SP-100 Control Drive Assembly Development

Thomas Gleason*, A. Richard Gilchrist*, Gary Schuster*

ABSTRACT

The SP-100 is an electrical generating nuclear power system for space operation. This paper describes the nuclear reactor control systems and the methods used to assure reliable performance for the 10-year design life. Reliable performance is achieved by redundancy and by selecting highly reliable components and design features. Reliability is quantified by analysis using established reliability data. Areas lacking reliability data are identified for development testing. A specific development test description is provided as an example to demonstrate how this process is meeting the system reliability goals.

INTRODUCTION

The nuclear system control and shutdown functions are provided by the moving reflector segments surrounding the reactor core and by the in-core safety rods. The moving reflector drive system is capable of precise reactor control as well as reactor shutdown while the safety rod drive system provides fail-safe reactor shutdown capabilities. Figure 1 shows the overall reactor system arrangement and the relative locations of the two reactor control systems. Figures 2 and 3 show components tested and typical results obtained. Table 1 gives the nominal design environments of the control systems.

DESIGN DESCRIPTION

Reflector Control System

Reactor power control is achieved by moving neutron reflecting material axially relative to the reactor core. Electromechanical drive units located aft of the radiation shielding provide the power to move the reflector sections. A ball nut and screw assembly converts the rotary motion of the drive motor to linear motion needed to move the reflectors. A brake assembly locks the reflector in position when it is not being driven. Figure 1 includes a figure of the single reflector drive assembly. The drive system is capable of moving the reflector segments in small increments and has precise positioning capabilities. Figure 2 shows some of the test results for the reflector components tested.

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*General Electric Company, San Jose, CA

Safety Rod

Reactor shutdown capabilities are provided by the incore safety rods for launch and for severe accidents. Figure 1 includes a schematic of a safety rod and its drive system. Figure 3 shows some of the test results and key features for the safety rod components. Each rod contains sufficient neutron poison to prevent operation. When the poison is located within the core region, the safety rod is mechanically locked in position to prevent inadvertent withdrawal. Electromechanical drive assemblies located aft of the reactor shielding provide the unlock and the drive functions needed to move the poison out of the reactor core region. Electromagnetic clutches and brakes connected to the drive motor are used to select the desired drive and/or unlock function. A spring motor device stores energy to move the safety rod to the shutdown position on command or automatically at predetermined reactor conditions.

Design Challenges

The mechanical designs of the two systems share many common features all of which share the challenge of reliable operation in the harsh environment of high temperature, vacuum and radiation. Both include stepper motors, clutches, brakes, bearings, sliding surfaces, and springs, all of which must remain functional and maintenance free for 10 years. Material selections are limited for this extreme environment. Changes in material properties and strength characteristics, dimensional stability, self-welding, diffusion and evaporation must be considered for each material selected and for each material couple.

Moving and sliding elements near the reactor core region are challenged by the extremely high temperatures. Refractory metals are needed for the structural materials with carbide coatings on the critical contacting surfaces. Radiation induced material swelling is a major concern for items located near the reactor core.

RELIABILITY CONSIDERATIONS

Overview

Reliability of the reflector control and safety rod drive assemblies for the overall 10-year mission depends upon the presence of initial operational reliability, operational reliability throughout the mission, and an end-of-life significantly beyond the mission time.

Initially, the reflectors and safety rods must be capable of moving to the operational positions and remaining there with high reliability. This depends on the drive assemblies 1) being capable of performing their functions subsequent to fabrication and assembly--confirmed by acceptance testing, 2) surviving the launch--assured by design and structural analysis according to prescribed NASA methodology, validated by component and subassembly testing, and 3) reliably deploying and going into initial operation, given that they survived launch--assured by qualification testing, low component failure rates and the short time lapse before initial operation.

For the duration of the mission between start-up and end-of-mission, redundancy and low component failure rates assure the reliability of the reflector and safety rod functions to hold, scram, and shutdown. For most functions, the loss of a reflector or a safety rod can be tolerated.

Satisfactory margins between the mission time and the mean lifetime of the reflector control and safety rod drive assembly critical components assures that wear will not be a source of mission failure. Identification of failure modes and associated failure mechanisms in Failure Modes and Effects Analysis provides the basis for failure mechanism analysis, a process whereby identified failure mechanisms are examined for adequacy of data to support lifetime validation. If sufficient data are available, design margin studies are performed to provide an assessment of the margin of lifetime beyond the mission time. If sufficient data are lacking, specific needs are identified and factored into development programs planned or underway.

Assurance of Initial Operation Reliability

Prior to the SP-100 System Design Review held in 1988, structural analyses were done for the reflector control and safety rod drive assemblies. As part of these analyses, the structural response of the drive assemblies to the dynamic loading and vibration of launch were evaluated. Satisfactory margins were demonstrated for both types of drive assemblies. Since the System Design Review, the designs of both drives have changed; the changes to the safety rod drive assembly are small enough that the analysis results still hold true. The reflector control drive assembly changes are significant and, therefore, the structural analysis will be repeated. In the interim, preliminary analysis indicates satisfactory margin is available.

Mission Reliability Enhancement Through Redundancy

In the reflector control drive assemblies, redundancy has been built into the coils of the motor, brake, and position sensors, allowing reflector failures to be tolerated while meeting mission requirements.

In the safety rod drive assemblies, redundancy has been built into the safety rod drive motors, clutches, and brakes, supporting particularly the withdrawal function necessary for initial operation. To enhance the operational reliability throughout the mission, dual coils are built into the scram clutches so that inadvertent scram is less likely due to coil wire failure or a controller false signal. Multiple safety rod drive assemblies assure that the scram function will be reliable over the mission time, since, for most anticipated events requiring safety rod action, insertion of one safety rod is sufficient to safely shutdown the reactor.

Lifetime Reliability Through Failure Mechanism Control and Design Margins

Understanding of life limiting failure mechanisms through failure mechanism analysis (FMA) and the validation that lifetime margins exist through design margin studies (DMS), provide assurance that component end-of-life is sufficiently beyond the mission time. To date, 23 FMA's and four DMS's have been completed for the reflector control and safety rod drive assemblies.

Of the completed DMS's, one addressed the reflector and safety rod cladding failure due to embrittlement from oxygen released from the beryllium oxide (BeO) during irradiation. The conclusion of this study was that over the mission time the oxygen released in the lattice by the beryllium transmutation can be easily accommodated within the BeO lattice itself. As such, no oxygen release by diffusion from the BeO will occur. The potential failure mechanism identified and evaluated is not operative over the 10-year mission and cannot lead to safety rod or reflector element cladding failure.

Another completed DMS addressed the reflector and safety rod cladding failure due to BeO volumetric bulk expansion from irradiation induced swelling or microcracking. End-of-life was defined to correspond with take-up of the gap that exists at beginning-of-life between the BeO and the cladding. This is a conservative limit in that actual failure would correspond to considerable expansion beyond take-up of the gap, producing cladding distortion and, ultimately, jamming of the safety rod or reflector. Detailed designs will provide gaps that assure the desired lifetime goal are met.

A third DMS addressed the crack/ship/spalling/wear failure mechanisms of the alumina coating used to protect reflector drive assembly tantalum-tungsten alloy components within self-aligning bearings. The conclusion was that the coating, on the basis of tests performed in the early 1970's in connection with the advanced zirconium hydride reactor control system drives, had a reasonable margin on lifetime. This result will be reviewed for consistency with the modified application of the self-aligning bearing as we change the design from the hinged to the sliding reflector concept.

The fourth DMS addressed one of several failure mechanisms that could lead to self-welding of the safety rod to the molybdenum alloy thimble liner - specifically, the liner material fusing to itself in the event of liner material pickup onto the hardfaced safety rod slider bearing. Three generic material transport processes were identified as applicable to this failure mechanism.

Sufficient data were available to show that two of these processes had very large margins to failure over the mission lifetime; data to close out the third will come from experiments planned in the development program.

Twelve planned DMS's will address life-limiting failure mechanisms affecting coils, insulation and mechanical components. Included are several DMS's which explore other failure mechanisms that could lead to self-welding of the safety rod to the thimble liner. One of these is self-welding of the actual safety rod slider bearing carbide coating to the molybdenum alloy liner of the thimble. Another is the loss of the carbide coating in that, should loss of coating occur, the PWC-11 substrate material of the slider bearing would then be exposed to the molybdenum alloy, resulting in a couple more prone to self-welding. The causes that drive or enable these mechanisms to process have been identified as thermal aging, thermal cycling, and radiation. The need to adequately understand these failure mechanisms and the respective lifetime margins are the basis for the development programs described below. This program is a typical example of the ongoing process development and material evaluation resulting from the failure mechanism analysis.

SAFETY ROD MATERIAL SELECTION AND TESTING

Theoretical considerations and practical experience suggest a refractory metal carbide paired with Mo-41Re alloy is a promising material couple for use in the control rod/thimble system. This combination should not self-weld. Furthermore, the chemical stability of these carbides and their refractory nature make them likely to withstand the reactor core environment. Testing is required under prototypic conditions to validate material selections and applications.

Table 1. Design Environment

	NOMINAL TEMPERATURE, K	NOMINAL PRESSURE, TORR
Reflector	1320	10^{-9}
Reflector Drive	811	10^{-9}
Safety Rod	1600	10^{-9}
Safety Rod Drive	811	10^{-9}

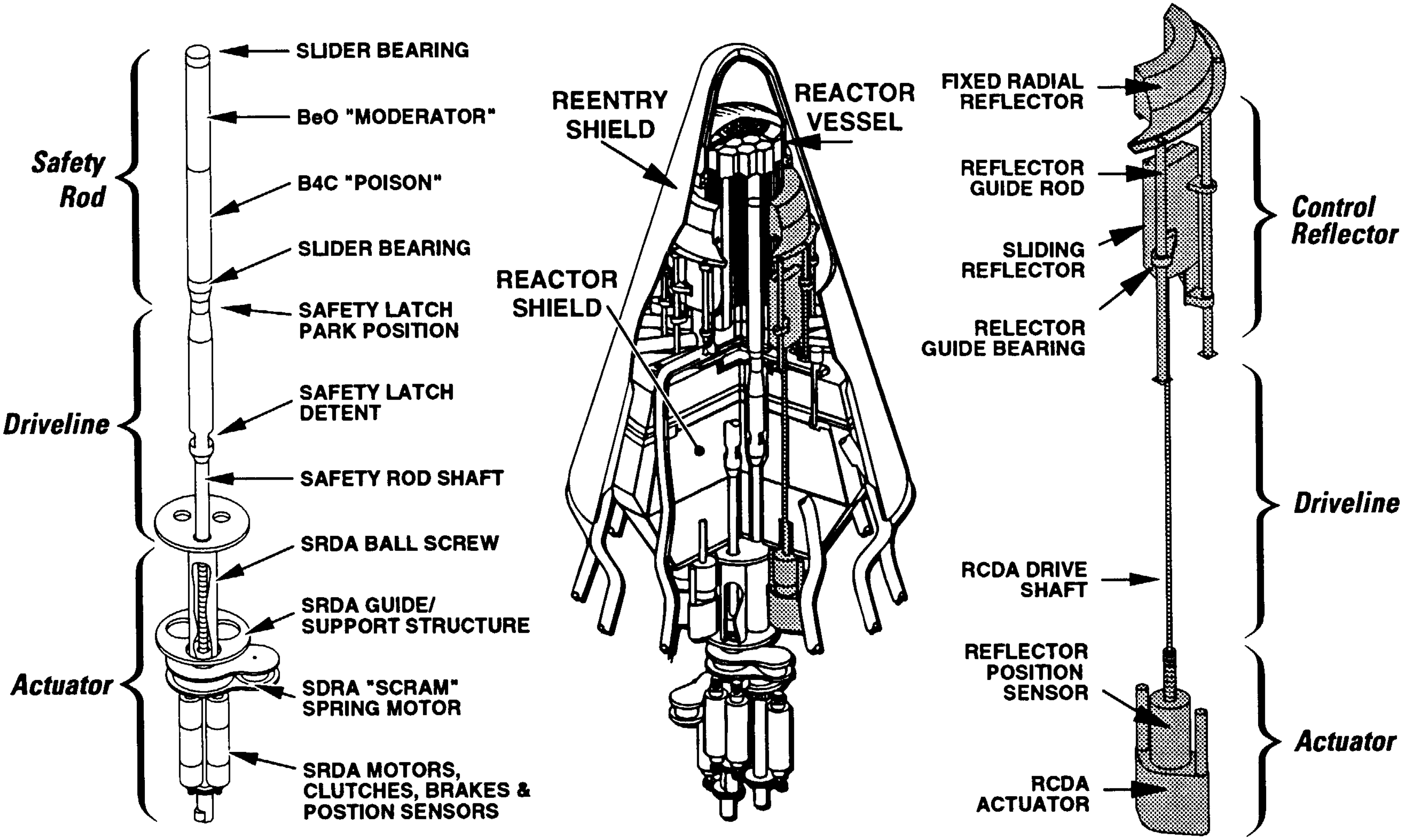

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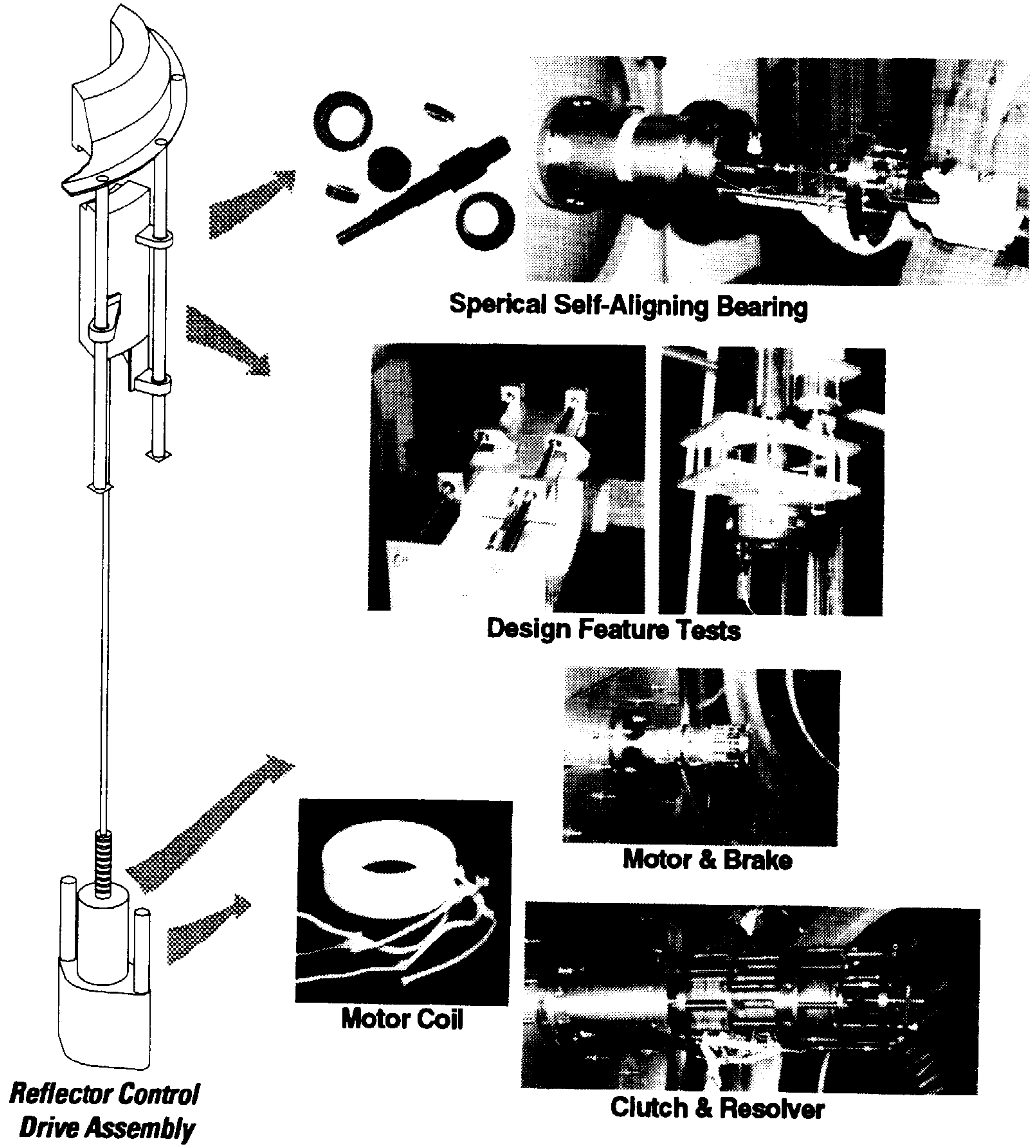
Figure 1. Control Drive Assemblies



- *Tested at 1180 K*
- *38,000 Operational Cycles*
- *27 Thermal Cycles >550 K*
- *Exceeded Requirements*

- *Demonstrated Assembly Operation*
- *Established Positioning Precision & Repeatability*
- *Demonstrated Failsafe Drive*

- *Tested Motor Coils at 895 K*
- *Tested First Generation Components*
- *Second Generation Components Fabricated*

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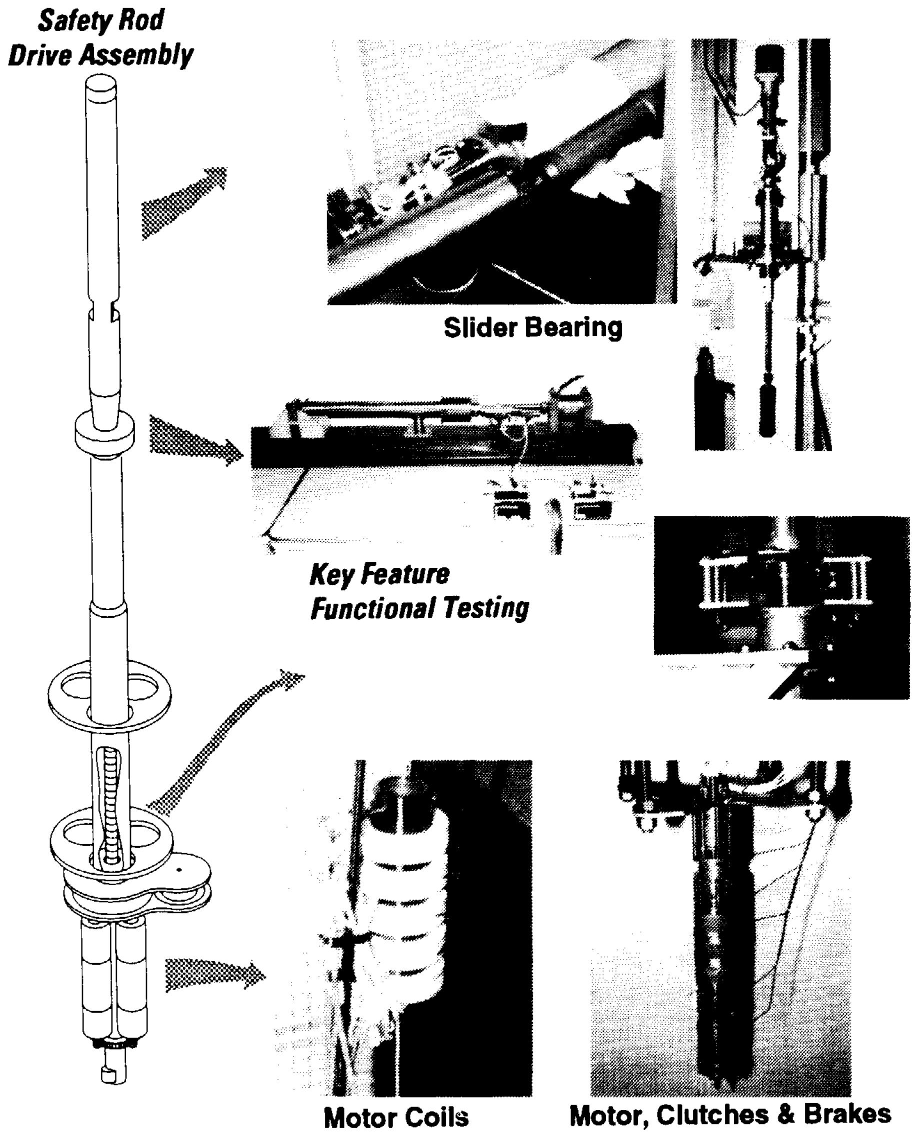
Figure 2. Reflector Drive Development



- Carbide Coating Process
- HfC Irradiation Test
- Carbide Thermal Aging Test Success at 1700 K
- Coating Met Requirements
  - Initiated Component Testing

- Key Safety Design Features Tested
  - Failsafe Shutdown Spring Motor
  - Safety Latch
  - Safety Rod Separation Joint

- Motor Coils Tested at 895 K
- Tested First Generation Components
- Second Generation Test Components Fabricated

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Figure 3. Safety Rod Drive Development

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The proceedings of the 27th Aerospace Mechanisms Symposium, which was held at the Ames Research Center, Moffett Field, California, on May 12, 13, and 14, 1993, are reported. Technological areas covered include actuators, aerospace mechanism applications for ground support equipment, lubricants, latches, connectors, robotic mechanisms, and other mechanisms for large space structures.

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