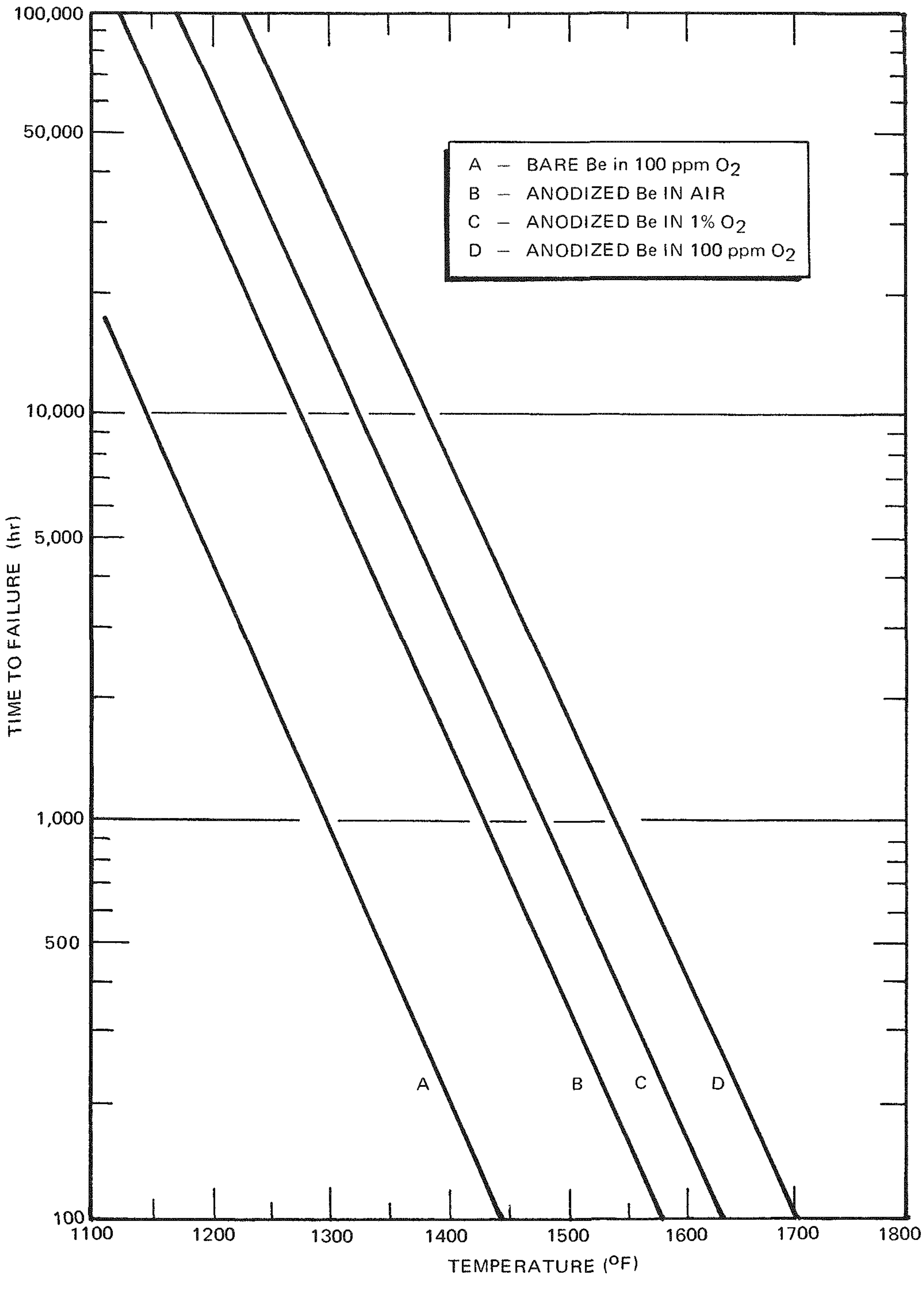

Figure 37. Projected Reflector Lifetime (Oxidation Limit)

chromium-nickel-cobalt oxide spinel. Both showed emittance values of 0.85 or better after 5000 hours at 1450° F and 10^{-6} torr. However, all coated specimens showed some degree of spalling following ten thermal cycles to 1375° F (20° F/min maximum heating rate).

It was therefore decided to retain the proven anodized coating and accept the lower emittance. All S8DR reflector and control-drum beryllium pieces were therefore anodized for oxidation protection. Post-test inspection of the anodized reflector segments, after 7500 hours at 600° F and 10^{-5} torr showed negligible deterioration of the anodized coating and no signs of oxidation. The 600° F was much lower than the predicted temperature of the reflector.

The 5-kwe thermoelectric reactor system (refer to Section III) also was designed to use beryllium control and reflector segments. Anodizing of the beryllium was again required for oxidation protection and emittance enhancement. However, the original supplier of the proprietary anodizing technique no longer performed that service and it was necessary to qualify a new vendor and verify that the new coating process resulted in a coating of equal quality.[34]

Beryllium test coupons were anodized and subjected to thermal stability testing at 1150° F and 10^{-6} torr and oxidation resistance testing at 1400° F in air. Emittance measurements of all coupons were made initially and periodically during thermal stability testing. Table 13 summarizes the emittance data measured at 800 and 1150° F. Contrary to previous tests conducted under the S8DR program (see Table 12), no degradation of emittance occurred after 5000 hours at 1150° F and 10^{-6} torr. The new coating was proven to have an emittance equal to or better than the S8DR vendor coatings. Figure 38 shows typical room temperature spectral emittance data vs wavelength for both the original and the requalified coatings. An integrated emittance over the full wavelength range shows no significant difference between the two coatings.

Oxidation resistance of the anodized coatings was tested at 1400° F in air. Tests were conducted for 200 hours on the S8DR and the new anodized coupons. Slight discoloration of all coatings occurred, but massive oxidation was restricted to areas where the anodized coating had been penetrated by scratches which occurred during emittance measurement handling. Figure 39 shows the condition of three coupons following testing. Note the difference between

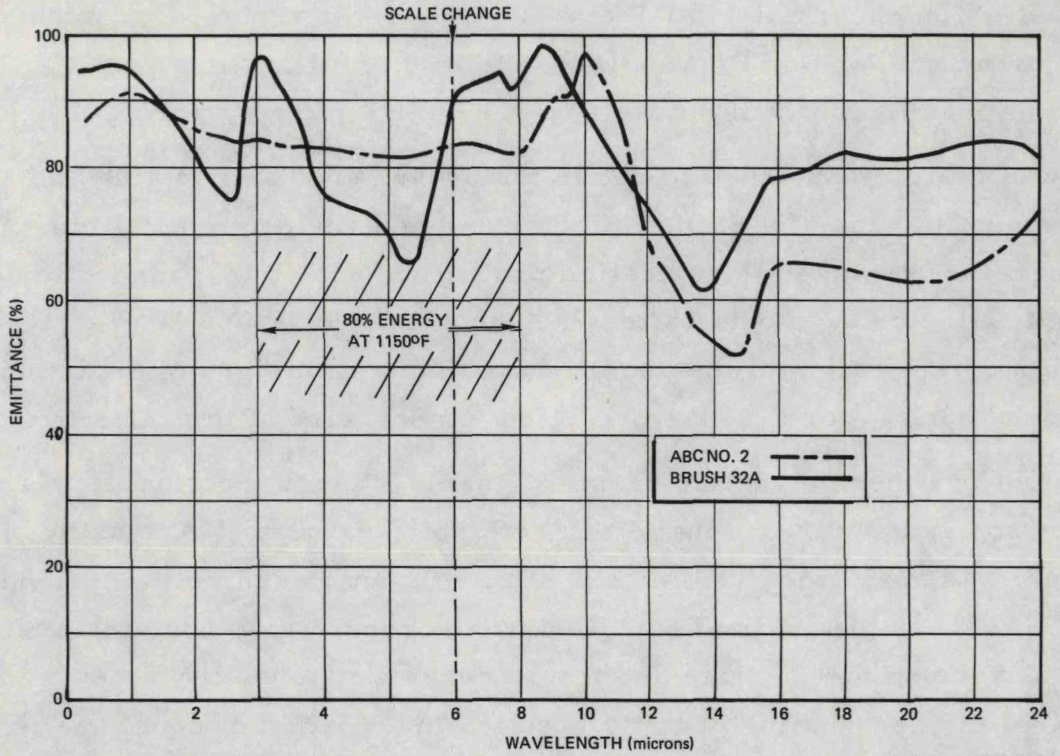

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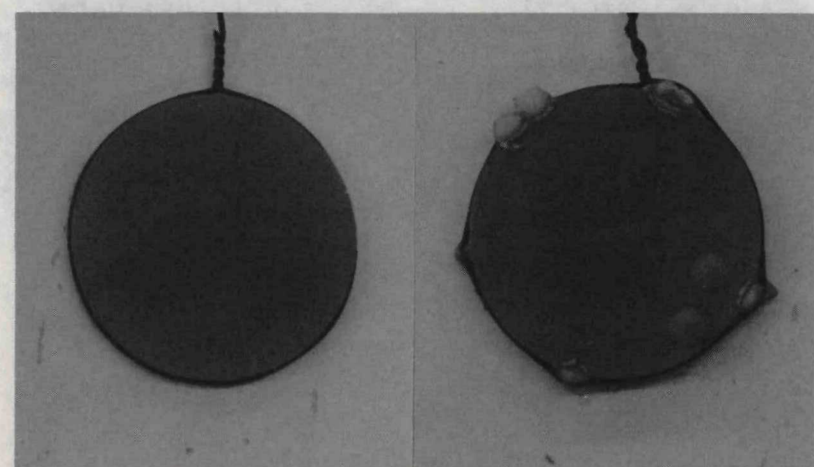
Figure 38. Room Temperature Spectral Emittance of Anodized Beryllium



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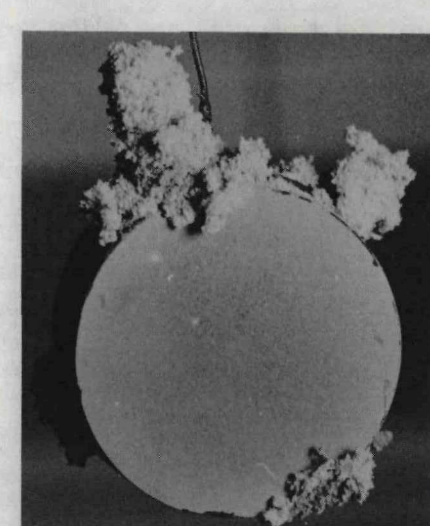
a. New Supplier Coatings



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b. S8DR Supplier Coating

Figure 39. Post-Test Anodized Beryllium Oxidation Test Coupons

TABLE 13

EMITTANCE TESTING OF ANODIZED BERYLLIUM COUPONS

Coating	Emittance at 800° F and 1150° F				
	"As Received"	1000 hr	1500 hr	3500 hr	5000 hr
S8DR Supplier	0.72 to 0.83	0.76 to 0.85	-	-	-
New Supplier	0.78 to 0.83		0.76 to 0.86	0.87 to 0.92	0.87 to 0.94

(1) the unaffected coupon which had no scratches, (2) the blistered coupon with minor scratches (scratches were mapped prior to testing and were correlated with blisters), and (3) the massive oxidation of the S8DR anodized coating with deeper scratches.

The above tests substantiated that the new anodized coating was equal to or better than the previously successful S8DR anodized coating and no further testing was conducted. A specification was prepared to ensure anodized reflector segments of continued high quality.

2. High Temperature Reactor Reflector Materials

Due to the increased temperature level of the fully shielded advanced ZrH reactor, many material changes and new coatings were required. The three major efforts were selection of a BeO material suitable for the reflector drums, a comparison study of Ta-10W and Eu_2O_3 for the reflector absorber material, and an investigation of potential emittance and oxidation inhibiting coatings for the structural materials and dry-wells.

a. BeO Selection

Based on analysis of reactivity requirements and control-drum operating temperatures beyond the capability of beryllium, beryllium oxide was selected as the reference reflector material. Nuclear grade BeO was readily available, and physical and mechanical properties were well established. Evaluation of BeO literature resulted in the selection of cold-pressed Thermalox-995A (Brush Beryllium Co.) for preliminary reflector drum tests; however, a more

TABLE 14

BERYLLIUM OXIDE MATERIAL PROPERTIES

Property	Thermalox-995	UOX + 0.5% MgO
Density (gm/cc)	(10 samples)	(11 samples)
Minimum	2.85	2.86
Maximum	2.87	2.92
Average	2.86	2.88
Grain Size, μ	(5 samples)	(2 samples)
Average	16.0 to 16.4	8.8 to 10.7
Maximum	66 to 73	
Modulus-of-Rupture (psi)	(9 samples)	(20 samples)
Room temperature, minimum	31,329	21,967
maximum	37,430	26,442
1500°F, minimum	31,000	-
maximum	37,000	-
1800°F, minimum	25,700	-
maximum	26,800	-

TABLE 15

BERYLLIUM OXIDE EMITTANCE

Material	Emittance				
	100°F	500°F	1000°F	1500°F	2000°F
Thermalox	0.67	0.60 to 0.66	0.72 to 0.77	0.63 to 0.70	0.47
UOX + 0.5% MgO	-	-	0.75	0.71	0.61

detailed study of irradiation properties showed cold-pressed and sintered UOX powder with 0.5% MgO to be a more stable material.[35] Preliminary studies were initiated with the Thermalox material, including the shock and vibration tests on BeO retention methods, as it was on hand.

Density, grain size, and modulus of rupture tests were conducted on unirradiated Thermalox-995 BeO. Test samples were made from cold-pressed and sintered blocks approximately 4-1/2 in. in diameter by 6 in. long. Similar tests were also made on cold-pressed and sintered UOX + 0.5% MgO BeO used for the development drum. Test data are tabulated in Table 14. It was found that the density of Thermalox-995 BeO was slightly less at the center of the block tested than at the periphery at one end. Grains in the center of the Thermalox-995 BeO block showed a slightly larger average and maximum grain size at the surface.

Thermalox-995 modulus-of-rupture samples were all core-drilled within a 1-in. circle at the center of each block, and the longitudinal axis of each sample was parallel to the longitudinal axis of the block. UOX + 0.5% MgO samples represent both axial and radial orientation of the reflector block. Modulus-of-rupture values of the axial samples were less scattered than for radial samples.

Emittance measurements of both the Thermalox-995 BeO and the UOX + 0.5% MgO were made. The Thermalox was measured between 100 and 2000°F. Table 15 summarizes the emittance data for both materials.[27] It can be seen that both grades of BeO suffer an emittance loss above 1500°F, with the Thermalox dropping off sooner and to a greater degree.

Material compatibility testing was initiated to study the interaction between the beryllium oxide, absorber, and cladding materials. The tests were conducted at 1800 and 2000°F at 10^{-7} torr air pressure. Table 16 lists material couples studied and Figure 40 shows typical compatibility test specimens assembled prior to thermal-vacuum testing.

After 4000 hours, a severe reaction between two couples of Ta-10W and Hastelloy-N was observed. No other reactions were apparent. An amalgam had occurred at this interface and was extruded out due to the pre-load on the samples.[36] The reaction zone was approximately 60% Ta, 33% Ni, and 7% Mo with the reaction products being binary systems of Ta-Mo, Ni-Ta, and Ni-Mo. This reaction is shown in Figure 41.

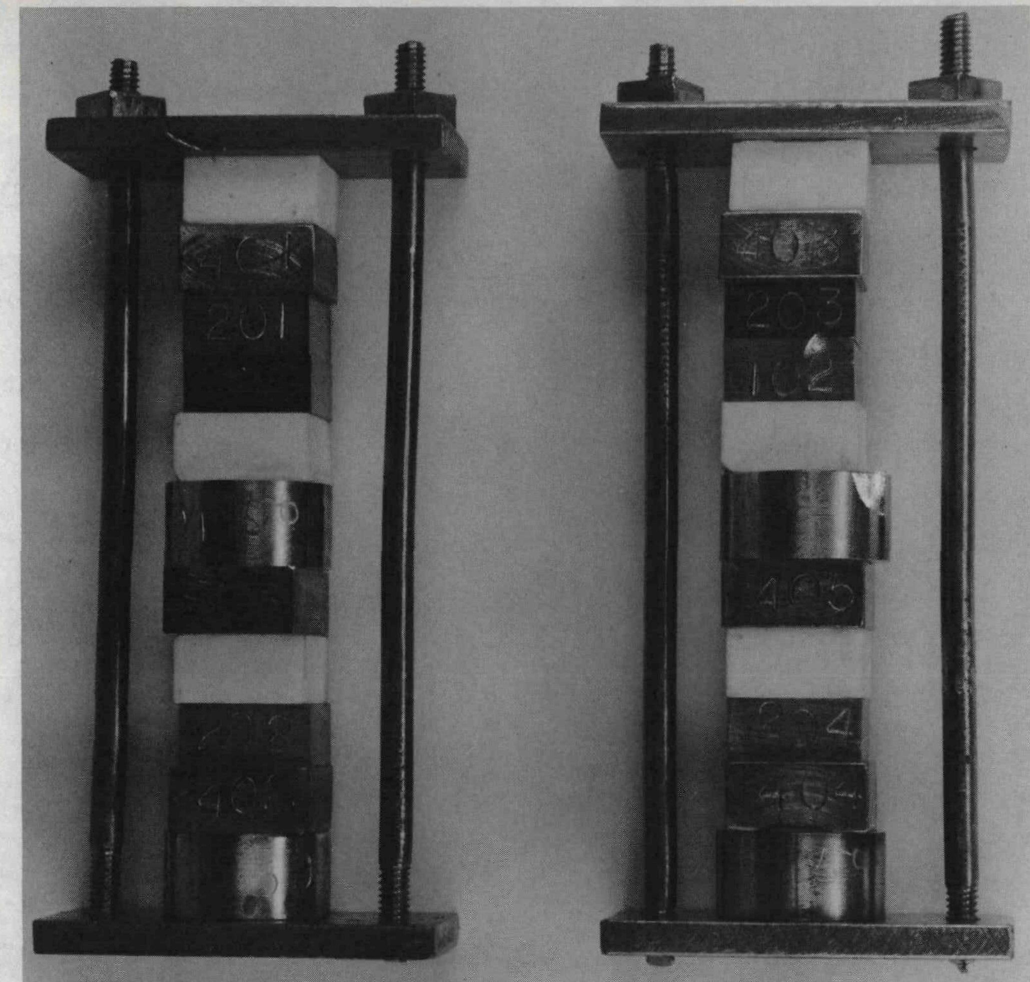

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Figure 40. Pre-Test Compatibility Coupons

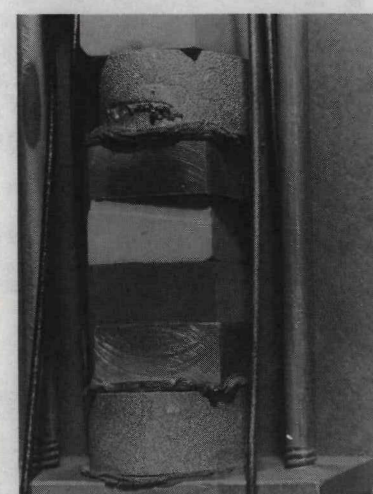

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Figure 41. Reaction Zone after 4000 Hours of Compatibility Testing

TABLE 16

MATERIAL* COMPATIBILITY TEST COMBINATIONS

BeO	vs	Ta-10W
		TZM
		Hastelloy-N
		Cb-752
Ta-10W	vs	Cb-752
		Hastelloy-N
TZM	vs	Cb-752

*For absorber retaining bands and cladding

Testing was terminated after 12,000 hours. Visual examination showed the same Hastelloy-N and Ta-10W reaction on other coupon stacks, and no other reactions were evident.[28] Hastelloy-N was dropped from further consideration as a BeO bonding or cladding material.

b. Absorber Material Selection

Preliminary analysis of reactivity requirements indicated a 3-in.-thick beryllium oxide reflector would provide sufficient excess reactivity for the ZrH reactor design life. Because the reactor was designed for 4π shielding, the void-backed drums would not be effective. Poison- or absorber-backed drums therefore became the reference design.[37]

A survey was made to determine control-drum worth for various poison materials. All materials except the following three, were rejected for reasons of cost, fabricability, or stability at high temperature in radiation.

1) Boron (natural or enriched)

2) Europium Oxide (Eu_2O_3)

3) Tantalum - 10 wt % tungsten (Ta-10W)

Table 17 shows a comparison of relative drum worth for various poison back configurations.

TABLE 17

DRUM WORTH FOR VARIOUS POISON MATERIALS

Poison Material	Worth of Ten Drums ($)
100% dense B_4C	12.55
40% boron in graphite	10.50
40% enriched (92% B^{10}) boron in graphite	15.10
93% dense Eu_2O_3	11.75
60% Eu_2O_3 in Ni	10.15
60% Eu_2O_3 in Ni cermets	10.05
60% Eu_2O_3 in stainless steel with 25% hole fraction filled with 93% dense Eu_2O_3	10.56
Ta-10W	10.70
Ta-10W with 25% hole fraction, filled with 93% dense Eu_2O_3	10.96

The enriched B^{10} in graphite sintered to B_4C shows the greatest worth, but B_4C has a distinct disadvantage of helium production through the (n, α) reaction and could present a growth problem. The Ta-10W is much heavier than the other candidates. Eu_2O_3 compacted with Ni or stainless steel offered good high temperature strength and no gas production, and was therefore chosen as the reference design. An in-house program was initiated to develop fabrication of Eu_2O_3 in Ni cermets. Pellets of 60 wt % rare earth oxides in Ni were successfully hot pressed at 2280°F to 88.4% theoretical density. The B_4C was chosen as a backup assuming the gas production could be accommodated.

In a continuing comparison study between the Eu_2O_3 in Ni and Ta-10W absorbers, it was decided to stop development work on the Eu_2O_3 and fabricate the reference absorber from Ta-10W. Lack of well-defined thermomechanical properties, niobium, and observed high temperature sublimation of the nickel binder all combined to discontinue its use. Ta-10W, while presenting a weight penalty of 27 lb (85 lb vs 58 lb) for the control drum, was a standard high-strength refractory alloy available from several manufacturers with well-defined properties. it is also machinable and weldable using conventional techniques. Results of a thermal analysis on the two drum configurations is shown in Table 18. The better transfer of heat away from the drum with a sector of tantalum vs transfer in the multilayered Eu_2O_3 assembly resulted in a lowered BeO temperature.

TABLE 18

PEAK DRUM TEMPERATURES AT 1200 kwt
(°F)

Drum Position	Absorber	
	Eu_2O_3 in Ni	Ta-10W
Absorber Out		
BeO	1930	1820
Absorber	1620	1680
Cb strongback	1750	--
Absorber In		
BeO	1800	1710
Absorber	1940	1850
Cb strongback	1850	--

A study was initiated to determine whether coatings would be required on the Ta-10W to prevent oxidation embrittlement and also to enhance emittance. Material compatibility tests were initiated (discussed above under BeO selection) to study any interactions between the various reference or backup material combinations.

Continued efforts to decrease system weight resulted in a modification of the absorber design by locating two 1.125-in.-diameter holes through the full length of the absorber.[38] The Ta-10W removed was replaced by segmented slugs of B_4C (Figure 42) and resulted in (1) an increase in drum net worth of $1.70 and (2) a decrease in weight and unbalanced moment, respectively, from 81 lb and 60 in.-lb to 60 lb and 31 in.-lb (25% and 47% decreases, respectively). The solid Ta-10W absorber concept was retained on Development Drum No. 1 which was already fabricated and undergoing thermal and vibration testing to

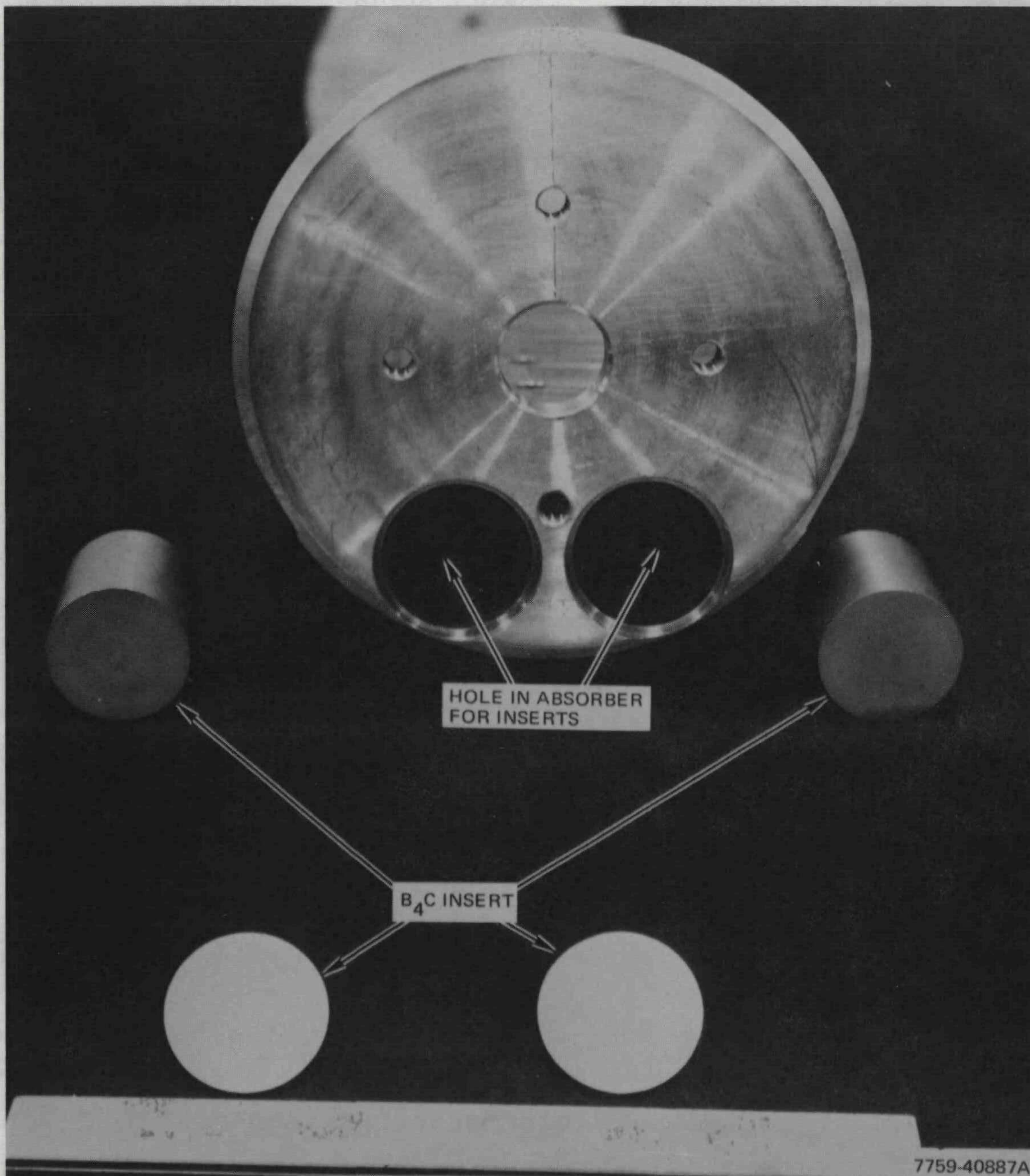

Figure 42. End View of Development Drum No. 2

evaluate BeO reflector block retaining methods reliability. The Ta-10W absorber with B_4C inserts was subsequently fabricated, assembled, and subjected to a criticality test.

At this point, the ZrH program was reoriented and the absorber studies were terminated. The basic concept of the Ta-10W absorber-strongback with the B_4C inserts to decrease weight and enhance drum worth was proven to be the preferred design. The composite absorber is shown in Figure 42.

e. Coatings for Refractory Metals

Following selection of Ta-10W for the reference absorber material, a study was initiated to investigate possible coatings to (1) prevent oxidation embrittlement of the Ta-10W, and (2) to enhance its surface emittance and heat dissipation.(38)

Based on previous experience and a brief literature survey, an aluminide coating appeared most promising of the coatings being investigated. A 0.001-in.-thick aluminide coating, Vac-Hyd Co. Coating No. 9, was applied to Ta-10W coupons.(39) The coated coupons and identical bare matt finished Ta-10W coupons were bend tested and measured for emittance before and after 50 thermal cycles between 400 and 2000°F at 10^{-7} torr. Table 19 shows emittance results.

TABLE 19

TEST COATING EMITTANCE DATA

Coupon	Temperature (°F)	Emittance	
		Pre-Thermal Cycle	Post-Thermal Cycle
Bare Ta-10W (Matt finish)	1000	0.23 to 0.26	0.24
	1500	0.24 to 0.27	
	2000	0.25 to 0.27	
Vac-Hyd Coated	1000	0.90	
	1500	0.91 to 0.92	0.76 to 0.77*
	2000	0.92	0.86 to 0.87†

*Side with coating flaked off
†Side with coating intact

Inspection of the coated specimen following thermal cycle testing showed heavy spalling of the coating on one side of the coupons and the coating appeared to be multilayered. The inner layer remained well bonded to the substrate. Even though the coating emittance was acceptable, spalling of the coating made it unacceptable as small particles could fall into the drum bearings and result in their seizure.

The coated Ta-10W strips, 0.010 in. thick, were subjected to bend tests before and after thermal cycling. Prior to thermal cycling, the coatings cracked when bend around a 1/2-in. radius, but were uneffected by a 1-in. radius bend. Similar results were obtained with the coating still adherent to post-test strips. Figure 43 shows the post-thermal test condition of emittance and bend test coupons. Following these failures, an iron-titanate coating was selected to replace the aluminide.[25] Due to poison problems with the originally selected Ta-10W cladding for the BeO, new claddings were being fabricated from a niobium (columbium) allov Cb-752, material.

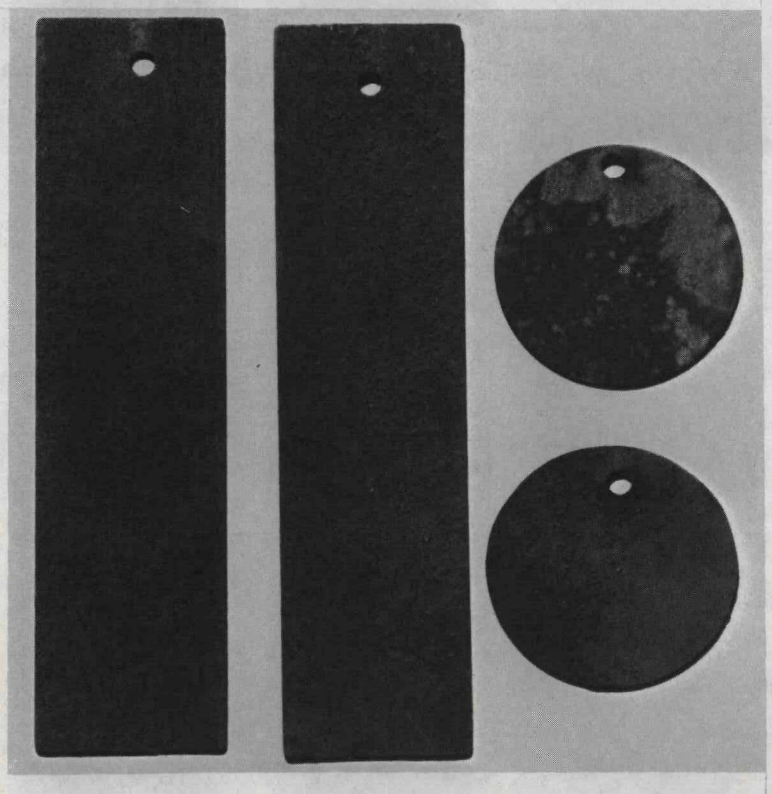

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Figure 43. Aluminide Coating Coupons Following Thermal Cycling

Table 20 shows the selection of oxidation prevention and emittance enhancement coatings selected for Development Drum No. 2.

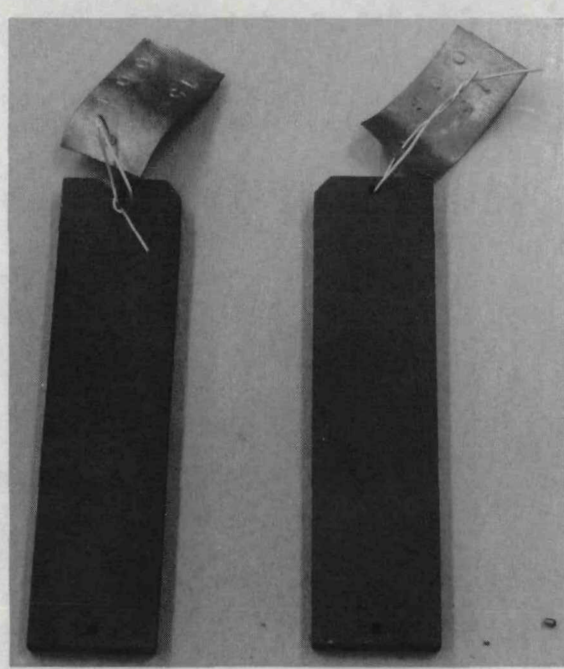
TABLE 20

DRUM DEVELOPMENT NO. 2 MATERIALS AND COATINGS

Component	Substrate	Base Coating	Emittance Coating
Absorber	Ta-10W	Tungsten	Iron titanate
Reflector Bands	Cb-1Zr	Molybdenum	None
Cladding	Cb-1Zr	Tungsten over molybdenum	Iron titanate

The tungsten and Fe_2TiO_5 coatings on the absorber are both plasma-sprayed coatings and are 0.001 and 0.004 in. thick, respectively.(36) The molybdenum and tungsten on the reflector bands and cladding are chemically vapor-deposited (CVD) coatings about 0.001 in. thick. The CVD tungsten is necessary over the molybdenum, as Oak Ridge National Laboratory experience shows the Fe_2TiO_5 will not properly adhere to CVD molybdenum.

Coating proof-testing was conducted in two phases with (1) endurance testing at 1600°F at 50 microns pressure, air, for 240 hours, and (2) ten thermal cycles to 1800°F at 50 microns.(40) The endurance test parameters were selected to permit the uncoated Cb-1Zr cladding material to absorb oxygen equivalent to that expected in a 20,000-hour ground test. Table 21 shows the samples which were tested. In all cases, the iron titanate adhered only to the plasma-sprayed tungsten undercoat. Analyses of the specimens showed uncoated substrates gained about 1% (10,000 ppm) oxygen during endurance testing, while CVD-coated specimens gained about 250 ppm of O_2 and plasma-sprayed specimens gained about 2500 ppm of O_2. Figure 44 shows typical post-test specimens with adherent and failed coatings.



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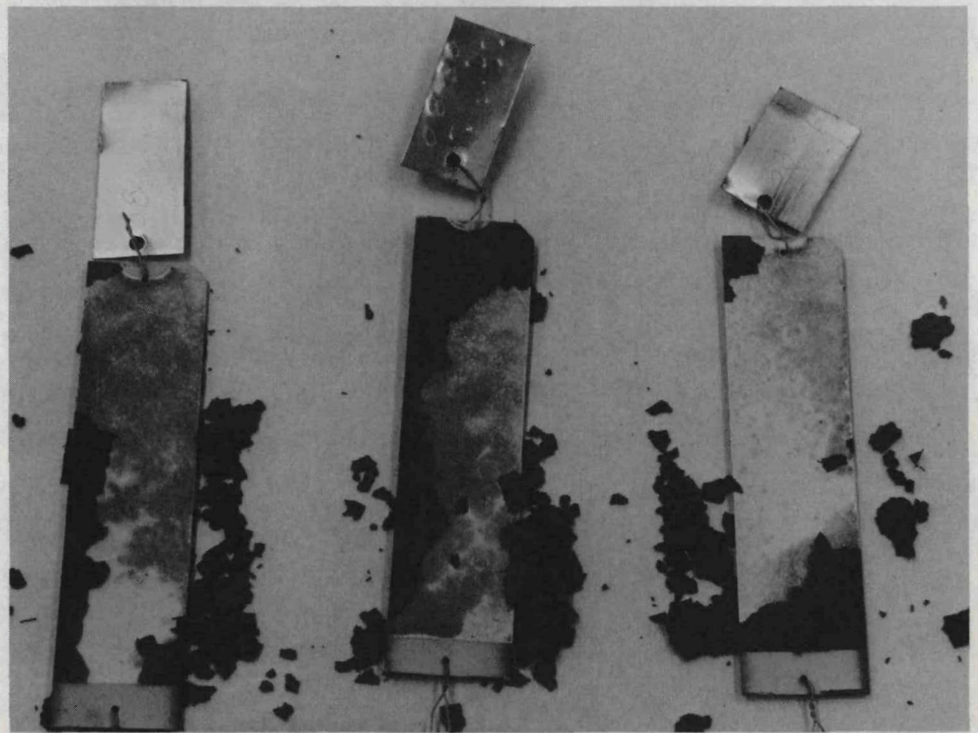
a. Adherent Coating Plasma-Sprayed W + Fe_2TiO_5



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b. Failed Coating CVD-Sprayed W + Plasma-Sprayed Fe_2TiO_5

Figure 44. Post-Endurance Proof-Coating Test Specimens

TABLE 21

COATING PROOF-TEST SPECIMENS

Substrate	Undercoat	Emittance	Test Result
Ta-10W	None	Iron titanate	Iron titanate flaked off
	W(CVD)	-	
	W(CVD) + Mo(CVD)	-	
	W(CVD) + Mo(CVD)	Iron titanate	Iron titanate flaked off
	W(plasma spray)	-	
	W(plasma spray)	Iron titanate	OK
Cb-1Zr	W(CVD) + Mo(CVD)	-	
	W(CVD) + Mo(CVD)	Iron titanate	Iron titanate flaked off
	W(CVD)	-	
	W(CVD)	Iron titanate	Iron titanate flaked off
	W(plasma)	-	
	W(plasma)	Iron titanate	OK

TABLE 22

SNAP 10A POSITION SENSOR AND DEMODULATOR REQUIREMENTS

Requirement	System	Sensor	Demodulator
1. Angular range	135°	135°	-
2. Temperature range	-	30 to 500°F	0 to 140°F
3. Accuracy	±3%	±2.5%	±0.5%
4. Linearity	-	±4% (±2% zero base)	-
5. Repeatability (as function of temperature)	-	±20 min (at fixed temperature)	±1.0% (through 0 to 140°F)
6. Repeatability (vs power supply variations)	±3%	-	±1% (with ±10% variation on 28 vdc and ±5% on 115 vac supplies)
7. Torque	-	4 in.-oz	-
8. Electrical power requirements	-	26 vrms ±1%, 1ϕ, 400 Hz ±0.02%	2 va, 115 ±2.3 vrms, 400 Hz ±0.02%, 1.5 w, 28 ±0.56 vdc
9. Electrical output	-	3.8 ±0.2 vrms, 1ϕ, 400 cps ±0.02% at zero and 135° electrical null at 67.5°	0 to 5 vdc in 135° (coarse) 0 to 5 vdc in 30° (fine)

TABLE 23

EVALUATION OF SENSING SYSTEM CONCEPTS

Type	Advantages	Disadvantages
Potentiometer	Minimum need for demodulator circuitry.	Self-welding problems with wiper-element contact.
Synchro-resolver with control transformer and servo amplifier	Relatively insensitive to temperature variations.	Complexity and weight. Self-welding problem with rotor wipers. Cost.
Variable capacitance sensor	Simplicity of construction. Ruggedness.	Possible effects due to cabling capacitance. Complex demodulation circuitry.
Digital magnetic pickup plus digital to analog converter	Simple sensor construction. Insensitive to temperature variations.	Complex and bulky electronics converter package. High system weight.
Variable reluctance sensor with ac to dc demodulator package	Simple rugged construction of sensor (no wipers or contacts).	Sensor temperature-sensitive. Relatively complex demodulator.

C. MISCELLANEOUS COMPONENTS

Each of the above reactor systems required a variety of control and diagnostic components which were initially developed for the SNAP 10A reflector assembly and were used with little change on succeeding systems.[4] These items include the drum position sensors, limit switches, the squib-type drum launch lock and EOL shutdown mechanisms, described in the following paragraphs. In addition, development of spring and electrical cable technology is presented.

1. Position Sensors

It is necessary to monitor the position of the reactor control drums during the operating life of the system. This information provides a continuous record of reactivity changes in the reactor caused by temperature changes, fuel burnup, and/or hydrogen loss. Drum position data is also useful in diagnosis of malfunctions or failures of the drum drives or other portions of the system.

a. SNAP 10A

The position sensor is mounted on the reflector assembly with its rotor shaft coupled to the control-drum shaft. The demodulator package supplies the sensor with regulated 400 cps, a-c voltage, and converts the sensor output a-c signal, which varies in amplitude and phase as the drum is rotated, to a d-c ramp voltage compatible with the flight vehicle telemetry system. The demodulator is mounted below the shield to protect its electronic components from severe radiation. Design requirements for the SNAP 10A position sensor are listed in Table 22, and various sensing system concepts are evaluated in Table 23. The requirements of SNAP 2 and 8 sensors are similar except for increases in operating temperatures.

The variable reluctance sensor, essentially a rotary differential transformer, was chosen as the best overall design for development. It consists of two main subassemblies, the stator and rotor. The stator contains the sensor windings and the journal bearings. There are three windings, of the simple bobbin-wound type. The rotor consists of a nonmagnetic shaft and a magnetic rotor shaped so that the mutual coupling between the primary and one secondary is at a maximum when the coupling with the other is at a minimum. The secondary windings are connected electrically in series with opposing polarity. A cross section of the sensor is shown in Figure 45.

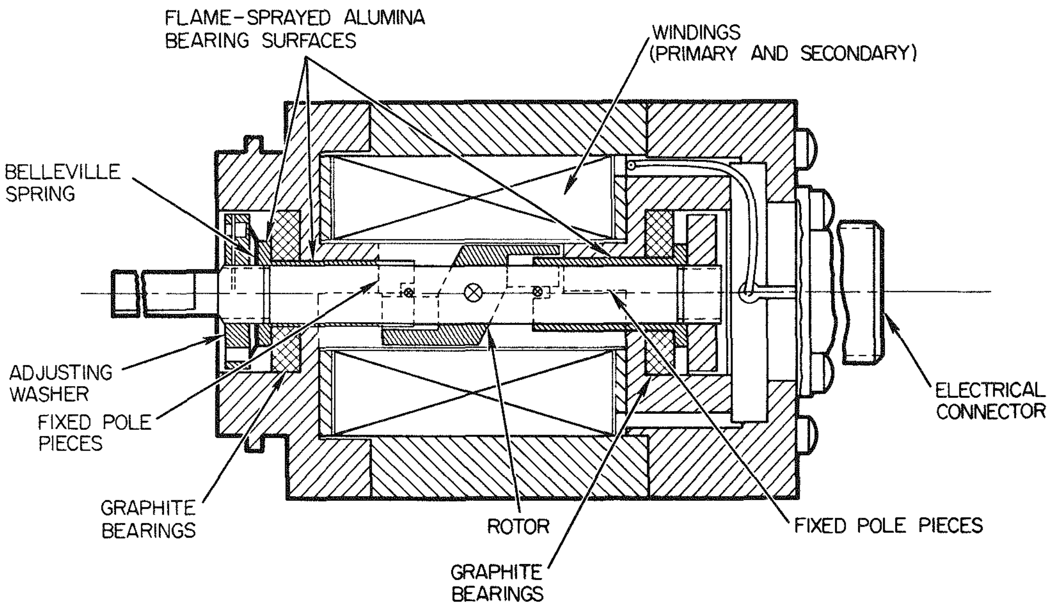

Figure 45. Cross Section of SNAP 10A Variable Reluctance Position Sensor

The magnetic portions of the sensor are fabricated of Relay No. 5 steel and Type 416 stainless steel. The nonmagnetic portions are titanium. The bearing surfaces on the shaft are flame-sprayed and ground alumina, working against graphite journal bearings. The bearing nearest the shaft extension is both a radial and thrust bearing. MoS_2 dry-film lubricant is applied to the rubbing surfaces during the assembly process. A split-washer adjusting disc is used to establish the rotor position and the sensor null point, and to insure adequate linear output range.

The windings are ceramic-insulated, nickel-clad copper wire (AWG No. 32), encapsulated with phosphate-bonded ceramic potting compound. Glass fiber tape is used for coil form insulation. A high temperature electrical connector is used.

b. SNAP 8

The SNAP 10A position sensor was modified to operate in the higher temperature and longer life environment of SNAP 2 and S8DRM. However, during development testing of S8DRM, problems were encountered and the position sensor was redesigned for S8DR operation. Figure 46 shows the redesigned sensor. Following redesign, testing was initiated to verify the operating characteristics of the new position sensor.

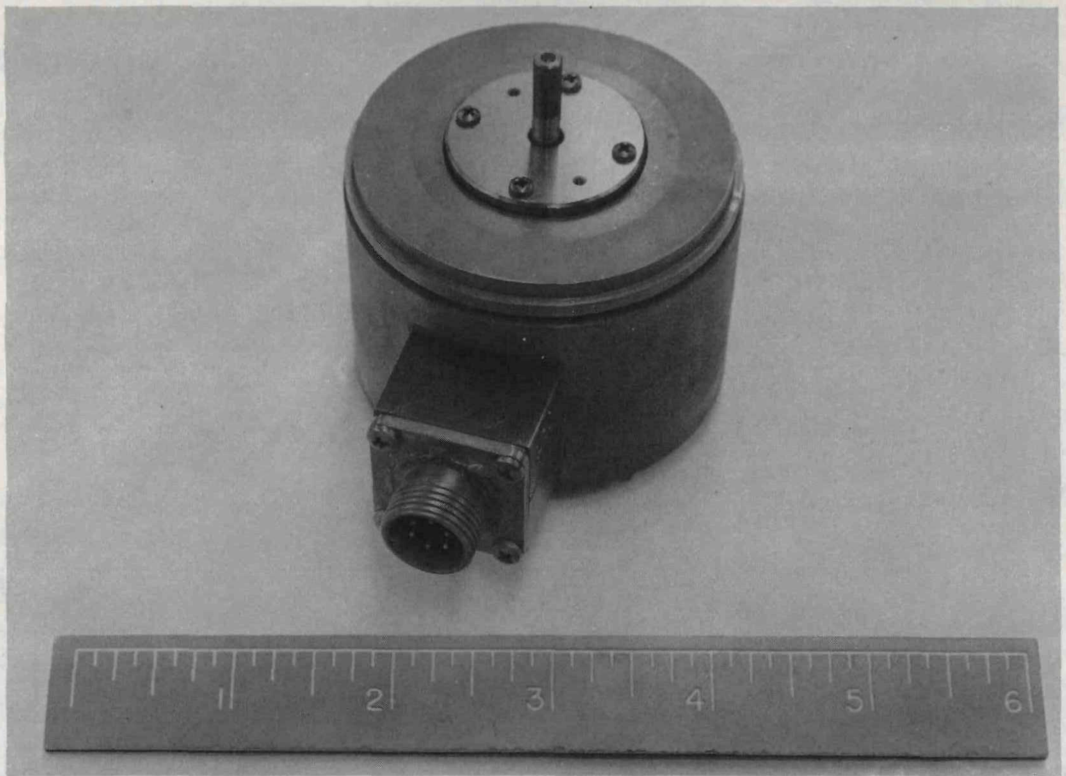

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Figure 46. S8DR Position Sensor

Two modified S8DR design position sensors completed 12,000-hour endurance tests at 800°F and 10^{-6} torr. Two other sensors completed 200 thermal cycles to 800°F and a 5000-hour endurance test at 800°F. Eight sensors successfully operated throughout the life of the S8DR reactor.

The two units functioned properly without incident throughout the 12,000-hour endurance tests. As observed with the first two units, considerable scatter existed in the output winding voltage readings with the input current held constant, and with the input current adjusted so that the sum of the output voltages was maintained constant. The magnitude of the scatter approached the equivalent of 10° rotation.

The room-temperature and 800°F insulation resistances of both units remained high throughout the test as shown on Table 24. Room-temperature resistances for both units and 800°F resistance of SN004 decreased slightly with time, while the 800°F resistance of SN003 showed an upward trend with time.

The shaft torques, as seen on Table 25, changed very little as a result of 12,000-hour endurance testing, showing a slight upward trend. All values were well within the specification limit of 4 in.-oz.

TABLE 24

S8DR POSITION-SENSOR RESISTANCE AT 50 VOLTS BEFORE AND AFTER 12,067 HOURS AND 61 THERMAL CYCLES

Terminals	Resistance (megohms x 1000)							
	Room Temperature				800°F			
	SN003		SN004		SN003		SN004	
	Before	After	Before	After	Before	After	Before	After
A-C	200	1.6	150	16.0	0.17	3.0	0.70	4.0
A-E	200	3.0	150	14.0	0.18	40.0	0.70	0.25
C-E	∞	4.0	600	20.0	0.95	40.0	1.90	1.60
A-GND	200	10.0	200	10.0	0.06	0.090	0.95	0.16
C-GND	∞	11.0	∞	18.0	1.40	1.7	2.80	0.90
E-GND	16	13.0	150	9.0	2.50	3.0	1.90	0.095

TABLE 25

ROOM-TEMPERATURE SHAFT TORQUE

Direction	Shaft Torque (in.-oz)			
	SN003		SN004	
	Initial	End	Initial	End
CW	0.8	0.8	0.5	0.7
CCW	0.6	0.8	0.5	0.8

2. Limit Switches

Limit switches are used to indicate control-drum full-in, intermediate, and full-out positions, and to indicate reflector ejection.(6) Signals obtained from the switches are used for control purposes or are delivered to the telemetry system and transmitted to receiving stations for diagnostic purposes.

The limit switches must be capable of operation in the temperature, vacuum, and irradiation environment in the vicinity of the reactor throughout the reactor operational life. The switches must also be capable of withstanding the shock and vibration of launch.

a. SNAP 10A

SNAP 10A limit switches were required to indicate the full-out and full-in drum positions, and to indicate when the reflector half was ejected. Each switch operated only once, but was qualified to 1000 cycles. They were required to operate on 28 vdc unregulated at 2 milliamperes and to operate with a force of 18 oz or less.

The development program consisted of surveying commercially available switches, evaluating promising ones, modifying the designs, and comprehensively testing the final designs. Several commercially available high temperature limit switches were evaluated to determine whether any appeared capable of modification to meet the environmental requirements of the SNAP 10A reactor application. One switch was selected as the most promising for development modification to meet the requirements. The switch is shown in Figure 47. It is a snap-action switch using a pre-stressed leaf spring to produce this action. A roller actuator is normally used with the switch, to prevent side loading of the plunger due to cam friction.

b. SNAP 8

Two types of switches, a snap-action and a shorting-bar design, were investigated for use on SNAP 8.

(1) Snap-Action Switch

The snap-action design is based on a switch which has previously been successfully tested at 1000°F in air.(13) Modifications were made for vacuum

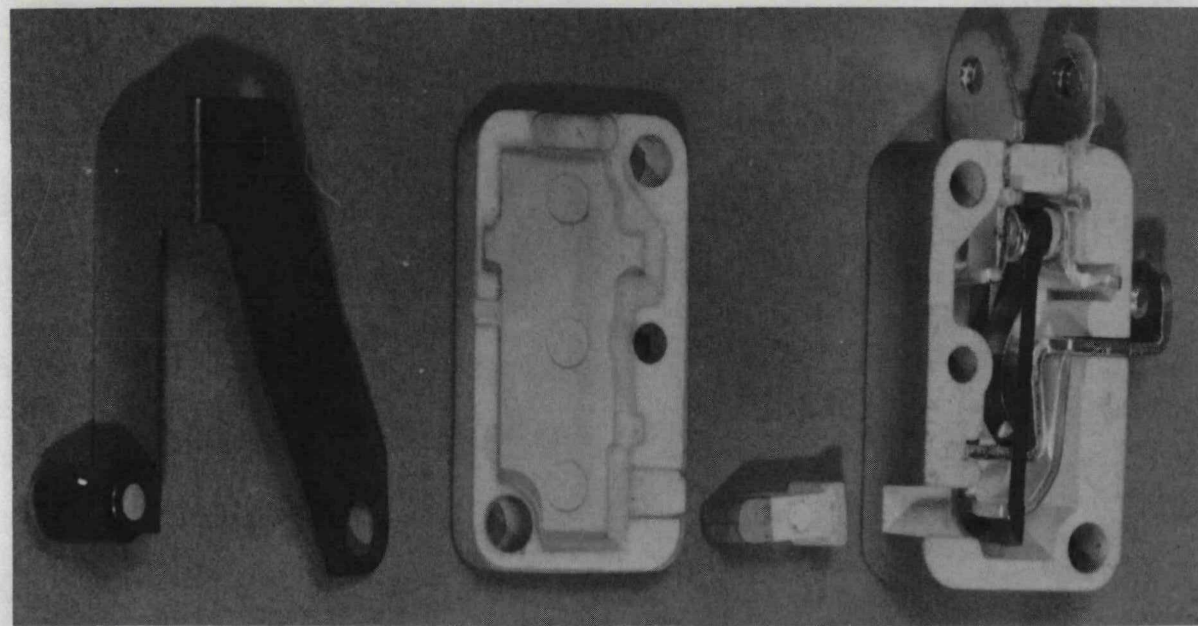

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Figure 47. SNAP 10A Limit Switch

environment primarily to prevent galling of rubbing metal parts. One modification is the application of dry-film lubricant to rubbing parts, a technique which was providing satisfactory performance in the S8DS scram mechanism temperature-vacuum performance tests. Another approach involves modification of the switch to substitute a graphite plunger to eliminate metal-to-metal bearing surfaces. Figure 48 shows the switch as modified for SNAP 8 use.

Five of these switches, three in the nonactuated position and two with the plunger depressed, were tested in a vacuum of 10^{-6} mm Hg at 1000°F for a period of 3 weeks. Examination of the parts after the test revealed that the two plunger-depressed switches had failed by cracking of the snap-action spring; actuating force for the other three switches remained approximately the same as before the test. Two other dry-film-lubricant coated switches, one with the plunger depressed and one in the nonactuated position, were tested in an air furnace at 1000°F for a period of 3 weeks. The force required to "make" the nonactuated switch under heat test was checked periodically. The actuating force was erratic on the normally open switch while undergoing the make and break force test possible due to difficulties with the test fixture. Measurements at room temperature at the end of the test showed a decrease from the original

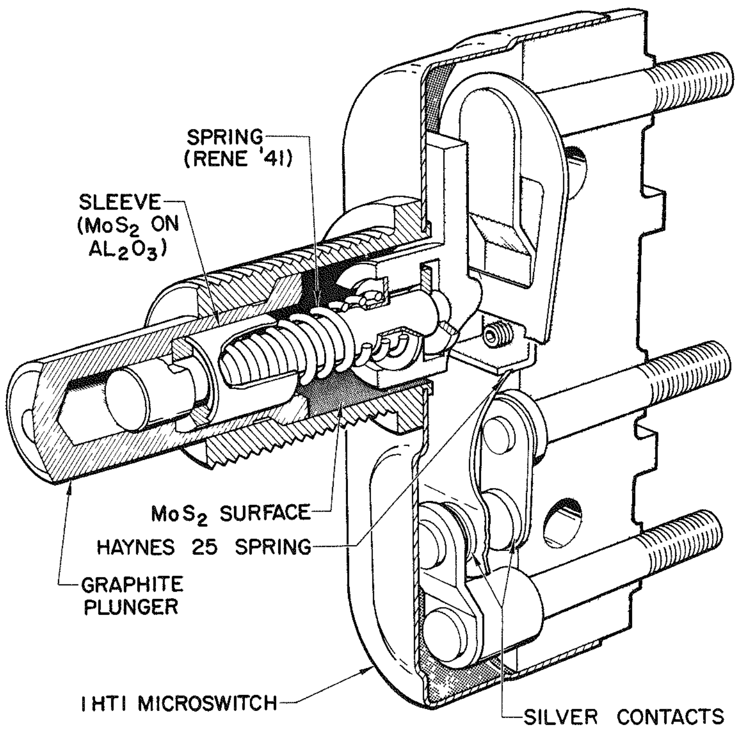

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Figure 48. Modified 1HT1 Microswitch

nominal force of 14 oz to approximately 8 oz. Hence, this switch concept was not acceptable.

(2) Shorting-Bar Switch

The shorting-bar switch, a slow-make-and-break type, is shown in cutaway in Figure 49. This switch does not use any highly stressed snap-action springs. When the plunger is depressed, switching occurs when the movable graphite disc contacts the two fixed contacts and provides a low resistance path between them. The contacts are formed from the pins of the electrical connector which is an integral part of the assembly.

The shorting bar switch proved to have the most advantages for SNAP 8 uses and was subjected to a series of thermal-vacuum and life operational tests. Table 26 summarizes the test history of the switch. The reliability of the switch was established and accepted for system operation.

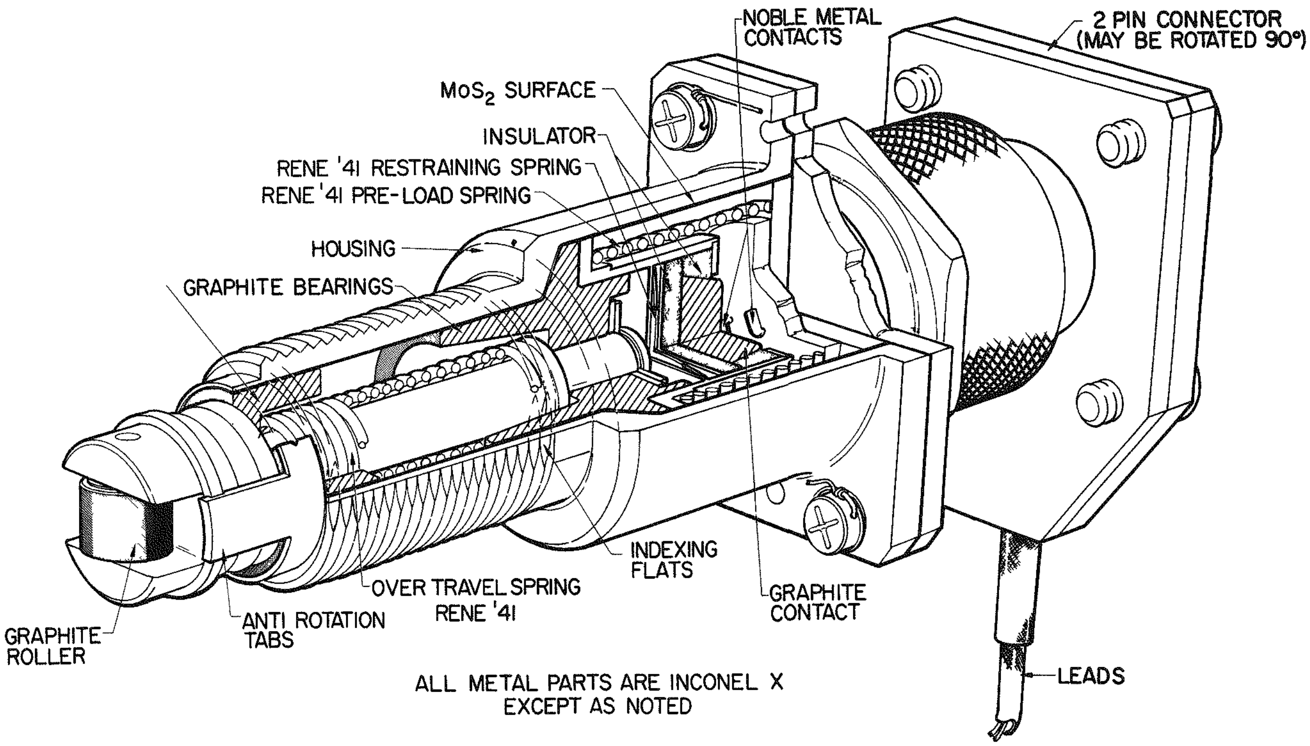

Figure 49. S8DR Shorting Bar Switch

TABLE 26

SNAP 8 LIMIT SWITCH TEST SUMMARY

Test	Number	Total Unit (hr)	Total Unit Thermal Cycles	Maximum Time Unit (hr)
Development	14	118,702	1212	24,807
Scram Kit	3	38,522	614	15,508
Irradiation	2	6,100	10	3,050
Verification	8	88,882	366	14,804
Reflector	17	>17,000	>850	>1,000
S8DR Operation	32	>224,000	>480	>7,000
S8DR Development	2	24,114	116	12,057
	78	517,320	3648	

3. Temperature Sensor Switch

The function of the temperature sensing device is to provide a contact closure when the reactor outlet coolant temperature drops below a preset limit. The temperature switch contacts are in the startup controller input circuit and when opened, initiate corrective action of the control system by stepping the reflector control drums "in" to raise the system reactivity level.[6]

The temperature detector provides voltage signals to the temperature switch which are proportional to the reactor outlet coolant temperature. The detector, in conjunction with the switch, establishes the limits of the reactor deadband and commands the controller to drive the drums whenever the outlet coolant temperature passes outside this deadband.

The temperature switch receives the output of the resistance temperature detectors (RTC's) and provides signals to the controller whenever the reactor outlet coolant temperature passes outside the deadband limits as defined by two preset points.

Figure 50 illustrates the final design of the SNAP 10A detector. The devices were selected based on simplicity, availability from commercial sources, and accumulated experience in the industry. Evaluation testing of the units was conducted and proved to meet SNAP 10A requirements. The only problems encountered were isolated instances of 5°F drift or more after 500 hours at 1000°F. It was recommended that future programs permit such short-time drift limits.

The S8DS design uses a platinum resistance temperature detector (RTD) which forms one leg of a three-wire Siemens bridge.[41] As the resistance of the detector changes with temperature, the output of the bridge to the control winding of a high-gain magnetic amplifier in the switch varies accordingly. The bridge is adjusted to null at that detector resistance corresponding to the temperature at the middle of the deadband.

High-temperature drift testing of three prototype S8DS detectors was done at 1335°F in air. One detector, SN-002, accumulated nearly 1000 hours of drift testing in addition to the 1000-hour stability test. The 500-hour calibration indicated the detector resistance had drifted 0.09 ohms or -0.58°F related to the

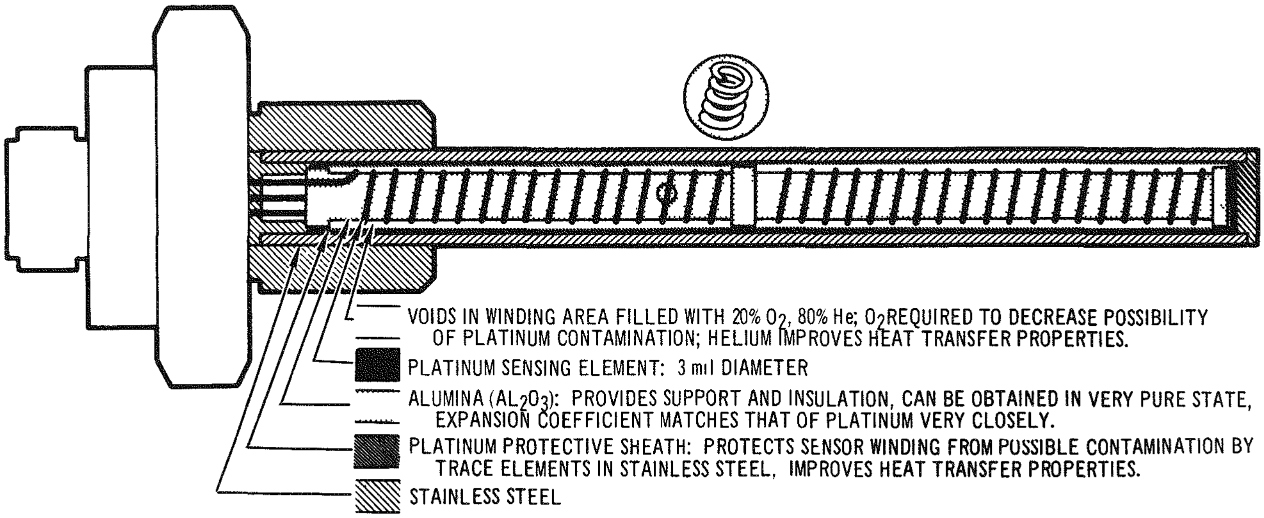

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Figure 50. Cross Section of the SNAP 10A Resistance Temperature Detector

setpoint. One detector, SN-001, failed during the first 500 hours of the 1000-hour stabilizing period. The failure was found to be an open circuit at the junction between the element wire and the platinum lead wire. SN-003 failed immediately following the 1000-hour stabilizing period. The failure mode of this unit was identical to that of SN-001.

Drift testing at 1300° F of evaluation RTD's was also conducted. These detectors were continuously maintained at 1300° F to simulate long-term operating conditions. They were checked for drift every 500 hours by calibration in a triple point of water cell (0.01° C) utilizing precision laboratory resistance measuring techniques. Accuracy of this calibration converted to equivalent temperature at 1300° F is ±0.2° F. Four detectors of an original 25 remained within the acceptable limits of -4° F shift in 10,000 hours. RTD No. 5, which had shown considerably drift at the 8000-hour calibration, failed during the next 500 hours and was removed from the test. The drift in terms of equivalent setpoint shift is shown in Figure 51. All data are referenced to zero after a 1000-hour stabilizing period. This stabilization will be performed by the manufacturer on future units prior to acceptance.

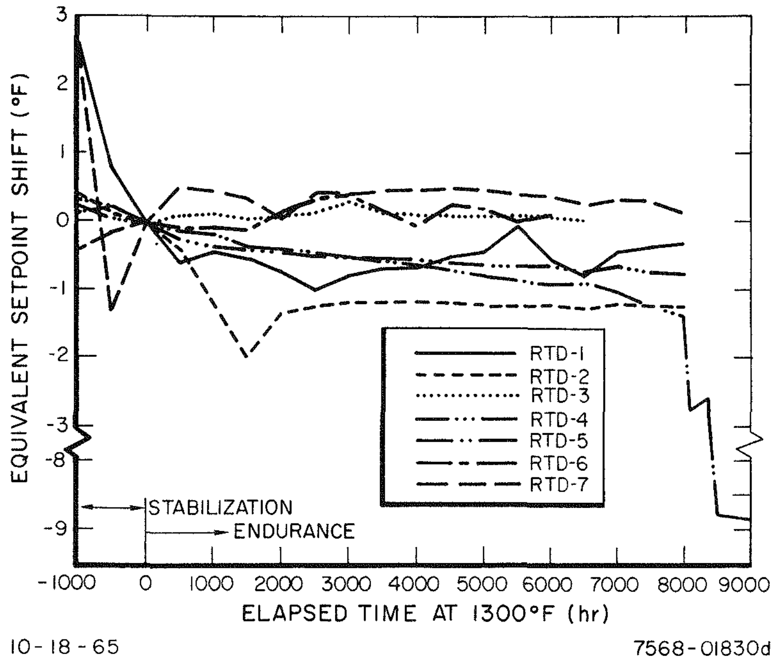

Figure 51. Resistance Temperature Detector Drift Characteristics at 1300° F in Air Environment

Final checkout of the S8DS detectors prior to starting the design verification tests at the vendor's facility demonstrated very erratic performance. Disassembly of one unit revealed cracks in the swaged gold protective tubing. The cracks were attributed to contamination originating from a ceramic sealant used to contain the insulating material inside the swaged gold tubing. Thorough analysis of these problems and the failure of the first two prototypes resulted in a complete redesign of the detector to eliminate the swaged gold tubing and the ceramic sealant, eliminate as many joints and connections as possible, and improve the design of the connector. The redesign simplifies the fabrication and improves reliability. The redesign was completed, new parts procured, and fabrication of the new units initiated. Figure 52 shows the final designs of the S8DR RTD.

Although performance of the S8DS design development switches, which were fabricated under controlled laboratory conditions, was within specification limits, the performance of the first S8DS system unit was erratic and very marginal. An effort was made to optimize the performance of this switch with the results given in Table 27.

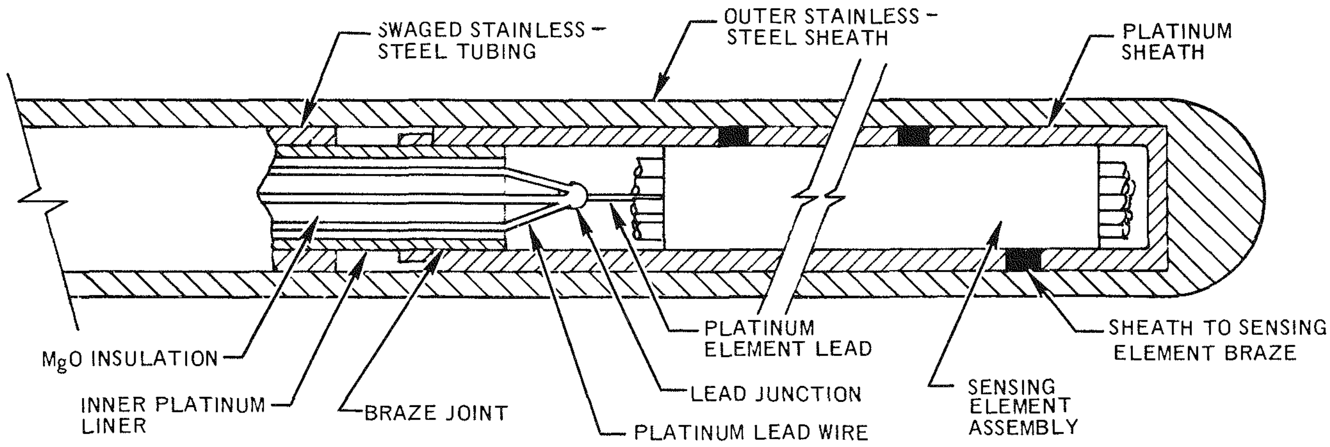

Figure 52. SNAP 8 Platinum Resistance Temperature Detector

TABLE 27

S8DS SWITCH PERFORMANCE CHARACTERISTICS

Test Condition	Setpoint Variation	Design Requirement
Ambient Temperature, 50 to 120° F	6-1/2° F	
Normal Room Ambient	2° F	±2° F
Line Voltage — Regulated	1° F	
Hysteresis	4-1/2° F	1-1/2° F

In addition to the above performance characteristics, the contact closure reliability was marginal. This reliability could be improved only at the expense of additional hysteresis. Therefore, the above performance was considered to be the optimum for this design switch.

A breadboard circuit representing a fundamental design revision was fabricated and tested, and showed improved performance. This approach is based on a null sensitive principle as compared to the voltage threshold operation of the current design. Test characteristics of the revised design are given in Table 28.

TABLE 28

SWITCH PERFORMANCE CHARACTERISTICS, S8DS REVISED DESIGN

Test Condition	Setpoint Stability
Ambient Temperature, 50 to 120°F	±1/2°F
Line Voltage ±10% Variation	±1/2°F
Hysteresis	1°F maximum

This design also exhibited very positive contact closure due to the higher inherent gain. A prototype of the revised switch was to be assembled and tested to evaluate performance.

4. Control-Drum Launch Lock

This assembly is composed of two components: (1) the drum release actuator, and (2) two electrically-fired squibs. The drum release actuator operates on gas pressure supplied by the pyrotechnic explosion of the squibs.[6] The design for SNAP 10A was modified only slightly for SNAP 2 and 8.

a. Drum Release Actuator

The drum release actuator is a squib-operated mechanical device that provides positive lockout of the control drums in the least reactive position during vehicle launch. Upon electrical command prior to reactor startup, it releases the control drums for rotation. There are a total of four drum release actuators in the reactor drum lockout subsystem. Two electrically-fired squibs are used as a power source for each one-shot drum release actuator in which gas energy is converted to useful mechanical output.

The drum release actuator consists of a titanium alloy cylinder and a titanium alloy piston, which is integral with the locking pin. Figure 53 shows the disassembled actuator. A lockwire prevents pin movement, so that inadvertent drum release will not occur. Two low-voltage M-130 squibs, one for redundancy, actuate the piston upon firing and drive the piston from the locked to the released position. The firing of either squib will generate enough force to shear the lock wire and pull the pin. In the released position, a spring collet receives and retains the piston to prevent further motion or bounce. The volume of the actuator chamber in the locked position is 0.248 $in.^3$

Figure 53. Drum Release Actuator, Disassembled

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The drum release actuator was statically and dynamically tested under ambient pressure and temperature, elevated temperature and vacuum, and low temperature and vacuum conditions. Variable gas chamber volumes were used in order to determine the volumetric margin of safety for reliable operation. Body proof pressure tests were performed to demonstrate adequate strength. Static tests of the drum release actuator were performed with the Instron tensile test machine, and the dynamic tests were performed by firing the McCormick Selph M-130 squibs within the actuator.

Design criteria required that both squibs be able to fire after undergoing 10 thermal cycles to 700°F (at 10^{-3} torr), launch vibration and shock loads, and a 48-hour soak at 250°F. Either squib is required to release the locking pin in 10 msec under a 5-lb side load. The actuator body must also withstand proof loads of 6000 psi and operate at a nominal 1470 psi.

In static force tests at ambient conditions, gas pressures less than 460 psi were required to release the locking pin. In dynamic tests, pressures to 1775 psi were required with full release requiring up to 6.8 msec.

High temperature dynamic tests required up to 9 msec to obtain full pin release following actuator soaks at 250°F and 10^{-7} torr for 48 hours.

Actuator assemblies survived pressures of 8000 psi, 5.4 times design pressure, with no dimensional changes or degradation.

Four flight-design drum release actuators successfully completed full qualification testing.

b. Squibs

The squibs used in the drum release actuators are also used on SNAP 10A to initiate expansion compensator lock release, heat shield ejection, and destruct charge device ejection. The squib is a small pyrotechnic explosive capsule capable of firing upon application of a 28 v current. They are one-shot power sources in which gas energy is converted to useful mechanical output.

The squibs are required to operate satisfactorily, with 96% reliability, following reactor checkout, launch shock and vibration loading, and a 48-hour soak at 250°F in vacuum. They must not fire under 0.5 amp, dc, but must fire with full pressure rise in less than 12 msec under a 2 to 5 amp current.

The McCormick-Selph M-130 squib was selected as a result of a comprehensive study and search for a suitable squib to meet SNAP 10A performance and environmental requirements. A significant factor in the choice of the M-130 squib was that it had been previously qualified by Lockheed Aircraft Corp. (Specification No. 1067248, "Electrically Fired, Pressure Sealed Squib") to conditions that were similar to SNAP 10A requirements. The M-130 Mod. 1 squib was originally developed by McCormick-Selph as an initiator for a fuel mixture or propellant. The squib consisted of a cadmium-plated, low-carbon-steel case which housed a primer charge of zirconium, ammonium perchlorate, and barium chromate, and a main charge of magnesium and potassium perchlorate. The dual initiating bridge wire was Ni-chrome wire. For redundancy there were two independent electrical circuits through two sets of connector pins. The charge was sealed by a 0.010-in.-thick aluminum closure potted with red epoxy. A ceramic header hermetically sealed the connector end. The pressure output of the M-130 squib is approximately 1700 psig/min in a 2.00 cc closed chamber at 70°F. The sure fire characteristic is 2.00 amp, and the no-fire characteristic is 0.50 amp.

Modifications were made to the basic squib, including plating the body with electroless nickel and replacing o-rings with copper gaskets, to provide for more stringent SNAP 10A environmental conditions.

The development test program for the M-130 squibs included the evaluation of pressure output at several bomb-chamber volumes at ambient, high, and low temperatures, at ambient pressures and vacuum, and after gamma irradiation. The input current to the squib was varied to determine the no-fire and all-fire criteria. The bomb chamber containing the squib was equipped with a pressure pickup connected to an amplifier. The bomb chamber was placed in a transite box equipped with heaters for high temperature tests and a dry ice (CO_2) air cooling system.

5. Shutdown Mechanisms

The shutdown mechanisms include a group of devices designed to shut down the operating reactor or to increase the shutdown margin of the system when it is not operating. These components also provide an end-of-life capability that will disassemble the reflector and control units from the reactor and allow for a more efficient reentry burnup. They may be operated by a command signal from the ground or from the reactor.[6] The reflector assembly (Figures 3 and 11) is composed of two halves which pivot at the base and are held together at the top by a retaining band. Springs mounted at the base of each half exert sufficient force against the reflector to eject the reflector half unless it is restrained by the retaining band. The band can be released by electrically energizing a heater device which weakens a joint in the band. The heater may be energized by telemetry signal or by a malfunction if the malfunction persists longer than 1 min.

The band can also be released by a temperature actuated device that severs a bolt joint in the band. This may be called an end-of-life device in that the actuator arms or cocks as a result of system temperature increase and severs a retaining bolt when the system temperature decreases.

a. <u>Temperature Actuated Band Release Device (TABRD)</u>

To allow for decay of radioactive materials before reentry, the reactor must be capable of automatic disassembly while still in orbit. This disassembly involves removal of the reflectors, which are spring-loaded and held to the reactor by a retaining band. Release of the band allows the reflectors to pivot out and away from the reactor. This capability must exist even in the event of a loss of telemetry signals.

In the event the reactor suffers a NaK coolant loss or a NaK pump failure, the reactor would be unable to produce any usable power. The battery-powered, electrically actuated band release device would then be employed to disassemble the reactor. Should this device fail, the temperature actuated band release device will operate automatically to detach the retaining band and cause the reflector halves to be ejected from the reactor.

The TABRD is attached directly to the NaK outlet pipe in the area just below the retaining band. It was decided that the NaK outlet pipe temperature would be an excellent indicator of the reactor condition as any major failure would decrease NaK outlet temperature. Therefore an automatic temperature-actuated device, sensing NaK outlet temperature, was selected as a backup for the electrically actuated band release device. The TABRD bolt holds the two ends of band together. The band tension must be resisted by the bolt (in shear) for the life of the reactor.

b. Electrically Actuated Band Release Device (EABRD)

Reactor shutdown is initiated by release and ejection of the neutron reflectors surrounding the reactor core.[6] Ejection of these reflectors prevents reactor startup or shuts down an operating reactor. The EABRD is one device used to shut down the reactor. An electrical signal to this device will sever the band which holds the reflector halves together. Once the band is severed, the reflectors are ejected by springs.

Three concepts were initially proposed for the electrical shutdown device. These were an explosive pin-puller, a solenoid latch, and a resistance heat switch. The explosive pin-puller concept, termed the reflector band release actuator, was chosen because of the low weight, simplicity, and high temperature and radiation capability. Later, however, a newer concept, called the fusible link EABRD was investigated and became the final choice.

(1) Reflector Band Release Actuator (Pin-Puller) EABRD (Figure 54)

The exploding bridge wire (EBW), squib-powered actuator was considered as the actuator for the pin-puller because it is an extremely effective, compact pressure generator. Two electrically-fired EBW's were used as a power source for the one-shot band release actuator in which gas energy was converted to useful mechanical output. The primer charge, which is sensitive to temperature soak, is eliminated in this type of squib. Additionally, the high voltage firing initiation requirement makes the EBW squibs insensitive to ordinary shock, stray currents, and radio frequency energy.

(2) Fusible Link EABRD

A second EABRD concept consisted of two concentric hollow cylinders joined together with a low melting point braze alloy and with a heating element encapsulated inside these cylinders to provide internal heat generation. This concept was designed to operate at 28 volts and actuate in 5 sec or less after voltage is applied. Production control to achieve a uniform and repeatable braze area proved unsuccessful and the concept was modified to eliminate the braze.

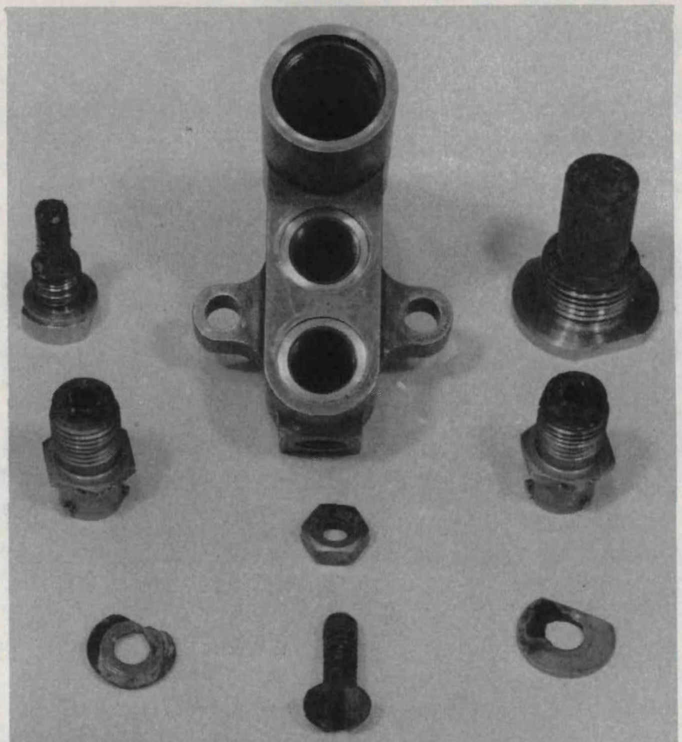

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Figure 54. Disassembled Band Release Actuator

(3) Rene 41 Tube EABRD

A single tube Rene EABRD housing was designed to eliminate the need for brazing. In this design, band release results from rupture of the thin tube-wall when the heater is energized, as opposed to melting a brazed joint in the previous design. The experience gained from development of the previous designs was factored into the new design. Figure 55 shows the assembled EABRD and also an EABRD housing and heater before final assembly. Numerous performance tests were conducted on the single tube Rene 41 EABRD design at these test conditions. The tests resulted in acceptable separation time and energy input; the maximum values obtained were 17 sec to separate, with 1320 watt-sec input energy.

To determine the structural quality of the single tube design, it was subjected to a short-term tensile test. The pull-test was conducted at 700°F (140% of the expected operating temperature). Rupture of the housing occurred in the end fitting at a tensile load of 690 lb (380% of the nominal design load).

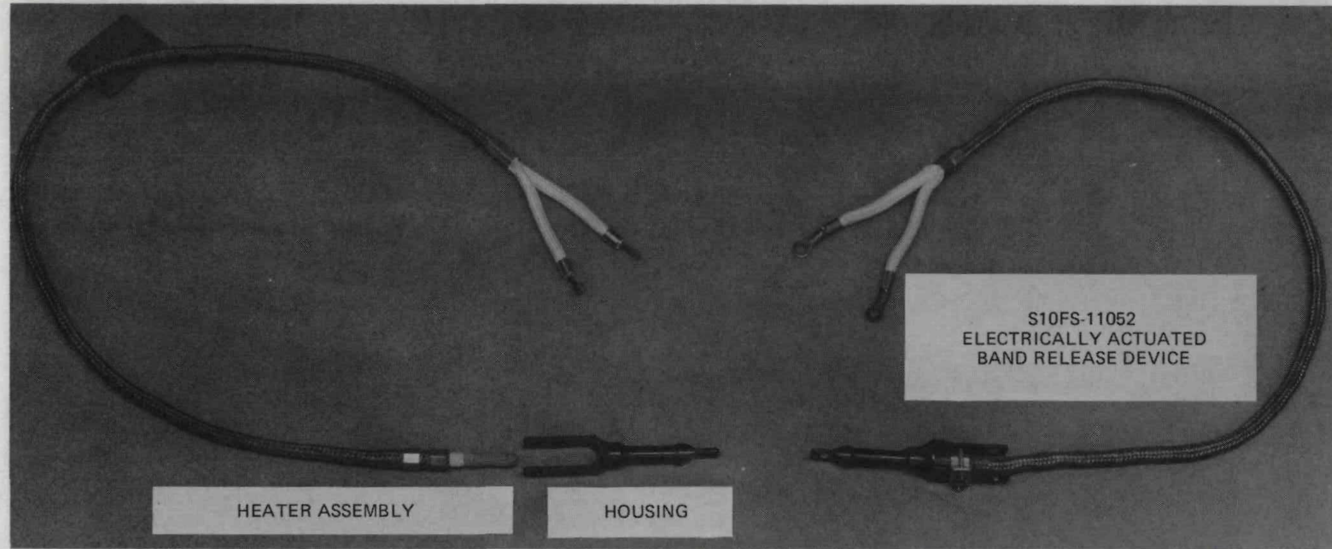

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Figure 55. Reference SNAP 10A Design Electrically Actuated Band Release Device (EABRD) Assembly

A method of supporting the heater cable to survive launch loads was investigated. Several types of cable restraining devices were installed on the single tube Rene 41 EABRD assemblies which were subjected to vibration and shock testing at the qualification test levels. EABRD assemblies without cable restraints were also tested. The electrical characteristics of the EABRD assemblies were not affected by the vibration and shock testing. However, chipping of the alumina adapter, and movement between the adapter and the bobbin were observed on EABRD assemblies without cable restraints. The most satisfactory cable restraint design was a U-bolt and backup plate configuration which clamped the cable to the structural housing. This design eliminated the alumina adapter and encapsulated the ferrule which attached the cable armor to the heater bobbin inside the EABRD housing. A favorable feature of this design was that all potting material was contained inside the housing and would not fall into other reactor components if flaking occurred.

During the final development stages, the reference design EABRD assembly was subjected to nineteen (19) firing tests, two (2) short-term tensile tests at 700°F, and six (6) shock and vibration tests at the component qualification test levels.

The single tube Rene 41 EABRD assembly with the one-piece heater bobbin and the U-bolt cable restraint was selected as the reference design for SNAP 10A. The selection was based on the ease of fabrication, the elimination of critical process braze requirements, and the repeatability of performance data (Table 29).

TABLE 29

SNAP 8 EABRD FIRING TEST DATA

EABRD Sample Number	Housing Material	Temperature (°F)	Tensile Load (lb)	Heater Resistance (ohms)	Line Resistance (ohms)	Wall Thickness (in.)	Heater Wire Diameter (in.)	Material	Time to Separate (sec)	Total Energy (watt-sec)	Remarks
22	René 41	650	650	0.294	0.54	0.0125	0.020	Tantalum	11.7	2800	Satisfactory separation
24	René 41	70	600	0.310	0.54	0.012	0.020	Tantalum	16.4	4000	Satisfactory separation

In the final design (Figures 56 and 57), a 0.040-in.-diameter tantalum wire was passed through the center of a lavite bobbin and a 0.020-in.-diameter tantalum wire was wound around it; the tantalum wires were joined together at one end of the bobbin and joined to individual lead wires.

6. Springs

A wealth of information about springs has been developed since 1920.[4] Basic spring designs, their behaviors, and materials effects are well established for most commonplace applications as well as for a number of exotic applications. However, the SNAP applications, requiring energy storage for very long durations at elevated temperature and in nuclear radiation environments, required an extension of existing spring technology.

Investigations of spring life and relaxation properties were initiated under the SNAP 10A program and were continued through SNAP 2 and SNAP 8. Two basic spring designs were utilized in the reflector assembly. The clock-type power springs used for the "snap-in" drive for the coarse control reflector drums on the SNAP 10A, 2, and S8DRM utilized torsional springs. These springs operated only on initial reactor startup and at ambient temperatures in nonradiation environments and were therefore within spring state-of-the-art design.

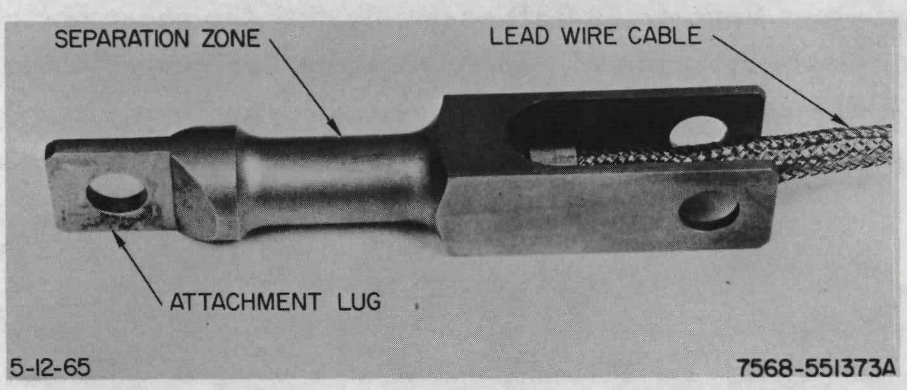

Figure 56. SNAP 8 Electrically Actuated Band Release Device Assembly

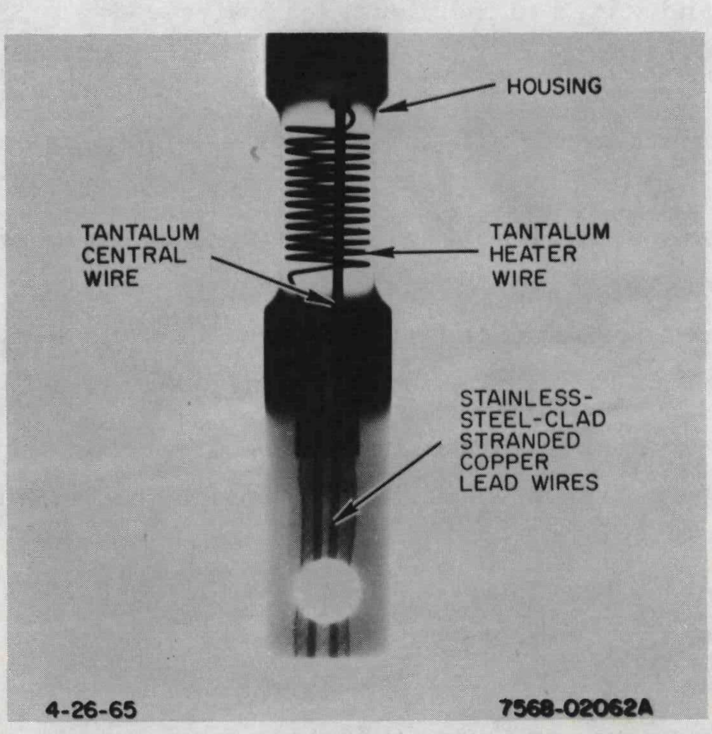

Figure 57. X-Ray of SNAP 8 EABRD

Scram springs later developed for SNAP 10A and SNAP 8 ground test kits were the clock-type springs and operated at elevated temperatures (up to 700° F) in the irradiation environment. These were fabricated of Rene 41 based on data obtained from the compressions spring evaluations and subjected to checkout tests.

The second type springs were helical compression springs and were used primarily for the end-of-life reflector ejection, and to maintain tension in the reflector retaining band to rupture the EABRD at end of life (Figures 3 and 11). These springs were required to function at the end of 10,000-hour reactor life after exposure to compression loading, radiation, and temperatures to 900° F.

Spring relaxation tests were initiated to measure spring deflection under a constant load as a function of time for SNAP 10A. Relaxation is defined as follows:

$$\text{Relaxation} = \frac{\text{Load}_{\text{Initial at Operating Temperature}} - \text{Load}_{\text{Final at Operating Temperature}})}{\text{Load}_{\text{Initial at Operating Temperature}}} \times 100\%$$

Both Inconel-X and Rene 41 torsion springs were tested. Results showed the Rene 41 springs were better than Inconel-X springs for the conditions tested and for design applications. Relaxation was 9.5% for Rene 41 springs deflected to 48,000-psi initial elevated temperature bending stress and held at constant deflection at 1200° F for 4300 hours. The relaxation was 13.0% for Inconel-X springs deflected to 43,000-psi initial elevated temperature bending stress and held at constant deflection at 1000° F for 1000 hours. Haynes-25 springs relaxed 22% when deflected to 36,700-psi initial elevated temperature stress and held at constant deflection for 500 hours. These data are shown in Figure 58.

Helical compression spring relaxation tests were performed in air at a constant height. These tests were operated measuring load with a 0.001-in. deflection from the constant height as a function of time. Nine reference design ejection springs were tested in three sets of three springs at 900, 1000, and 1100° F, respectively. Representative curves for each temperature of load vs time is shown on Figure 59, and a tabulation of spring data is shown in Table 30.

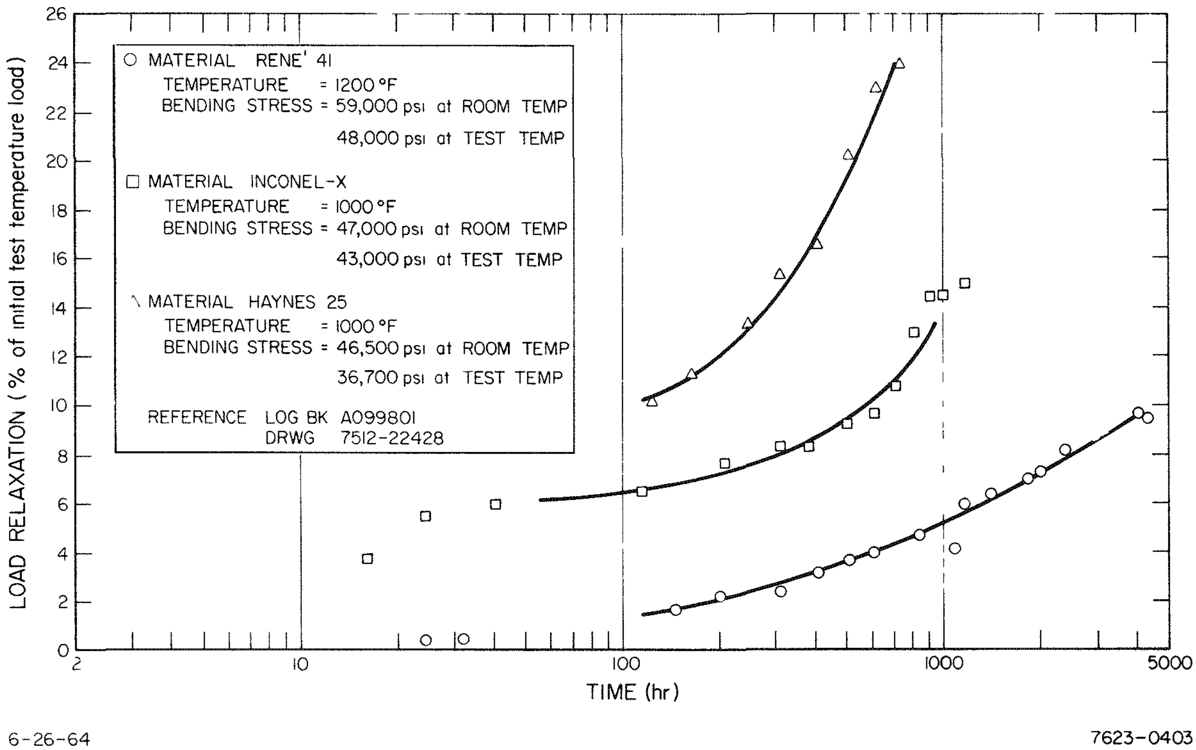

Figure 58. Load Relaxation of Torsion Springs at Constant Deflection

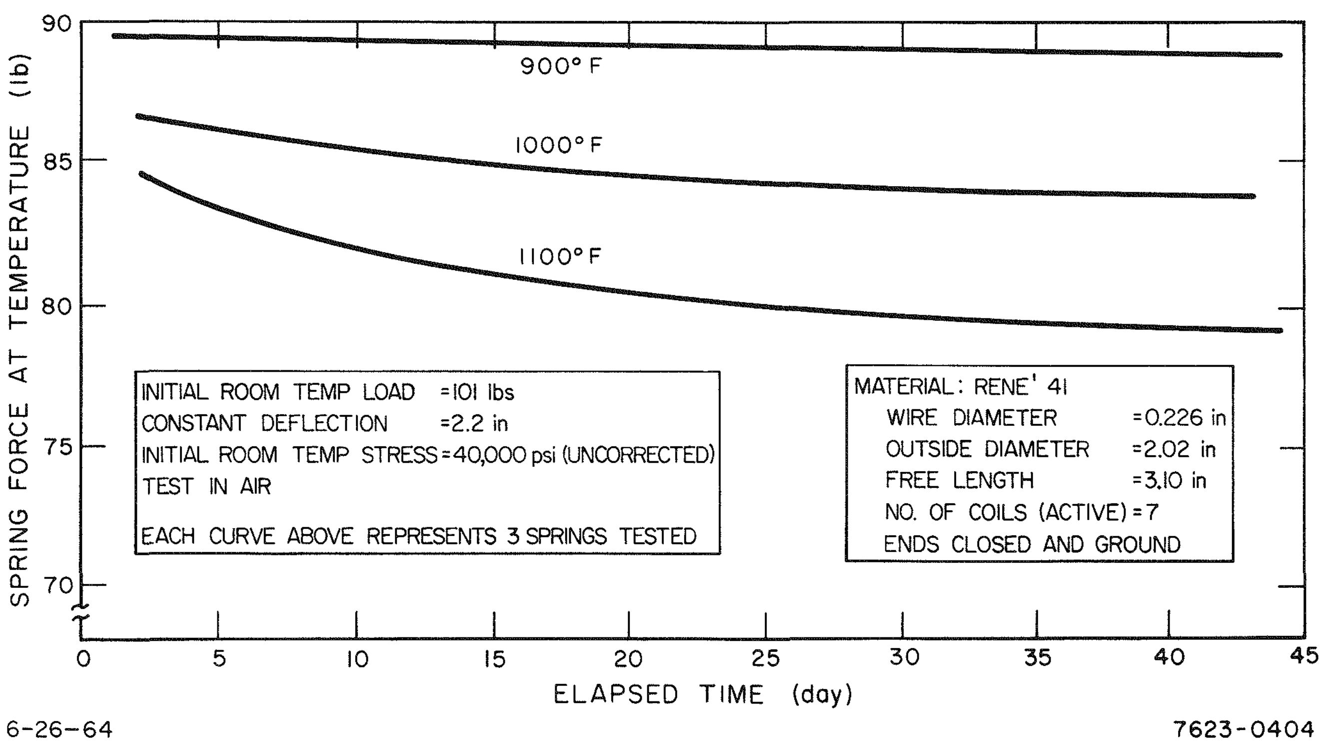

Figure 59. Helical Compression Spring Relaxation Test

TABLE 30

SUMMARY OF HELICAL SPRING TESTS
Material: Rene 41
Loading: Constant Height at 2.200 in.

Test Temperature	900°F			1000°F			1100°F		
Sample Serial No.	1	2	6	3	4	5	7	8	9
Pretest load at room temperature (lb)	103.3	100.6	101.8	101.4	101.4	103	102.5	99.9	97.8
Posttest load at room temperature (lb)	100.8	102.7	102.2	100.6	99.1	99.0	95.8	92.9	92.8
Pretest maximum corrected stress at room temperature (psi)	44,300	43,300	43,700	43,000	43,400	41,700	44,200	43,500	42,400
Test duration at elevated temperature (hr)	866	866	866	1,080	1,080	1,490	1,030	1,030	1,030
Load at end of test at elevated temperature (lb)	88.4	88.3	89.9	83.9	83.4	83.9	78.8	76.7	96.2
Total load loss from pretest at room temperature to posttest at elevated temperature (%)	14.4	12.4	11.7	17.5	18.0	18.6	23.2	23.2	21.1
Time to relax final 1% (hr)	500	866	866	500	500	500	300	300	300
Relaxation from initial elevated temperature to final elevated temperature reading (%)	1.2	1.0	0.3	3.0	3.5	4.0	9.0	8.7	8.3

There was high confidence that the reference design Rene 41 ejection springs on SNAP 10A would not relax beyond the criteria of 70 lb force available after 10,000 hours at 900°F in a nonradiation environment. Although irradiation testing results were not available, investigation indicated that radiation would not present a problem for SNAP 10A.

Considerable literature searching and testing of springs in support of SNAP 8 and subsequent reflector systems was done. Reference 42 reports on irradiation tests of Rene 41 helical springs. Tables 31 and 32 summarize some data on non-irradiated and irradiated Rene 41 springs.

Inconel 750 was selected for springs on the 5-kwe reactor based on data in REIC and NASA reports.[43,44] The REIC document also listed additional data on irradiated Rene 41.

TABLE 31

SUMMARY OF DATA ON NONIRRADIATED RENE 41 SPRINGS

Test Temperature (°F)	Test Time (hr)	Spring Stress (psi)	% Change: In Initial Deflection	% Change: In Spring Rate	% Change: In Spring Force	% Change: In Spring Stress	Heat Treatment	Wire Sizing Operation	"Heat-set"	Cold Work	No. of Springs Tested
1051*	3800	40,000	-10.3	+2.0	-7.8	Not calculated†	Anneal at 1950°F Age at 1400°F for 16 hours	Drawn and annealed, coiled as received	No	None (only due to coiling operation)	1
1149*	3800	40,000	-27.1	+2.5	-25				No		1
1154*	3800	40,000	-20.5	+1.6	-18.2				No		1
1000	950	43,000	-4.35	+2.9	-1.9	Not calculated†	Same as above	Not known	Not known	Not known	1
1000	950	43,000	-3.62	+0.2	-3.2						1
700	2200	45,000 at R. T.	-14.14	-1.0	-10.5	Not calculated†	Same as above	Drawn and annealed, coiled as received	No	None (only due to spring coiling)	1
700	2200	45,000 at R. T.	-15.9	+1.4	-11.6				No		1
700	2200	65,000 at R. T.	-16.88	+1.3	-11.9				No		1
1100	16.7	30,000	Not known	Not known	Not known†	-21	Not known	Not known	Not known	15% (not including that due to spring coiling)	1
1100	16.7	60,000				-28					1

*Reference 42

†The % change in stress is the same as the % change in load or force, assuming the modulus of elasticity does not change with time at elevated temperature.

TABLE 32

SUMMARY OF DATA ON IRRADIATED RENE 41 SPRINGS

Test Temperature (°F)	Test Time (hr)	Spring Stress (psi)	Fast Neutron Dose Rate (nvt)	% Change In Initial Deflection	In Spring Rate	In Spring Force	In Spring Stress	Heat Treatment	Wire Sizing Operation	"Heat-set"	Cold Work	No. of Springs Tested
706	2000	73,500	1×10^{16}	-4.16	Not known	Not known	Not calculated†	Anneal at 1950°F, age 1400°F/16 hr	Centerless grinding	Yes	None (only due to spring coiling)	1
706	8000	42,000	1×10^{16}	-4.16								1
700	3200	40,000	1.31×10^{19}	-16	+5.4	-6.7	Not calculated†	Same as above	Drawn and annealed, coiled as received	No	Same as above	1
1050	3200	40,000	1.98×10^{19}	-10.54	+2.4	-4.1				No		1
1150	3200	40,000	1.01×10^{19}	-26.1	+0.6	-21.2				No		1
1150	3200	40,000	3.11×10^{18}	-22.7	+1.2	-18.4				No		1
1150	3200	40,000	2.36×10^{17}	-10.3	+2.9	-6.9				No		1
1000	950	43,000	4.8×10^{18}	-0.54	Not known	Not known†	Not known	Same as above	Not known	Not known	Not known	1
1000	950	43,000	4.8×10^{18}	+0.54			-2.8 average					1
1000	950	43,000	4.8×10^{18}	+0.76								1
700	2200	45,000 at R. T.	1.55×10^{19}	-50.8	+0.6	-57.2	Not calculated†	Anneal at 2150°F, age at 1650°F/4 hr	Drawn and annealed, coiled as received	No	None (only due to spring coiling)	1
700	2200	45,000 at R. T.	1.47×10^{19}	-40.3	+0.3	-37.2				No		1
700	2200	65,000 at R. T.	1.47×10^{19}	-59.9	+1.9	-62				No		1

Reference 42

†The † change in stress is the same as the % change in load or force, assuming the modulus of elasticity does not change with time at elevated temperature and irradiation.

The general conclusions that can be made regarding spring design for use in a high vacuum, high temperature, neutron radiation environment is that below 1000°F, Inconel 750 should be usable. Rene 41 appears usable to 1100°F. Above that temperature, no materials that have been tested could be considered satisfactory.

7. Electrical Cables

The cable harness is required on SNAP reactors to transmit power from the instrument compartment to the control-drum actuators, temperature and position sensors, squibs, and the safety components.[4] It must also transmit electronic signals from the diagnostic components to the instrument compartment. Provision must be made for detachable connections to components and radio frequency interference (RFI) protection must be provided.

The original design concept consisted of an insulated flexible cable joined to either terminal lugs or electrical connectors to form a cable harness. The connectors included mating parts on the reflector drive actuator, actuator brake, and position sensor while the terminal lugs were fastened to the limit switches and squibs. This concept was not significantly altered throughout the S10A developmental program.

A survey was first made of commercially available high temperature materials from which to fabricate the harness. The original selection of materials was based on short-term tests and product literature. The materials chosen and the considerations governing each choice are outlined below.

To minimize the voltage drop over the length of cable, copper was considered to be the best conductor material. Cladding of the copper wire was necessary to reduce corrosion during thermal cycling in acceptance testing. Interdiffusion of copper and most cladding materials occurs at SNAP 10A temperatures, causing an increase in resistance with time. Stainless-steel-clad copper was shown to be free of this defect and was chosen as the conductor material. Subsequent tests on cable samples and application in cable harnesses on SNAP 10A systems showed no evidence of failure in the conductor. Therefore, the stainless-steel-clad copper wire was the choice for the cable conductor.

3

Since organic insulating materials cannot be used above 500°F, it was necessary to find inorganic material which would combine flexibility with good insulation resistance at operating temperatures. The only materials which meet these requirements are glass or quartz fibers. Pure quartz is known to have excellent dielectric properties and was chosen as the insulation on the first SNAP 10A cable harness. A stainless-steel sheath was braided over the insulation for RFI protection. For added RFI protection, the conductors were twisted 12 times/ft to cancel out any interference. The first SNAP 10 DRM-1 cable harness was fabricated with quartz fiber insulation but failed seriously. A lack of strength in the quartz fibers had caused electrical shorts as the insulation had frayed and ruptured during assembly on the reactor.

Glass fiber insulation with epoxy sizing was substituted for quartz. The change gave more reliability and early tests showed the insulation properties to be adequate. This glass can be used to temperatures in excess of 1200°F.

In the SNAP 10A cable harness, two layers of the glass fiber were placed around each individual conductor. After the conductors were twisted to provide RFI protection, another layer of glass fiber was woven around the bundle of conductors to form a multiconductor cable. For further RFI protection, a stainless-steel sheath was braided over the cable, followed by a layer of glass fiber, and finally another stainless-steel sheath for mechanical protection. Figure 60 illustrates construction details. Figure 61 shows the S10FSM-1 harness employing this insulation scheme and assembled onto the reactor.

Commercially available connectors were purchased for use at SNAP 10A temperatures. A series of short-time screening tests were conducted on several types of glass-insulated connectors to determine the connector best qualified for SNAP 10A.

Coincident with the screening of cable, conductor, and connector materials, considerable effort was directed towards termination of the electrical conductors in the cable. The first termination attempt of the stranded conductor was to heliarc the wire directly to the connector pin. This method was unsatisfactory due to the embrittlement of the wire following the welding procedure. The silver brazing technique was then attempted but abandoned due to lack of control of the

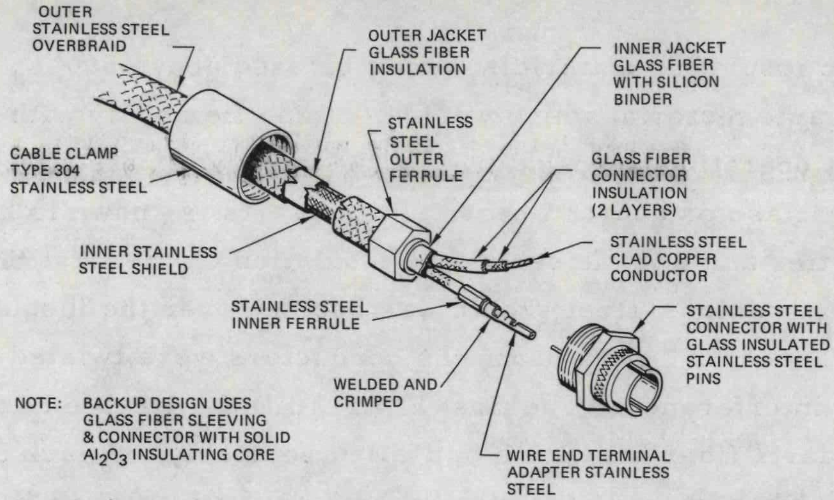

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Figure 60. Cable Conductor Termination

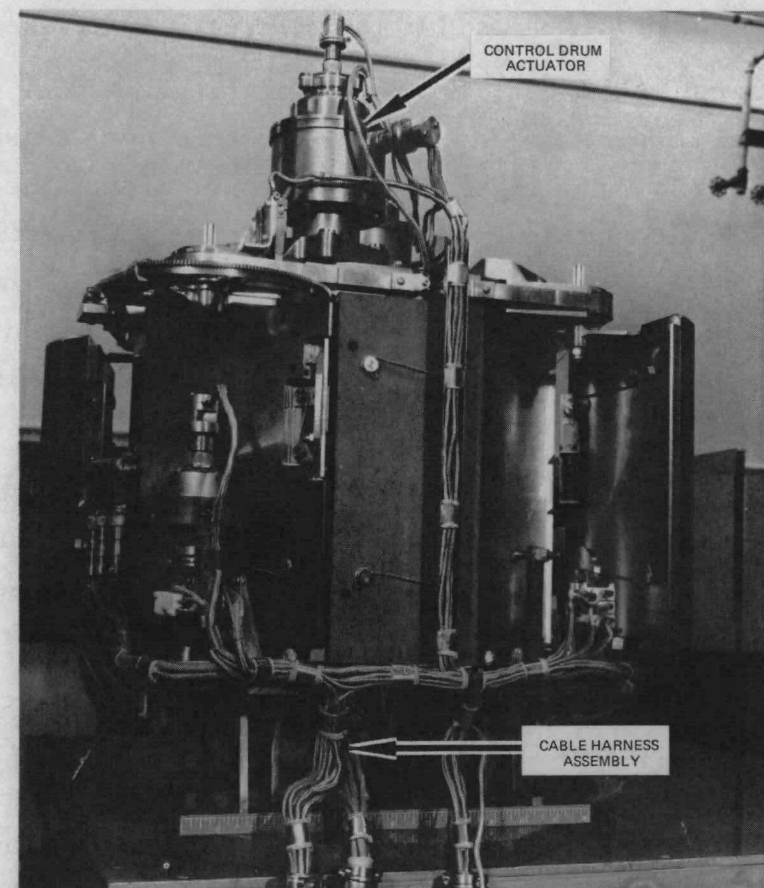

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Figure 61. Cable Harness of the S10FSM-1 System

brazing process. No reproducibility or reliability could be attained with a straight brazed joint. Finally, a double ferrule was clamped directly onto the stranded conductor to anchor the insulation on the cable. The ferrule has an open weld-cup which is crimped and spot-welded to the connector pin.

After successful solution of the initial termination and routing problems, environmental testing was conducted on cable and connector samples to determine the degradation of electrical insulation as a function of time at elevated temperatures and pressures to 10^{-6} mm Hg.

Figure 62 shows the results of tests conducted on samples of high temperature electrical cable. The first cable tested was the glass fiber insulation with epoxy sizing. The insulation resistance remained at approximately 30 megohms for 200 hours at 700°F and 10^{-5} mm Hg.

A test was then conducted at 750°F and 10^{-8} mm Hg on a 3-ft length of the cable with epoxy sizing, joined to the electrical connector. This combination was the proposed reference design cable harness for SNAP 10A. Since this reference design cable harness had reached the lower limit of insulation resistance (10^5 ohms) in approximately 1000 hours at 750°F, the cable material was considered unsuitable for SNAP 10A service of 1 year at 700°F.

Cable materials, with silicone sizing, were obtained from two new vendors. The difference in the performance of these two cables at 1200°F and 10^{-5} mm Hg over a 1700-hour period was attributed mainly to the carburization of the silicones in one material. The other material had been baked out by the vendor to remove organics introduced during fabrication.

The cable insulation retained a relatively high degree of workability, indicating that not all of the silicones are removed in the bake-out process. The workability, or abrasion resistance, of the insulation is an extremely critical parameter, since the insulation must retain its physical integrity during fabrication of the harness and subsequent assembly onto a SNAP reactor system.

Long-term tests of up to 2000 hours at temperatures of 700°F or greater indicate the glass fiber cable with silicone sizing (baked) and commercial connectors would perform reliably on the SNAP 10A systems. The second cable material showed comparable performance but was more sensitive to handling as it is baked out before receipt from the vendor.

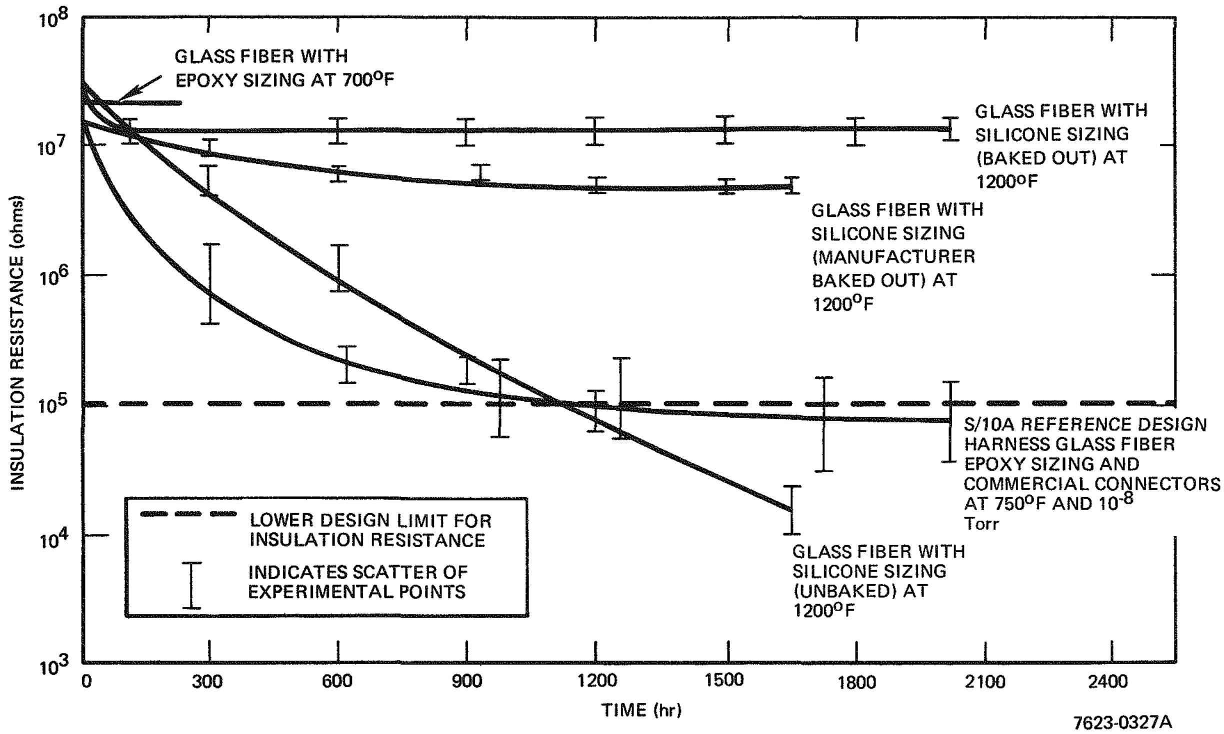

Figure 62. Effect of Temperature and Vacuum on Insulation Resistance of Electrical High Temperature Cable

Cable harnesses developed for SNAP 10A were used on SNAP 2 and SNAP 8 systems essentially unchanged, except that glass fiber with baked silicone sizing was used.

Development of the advanced ZrH Reactor required cabling which must operate at a higher temperature and for double the 10,000-hour life of SNAP 8. A survey of new insulation and cable materials and fabrication techniques was reviewed.[45]

The results of the study showed the most reliable technique was the use of sheathed cabling much the same as standard stainless-steel-sheathed thermocouple material. The sheathed cabling and the necessary terminations were developed under the actuator program and are discussed in Reference 5. The conceptual design consisted of 0.040-in.-diameter, stainless-steel-clad copper conductor wire with MgO insulation swaged inside a 0.090-in.-diameter Type 304 stainless-steel sheath.

Limited testing was conducted to evaluate fatigue limits of the wire due to coiling and bending during handling, and long-term insulation resistance characteristics. The hard cabling was also to be used on position sensors, limit switches, and other control and diagnostic components with termination housings similar to those of the actuator. No operational testing was conducted due to termination of the reactor efforts.

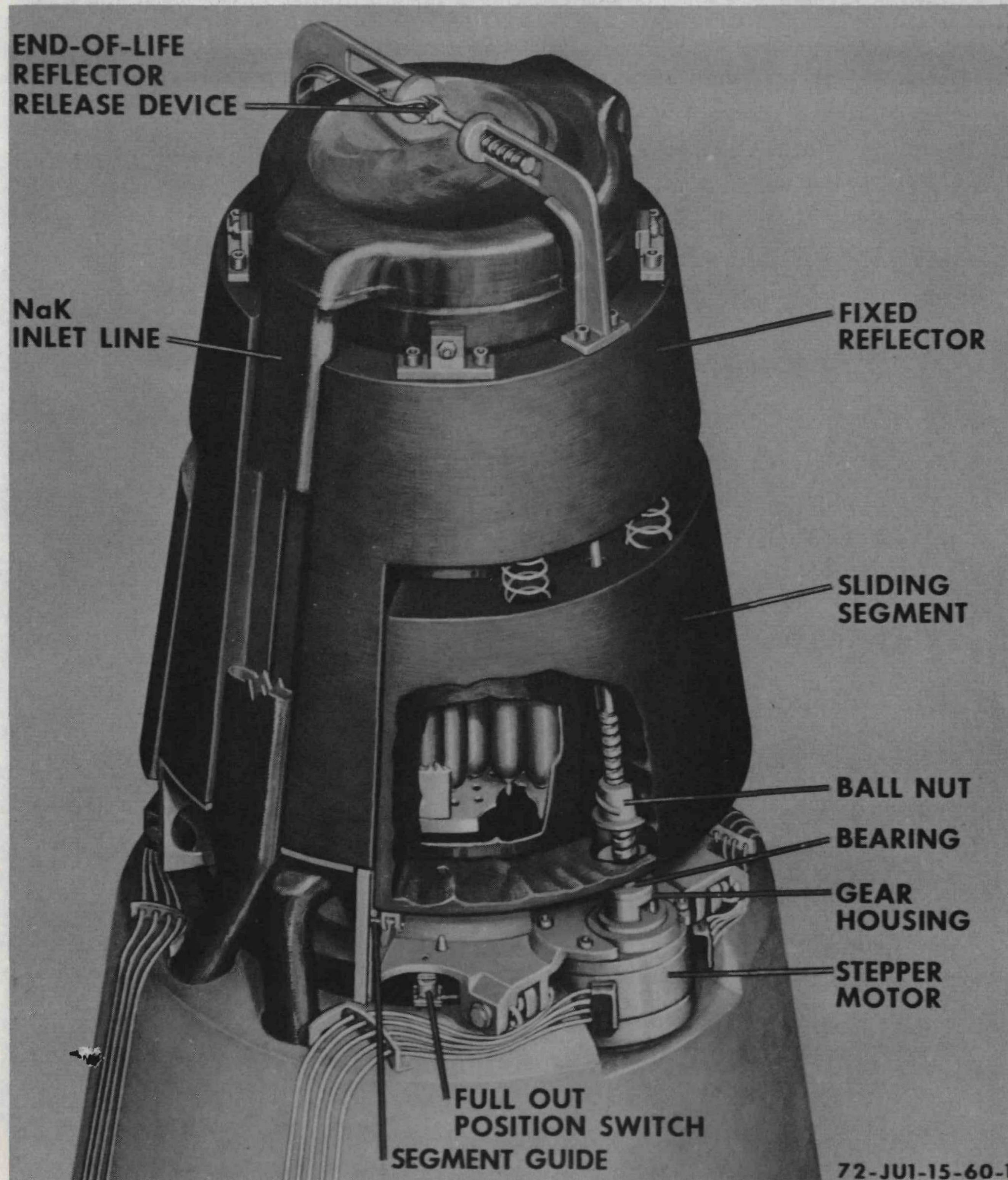

Figure 63. 5-kwe Thermoelectric Reflector Assembly

III. 5-kwe REACTOR THERMOELECTRIC REFLECTOR SYSTEM

The 5-kwe thermoelectric reactor is the last SNAP-type system designed by AI and is the culmination of 15 years of compact reactor development. The reactor, shown in Figure 63, is designed for 5-year unmanned space missions with a nominal 5-kwe thermoelectric power conversion system.

A. BASIC DESIGN REQUIREMENTS

The 5-kwe reactor is a shadow-shielded system with the reactor located at the apex of the shielded cone. The cylindrical core is surrounded by the reflector and control segments in the shape of a conical section.[46]

The operational requirements of the 5-kwe reflector system are listed in Table 33 and summarized in Table 1.

B. CONCEPT OPTIMIZATION STUDIES

Based on technology developed in previous SNAP programs, the basic reactor control concept is that of a cylindrical reactor core with a beryllium reflector sleeve. Control is by closing windows in the reflector sleeve. Configuration and control techniques were optimized through detailed studies.

1. Fixed Reflector and the Control Segments

The frustrum-of-a-cone shape of the reflector was chosen to minimize overall system weight. The cone is determined by the reflector diameter at the core midplane, the diameter of the dose plane, and the distances to the dose plane. When the cone shape, core diameter, and reflector thickness were defined, various reflector concepts were analyzed. The basic requirement in these analyses is that at operating conditions, portions of the movable control element must not protrude outside the cone. Protruding portions would cause radiation scatter on to the dose plane so the shield diameter would have to be increased. Configurations analyzed were: (1) a cylindrical reflector with rotating control drums, (2) a tapered cylindrical reflector with tapered rotating drums, and (3) a tapered cylindrical reflector with reflector segments sliding parallel to the core. The first two concepts utilized control-drum-drive motors on top of the core, while the sliding reflector concept was studied with drive motors at either the top or bottom of the core. Figures 64 and 65 show the basic conceptual layouts. Each design was also studied for a two-or four-control-drum

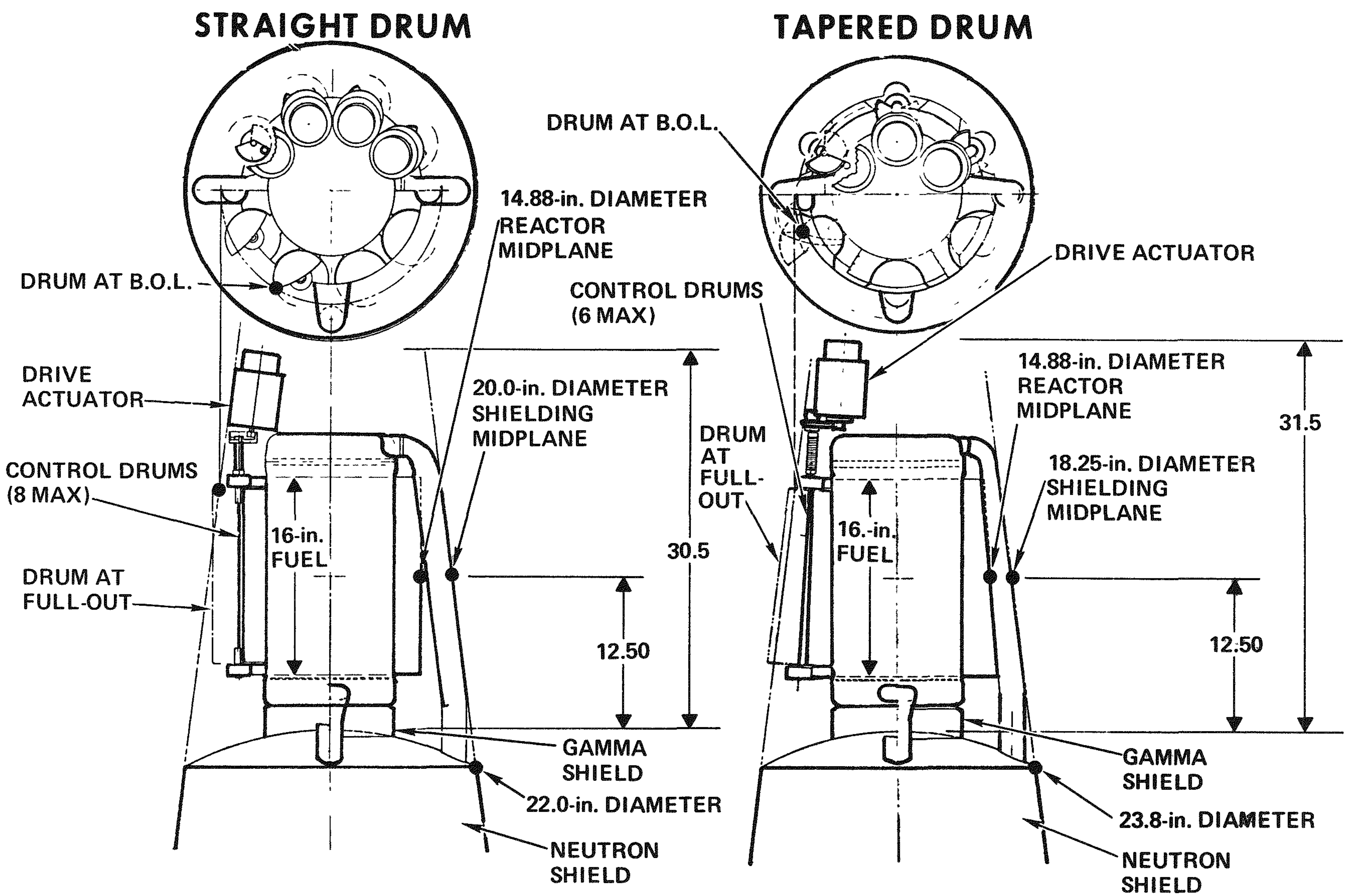

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Figure 64. Rotating Reflector Drum Control

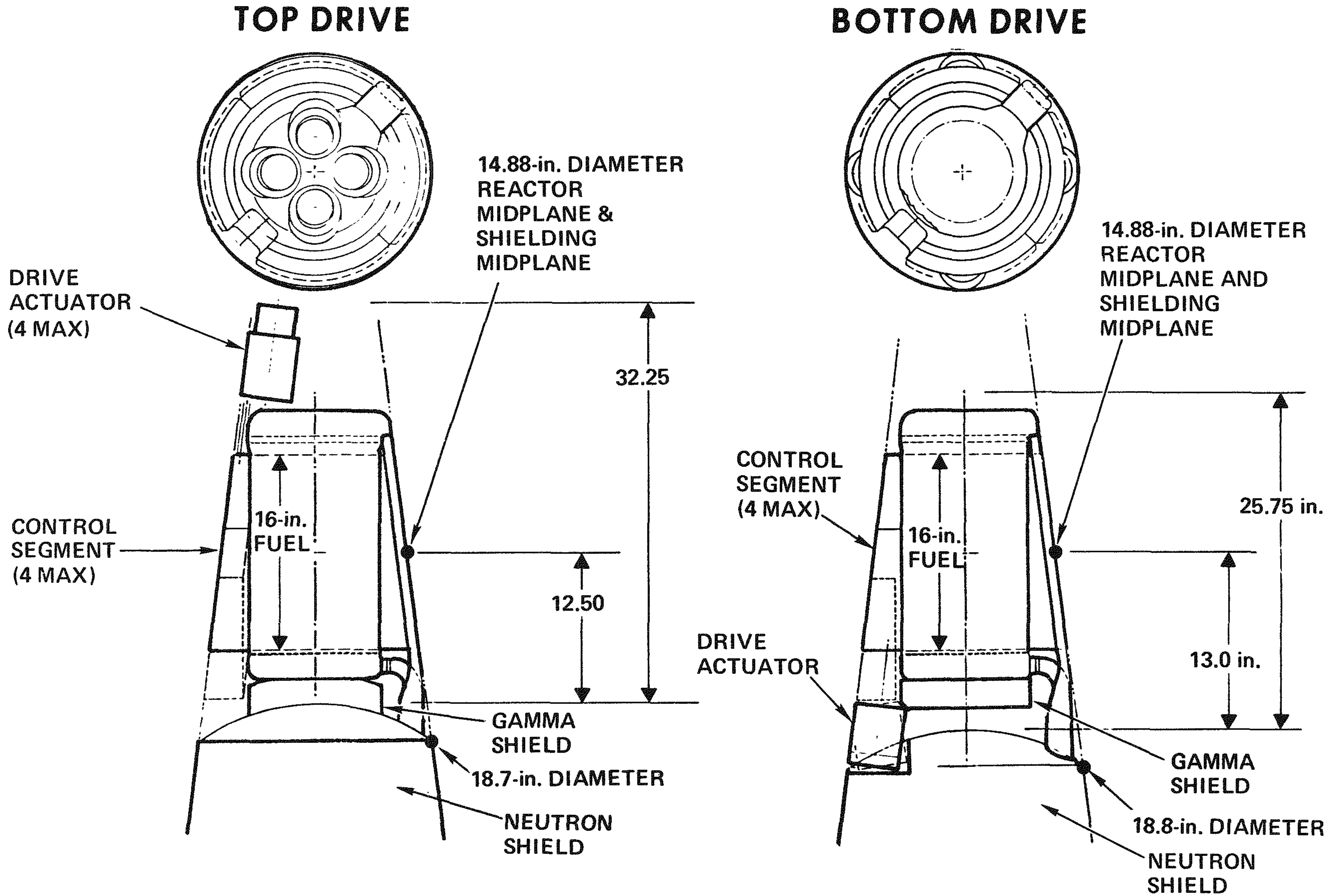

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Figure 65. Sliding Reflector Segment Control

TABLE 33

OPERATIONAL REQUIREMENTS OF THE 5-kwe THERMOELECTRIC REFLECTOR SYSTEM

Item	Function
Control Reflector Segment	0 to 4 in. Vertical movement (2 segments)
Control Motion	0.005 in. /step (1 electrical revolution of actuator phases)
Control Stepping Rate	1 step/sec or slower (alternate reflector segments)
Drive Train Backlash	< 0.005 in. axial and < 4.0° rotational
Flight Safety	
Launch	Control section locked in shutdown (out) position
End of Life (EOL)	Reflector assemblies rotatable away from core vessel to achieve shutdown
Ground Test Safety	
Normal Scram	Simultaneous withdrawal of both reflector segments at 5 steps/sec
Backup Shutdown	EOL reflector assembly rotation with stored energy. Reflector assemblies repositionable for restart

drive system. The sliding reflector design resulted in a shield weight savings of some 100 lb or more over the rotating drum concepts (approximately 350 vs up to 470 lb).

2. Control Reflector Drive

Following selection of the sliding reflector as the reactor control mode, a conceptual design study was conducted on the method of reflector support, the type of drive mechanism, gearing and bearing requirements, and reflector anti-rotation devices. Studies were conducted to determine the preferred location of drive motors and other components on the basis of minimum envelope and weight constraints. A key restraint was the requirement that backup EOL shutdown for ground test be accomplished by swinging the reflector halves away from the core.

Reflector drive options were narrowed to a ball screw, plain screw, or rack and pinion. The traveling rack and traveling screw options were eliminated as they required penetrations into the shield and, consequently, complicated EOL mechanism design. The plain screw was dropped because of high friction. A ball-screw with a translating nut was selected as the final drive design, because it is efficient and simple. The major advantages are low drive torque, minimum self-welding potential, simple and reliable design, and availability of supporting test data at operational conditions.

The actuator was located near the shield instead of at the opposite end of the reactor because of greater design flexibility and because more space is available in which to locate the drive components. In addition, this layout shortens the screw and locates it near the center of gravity of the segment, locates the actuator adjacent to the load carrying structure, and shortens the electrical cables.

Expected operational conditions of the ball-screw and drive mechanism are 800°F and 1×10^{-5} torr (air) or less for 5 years. A detailed study of ball-screw design state of the art was conducted, and visits were made to the engineering departments of the two major manufacturers of special application ball-screws. Table 34 lists experience with ball screws operated under similar conditions. The key criteria is the selection of ball nut, screw, and ball materials. A variety of high temperature, high strength alloys are available with test experience. Experiments also show no problem with application of MoS_2 dry-film lubricants which was planned to further lower friction and reduce any self-welding potential.

The drive support bearings and gears are based on state-of-the-art technology generated and proven in the SNAP 8 and Advanced ZrH Reactor Programs. The drive support bearings utilize a self-aligning spherical bearing with a

TABLE 34

HIGH TEMPERATURE BALL SCREW EXPERIENCE

Test	Design	Experience
NASA Lithium Valve Loop	17-4 PH Nut, Hipercut Screw, WC-6Co Ball, 3/8-in.-diameter by 1/8-in. Lead, No Lubrication	5,000 hr at ~800°F in 10^{-7} torr, 500 to 1000-hr dwell under ~1000-lb axial load, 95 cycles (3 turns) on 1 unit, 600 cycles (1 to 3 turns) on 1 unit
NASA Nb-1Zr Corrosion Loop	17-4 PH Nut, Hipercut Screw, WC-6Co Ball, 3/8-in. -diameter by 1/8-in. Lead, No Lubrication	2 units used to control throttle valve during 10,000-hr test, >500°F, 10^{-7} torr
Concorde Jet Silencer Drive (Air-Research)	Nickel Plated H-11, Nut and Screw, WC-6Co Ball, 3/4-in. -diameter by 1/16-in. Lead, X-15 Dry Lubrication	4,000 cycles (~48 turns) under 1700-lb load (~90 hr), 450°F in air, efficiency ~93% (1 unit) - 88% (final)
FFTF IVHM Drive (LMEC)	Inconel-718 Nut, and Screw, Stellite Star-J Ball, 2-7/8-in. -diameter by 0.66 Lead	Soaked in 1100°F sodium and operated at 450°F under 1,450-lb and higher loads

carbon-graphite against alumina friction couple. This combination has accumulated in excess of 70,000 hours testing under elevated temperature-vacuum conditions and individual bearing sets have completed 18,000 hours at 1150°F and 1×10^{-5} torr pressure. No incidents of bearing failure have been encountered. The drive gears are also of proven design with a MoS_2 dry-film lubricant on the gear teeth for low friction operation. The coating has performed well in repeated long-term operational tests, both nuclear and nonnuclear. Table 35 gives the test background of gear performance for previous reactor programs.

Two techniques were studied to prevent rotation of the reflector segment as a result of ball-screw reaction. One scheme consisted of a torsion bellows rigidly attached to the reflector segment and the base plate on the ball screw

TABLE 35

MoS_2-COATED CONTROL DRUM GEAR HISTORY

System	Material	Tests*
SNAP 10A	Stellite 6B (Pinion), Titanium + MoS_2, 13.6:1 Ratio	1) 90 days at 700° F, 10^{-9} torr 2) 500 hr at 800° F, 10^{-5} torr 3) Shock and vibration 4) SNAP 10A nuclear ground test 5) SNAP 10A space operation
SNAP 8	Inconel 750 (Pinion), Inconel 750 + MoS_2, 13.8:1 Ratio	1) 15,000 hr at 800° F, 10^{-5} torr (scram kit tests) 2) S8DR half reflector acceptance test 3) S8DRM shock and vibration 4) S8DR 7,000-hr nuclear ground test

*No significant wear, no self-welding, were noted for either material combination.

centerline. Calculations indicated the resulting bellows was practical, but the drive screw support and gear area became highly congested.

The selected approach uses a single guide track and translating spherical roller on one edge of the sliding reflector. The guide is in an uncongested area, and the reaction force is small due to the large moment arm. The spherical ball and the track design is immune to thermal misalignment between the sliding and fixed reflectors. Use of a MoS_2 dry-film coated ball, or a carbon-graphite ball against an alumina-coated track utilizes a proven low friction couple for the reactor environment.

C. DESIGN DESCRIPTION

The final conceptual design of the reactor control reflector system is shown in Figure 66. Two half-reflector assemblies are individually hinged to the core vessel structure near the coolant outlet, and are held together at the opposite end by a retaining device. The device incorporates a spring to take up the deflection between the two reflector halves caused by the thermal expansion of the core vessel.

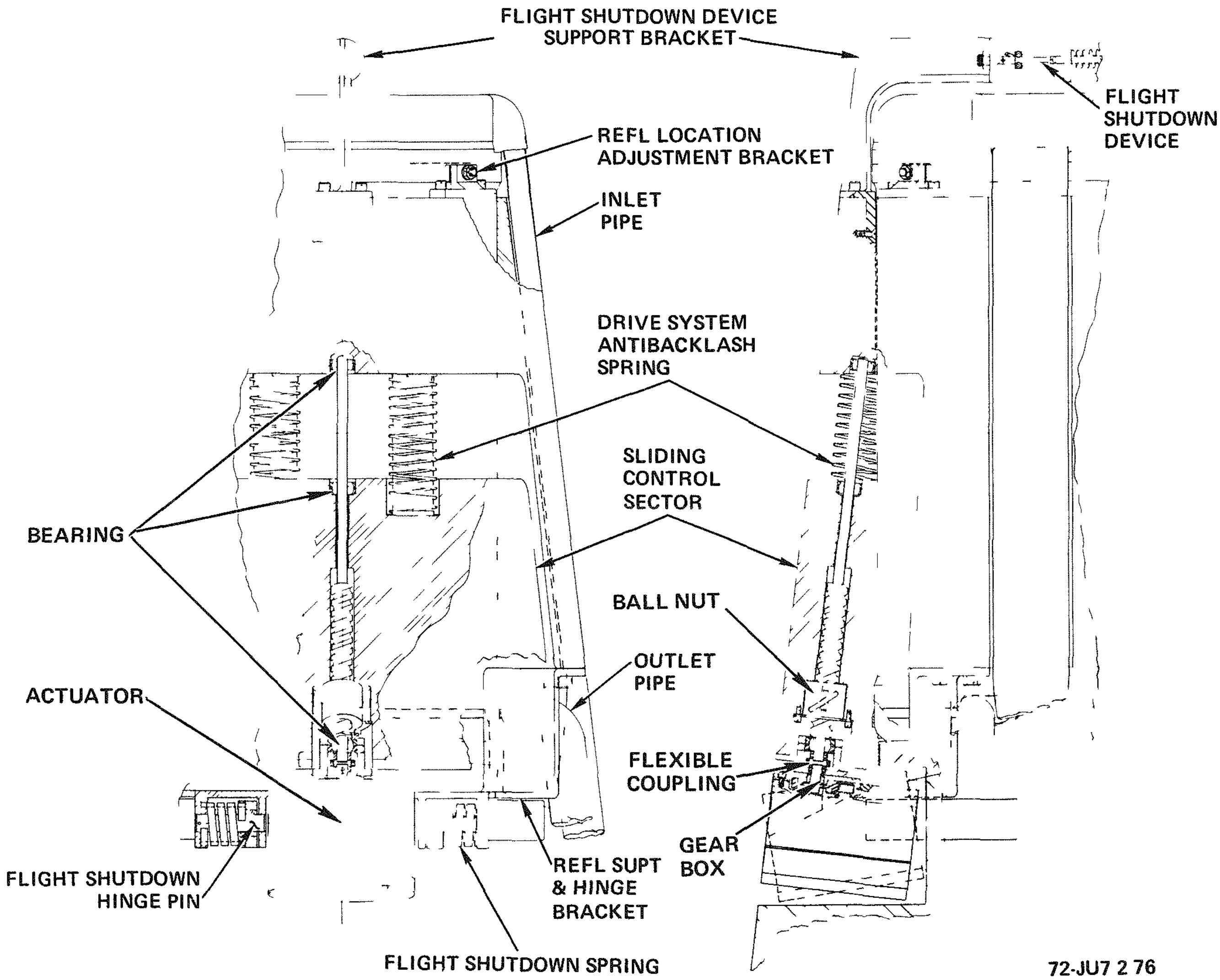

Figure 66. Sliding Reflector Control Translating Nut Ball Screw Drive

The reactor control reflector is essentially a 16-in. high, thick-walled beryllium cylinder, with an ID of 10.7 in. and a minimum wall of 1.2 in. at one end, increasing uniformly at a half cone angle of 8.5°. Each fixed half reflector has a 10-in. -high window which subtends an angle of 117.5°, located at the thick end, to accommodate the movable control segment. The fixed reflector and the lower support bracket form the basic structure of each half reflector assembly. The reflector hinges, locating and retention devices, the movable control segment, and its guide and drive mechanisms are attached to the main structure. The fixed reflector and the control segments are made of nuclear grade beryllium. The surfaces facing outward are black anodized, and surfaces facing the reactor core vessel are uncoated to minimize the beryllium temperatures.

The reactor operation, from the safe shutdown through startup and long-term power operation, is controlled by the axial positioning of the two control segments which adjust the width of the neutron leakage in the reflector system. A simple translating ball screw mechanism both guides and drives the control segment. Basically, the control segment is supported by the translating nut and the guide bearing, both of which translate on the main drive screw. The drive screw, in turn, is supported by bearings in the fixed reflector and the lower support bracket. All three of the guide bearings are of the self aligning mono-ball design and are identical. The configuration and material combination of carbon graphite ball within the alumina-coated spherical socket, rotating on an alumina coated shaft, is the same as the S8DR control drum bearings. The bearing motion and loading (radial only or radial and thrust) on the drive screw shaft bearings are similar to the S8DR. The control segment guide bearing undergoes simultaneous rotation and translation under very light radial loads. While this type of bearing action was not present on the S8DR, pure translational carbon-graphite bearings were successfully operated on the S8DR scram snubbers. In addition, MoS_2 dry-film lubricant on the bearing surfaces will lower friction and enhance bearing operation.

The critical ball screw parameters (ball diameter, pitch diameter, and materials) of the conceptual design were selected to provide a large design margin under the expected operational conditions. The calculated life is 10^6 in. of travel under 350-lb load, compared to the maximum operational requirement of 1.8×10^3 in. of travel under 26 lb. The double ball circuit feature was selected to resist the overturning moment induced by the center of the gravity of the control segment being located off the drive screw center line.

To allow for the thermal expansions over the wide operation temperature range, adequate physical clearances between moving parts of the drive system are provided. The resulting axial backlash at the control segment is eliminated by spring loading the control segment in one direction.

A variable reluctance d-c stepping actuator generates the motive torque for the reflector drive. This actuator is a configurational and dimensional modification of the successfully tested S8DR actuator design. The materials, electromagnetic design, and the coil fabrication techniques are identical to the S8DR. As with the S8DR, the actuator produces discrete steps of 1.8° of rotation when the successive phases are energized. The 2.78:1 ratio of the integral gear box coupled with the 0.75-in. lead of the ball screw results in 0.0054 in. of control segment motion (0.5¢ of reactivity change) for each 7.2° rotation of the actuator. The 7.2° actuator rotation per control step, which represents a complete electrical revolution of the electromagnetic phases, was selected to simplify the controller requirements. Because the actuator always starts and stops at the same phase, the controller does not require any memory, such as was required for the S8DR where 3.6° per control step was used.

A built-in mechanical brake locks the actuator rotor in place except when stepping motion is required. Face gears on the mating brake discs provide positive braking with minimal braking force. Rotational backlash of the brake is eliminated by utilizing a torsionally rigid bellows to give the fixed brake disc axial flexibility for the engagement and disengagement. The brake is mechanically designed to hold the control segment in place during the spacecraft launch.

Both the actuator stator and the brake are designed to accommodate the sheathed cable wiring. The sheath of each single conductor cable is clamped at the terminal box, and the conductor is welded to a cable junction which, in turn, is clamped at an insulated terminal strip. The termination design permits attachment of "jumper cables" to operate the actuator until the final installation and welding of the system cables.

The actuator assembly is attached to the lower reflector bracket, and the output shaft of the gear box is attached to the shaft of the ball screw drive through a bellows-type flexible coupling. The axial and angular flexibility of the coupling separates the bearings and shaft of the actuator gear box and those of the ball-screw drive to prevent any binding reaction between the two units.

Two tapered lock pins on the lower reflector bracket engage mating holes in the control sector when the sector is in the full-out position. These pins not only act as mechanical full-out stops, but also prevent rotation of the control segment during the launch. The normal anti-rotation device is unloaded at this segment position. In the normal reactor-up launch vehicle configuration, the full-out stop function of these pins prevents axial segment motion induced by the spacecraft forward acceleration. In the reactor-down launch configuration, the control segment is locked (from the more reactive position) by the mechanical brake of the actuator through the ball screw drive and the reduction gears.

An S8DR-type switch signals that the control segment is in the full-out position. By slight modification of the tapered pins and limit switch actuating lever, any intermediate full-out position of the control segment may be selected.

The hinge mounting feature of each reflector half assembly is utilized to achieve end-of-life shutdown. Torsional springs located at each hingepin are designed to overcome the bending resistance of the hard cable to rotate the reflector assembly away from the core vessel when the retaining device is separated. The reflector retaining device will be an electrically actuated fusible link similar to that of the SNAP 10A system. Upon receipt of the shutdown signal, electrical energy is applied to a small heater located within the device, heating the housing until its strength falls below the applied load, causing rupture and separation. The thermal expansion spring at the reflector retaining device has sufficient force not only to overcome the torsional hinge springs, but also to resist the lateral launch acceleration on the reflector assemblies. The end-of-life spring force on the reflector retaining link is adequate to cause rapid rupture of the link when its temperature is increased by the heater. If the reflector has not been ejected prior to entry of the assembly in the earth's atmosphere, the link will heat up and break to initiate ejection of the reflectors.

The normal scram requirement is achieved by the rapid withdrawal of both control segments by the continuous operation of both actuators. In this operational mode, the actuator brake is disengaged by continuously energizing the brake solenoid, while the actuator is being stepped at a 6-rpm rate until the full-out limit switch is actuated. At the end of the scram, the brake solenoid is de-energized and the mechanical brake engaged to lock the control segment prior to deactivating the actuator phases.

The end-of-life shutdown capability of the reflector system is also used to provide a backup shutdown feature for ground testing. As shown in Figure 67, the reflector system is modified slightly and reflector latching and reset mechanisms are added. The reflector retaining device and its thermal expansion spring are removed from the reflector, and a restart arm is attached to each reflector half assembly. This arm contains the armature of the scram magnet and the thermal expansion spring. A dual coil magnet acting on the armature, which, in turn, is spring-mounted to the arm, holds each reflector-half assembly against the core vessel during normal operation. When the backup shutdown signal is initiated, the power to both coils of the magnet is shut off, de-energizing the magnet, allowing the end-of-life shutdown torsion springs at the hinges to rotate each reflector-half assembly away from the core. In the expected coolant-inlet-down orientation of the ground test, the center of gravity effect of each reflector half assists in the rotation away from the core. A snubber spring within the pneumatic reset cylinder cushions the reflector assembly at the end of the rotation. The thermal expansion spring, which mounts the magnet armature, acts as a secondary snubber.

To reset the reflector assembly for the reactor restart, each pneumatic reset cylinder is pressurized with inert gas to rotate the reflector half against the core vessel. A slight additional force compresses the expansion spring to permit contact between the magnet armature and the magnet face, establishing the magnetic latching. A limit switch is actuated when the reflector half is in the reset position. Upon depressurization of the pneumatic cylinder, the return spring within the cylinder repositions the piston to the ready-to-snub location. An indicator switch on the cylinder indicates when this piston position is re-

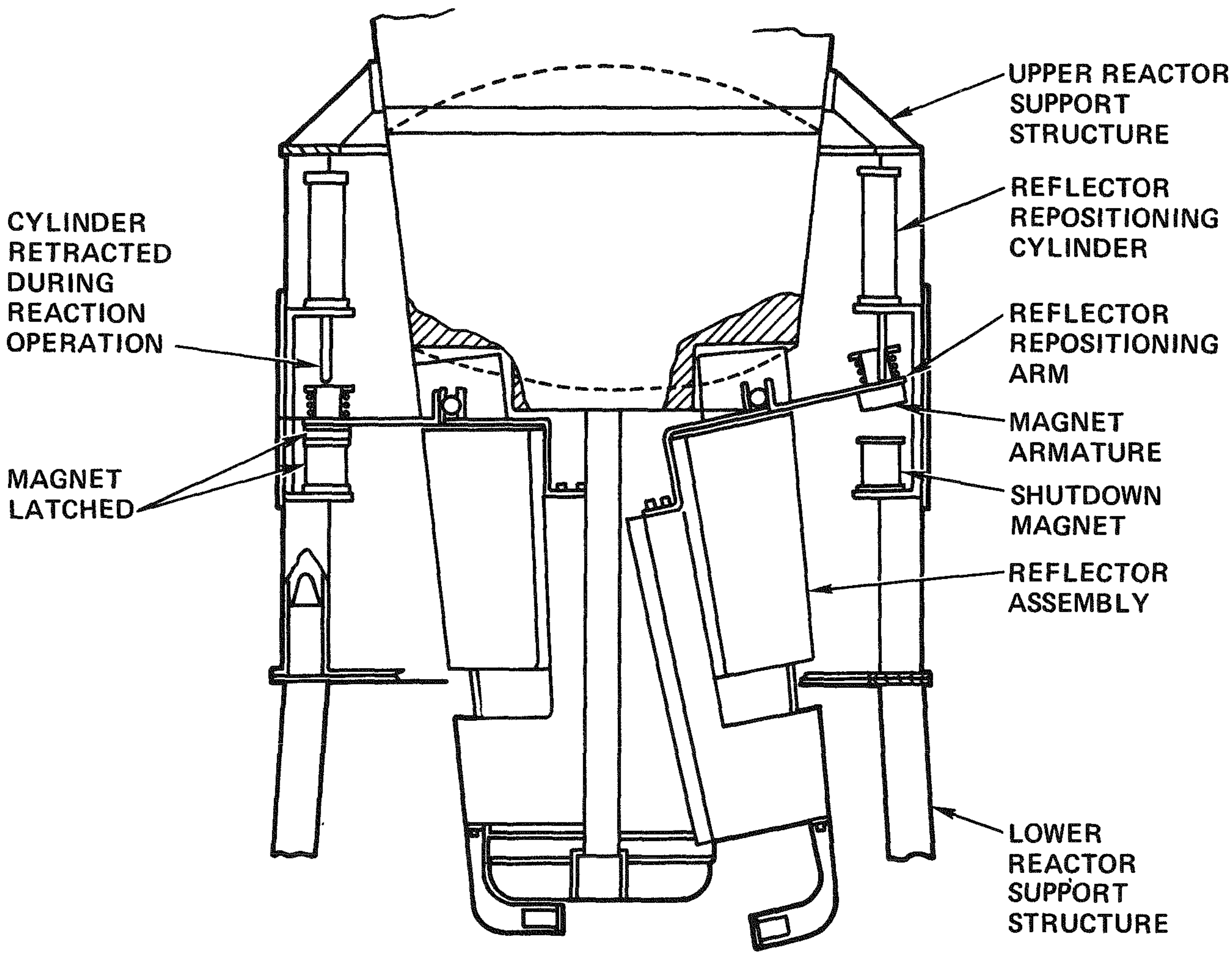

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Figure 67. Backup Shutdown-Restart Mechanism

established. This signal is necessary, prior to reactor startup, to assure that each reflector assembly is capable of another backup shutdown operation.

The backup shutdown holding magnets are designed similar to the brake solenoid of the drive actuator, using the same materials and coil winding techniques. Each coil of the dual coil is designed to hold the reflector with adequate force margin. The reflector reset limit switch is identical to the control sector full-out switch. The pneumatic cylinder is of commercial design, modified for

for the test environment. The snubber and return spring are designed for this application. The piston return switch is of the reed design. The magnets and the reset cylinders are mounted on the upper half of the ground test reactor support structure.

In the coolant-inlet-down orientation of the reactor during the ground test, the gravitational effect on the movable control segment is toward the more reactive direction. Normally, the actuator brake holds the control segment at its position except during stepping. The torque generated at the actuator rotor during stepping is adequate to raise or lower the segment against the gravitational pull. If, however, one or more actuator phases are inactive, and the stepping is initiated, the gravitational pull on the segment may cause it to move downward until the stepping is completed and the brake is, again, mechanically applied. Such a failure of the actuator phase could be caused by the following malfunctions: open circuit in both coils of a phase, failure in the electrical cables between the controller and the actuator terminals, or malfunction of the controller. To preclude this possible incident, the weight of the control segment is counterbalanced. The normal flight anti-backlash springs between the fixed reflector and the segment are replaced with heavier anti-gravity springs. The counter balancing action of these springs is sufficient to prevent inadvertent uncontrolled downward (inward) motion of the control segment in the event of actuator malfunction.

D. EXPECTED PERFORMANCE

The conceptual reflector system is designed to structurally withstand the launch environment and, subsequently operate for 5 years in a space environment. Additionally, the system is capable of operation in the ground test environment of 10^{-5} torr or less pressure and 1 g.

During reactor startup, the actuators are stepped to move alternate segments at selected rate(s) not exceeding one 7.2° step (~0.5¢)/sec. Once the power operation is established, an actuator is stepped periodically only to maintain the power level or to change power level. This periodic actuator motion will continue until both segments are moved to the full-in position or the shutdown signal is given.

In addition to the startup and periodic stepping, reactor scram (5¢/sec) by the rapid rotation of the actuator may be required during the ground test. The system design is capable of 50 scrams and subsequent restart during the 5-year lifetime. The number of shutdowns employing the backup shutdown system is expected to be very limited. The possible limitation to the number of this type of shutdowns may be the flexing endurance of the electrical cables. This endurance has not been established, although tests are planned.

1. Control Segment Driving and Braking Torques

The torque required at the actuator rotor to position the control segment under the normal control mode is dependent on the net effective weight of the segment, bearing loads, the friction coefficient of the bearings, and the efficiencies of the ball screw and gear drives. Figure 68 shows a summary of friction data used for design of the reflector drive torque requirements. An expected value of 0.35 was selected for performance predictions with 0.10 and 0.60 as the possible lower and upper limits. The expected torque requirements under the ground test and flight conditions are shown in Figures 69 and 70. The torque values for friction coefficients of 0.35 and 0.60 were based on the lowest expected ball screw efficiency of 0.70, while the highest expected efficiency of 0.90 was used with the friction coefficient of 0.10. The gear efficiency was maintained at 90% for all cases.

Control segment scram, during ground test only, will require movement toward the full-out position. The maximum torque required to move the segment in this direction is approximately 66% of the maximum torque required to move the segment to full-in. The expected torque output of S8DR type actuator at the scram speed of 6 rpm is approximately 70% of slow speed stepping torque output. Thus, an actuator designed to meet the torque requirement to step the segment to full-in has adequate torque capability for the scram requirement. The actuator torque requirements of 100 oz-in., during stepping and 70 oz-in. during scram were selected to allow approximately 33% margin over the maximum expected drive requirements.

The actuator brake torque under the flight or ground test operation need only be sufficient to hold the control segment against acceleration or gravity effect on it between actuator stepping. During normal launch, the mechanical

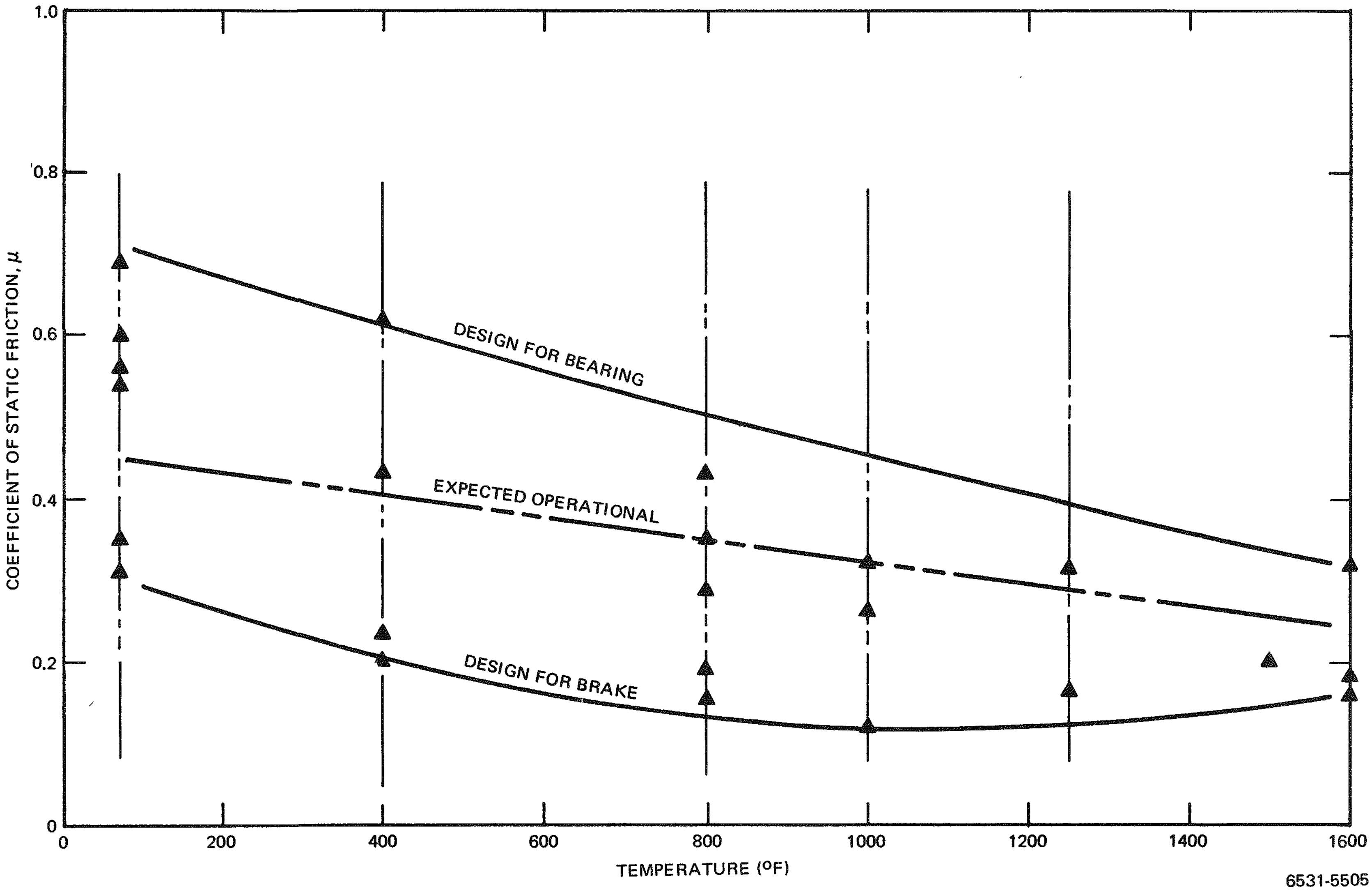

Figure 68. Alumina vs Carbon-Graphite Friction

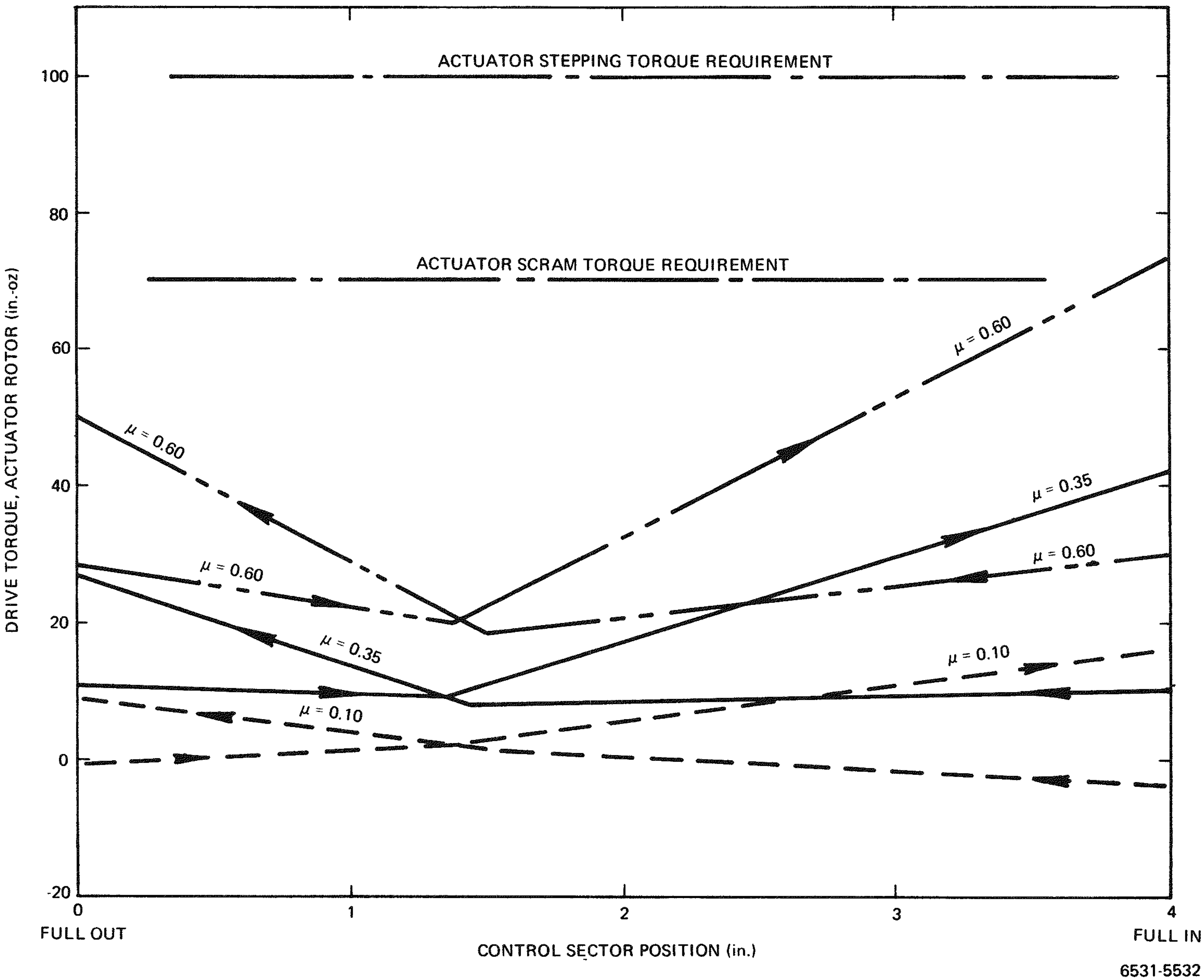

Figure 69. Ground Test Torque Requirements

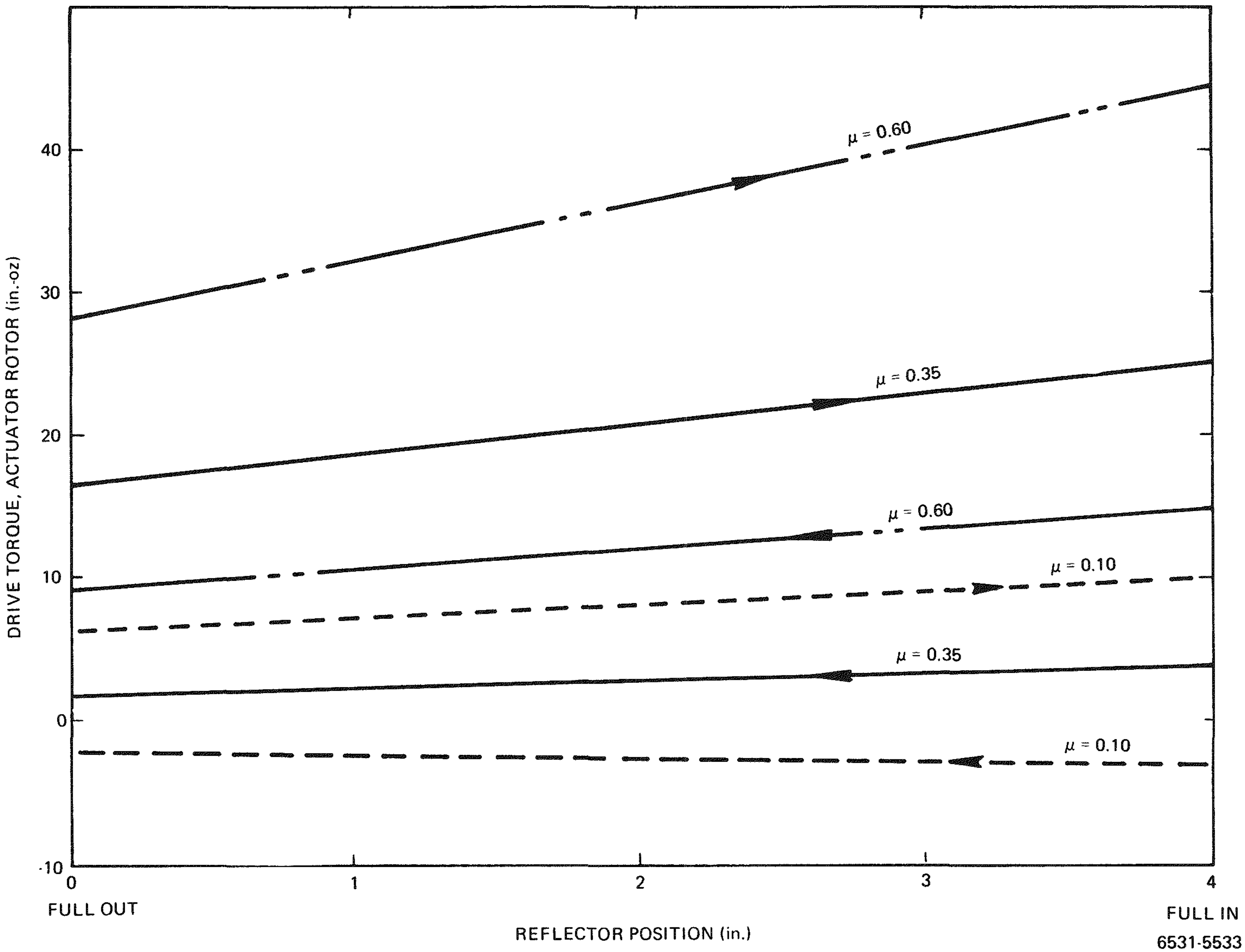

Figure 70. Flight System Torque Requirements

full-out stops restrain the segment against the reaction to forward acceleration. However, in the inverted (reactor-down) launch, the actuator brake must lock the control segment against the launch acceleration generated forces. This torque was calculated using the minimum friction coefficient of 0.10, maximum drive screw efficiency of 0.90 and gear efficiency of 0.90. The stated 16.25-g launch acceleration includes 25% margin. The actuator brake torque requirement of 180 oz-in. was selected to provide approximately 33% margin over the maximum expected requirements.

2. Control Segment Locking During Ground Test

As mentioned earlier, for ground testing, the control segment anti-backlash springs are replaced with heavier anti-gravity springs. The drive torque requirement curves of Figure 70 show that positive actuator torque is required to drive the control segment in either direction if the coefficient of friction is 0.35 or 0.60. If the friction coefficient drops to 0.10, positive actuator torques are still required to move the segment in. When the segment is more than 50% in, the loss of any actuator braking will cause the segment to move outward to approximately the midpoint of travel. Thus, for this system, the control segment should not move toward the more reactive position in the event of the postulated malfunction of the actuator, electrical cables, or controller. In fact, under normal conditions, the segment should remain at its position at the time of failure.

E. VERIFICATION TESTS

Reflector drive system verification tests were divided into four areas: (1) thermal-vacuum testing of conventionally applied MoS_2 dry-film lubricants and newer ion sputter applied MoS_2 on developmental ball bearing screws under expected reflector conditions of 800°F and 10^{-5} torr, (2) launch shock and vibration and operational thermal-vacuum testing of prototype ball screws, (3) simulated life testing of a complete reflector and drive system, and (4) proof testing of a ground test backup shutdown mechanism.

Prior to tests of developmental ball bearing screws (with MoS_2 lubricant), additional basic friction studies were conducted for MoS_2 against MoS_2 on Rene 41 or Inconel-750.[36] Table 36 summarizes friction coefficients and test conditions for the friction tests (discussed in Reference 11) and Figure 71 presents an overall comparison of MoS_2 friction coefficient values against MoS_2, carbon-graphite, and bare Inconel-750. All three conditions could exist during operation of the ball screw drive.

TABLE 36

MoS_2 FRICTION AND WEAR LIFE CAPABILITY

Test Temperature (°F)	Vacuum (torr)	Wear Cycles	Test Time (hr)	Friction	
				Static	Dynamic
500	10^{-7}	1200	~100	0.12 to 0.13	~0.10
1150	10^{-7}	600	~100	0.13 to 0.16	~0.10
600	10^{-3}	424	411	0.15 to 0.22	0.07 to 0.15
800	10^{-3}	520	433	0.12 to 0.16	0.08 to 0.10
900	10^{-3}	200	108	0.16 to 0.22	0.10 to 0.14
1000	10^{-3}	135	117	0.17 to 0.31	0.10 to 0.20

Tests were conducted on three ball screws to compare an unlubricated assembly to ones that had MoS_2 applied by spraying and sputter-ion methods. The sprayed coating was 0.0006 to 0.0011 in. thick and was MoS_2 in a sodium-silicate binder that was heat cured after application. The sputtered coating was eight angstroms thick applied in vacuum by a d-c triod process. The screw and nut were made of 17-4 PH steel, while the balls were tungsten carbide.

The coated assemblies were subjected to six temperature cycles from 300 to 800°F in a 10^{-5} torr pressure. This was followed by 7600 wear cycles on the sprayed coating and 3892 wear cycles on the sputtered coating. Performance was gauged by efficiency calculations for the ball screws using measured driving torques. The MoS_2 spray-coated assembly gave efficiencies in the 0.82 range, while the sputter coated assemblies gave efficiencies in the 0.84 range. Both are well above the 0.70 efficiency used for actuator sizing for the drive system. The unlubricated assembly was inadvertently overheated to 1150°F during the first cycle to 800°F and was not tested further. Both coatings were judged suitable for the use but a preference was given to the sprayed coating because it was less expensive to apply and was thicker which gives more assurance of MoS_2 being present after 5 years in vacuum.

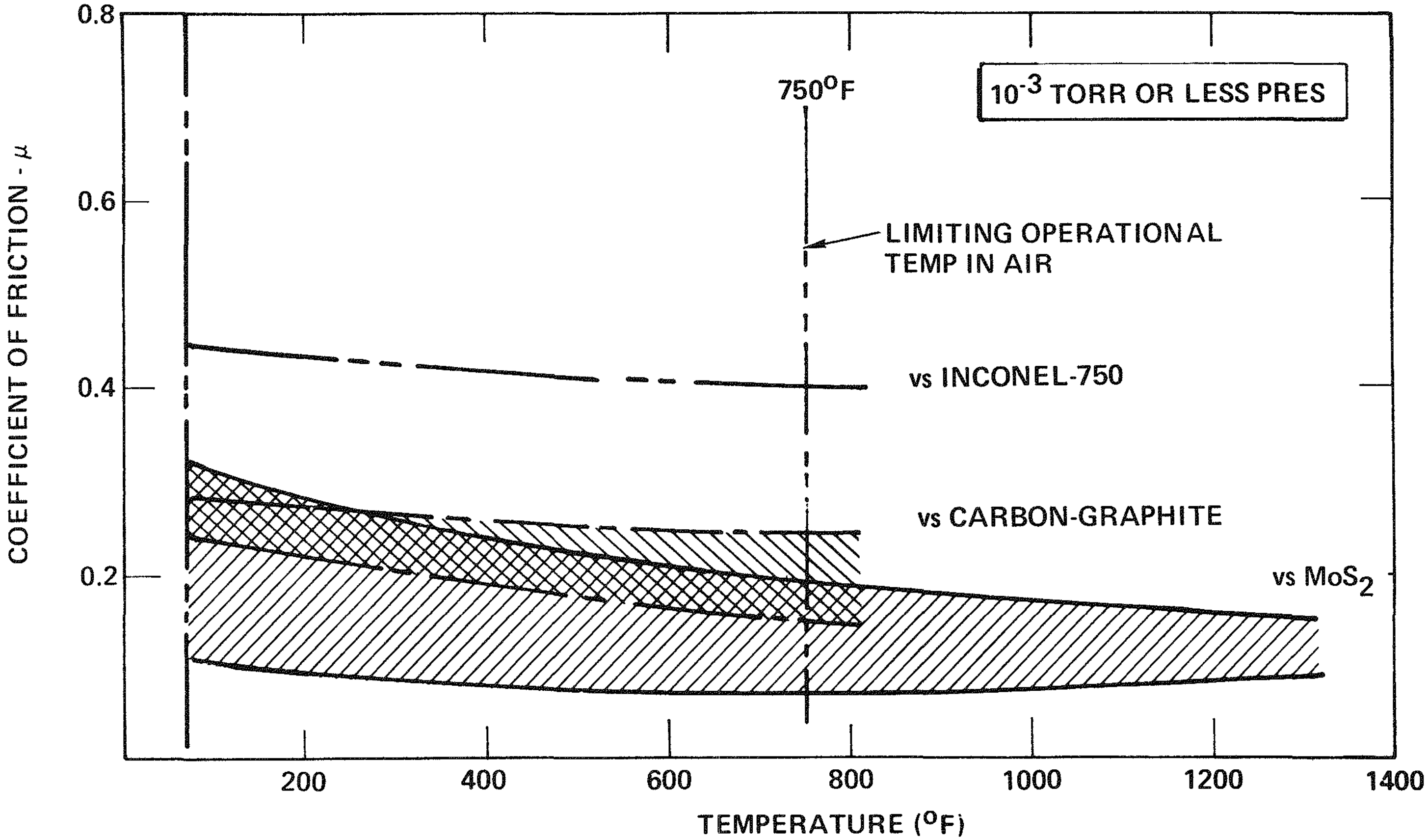

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Figure 71. MoS_2 Friction Coefficients

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