Subcontract NP-1

**Westinghouse
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WANL-TME-1984
January 1970

DATA ITEM S-54

CONTROL DRUM ACTUATOR

TRADE STUDY NO. 754

MASTER

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JUL 10 1970

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Attention: Mr. P. P. Ventura

Subject: Errata Sheet to WANL-TME-1984, Control Drum
Actuator Trade Study No. 754, S-054

Gentlemen:

Ten (10) copies of the subject errata sheet are enclosed for making corrections to the report (WANL-TME-1984) transmitted to you on March 10, 1970.

Respectfully,

ORIGINAL SIGNED

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Enclosure: Ten (10) copies
Errata Sheet

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ERRATA

WANL-TME-1984, JANUARY, 1970

DATA ITEM S-54

CONTROL DRUM ACTUATOR

TRADE STUDY NO. 754

Pages xi, xii, xiii, and xiv: Replace with the attached Lists of Tables.

Page 4-2: The title of Table 4-1 should be changed to read:
"Control Drum Actuator Trade Study - Summary
Evaluation Matrix".

The last item of the "Weighting Factor" column
should read: "Binary Pneumatic Valve Actuators
with Valve".

In the last line of the "Safety" column, the second
number should be changed from .100 to .068.

Issue Date: April 15, 1970

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DATA ITEM S-54

CONTROL DRUM ACTUATOR

TRADE STUDY NO. 754

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1.0 PURPOSE OF THE DESIGN TRADE STUDY

This trade study of selected control drum actuator concepts is initiated to select one actuator candidate for development to eventually meet the program requirements. The intent is to select the best candidate from the analog actuators and also the best candidate from the two-position actuators. Trade Study No. 701, "Controls Concept Trade Study" had to select between analog and two-position. This trade study considers those features that influence the performance parameters of the actuator system, those features that can be classed as physical parameters of the actuator systems, and those features that affect the reliability of the actuator system as it applies to the performance of its designated function in the nuclear subsystem (NSS).

The physical features of the actuator should be minimized because unneeded weight and size subtract from the vehicle payload. The physical features of all considered concepts, when subjected to an intensive development program, can be designed to meet the physical requirements and constraints imposed by the nuclear subsystem. The severity of the nuclear subsystem restraints and, therefore, the difficulty of meeting actuator size and space limitations increases with an increase in the number of control drums. For this study, most actuators are designed to satisfy the size limitations imposed by a nuclear subsystem containing 36 control drums. Since actuator performance requirements change very little with number of drums, the logical assumption is made that an actuator suitable for use with a 36 control drum nuclear subsystem could be adapted with very little change, if any, to a nuclear subsystem with fewer drums. The number of drums will be determined by the results of the reactor controls concept trade study. This assumption provides the smallest and lightest actuator for any given application. Several concepts considered are not directly adaptable to a 36 drum system and are, in general, heavier and larger than other considered concepts. In these cases, size and weight are disadvantages of the particular design.

The performance requirements of CP 677585 as modified by DRM 51414 are basic inputs to this trade study. Actuator candidates have been sized to meet or exceed the required performance parameters such as velocity, acceleration, bandwidth and resolution. The performance

requirements are not severe or restrictive; therefore, they do not limit the selection of candidates but, conversely, allow consideration of almost any concept. Any of the design concepts considered can, therefore, be optimized to meet the performance and environmental conditions imposed by the nuclear subsystem. The operating and storage environments must be considered in the detail design phase. Preliminary estimates as well as past test history indicate that the environmental condition (vibration, shock, temperature, temperature rate, etc.) impose design considerations which are more restrictive from a dynamic operating standpoint than from a structural design standpoint. Materials used in actuators are not, in general, required to operate near their operating limits and, as such, are not severe design problems.

The reliability requirements for an actuator system are unprecedented and, therefore, represent by far the major area for design improvements, assessments and justifications. Analytical evaluation of an actuator on a component-by-component basis allows prediction of system reliability. Actual reliability can only be proven by an intensive and expensive test program. It is the intent of this trade study to estimate the reliability of each concept and to use that estimate as one input to the final selection of a candidate.

1.1 FUNCTIONAL DESIGN REQUIREMENTS

The functional design requirements of the actuator system are as follows:

- 1.1.1 The actuator system must move and maintain the drum system in response to a command from the reactor control system.
- 1.1.2 Maintainability and access should be in accord with the reliability and operational characteristics of the actuator system.
- 1.1.3 The actuator system must operate with the desired reliability in the specified combined environments and utilize basic power, coolant and working fluids that are readily available for the useful life of the equipment.

1.2 TECHNICAL DESIGN REQUIREMENTS (CP 677585 as modified by DRM 51414)

The technical design requirements of the system are as follows:

- 1.2.1 The Control Drum Drive System (CDDS) shall have a velocity capability of $\pm 10^{\circ}/\text{sec}$.
- 1.2.2 The CDDS shall have an acceleration capability of $\pm 20^{\circ}/\text{sec}/\text{sec}$.
- 1.2.3 The actuator shall have a bandwidth of 1.0 Hz with a 1 degree P-P input signal. This is defined as the point where the amplitude ratio of output to input is down 3 db.
- 1.2.4 The CDDS shall position the drums with a resolution of 0.2 degrees. This is defined as the maximum degree error required to produce an output motion from the actuator system.
- 1.2.5 The actuator shall have a minimum stall torque capability of 100 in.-lbs.
- 1.2.6 The CDDS shall not require any scheduled maintenance, repair or replacement during the useful life of the NSS.
 - 1.2.6.1 The CDDS must be capable of being repaired and/or replaced prior to NSS operation.
 - 1.2.6.2 The CDDS actuators shall be remotely or manually removable.
- 1.2.7 The CDDS must be capable of a total of 150 hours of non-irradiated operation or until accumulation of two hours of irradiated operation.
- 1.2.8 Storage life must be compatible with that specified for the NSS.
- 1.2.9 The CDDS must operate in space and induced environments specified in CP-677555 for the NSS.
- 1.2.10 The CDDS must operate on H_2 , H_e , and/or electrical power specified by CP-677555.

- 1.2.11 The apportioned reliability goal for the CDDS shall be a probability of 0.99989 that it will not cause an NSS failure under environmental conditions and during the useful life as specified.

2.0 POSSIBLE DESIGN APPROACHES

The designs evaluated in this section are selected to include and consider at least one candidate from each concept type. Each candidate is evaluated as objectively as possible and is not abandoned prematurely in the study effort. No candidate had a detailed design effort, although past NERVA experience is reflected in the pneumatic rack and pinion designs. The selection of a recommended design is based on design studies only and, as hardware evolves, problem areas can be expected to appear. However, each design is evaluated in enough depth to assure ultimately achieving functional and performance objectives.

As the program progressed, new concepts were added as required for completeness. If different manufacturers had different mechanizations of the same concept and if the differences were significant, then both concepts were included in the study.

A summary of the evaluated concepts is given in Figure 2-1. The two functional types considered are the proportional type and the two-position concept. Although, as originally envisioned, the two-position concept includes different types of pneumatically operated devices as well as different types of electrically operated devices, the drum mounted vane type pneumatically operated two-position actuator appears to provide the simplest method of moving the drums. So other two-position candidates, including all electric concepts, are given little attention. If it is determined that drum mounting is unacceptable, and that the actuators must be dome-mounted, then the advantages of the pneumatic vane concept are not as obvious, and other concepts will have to be re-evaluated.

In the trade study evaluation of proportional devices, major critical components, developed for the XE program and incorporated in the trade study actuator designs, are evaluated for appliance of redesign to gain improved reliability through simplicity of design. Drum position indicating devices which are components in all the proportional concepts appear to be an area of investigation. The servovalve, including a torque motor, is the interface between the electrical input and mechanical output of all the pneumatic concepts and is, therefore, a good area for design effort.

Figure 2-1. Actuator System Concepts

2.1 RACK AND PINION PROPORTIONAL PNEUMATIC CONCEPT

2.1.1 Mechanical Description

The rack and pinion proportional pneumatic actuator is shown in Figure 2-2. This design is the result of two redesign efforts on the XE-type proportional pneumatic actuator shown in Figure 2-3. The intermediate design is shown in Figure 2-4.

The designs in Figures 2-2 and 2-4 are major simplifications of the original concept in Figure 2-3, but they maintain the basic principles involved. This section is a description of the actuator in Figure 2-2. The designs of Figures 2-3 and 2-4 are included for historical purposes only.

For discussion purposes, the actuator is divided into four main categories.

- A. Servovalve assembly
- B. Feedback potentiometer
- C. Drive train (piston and rack assembly; pinion output shaft-output shaft bearings; and rack backup bearing assembly)
- D. Housing enclosure

Basically, the servovalve converts the command signals from the control system into a pressure differential across the piston mechanism. This pressure differential causes translation of the piston and rack assembly thereby producing a rotation of the output shaft. The feedback potentiometer, which is driven directly by the output shaft, produces a signal proportional to output shaft rotation (i.e., drum position). This electrical signal is fed back to the control system. Any difference between the command and feedback signals results in a rotation of the drums until the feedback signal equals the command signal. The housing enclosure physically contains the other parts and also provides porting for the required fluids.

2.1.1.1 Servovalve Assembly

The servovalve is shown in the actuator schematic in Figure 2-5. The servovalve converts electrical input signals into pressure differentials and is the interface between the control system and the required mechanical motion of the control drums. The major components of the servovalve are the torque motor and valve assembly.

Figure 2-2. Pneumatic Rack and Pinion Actuator - Single Piston

Figure 2-3. Pneumatic Rack and Pinion Actuator - XE Type

Figure 2-4. Pneumatic Rack and Pinion Actuator - 1st Redesign

Figure 2-5. Actuator Single Piston Rack and Pinion Schematic

The torque motor changes the electrical input signals to a mechanical output motion of the torque motor armature. The torque motor armature is centered in a magnetic field by a centering spring. The magnetic field is supplied by four Alnico permanent magnets. The electrical signal inputs to the torque motor coils polarize the armature causing output rotation about the centering spring. Output motion is parallel to the magnetic flux in the air gap. The amount of output motion is determined by the balance of the magnetic force and the spring centering force. When the torque motor is combined with the valve, pressure forces must also be considered in the force balance.

The valve is a single stage, flapper-nozzle, push-pull device operating about a null pressure. It consists of two fixed orifices and two variable orifices. The unique feature of this valve is the use of variable orifices which employ annular nozzles. This concept allows greater flows without the disadvantage of large negative feedback pressure forces. The supply gas to the valve splits and flows two ways through the valve (Figure 2-5). The flow in each side goes through a fixed orifice and a variable orifice in series. The cylinder pressure is the pressure between the two orifices and is a function of the relative areas of the fixed and variable orifice. The null pressure and any pressure bias is established by the mechanical adjustment of the variable nozzles. The differential pressure across the piston is determined by the position of the armature and is continuously variable to about 3/4 of supply pressure in each direction. As explained, electrical inputs to the torque motor cause an output motion which produces the variable feature of the annular nozzles. For example, if an electrical signal caused a clockwise rotation of the armature, the right-hand nozzle discharge area would be reduced while the left-hand nozzle area would be increased. Consequently, the pressure increases on the right side of the piston and decreases on the left side. This differential pressure would cause piston and rack movement to the left. An electrical input of opposite polarity would cause the piston assembly to move to the right.

2.1.1.2 Potentiometer

The potentiometer produces an electrical output that is proportional to the shaft position of the actuator and is, therefore, a measure of drum position. This potentiometer is a three-deck device which provides threefold redundancy to the position feedback signal. Each deck is electrically independent.

The potentiometer is assembled concentrically with the main output shaft of the actuator and uses the main actuator bearings for alignment. This feature produces the simplest assembly and eliminates many parts required in separately mounted potentiometers. The potentiometer is assembled and aligned on the output shaft by the manufacturer to eliminate error in assembly.

2.1.1.3 Drive Train

The drive train consists of the piston and rack assembly, the output shaft which contains the pinion, the output shaft support bearings, and the rack backup bearing assembly. The servovalve develops a differential pressure across the piston. The two sides of the piston are pneumatically isolated by a piston ring and the piston is held from contacting the liner by a guide ring. The differential pressure across the piston produces a linear motion of the piston and rack assembly. This linear motion is converted to rotary motion by the pinion and is transmitted to the load by the output shaft which is machined integrally with the pinion gear. The output shaft is supported in the housing by the two shaft bearings. The rack is held in contact with the pinion by the backup bearing assembly. The bearings contact the back of the rack and maintain rack/pinion engagement. A very small separation of the rack and pinion is permitted to allow small amounts of contamination to pass through without jamming the assembly.

2.1.1.4 Housing Enclosure

The housing ties together all of the functional parts of the actuator. Passages drilled in the housing carry drive gas and coolant gas to the various ports and locations of the actuator. Drive gas pressure is expected to be about 215 psia and coolant gas, which comes from the reactor dome, will vary from zero before reactor startup to about 700 psia at reactor full power. Two external covers, a cylinder cover and a rack bearing cover, form a part of the actuator. They serve as assembly access ports and also contain the internal working fluids.

All electrical power, input command signals and output position signals enter and exit the actuator by way of the electrical connector.

Drive gas enters the actuator across the actuator mounting interface, through the drive gas filter, and is ported directly to the servovalve.

The coolant gas enters the actuator from the reactor dome through the coolant filter which is located in the center of the output drive shaft.

Two shaft seals, one at the top and one at the bottom, isolate high pressure coolant from the drive gas and reactor dome, respectively. A series of small, radially drilled metering holes in the shaft allow the correct quantity of coolant to enter the actuator. Flow through the aft series of holes cools the aft bearing and potentiometer. Flow through the forward series of holes is ported to the spirally cut groove in the cylinder liner. From the cylinder liner the gas flows into the servovalve cavity and is used to cool the torque motor. All drive and coolant gas is collected in the servovalve cavity for disposal or other use. A suggested use is to pressurize the run tank. Actuator performance will not be affected by exhaust back pressure up to 50 psia.

2.1.2 System Description

A block diagram of the rack and pinion proportional pneumatic actuator system is shown in Figure 2-6. This block diagram shows all of the subassemblies that make up the actuator system and the interrelationship of these subassemblies with other systems within the NERVA engine system. The components in the diagram that constitute the actuator system are the actuator mechanism, the actuator amplifier (including compensation and associated logic) and the actuator output drive shaft.

The actuator mechanism mounts to a flange on the pressure vessel closure which provides the interface for remote or manual removal and replacement. Drive gas, coolant gas, exhaust gas and output drive shaft cross this interface to perform their respective functions. All electrical wires enter and exit the actuator through a plug mounted directly to the actuator body. This plug also is designed with remote removal and replacement in mind.

The amplifier, combined with the actuator mechanism and supplied with the proper electrical and pneumatic inputs, constitutes a closed loop drum position control system. This servomechanism positions the actuator output shaft (and therefore changes drum position and

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Figure 2-6. Rack and Pinion Proportional Pneumatic Actuator System Block Diagram

reactor reactivity) in accordance with the difference between the commanded drum angle and the measured drum angle. Actuator movement reduces the magnitude of this difference to zero.

The number of these actuator systems on a reactor is equal to the number of control drums in the reactor and, therefore, has not been fixed. However, the use of 12, 18, 24 or 36 control drums are now under consideration. This actuator system is suitable for any of these reactor drum combinations up to and including 36.

2.1.3 Radiation Evaluation

The calculated nominal radiation environment at the proposed location on the pressure vessel closure selected for this actuator concept is summarized in Table 2-1. Listed in the table are the total, fast, and thermal neutron flux levels and gamma dose rate at rated thermal power, 1575 Mw. These levels may be multiplied by the time at power (The effective time at power, including operation at intermediate powers, may be calculated by dividing the integrated energy in Mw-sec by 1575 Mw.) for a given mission to obtain a measure of the cumulative radiation damage to candidate actuator materials in the absence of annealing effects. For perspective, the integrated values are given for a 60 minute run at rated power.

As a relative measure of the expected actuator heat removal and coolant requirements, heating rates are given for stainless steel and aluminum. For other actuator structural materials, e.g., titanium, stainless steel may be used due to the almost constant gamma energy absorption per unit mass of structural metals.

The values in Table 2-1 were calculated for an earlier NSS Reference Design shown in WANL Drawing Number 939J685A which contained a BATH internal shield; they are applicable at the same location relative to the core in the current NSS design, Drawing Number 939J685E. Further information on the NSS radiation environment is given in DRM-1076 and 1069. The values shown are for the unperturbed radiation levels in the absence of an actuator.

As a preliminary estimate of the maximum value of these levels including calculational uncertainty, a factor of three is recommended, reflecting past experience in NRX reactor testing. A more precise estimate of the uncertainty in each parameter will be developed by a systematic analysis of all available experimental data. Even with the suggested uncertainty,

TABLE 2-1

NOMINAL RADIATION ENVIRONMENT AT ACTUATOR LOCATION
FORWARD OF PRESSURE VESSEL CLOSURE (1)

<u>Item</u>	<u>Radiation Level at 1575 Mw(2)</u>	<u>Time-Integrated Fluence or Dose in 60 Minutes</u>
1) Total Neutron Flux	$2.1 \times 10^{11} \text{ n/cm}^2\text{-sec}$	$7.6 \times 10^{14} \text{ n/cm}^2$
2) Fast Neutron Flux ($E > 1 \text{ Mev}$)	$6.4 \times 10^{10} \text{ n/cm}^2\text{-sec}$	$2.3 \times 10^{14} \text{ n/cm}^2$
3) Thermal Neutron Flux ($E < 1.4 \text{ ev}$)	$2.7 \times 10^8 \text{ n/cm}^2\text{-sec}$	$9.7 \times 10^{11} \text{ n/cm}^2$
4) Gamma Ray Dose	$1.8 \times 10^6 \text{ rads-C/hr}$	$1.8 \times 10^6 \text{ rads-C}$
5) Heating Rate, Stainless Steel	2.6 watt/lb $= 0.0057 \text{ watt/gm}$ $= 8.9 \text{ Btu/hr-lb}$ $= 2.5 \text{ Btu/hr-in}^3$	
6) Heating Rate, Aluminum	2.3 watt/lb $= 0.0051 \text{ watt/gm}$ $= 7.8 \text{ Btu/hr-lb}$ $= 0.76 \text{ Btu/hr-in}^3$	

(1) A factor of three uncertainty (1σ) is associated with these values. The location assumed is at reactor coordinates $R = 23.4 \text{ in.}$, $Z = 53.7 \text{ in.}$ (Station zero is at dome end of core.)

(2) Calculated at end of 60 minute full power run.

the maximum radiation levels are relatively low at the specified actuator location as a consequence of the shielding provided by the NSS internal shield.

A comparison of the experimental data with the materials radiation damage limits given in Section 2.1.6 reveals that no significant radiation damage problem exists with this concept.

2.1.4 Thermal Evaluation

A preliminary thermal evaluation of the rack and pinion proportional actuator shown in Figure 2-4 has been performed and is reported in DRM-1091. That analysis, together with operational experiences with this type of mechanism in the NRX-A6 side-by-side test and XE reactor series (shown in Figure 2-3), generally indicates that temperature levels in the actuators will be within material capability during normal steady state operation. The analyses in DRM-1091 are based on heating rates obtained from WANL-TME-1798, Vol. 5. They indicate that heat generations of 51.2 BTU/hr/lb (XE design is based on 1200 BTU/hr/lb) occur in the actuator region and that actuator coolant gas is affected by four primary sources, heat generated in the actuator, heat conducted from the actuator drive gas, heat conducted from the reactor pressure vessel, and heat transferred between the actuator and the ambient environment.

The coolant gas temperature rise from these sources is estimated to be about 50°R , resulting in a coolant exit gas temperature about 250°R . With these coolant temperatures, the actuator maximum material temperature is estimated to be 350°R .

A more detailed analysis of the actuator is presented in R641811, the vendor's design and development report for the pneumatic actuators for the NERVA XE series. That analysis shows that the maximum temperature in the actuator occurs in the Marman clamp bolt; therefore, using that as a base line, a calculation of the appropriate actuator hardware (Figure 2-4) (bolt, nut, strap, and housing) indicates that a maximum bolt temperature of 105°R or 455°R would occur above the aft end of the housing. Using a factor of three as the uncertainty on the heating rates, the maximum bolt temperature is 515°R . The recent heating rate values of 2 to 3

watts/lb (7 to 10 BTU/hr/lb), calculated for the reference NERVA reactor for the actuator environment reported in this study, reduce the thermal gradients with the actuator even more.

In general, the regions of primary thermal analysis interest will include the relatively thick metal sections, such as housing flanges, or the asymmetrical metal sections, where maximum temperature levels or thermal distributions would be expected to occur.

The second redesign of the pneumatic rack and pinion actuator (Figure 2-2) is designed to conveniently and easily supply and distribute coolant as it is required to all components of the actuator. Apparently, there is no major or heavy material mass which would be expected to cause high thermal gradients or temperature levels. The major material in the actuator is aluminum, which has a low volumetric heating rate and excellent thermal conductivity. The steel rack, pinion and output shaft can be fully exposed to coolant gas environment. There is no major asymmetric thermal condition readily apparent in the actuator design.

2.1.5 Structural Evaluation

A preliminary structural analysis has been performed on the critical structural components of the proportional pneumatic rack and pinion actuator shown in Figure 2-4. This analysis is documented in DRM-51128 and 51544. The results of this analysis show that all of the components analyzed are structurally adequate for the anticipated loadings.

The proportional pneumatic rack and pinion actuator in Figure 2-2 is a second redesign of the XE-type actuator. This actuator consists of four main assemblies, servovalve assembly, feedback potentiometer, drive train and housing enclosure.

The major structural component in the servovalve assembly is the torque motor centering spring. This centering spring is a torsion bar which positions the torque motor armature in a magnetic field. As reported in DRM-51544, the margin of safety of the torsion spring was calculated to be 35 percent for an armature movement of ± 0.010 inch. No structural problems are anticipated in this servovalve assembly and the reliability of the assembly can be verified by component testing.

The feedback potentiometer is primarily an electrical device used to measure drum position and no structural problems are expected.

The drive train consists of the piston/rack assembly, pinion shaft, and bearings which are similar to the corresponding components in Figure 2-4. Based on previous stress analysis of Figure 2-4 actuator drive train components, no structural problems are expected with the single piston actuator drive train. During the detail design and analysis phase, contact stresses, surface wear, fatigue life, velocity capability and material selection for the bearings and rack and pinion gear teeth will be considered in depth if this design is selected.

The housing enclosure is the basic structure to which all of the actuator components are assembled and it also is the pressure envelope which must contain the operating pressures. The major structural components in the housing enclosure are the main housing, cylinder cover, rack bearing cover, static seals and the flange mounting bolts. Based on the stress analysis of similar components in the actuator in Figure 2-4, the main housing, cylinder cover and rack bearing cover should be structurally adequate for the anticipated operating pressures (drive gas supply is equal to 215 psia and cooling gas supply is equal to 700 psia). During the detail design and analysis phase, additional areas of structural analysis concern will include the flange bolt loads and stresses and thermal stresses that may exist in the housing enclosure components if this design is selected. Proof tests can be performed on the static seals to determine leakage rates and the asymmetrical housing enclosure to confirm the analytical stress analysis.

2.1.6 Radiation Effects Evaluation

The total expected radiation environment to which this actuator will be subjected is given in Section 2.1.3. To assess the effects of this environment on the actuator, a comparison of known test environments with this expected environment will indicate the sensitivity of any given concept to successful operation in the expected radiation levels. The sensitive components in this concept are the torque motor, potentiometer, piston rings and shaft seals, and electrical insulation and potting compounds. All other materials used in the construction of the actuator are metals. Although detail designs are not available, final material selection will be made from lists of qualified materials or will be separately qualified.

2.1.6.1 Torque motor

The torque motor contains two items which are considered sensitive to a radiation environment, the permanent magnets and the electrical coil. Changes in magnetic properties are reported after radiation exposures approximating $3 \times 10^{18} \text{ n cm}^{-2}$ (1, 2). This is approximately three orders of magnitude above the expected NERVA level. Other experiments at approximately the same neutron fluence show very little effect. Irradiation of a torque motor, similar to the NERVA design in the GTR facility, to $7 \times 10^{16} \text{ n cm}^{-2}$ produces an anomaly in the torque motor behavior. This anomaly is probably caused by the cryogenic environment rather than the radiation. The anomaly does not affect the performance of the torque motor. In addition, a prototype torque motor was operated in the NRX-A6 pneumatic actuator side-by-side test⁽³⁾ to levels approximately two orders of magnitude higher than the expected NERVA levels with no evidence of change. Test results of the Lewis Research Center Program⁽⁴⁾ at the Plum Brook Reactor also show no anomalies.

Electrical coils are part of all the mentioned torque motor tests and evidence no signs of damage. However, it is planned to take advantage of improvements in the state-of-the-art in insulation materials and use the polyimide series for future wire insulation to improve radiation tolerance and increase coil reliability.

2.1.6.2 Potentiometer

A prototype potentiometer is also included in the tests. A reported failure in the Lewis tests⁽⁴⁾ caused some concern until a subsequent post-irradiation examination revealed that the failure was caused by a softening and subsequent flowing of a potting compound not included in the GTR and NRX-A6 tests. The material that failed was included in very early potentiometers but has since been removed. Future controls will assure using only those specified materials that will not be subject to property changes under radiation environment.

2.1.6.3 Piston Rings, Shaft Seals, Electrical Insulation and Potting Materials

Although these items and materials are adequate for use in the NERVA environment, it is planned to take advantage of the improvements in the state-of-the-art in insulation materials. Polyimide materials, now used in the piston rings and seals, will be used in wire insulation and potting materials to increase radiation tolerance and reliability.

2.1.7 Reliability and Safety Evaluation

2.1.7.1 Fault Tree Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliability of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale from 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection, assembly and testing the identified component's ability to perform during its useful life in the actuator. The number 100 represents the most difficult level and the number 1, the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event identified on the tree, and has assigned a relative weighting number to each failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-7 shows in summary form the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific components within the actuator concept that contribute to the main block failure. The numbers in parenthesis are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A listing of the failure events is shown in Table 2-2. These failure events are located in the fault tree by their identifying numbers which appear above the blocks on

Figure 2-7. Single Piston Pneumatic Actuator Summary Fault Tree

TABLE 2-2
DETAILED FAULT TREE ANALYSIS

Single Piston - Rack & Pinion Proportional Pneumatic Actuator
Reliability - Fault Tree
Analysis 939J471 Estimated Reliability 9586

1431

1. Actuator Coolant Gas Consumption Rate Exceeds Specified Rate Limits	57
1.1 Interface Seal Joint Fails	47
1.1.1 Pressure Vessel Seal Surface Fails to Contain Pressure	AGC
1.1.2 Actuator Seal Surface Fails to Contain Pressure	1
1.1.3 Seal Fails to Contain Pressure	30
1.1.4 Seal Joint Separates	16
1.1.4.1 Actuator Flange Fractures	1
1.1.4.2 Pressure Vessel Flange Fractures	AGC
1.1.4.3 Hold Down Bolts Lose Force	15
1.1.4.3.1 Bolts Loose Torque	5
1.1.4.3.2 Belleville Lose Gradient	10
1.2 Actuator Mechanism Fails to Control Coolant	10
1.2.1 Lower Shaft Seal Fails	10
2. Actuator Fails to Achieve Time/Position Band	1314
2.1 Actuator Piston Pressures are not Correct Values	673
2.1.1 Servovalve Converts Signal Incorrectly	135

TABLE 2-2 (Continued)

2.1.1.1	Torquemotor Characteristics Change		119
2.1.1.1.1	Coil Fails	60	
2.1.1.1.2	Armature Assembly Fails	25	
2.1.1.1.2.1	Weld Fails	10	
2.1.1.1.2.2	Armature Spring Fails	2	
2.1.1.1.2.3	Frame Fails	3	
2.1.1.1.2.4	Armature Fails	10	
2.1.1.1.3	Field Assembly Fails	4	
2.1.1.1.3.1	Pole Piece Fails	1	
2.1.1.1.3.2	Bottom Shunt Fails	1	
2.1.1.1.3.3	Top Piece Fails	1	
2.1.1.1.3.4	Magnets Fail	1	
2.1.1.1.4	Coil Lead Wires Fail	30	
2.1.1.2	Valve Characteristics Change		16
2.1.1.2.1	Flapper Screw Fails	7	
2.1.1.2.1.1	Screw Breaks Mech.	2	
2.1.1.2.1.2	Lock Screw Fails Allowing Flapper Screw to Move	5	
2.1.1.2.2	Nozzle Assembly Fails	4	
2.1.1.2.2.1	Nozzle Core Fails	3	
2.1.1.2.2.2	Manifold Fails	1	
2.1.1.2.3	Fasteners Fail	5	

TABLE 2-2 (Continued)

2.1.2	Actuator System Looses Drive Gas Pressure		538
2.1.2.1	Flow Passages Blocked by Contamination		10
2.1.2.2	Mechanisms Pressures Wrong Value		480
2.1.2.2.1	Gas Filters Drop Pressure Due to Contamination	AGC	
2.1.2.2.2	Housing Assembly Fails	54	
2.1.2.2.2.1	Mechanism Body Mails	1	
2.1.2.2.2.2	Cylinder Line Fails	1	
2.1.2.2.2.3	Piston Fails	10	
2.1.2.2.2.4	Cylinder Cover Fails	5	
2.1.2.2.2.5	Rack Backup Bearing Seal Joint Fails	37	
2.1.2.2.2.5.1	Seal Fails	30	
2.1.2.2.2.5.2	Backup Bearing Container Seal Surface Fails	1	
2.1.2.2.2.5.3	Housing Seal Surface Fails	1	
2.1.2.2.2.5.4	Fasteners Fail	5	
2.1.2.2.3	Internal Seal Joints Fail	426	
2.1.2.2.3.1	P-1 Nozzle Seal Joint Fails	67	
2.1.2.2.3.1.1	Bottom Seal Fails	30	
2.1.2.2.3.1.2	Top Seal Fails	30	
2.1.2.2.3.1.3	Nozzle Sealing Surface Fails	1	
2.1.2.2.3.1.4	Port Sealing Surface Fails	1	

TABLE 2-2 (Continued)

2.1.2.2.3.1.5	Fasteners Fail Allowing Joint to Separate	5
2.1.2.2.3.2	P-2 Nozzle Seal Joint Fails	67
2.1.2.2.3.2.1	Bottom Seal Fails	30
2.1.2.2.3.2.2	Top Seal Fails	30
2.1.2.2.3.2.3	Nozzle Sealing Surface Fails	1
2.1.2.2.3.2.4	Port Sealing Surface Fails	1
2.1.2.2.3.2.5	Fasteners Fail	5
2.1.2.2.3.3	Cylinder Liner Housing Seal Joint Fails	2
2.1.2.2.3.3.1	Liner Fails	1
2.1.2.2.3.3.2	Housing Fails	1
2.1.2.2.3.4	P-2 Inlet/Lee Plug Joint Fails	2
2.1.2.2.3.5	P-1 Cylinder Cover/Liner Joint Fails	35
2.1.2.2.3.5.1	Seal Fails	30
2.1.2.2.3.5.2	Cylinder Seal Surface Fails	1
2.1.2.2.3.5.3	Cover Seal Surface Fails	3
2.1.2.2.3.5.4	Cover Fasteners Fail	3
2.1.2.2.3.6	P-2 Shaft Seal Joint Fails	130
2.1.2.2.3.6.1	Shaft Fails at Seal Support	10
2.1.2.2.3.6.2	Housing Seal Surface Fails	20
2.1.2.2.3.6.3	Seal Fails	100

TABLE 2-2 (Continued)

2.1.2.2.3.7	P-1 Piston Seal Joint Fails	121	
2.1.2.2.3.7.1	Piston Seal Fails	100	
2.1.2.2.3.7.2	Cylinder Liner Seal Surface Fails	20	
2.1.2.2.3.7.3	Piston Seal Surface Fails	1	
2.1.2.2.3.8	Supply Port Tee Plug Fails	2	
∞ 2.1.2.3	Mechanism/Pressure Vessel Seal Joint Fails		48
2.1.2.3.1	Pressure Vessel Seal Surface Fails		1
2.1.2.3.2	Mechanism Seal Surface Fails		1
2.1.2.3.3	Drive Supply Seal Fails		30
2.1.2.3.4	Seal Joint Separates		16
2.1.2.3.4.1	Actuator Flange Fractures	1	
2.1.2.3.4.2	Pressure Vessel Flange Fractures	AGC	
2.1.2.3.4.3	Hold Down Bolts Loose Force	15	
2.1.2.3.4.3.1	Bolts Loose Torque	5	
2.1.2.3.4.3.2	Belleville Gradient Changes	10	
2.1.3	Exhaust Restricted Causing High Back Pressure		AGC
2.1.4	Drive Gas Supply to Mechanism is not Proper Value		AGC

TABLE 2-2 (Continued)

2.2	Actuator Receives Improper Command Signal from Amplifier		249
2.2.1	Amplifier Supply Voltage is not Correct Value		AGC
2.2.2	Amplifier Fails Internally		30
2.2.3	Amplifier Receives Improper Feedback Signal		219
2.2.3.1	Potentiometer Supply Voltage is Wrong Value	30	
2.2.3.1.1	Mechanism Wiring Harness Fails	30	
2.2.3.1.2	Voltage Supplied to System is in Error	AGC	
2.2.3.2	Feedback Potentiometer Output Fails	154	
2.2.3.2.1	Potentiometer Electrically Fails	101	
2.2.3.2.1.1	Track Resistance Value Changes	10	
2.2.3.2.1.2	Protective Resistor Changes Value	10	
2.2.3.2.1.3	Wiper Resistance Changes Value	1	
2.2.3.2.1.4	Wiper/Track Contact Resistance Changes	80	
2.2.3.2.2	Angular Relationship Pot to Drum Changes	21	
2.2.3.2.2.1	Pot Position Changes Relative to Output Shaft	20	
2.2.3.2.2.3	Output Shaft Changes Relative to Drum	1	
2.2.3.2.3	Potentiometer Mechanically Fails	32	
2.2.3.2.3.1	Potentiometer Shaft Fails	1	
2.2.3.2.3.2	Wiper Spring Gradient Changes	1	
2.2.3.2.3.3	Bearings Fail	10	
2.2.3.2.3.4	Potentiometer Housing Fractures	20	

TABLE 2-2 (Continued)

2.2.3.3	Feedback Signal Transmitted Improperly	35	
2.2.3.3.1	Wiring Harness Actuator/Amplifier Fails	AGC	
2.2.3.3.2	Mechanism Wiring Harness Fails	30	
2.2.3.3.3	Electromagnetic Interference Distorts Signal	5	
2.3	Output Shaft Fails to Position Drums		110
2.3.1	Crown Spline Fails	10	
2.3.2	Shaft Breaks	20	
2.3.3	Rack/Pinion Joint Fails	80	
2.4	Actuator Internal Load Changes		282
2.4.1	Potentiometer Load Changes	10	
2.4.2	Actuator Drive Train Loads Change	272	
2.4.2.1	Rack Backup Bearing Assembly Changes	32	
2.4.2.1.1	Retainer Fails	2	
2.4.2.1.2	Spring Fails	10	
2.4.2.1.3	Bearings Fail	10	
2.4.2.1.4	Shaft Fails	5	
2.4.2.1.5	Fasteners Fail	5	
2.4.2.2	Cylinder Liner Changes Load Value	80	
2.4.2.3	Pinion Bearings Change Load Value	60	
2.4.2.4	Pinion Changes Loading	20	
2.4.2.5	Piston/Rack Assembly Changes Load Value	80	
2.4.2.5.1	Piston Head Fails	10	

TABLE 2-2 (Continued)

2.4.2.5.2	Piston/Rack Joint Fails	10	
2.4.2.5.3	Piston Seal Fails	20	
2.4.2.5.4	Piston Ring Fails	20	
2.4.2.5.5	Rack Fails	10	
2.5	Control Drum Characteristics Change	10	EC677559
3	Actuator Electrical Power Consumption Rate Exceeds Limits		60
3.1	Actuator/Amplifier External Cable Short Circuits		AGC
3.2	Actuator Amplifier Short Circuits		20
3.3	Mechanism Short Circuits Internally		40
3.3.1	Potentiometer Short Circuits	10	
3.3.2	Wiring Harness System Short Circuits	20	
3.3.2.1	Wiring Insulation Fails	10	
3.3.2.2	Connector Short Circuits	10	
3.3.3	Torque Motor Short Circuits	10	

the fault tree. The events are listed in an indented manner which also indicates levels on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the sub-totals progress toward the right of the page.

The final total of the weighted numbers (1431) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree have been indicated in parenthesis in the blocks of the summary fault tree, Figure 2-7. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

The calibration process (Section 2.1.7.1.1) consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

2.1.7.1.1 Fault Tree Calibration. The calibration process for the fault tree consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method and comparing the probability of failure computed thereby, with the weighting number previously assigned in the reliability evaluation list. By adjusting the computed probability of failure in the ratio of the previously assigned weighting number for that single failure event to the total relative probability of failure obtained from the reliability evaluation list, an estimate of the true probability of failure for the complete actuator system is obtained.

Calibration: Single Piston Rack and Pinion Proportional Pneumatic
CD Actuator (939J470) Fault Tree (939J471)

1) Design Data - Pinion Gear

Teeth - Design Data	N = 28 Teeth
	P = 32
	P.D. = 0.875 in.
	$\phi = 20^\circ$ (Pressure Angle)
	f = 0.875 (Face Width at P.D.)

Piston - Design Data	Dia. = 1.800 in.
	Area = 2.54 in. ²

2) Applied Loads - Pinion Gear

Load Applied to Teeth by Drive Pressure

Mean Supply Pressure = 200 psig

Mean load assuming 3/4 of supply pressure can be impressed across piston by servovalve.

$$\text{Mean Load} = \frac{3}{4} P_s A = \frac{3}{4} (200) (2.54) = 380 \text{ lb}$$

Maximum Supply Pressure = 250 psig

$$\text{Maximum Load} = \frac{3}{4} P_s A = \left(\frac{3}{4}\right) (250) (2.54) = 475 \text{ lb}$$

3) Pinion Tooth Stress

Lewis Equation⁽⁵⁾

$$\sigma = \frac{F_T P}{f_y}$$

$$y = 0.353$$

$$\text{Mean Stress } \sigma_{\text{mean}} = \frac{(380)}{(0.875)} \frac{(32)}{(0.353)} = 39,400 \text{ psi}$$

$$\text{Maximum Stress } \sigma_{\text{maximum}} = \frac{(475)}{(0.875)} \frac{(32)}{(0.353)} = 49,200 \text{ psi}$$

4) Standard Deviation Calculation

Assume the above stresses are population statistics. •• Sample size $N_L = \infty$.

$$\bar{X}_L = 39,400 \text{ psi}$$

$$3 \sigma \text{ limit load} = \sigma_{\text{max}} = 49,200 \text{ psi}$$

$$S_L = \frac{\sigma_{\text{max}} - \bar{X}_L}{3} = \frac{49,200 - 39,400}{3} = \frac{9,800}{3} = 3,270$$

$$S_L = 3,270 \text{ psi}$$

5) Material Property Data

$$\bar{X}_M = 125,000 \text{ psi}^{(6)}$$

Assume $N_M = \infty$.

$$\text{Assume } S_M = 0.1 \bar{X}_M = (125,000) (0.1) = 12,500.$$

(From similar materials, S_M is equal to $0.05 X_M$; therefore, 10 percent is conservative.)

$$S_M = 12,500 \text{ psi}^{(7)}$$

6) Reliability Calculation

$$X_R = \frac{X_M - X_L}{\sqrt{S_M^2 + S_L^2}} = \frac{125,000 - 39,400}{\sqrt{(12.5 \times 10^3)^2 + (3.27 \times 10^3)^2}}$$

$$= \frac{85,600}{\sqrt{(156 \times 10^6) + (10.7 \times 10^6)}} = \frac{85,600}{\sqrt{166.7 \times 10^6}} = \frac{85,600}{12,900}$$

$$X_R = 6.64$$

7) Technique⁽⁸⁾

$$X_R = 6.64$$

$$\text{Reliability} = .9_{10}^{83}$$

$$\text{Failure Probability} = 17 \times 10^{-12}$$

8) Estimated Reliability

Using this calibration as representative of an arbitrary figure 80 on Fault Tree 939J471 for the "Rack/Pinion Fault Failure" (Block 2.3.3), a failure probability for the total concept can be obtained.

$$\frac{F. P}{17 \times 10^{-12}} = \frac{1431}{80}$$

$$F. P. = (17 \times 10^{-12}) \left(\frac{1431}{80} \right)$$

$$F. P. = (17 \times 10^{-12}) (17.9) = 305 \times 10^{-12}$$

$$\text{Concept Estimated Reliability } R_M = .9_{9}^{695}$$

2.1.7.1.2 Alternate Calibration. In order to increase the degree of confidence, the calibration process is repeated using a second selected failure event and the most conservative estimate thereby obtained used as the estimate of the true probability of failure.

Calibration: Torquemotor

1) Torsion Bar - Refer to Drawing 800C664 (Fault Tree 939J471, Block 2.1.1.1.2.2).

Assume armature has a maximum end motion of ± 0.010 in. at a radius of 0.825 in.

Maximum rotation (twist) of torsion bar

$$\tan \theta = \frac{0.010}{0.825}$$

$$\theta = 0.01212 \text{ rad}$$

Torque required to rotate rod through angle θ

$$T^1 = \frac{T}{2} = \frac{GL}{L} \theta$$

From Drawing 800C664

$$D = 0.0732$$

$$L = 0.187 - 2(0.020) = 0.147 \text{ in.} \quad (\text{Minimum Length})$$

$$J = \frac{\pi r^4}{2} = \frac{\pi(0.0366)^4}{2} = \frac{\pi 180 \times 10^{-8}}{2} = 282 \times 10^{-8}$$

$$J = 2.82 \times 10^{-6}$$

$$G = 10.6 \times 10^6 \text{ psi (301 SS - AGC 2275)}$$

$$T^1 = \frac{10.6 \times 10^6 (2.82 \times 10^{-6})}{0.147} (1.212 \times 10^{-2}) = 2.47$$

$$T^1 = 2.47 \text{ in.-lb}$$

$$\text{Stress in bar} = \frac{T_r}{J} = \frac{2.47 (0.0366)}{2.82 \times 10^{-6}} = 32,100 \text{ psi}$$

$$\text{Shear stress} = 32,100 \text{ psi}$$

2) Standard Deviation Calculation

Assume this is the mean assembly stress in bar.

$$\therefore \bar{X}_L = 32,100 \text{ psi}$$

Assume the standard deviation is 0.1 of the mean.

$$\therefore S_L = 0.1 \bar{X}_L = 3,210 \text{ psi}$$

Let $N_L = \infty$ and the above sample statistics become population statistics.

$$\therefore \bar{\mu}_L = \bar{X}_L = 32,100 \text{ psi}$$

$$\sigma_L = S_L = 3,210 \text{ psi}$$

3) Material Property Data

Assume material is AISI 301, full hard condition.

DRM 51239 (Material Property Estimates)

at 75°F - yield strength

$$\bar{\mu}_m = 154,900 \text{ psi}$$

$$\sigma_m = 7,000 \text{ psi}$$

But the shear strength is equal to 0.5 yield strength and assume the variation is the same.

$\therefore$ Shear yield

$$\bar{\mu}_m = 77,450 \text{ psi}$$

$$\sigma_m = 7,000 \text{ psi}$$

4) Reliability Calculation

$$X_R = \frac{\bar{\mu}_m - \bar{\mu}_L}{\sqrt{\sigma_m^2 + \sigma_L^2}} = \frac{77,450 - 32,100}{\sqrt{7,000^2 + 3,210^2}} = \frac{45,350}{\sqrt{49 \times 10^6 + 10.3 \times 10^6}}$$

$$X_R = \frac{45,350}{\sqrt{59.3 \times 10^6}} = \frac{45,350}{7,700} = 5.9$$

$$X_R = 5.9^{(8)}$$

5) Technique

$$X_R = 5.9^{(8)}$$

$$\text{Reliability} = .98$$

$$\text{Failure Probability} = 2 \times 10^{-9} \quad (\text{For torsion bar})$$

6) Estimated Reliability

Using this calibration as representative of an arbitrary figure 2 on Fault Tree 939J471 for the "Armature Spring Fails" (Block 2.1.1.1.2.2):

$$\frac{F. P.}{2 \times 10^{-9}} = \frac{1431}{2}$$

$$F. P. = (2 \times 10^{-9}) (715.5)$$

$$F. P. = 1431 \times 10^{-9}$$

$$R_M = .9586$$

2.1.7.2 Failure Mode Evaluation

A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts are not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component is analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another.⁽⁹⁾ The total number indicates the relative reliability of the actuator concept; the lower the number, the more reliable the particular concept is relative to the others. Each concept is compared with the others on the basis of the total relative failure probability number. The failure mode analysis for the single piston rack and pinion pneumatic actuator is shown in Table 2-3. A similar failure mode analysis for the double piston rack and pinion pneumatic actuator is shown in Table 2-4.

2.1.7.3 Safety Evaluation

The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and criticality ranking for each concept, failure modes are identified. For each of the failure modes listed, mechanisms of obtaining that failure mode are established as they relate to a particular design. Each of these failure mechanisms is given a numerical ranking consistent

TABLE 2-3
COMPONENT FAILURE MODES ANALYSIS

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
DATE _____ APPROVED BY RAC COMPONENT Torque Motor DWG NUMBERS 939J470

W59150

Relative Ranking 171

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Torque motor characteristics change to bias its output to the full out or the full in position	a. Pole piece breaks b. Bottom shunt breaks c. Top field piece breaks d. Magnet loses magnetic properties e. Armature assembly weld breaks f. Armature spring breaks g. Frame breaks h. Armature breaks i. Coil shorts or coils open (full in position failure only) j. Coil lead wire shorts or lead wires open (full in position failure only)	Start-up and Steady State	1 1 1 1 1 1 1 1 6 3
1.2	Torque motor characteristics change as to become unstable	a. Bottom shunt breaks b. Top field piece breaks c. Armature assembly weld breaks d. Armature spring breaks e. Frame breaks /	Start-up and Steady State	Combined with b,c,e,f,&g above.

TABLE 2-3 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY RAC COMPONENT Servo Valve DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.1	Servo valve characteristics change to bias its output to the fullout or the full in position	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle) e. Flapper screw breaks (P_2 flapper or P_1 flapper) f. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	1 1 1 1 1 1
2.2	Servo valve characteristics change to inhibit the operating range.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	Combined with a,b,&f above.
2.3	Servo valve characteristics change to inhibit velocity control capability	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle)	Start-up and Steady State	Combined with a,b,c,&d above

TABLE 2-3 (Continued)

DATE 8-13-69 PREPARED BY I. R. Soezialetti DEPARTMENT Reliability SUBSYSTEM ActuatorDATE _____ APPROVED BY R.G.C. COMPONENT Drive Train DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Drive train mechanical load increases	a. Piston head contacts liner and increases friction	Start-up and Steady State	1
		b. Piston seal drags and increases friction		1
		c. Piston ring drags and increases friction		1
		d. Piston/Rack joint cocks and increases friction		1
		e. Rack and Pinion joint have surface damage and increases friction		1
		f. Pinion bearings have surface damage and increase friction		4
		g. Cylinder liner surface damage increases friction		6
		h. Rack back-up bearing increases friction		1
		i. Rack back-up shaft breaks and increases friction		1
		j. Rack back-up bearing retainer breaks and increases friction		1

TABLE 2-3 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY RCC COMPONENT Drive Train DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.2	Drive train gains in some position between full in and maximum operating range.	a. Piston head breaks and jams mechanism b. Piston seal breaks and jams mechanism c. Piston ring breaks and jams mechanism d. Rack and pinion joint break and jam mechanism e. Pinion bearings seize f. Cylinder liner surface damage jams mechanism	Start-up and Steady State	1 1 1 1 2 2
3.3	Drive train mechanical load decreases	a. Rack back-up bearing shaft breaks b. Rack back-up bearing retainer breaks c. Rack back-up bearing spring loses spring gradient	Start-up and Steady State	1 1 1
3.4	Drive train fails to contain drive gas pressure so as to bias the actuator to the full out position.	a. Piston seal leaks b. Piston seal surface damage c. Cylinder liner seal surface damaged d. Cylinder liner/leaks at seal joint with housing e. Piston breaks f. Cylinder liner breaks	Steady State and Start-up	8 1 2 1 1 1

TABLE 2-3 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY *RAC* COMPONENT Drive Train DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.5	Drive train fails to contain drive gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Shaft seal housing seal surface damage b. Shaft seal surface damaged c. Cylinder liner breaks d. Cylinder liner leaks at seal joint with housing.	Steady State and Start-up	2 1 1 1
3.6	Drive train fails to provide output torque.	a. Rack and pinion joint breaks b. Output shaft breaks c. Shaft crowned spline joint breaks	Steady State and Start-up	8 2 1
4.1	Potentiometers fail to provide feedback signal	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up State Steady State	1 1 1 4 2
4.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	1 2
4.3	Potentiometers provide a single constant position signal	a. Potentiometers bonded joint with pinion output shaft breaks	Start-up and Steady State	1
4.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance c. All potentiometer wiper to track contacts change in resistance	Start-up and Steady State	1 1 8

TABLE 2-3 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY RGL COMPONENT Housing and Covers DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full out position	a. Housing breaks and P_1 supply port to servo valve b. Housing seal surface at P_1 nozzle damaged c. Rack back-up bearing cover breaks d. Rack back-up bearing cover fasteners break or loosen e. Rack back-up bearing cover seal surface damaged.	Start-up and Steady State	1 1 1 1 1
5.2	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Housing breaks at P_2 supply port to servo valve b. Housing seal surface at P_2 nozzle damaged c. Plug in housing at P_2 supply port leaks d. Plug in housing at supply line port leaks e. Housing flange breaks f. Cylinder cover breaks g. Cylinder cover fasteners break h. Cylinder cover seal surface damaged i. Supply gas filter clogs j. Filter interface seal surface damaged	Start-up and Steady State	1 1 1 1 1 1 1 1 2 1
5.3	Housing fails to contain coolant gas pressure	a. Housing/mounting flange breaks b. Interface seal surface damaged	Start-up and Steady State	1 1

TABLE 2-3 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY RGC COMPONENT Seals, Working Fluid DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full out position	a. P_1 nozzle bottom seal leaks b. Rack back-up bearing cover seal leaks c. Output shaft upper seal leaks	Start-up and Steady State	3 3 10
6.2	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Cylinder cover seal leaks b. P_1 nozzle top seal leaks c. P_2 nozzle top seal leaks d. P_2 nozzle bottom seal leaks e. Filter interface seal leaks f. Drive gas supply connector seal leaks	Start-up and Steady State	3 3 3 3 3 3
7.1	Coolant seals fail to contain gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range; and to increase coolant gas consumption.	a. Actuator coolant interface seal leaks b. Both lower end output shift seals leak	Start-up and Steady State	3 1

TABLE 2-3 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY RCC COMPONENT Mounting Studs DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
8.1	Mounting stud fails to maintain proper clamping force	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action allowing nut to loosen	Start-up and Steady State	1 1 1 1
9.1	Electrical wiring harness to torque motor fails to carry proper command signal	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	1 2
9.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	1 2

TABLE 2-4
COMPONENT FAILURE MODES ANALYSIS

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
DATE _____ APPROVED BY [Signature] COMPONENT Torque Motor DWG NUMBERS 939J710

W59150

Relative Ranking 220

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Torque motor characteristics change to bias its output to the full out or the full in position.	a. Pole piece breaks b. Bottom shunt breaks c. Top field piece breaks d. Magnet loses magnetic properties e. Armature assembly weld breaks f. Armature spring breaks g. Frame breaks h. Armature breaks i. Coil shorts or coils open (full in position failure only) j. Coil lead wire shorts or lead wires open (full in position failure only)	Start-up and Steady State	1 1 1 1 1 1 1 1 6 3
1.2	Torque motor characteristics change as to become unstable.	a. Bottom shunt breaks b. Top field piece breaks c. Armature assembly weld breaks d. Armature spring breaks e. Frame breaks	Start-up and Steady State	Combined with b,c,e,f,&g above.

/

TABLE 2-4 (Continued)

DATE 8-15-69 PREPARED BY I. R. Specialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY RAC COMPONENT Servo Valve DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.1	Servo valve characteristics change to the full out or the full in position.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged e. Flapper screw breaks (P_2 flapper or P_1 flapper) f. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	1 1 1 1 1 1
2.2	Servo valve characteristics change to inhibit the operating range.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	Combined with a,b,&f above.
2.3	Servo valve characteristics change to inhibit velocity control capability	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle)	Start-up and Steady State	Combined with a,b,c,&d above.

TABLE 2-4 (Continued)

DATE 8-15-69 PREPARED BY I. R. Specialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Drive train mechanical load increases	a. Piston head contacts liner and increases friction. (P_1 or P_2 piston)	Start-up and Steady State	2
		b. Piston seal drags and increases friction (P_1 or P_2 piston seals)		2
		c. Piston ring drags and increases friction (P_1 or P_2 piston rings)		4
		d. Piston/Rack bearing has surface damage and increases friction.		1
		e. Rack and pinion joint have surface damage and increases friction		1
		f. Pinion bearings have surface damage and increase friction.		4
		g. Cylinder liner surface damage increases friction (P_1 or P_2 liner)		12
		h. Rack back-up bearing increases friction		1
		i. Rack back-up bearing shaft breaks and increases friction		1
		j. Rack back-up bearing retainer breaks and increases friction		1

TABLE 2-4 (Continued)

DATE 8-15-69 PREPARED BY I R Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 939J710

W59150

Mode Ident No	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3 2	Drive train jams in some position between full in and maximum operating range	a. Piston head breaks and jams mechanism (P_1 or P_2 piston) b. Piston seal breaks and jams mechanism (P_1 or P_2 piston seal) c. Piston ring breaks and jams mechanism (P_1 or P_2 piston rings) d. Rack and pinion joint break and jam mechanism e. Pinion bearings seize f. Cylinder liner surface damage jams mechanism (P_1 or P_2 liner)	Start-up and Steady State	1 2 2 1 2 4
3 3	Drive train mechanical load decreases	a. Rack back-up bearing shaft breaks b. Rack back-up bearing retainer breaks c. Rack back-up bearing spring loses spring gradient.	Start-up and Steady State	1 1 1
3 4	Drive train fails to contain drive gas pressure so as to bias the actuator to the full out position.	a. Piston seal leaks (P_1 or P_2 piston seals) b. Piston seal surface damage (P_1 or P_2 pistons) c. Cylinder liner seal surface damaged (P_1 or P_2 liners) d. Piston breaks (P_1 or P_2 piston) e. Cylinder liner breaks (P_1 or P_2 liner)	Steady State and Start-up	16 2 4 2 2
3 5	Drive train fails to provide output torque	a. Rack and pinion joint breaks b. Output shaft breaks c. Shaft crowned spline joint breaks	Steady State and Start-up	8 2 1

TABLE 2-4 (Continued)

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator

DATE APPROVED BY RGE COMPONENT Potentiometers DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
4.1	Potentiometers fail to provide feedback signal	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open.	Start-up and Steady State	1 1 1 4
4.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft c. Potentiometers housing breaks	Start-up and Steady State	1 2 2
4.3	Potentiometers provide a single constant position signal	a. Potentiometers coupling with pinion output shaft breaks	Start-up and Steady State	1
4.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance c. All potentiometer wiper to track contacts change in resistance	Start-up and Steady State	1 1 8

TABLE 2-4 (Continued)

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY *MAC* COMPONENT Housing and Covers DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full out position.	a. Housing breaks at P_2 supply port to servo valve b. Housing seal surface at P_2 nozzle damaged. c. P_2 cylinder cover breaks d. P_2 cylinder cover fasteners break or loosen e. P_2 cylinder cover seal surface damaged	Start-up and Steady State	1 1 1 1 1
5.2	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Housing breaks at P_1 supply port to servo valve b. Housing seal surface at P_1 nozzle damaged c. P_1 cylinder cover breaks d. P_1 cylinder cover fasteners break or loosen e. P_1 cylinder cover seal surface damaged f. Supply gas filter clogs g. Filter interface seal surface damaged	Start-up and Steady State	1 1 1 1 1 2 1
5.3	Housing and covers fail to contain coolant gas pressure, increasing coolant consumption.	a. Housing mounting flange breaks b. Housing interface seal surface damaged c. Potentiometer cover breaks d. Potentiometer cover fasteners break or loosen e. Potentiometer cover seal surface damaged f. Shaft lock plug seal surface damaged	Start-up and Steady State	1 1 1 1 1 1

TABLE 2-4 (Continued)

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY *R. L. C.* COMPONENT Seals, Working Fluid DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full out position.	a. P ₂ cylinder cover supply seal leaks b. P ₂ supply seal at housing to pedestal interface leaks c. P ₂ nozzle bottom seal leaks d. P ₂ cylinder cover to cylinder liner seal leaks.	Start-up and Steady State	3 3 3 3
6.2	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. P ₁ cylinder cover supply seal leaks b. P ₁ supply seal at housing to pedestal interface leaks c. P ₁ nozzle bottom seal leaks d. P ₁ cylinder cover to cylinder liner seal leaks e. Supply gas connector seal leaks	Start-up and Steady State	3 3 3 3 3
7.1	Coolant seals fail to contain coolant gas pressure, increasing coolant gas consumption.	a. Gap seals leak b. Housing to pedestal interface seals leak c. Cylinder cover seals leak (P ₁ or P ₂ cylinder cover seal) d. Potentiometer cover seal leaks e. Shaft lock plug seal leaks	Start-up and Steady State	1 6 6 3 3
8.1	V-Band clamp fails to maintain proper clamping force, resulting in loss of coolant gas and possibly loss of drive gas pressure so actuator operating range is inhibited.	a. Left or right hand bolt breaks or loosens b. Clamp loses spring gradient	Start-up and Steady State	1 1

TABLE 2-4 (Continued)

DATE 8-15-69 PREPARED BY I R Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY KGC COMPONENT Wiring Harness DWG NUMBERS

W59150

Mode Ident No	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
9 1	Electrical wiring harness to torque motor fails to carry proper command signal	a. Harness wires short or open (pedestal or mechanism harness) b. Connector pins short or open (internal or external connector).	Start-up and Steady State	2 4
9 2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short or open (pedestal or mechanism harness) b. Connector pins short or open (internal or external connector) c. Hermetic feed through shorts or causes open	Start-up and Steady State	2 4 1
10 1	Mounting pedestal fails to contain drive gas pressure as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Drive gas inlet port breaks b. Pedestal body breaks c. Pedestal to actuator mounting flange breaks d. Pedestal seal surface at P_1 supply port damaged. e. Drive gas inlet connector fitting breaks	Start-up and Steady State	1 1 1 1 1
10 2	Mounting pedestal fails to contain coolant gas pressure, increasing coolant gas consumption.	a. Pedestal to actuator mounting flange breaks b. Pedestal body breaks c. Pedestal interface seals surface damaged d. Shaft lock seal surface damaged e. Pedestal seal weld breaks	Start-up and Steady State	1 1 1 1 1
10 3	Mounting pedestal disengages the pressure vessel, resulting in loss of reactor propellant, and the control drum in the full in position.	a. Pedestal breaks b. Retainer threads break c. Locking device breaks and retainer nut loosens.	Start-up and Steady State	1 1 1

with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reductions in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.
1	Failures resulting in insignificant effects on chamber temperature/pressure.

By assigning each mechanism of failure to one of the above categories and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-5 presents a tabulation of the failures, mechanism of failure and criticality ranking of failure for the single piston rack and pinion pneumatic actuator. Also shown is the total criticality ranking for this concept. Table 2-6 presents the same information for the double piston rack and pinion pneumatic actuator.

TABLE 2-5
COMPONENT SAFETY CRITICALITY

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
DATE _____ APPROVED BY RGC COMPONENT Torque Motor DWG NUMBERS 939J470

W59150

Total Criticality Rating 346

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Torque motor characteristics change to bias its output to the full out or the full in position	<ul style="list-style-type: none"> a. Pole piece breaks b. Bottom shunt breaks c. Top field piece breaks d. Magnet loses magnetic properties e. Armature assembly weld breaks f. Armature spring breaks g. Frame breaks h. Armature breaks i. Coil shorts or coils open (full in position failure only) j. Coil lead wire shorts or lead wires open (full in position failure only) 	Start-up and Steady State	<ul style="list-style-type: none"> 4 4 4 4 4 4 4 4 4 4
1.2	Torque motor characteristics change as to become unstable	<ul style="list-style-type: none"> a. Bottom shunt breaks b. Top field piece breaks c. Armature assembly weld breaks d. Armature spring breaks e. Frame breaks 	Start-up and Steady State	<ul style="list-style-type: none"> 2 2 2 2 2
2.1	Servo valve characteristics change to bias its output to the fullout or the full in position	<ul style="list-style-type: none"> a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle) e. Flapper screw breaks (P_2 flapper or P_1 flapper) f. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock) 	Start-up and Steady State	<ul style="list-style-type: none"> 4 4 4 4 4 4
2.2	Servo valve characteristics change to inhibit the operating range.	<ul style="list-style-type: none"> a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Flapper² lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock) 	Start-up and Steady State	<ul style="list-style-type: none"> 2 2 2

TABLE 2-5 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY RAC COMPONENT Servo Valve DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.3	Servo valve characteristics change to inhibit velocity control capability	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle)	Start-up and Steady State	1 1 1 1
3.1	Drive train mechanical load increases	a. Piston head contacts liner and increases friction b. Piston seal drags and increases friction c. Piston ring drags and increases friction d. Piston/Rack joint cocks and increases friction e. Rack and Pinion joint have surface damage and increases friction f. Pinion bearings have surface damage and increase friction g. Cylinder liner surface damage increases friction h. Rack back-up bearing increases friction i. Rack back-up shaft breaks and increases friction j. Rack back-up bearing retainer breaks and increases friction	Start-up and Steady State	1 1 1 1 1 1 1 1 1 1

TABLE 2-5 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.2	Drive train gains in some position between full in and maximum operating range.	a. Piston head breaks and jams mechanism b. Piston seal breaks and jams mechanism c. Piston ring breaks and jams mechanism d. Rack and pinion joint break and jam mechanism e. Pinion bearings seize f. Cylinder liner surface damage jams mechanism	Start-up and Steady State	4 4 4 4 4 4
3.3	Drive train mechanical load decreases	a. Rack back-up bearing shaft breaks b. Rack back-up bearing retainer breaks c. Rack back-up bearing spring loses spring gradient	Start-up and Steady State	2 2 2
3.4	Drive train fails to contain drive gas pressure so as to bias the actuator to the full out position.	a. Piston seal leaks b. Piston seal surface damage c. Cylinder liner seal surface damaged d. Cylinder liner/leaks at seal joint with housing e. Piston breaks f. Cylinder liner breaks	Steady State and Start-up	4 4 4 4 4 4
3.5	Drive train fails to contain drive gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Shaft seal housing seal surface damage b. Shaft seal surface damaged c. Cylinder liner breaks d. Cylinder liner leaks at seal joint with housing.	Steady State and Start-up	4 4 4 4
3.6	Drive train fails to provide output torque.	a. Rack and pinion joint breaks b. Output shaft breaks c. Shaft crowned spline joint breaks	Steady State and Start-up	4 4 4

TABLE 2-5 (Continued)

W59150

Mode Ident No	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Potentiometers fail to provide feedback signal	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up State Steady State	4 4 4 4 4
4.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	2 2
4.3	Potentiometers provide a single constant position signal	a. Potentiometers bonded joint with pinion output shaft breaks	Start-up and Steady State	4
4.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance c. All potentiometer wiper to track contacts change in resistance	Start-up and Steady State	2 2 2

TABLE 2-5 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY RGL COMPONENT Housing and Covers DWG NUMBERS 939J470

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full out position	a. Housing breaks and P_1 supply port to servo valve b. Housing seal surface at P_1 nozzle damaged c. Rack back-up bearing cover breaks d. Rack back-up bearing cover fasteners break or loosen e. Rack back-up bearing cover seal surface damaged.	Start-up and Steady State	4 4 4 4 4
5.2	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Housing breaks at P_2 supply port to servo valve b. Housing seal surface at P_2 nozzle damaged c. Plug in housing at P_2 supply port leaks d. Plug in housing at supply line port leaks e. Housing flange breaks f. Cylinder cover breaks g. Cylinder cover fasteners break h. Cylinder cover seal surface damaged i. Supply gas filter clogs j. Filter interface seal surface damaged	Start-up and Steady State	4 4 4 4 4 4 4 4 4 4
5.3	Housing fails to contain coolant gas pressure	a. Housing mounting flange breaks b. Interface seal surface damaged	Start-up and Steady State	2 2
6.1	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full out position	a. P_1 nozzle bottom seal leaks b. Rack back-up bearing cover seal leaks c. Output shaft upper seal leaks	Start-up and Steady State	4 4 4
6.2	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Cylinder cover seal leaks b. P_1 nozzle top seal leaks c. P_2 nozzle top seal leaks d. P_2 nozzle bottom seal leaks e. Filter interface seal leaks f. Drive gas supply connector seal leaks	Start-up and Steady State	4 4 4 4 4 4

TABLE 2-5 (Continued)

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Coolant seals fail to contain gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range; and to increase coolant gas consumption.	a. Actuator coolant interface seal leaks b. Both lower end output shift seals leak	Start-up and Steady State	4 4
8.1	Mounting stud fails to maintain proper clamping force	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action allowing nut to loosen	Start-up and Steady State	4 4 4
9.1	Electrical wiring harness to torque motor fails to carry proper command signal	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	4 4
9.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	4 4

2-59

TABLE 2-6
COMPONENT SAFETY CRITICALITY

DATE 8-15-69 PREPARED BY J. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
DATE APPROVED BY RCE COMPONENT Torque Motor DWG NUMBERS 939J710

W59150				Total Criticality Ranking 364
Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Torque motor characteristics change to bias its output to the full out or the full in position.	a. Pole piece breaks b. Bottom shunt breaks c. Top field piece breaks d. Magnet loses magnetic properties e. Armature assembly weld breaks f. Armature spring breaks g. Frame breaks h. Armature breaks i. Coil shorts or coils open (full in position failure only) j. Coil lead wire shorts or lead wires open (full in position failure only)	Start-up and Steady State	4 4 4 4 4 4 4 4 4 4
1.2	Torque motor characteristics change as to become unstable.	a. Bottom shunt breaks b. Top field piece breaks c. Armature assembly weld breaks d. Armature spring breaks e. Frame breaks	Start-up and Steady State	2 2 2 2 2
2.1	Servo valve characteristics change to the full out or the full in position.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged e. Flapper screw breaks (P_2 flapper or P_1 flapper) f. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	4 4 4 4 4 4
2.2	Servo valve characteristics change to inhibit the operating range.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	2 2 2

TABLE 2-6 (Continued)

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY KAC COMPONENT Servo Valve DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.3	Servo valve characteristics change to inhibit velocity control capability	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P ₂ nozzle or P ₁ nozzle) c. Manifold breaks ¹ d. Nozzle seal surface damaged. (P ₁ nozzle or P ₂ nozzle)	Start-up and Steady State	1 1 1 1
3.1	Drive train mechanical load increases	a. Piston head contacts liner and increases friction. (P ₁ or P ₂ piston) b. Piston seal drags and increases friction (P ₁ or P ₂ piston seals) c. Piston ring drags and increases friction (P ₁ or P ₂ piston rings) d. Piston/Rack bearing has surface damage and increases friction. e. Rack and pinion joint have surface damage and increases friction f. Pinion bearings have surface damage and increase friction. g. Cylinder liner surface damage increases friction (P ₁ or P ₂ liner) h. Rack back-up bearing increases friction i. Rack back-up bearing shaft breaks and increases friction j. Rack back-up bearing retainer breaks and increases friction	Start-up and Steady State	1 1 1 1 1 1 1 1 1 1

TABLE 2-6 (Continued)

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.2	Drive train jams in some position between full in and maximum operating range.	a. Piston head breaks and jams mechanism (P_1 or P_2 piston) b. Piston seal breaks and jams mechanism (P_1 or P_2 piston seal) c. Piston ring breaks and jams mechanism (P_1 or P_2 piston rings) d. Rack and pinion joint break and jam mechanism e. Pinion bearings seize f. Cylinder liner surface damage jams mechanism (P_1 or P_2 liner)	Start-up and Steady State	4 4 4 4 4 4
3.3	Drive train mechanical load decreases	a. Rack back-up bearing shaft breaks b. Rack back-up bearing retainer breaks c. Rack back-up bearing spring loses spring gradient.	Start-up and Steady State	2 2 2
3.4	Drive train fails to contain drive gas pressure so as to bias the actuator to the full out position.	a. Piston seal leaks (P_1 or P_2 piston seals) b. Piston seal surface damage (P_1 or P_2 pistons) c. Cylinder liner seal surface damaged (P_1 or P_2 liners) d. Piston breaks (P_1 or P_2 piston) e. Cylinder liner breaks (P_1 or P_2 liner)	Steady State and Start-up	4 4 4 4 4
3.5	Drive train fails to provide output torque.	a. Rack and pinion joint breaks b. Output shaft breaks c. Shaft crowned spline joint breaks	Steady State and Start-up	4 4 4

TABLE 2-6 (Continued)

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY RGC COMPONENT Potentiometers DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Potentiometers fail to provide feed-back signal	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open.	Start-up and Steady State	4 4 4 4
4.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft c. Potentiometers housing breaks	Start-up and Steady State	2 2 2
4.3	Potentiometers provide a single constant position signal	a. Potentiometers coupling with pinion output shaft breaks	Start-up and Steady State	4
4.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance c. All potentiometer wiper to track contacts change in resistance	Start-up and Steady State	2 2 2

TABLE 2-6 (Continued)

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY *McC* COMPONENT Housing and Covers DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full out position.	a. Housing breaks at P_2 supply port to servo valve b. Housing seal surface at P_2 nozzle damaged. c. P_2 cylinder cover breaks d. P_2 cylinder cover fasteners break or loosen e. P_2 cylinder cover seal surface damaged	Start-up and Steady State	4 4 4 4 4
5.2	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Housing breaks at P_1 supply port to servo valve b. Housing seal surface at P_1 nozzle damaged c. P_1 cylinder cover breaks d. P_1 cylinder cover fasteners break or loosen e. P_1 cylinder cover seal surface damaged f. Supply gas filter clogs g. Filter interface seal surface damaged	Start-up and Steady State	4 4 4 4 4 4 4
5.3	Housing and covers fail to contain coolant gas pressure, increasing coolant consumption.	a. Housing mounting flange breaks b. Housing interface seal surface damaged c. Potentiometer cover breaks d. Potentiometer cover fasteners break or loosen e. Potentiometer cover seal surface damaged f. Shaft lock plug seal surface damaged	Start-up and Steady State	2 2 2 2 2 2
6.1	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full out position.	a. P_2 cylinder cover supply seal leaks b. P_2 supply seal at housing to pedestal interface leaks c. P_2 nozzle bottom seal leaks d. P_2 cylinder cover to cylinder liner seal leaks.	Start-up and Steady State	4 4 4 4
6.2	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. P_1 cylinder cover supply seal leaks b. P_1 supply seal at housing to pedestal interface leaks c. P_1 nozzle bottom seal leaks d. P_1 cylinder cover to cylinder liner seal leaks e. Supply gas connector seal leaks	Start-up and Steady State	4 4 4 4 4

TABLE 2-6 (Continued)

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY *RAC* COMPONENT Seals, Coolant DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Coolant seals fail to contain coolant gas pressure, increasing coolant gas consumption.	a. Gap seals leak b. Housing to pedestal interface seals leak c. Cylinder cover seals leak (P_1 or P_2 cylinder cover seal) d. Potentiometer cover seal leaks e. Shaft lock plug seal leaks	Start-up and Steady State	2 2 2 2 2
8.1	V-Band clamp fails to maintain proper clamping force, resulting in loss of coolant gas and possibly loss of drive gas pressure so actuator operating range is inhibited.	a. Left or right hand bolt breaks or loosens b. Clamp loses spring gradient	Start-up and Steady State	4 4
9.1	Electrical wiring harness to torque motor fails to carry proper command signal.	a. Harness wires short or open (pedestal or mechanism harness) b. Connector pins short or open (internal or external connector).	Start-up and Steady State	4 4
9.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short or open (pedestal or mechanism harness) b. Connector pins short or open (internal or external connector) c. Hermetic feed through shorts or causes open	Start-up and Steady State	4 4 4

TABLE 2-6 (Continued)

DATE 8-15-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY *R. C. E.* COMPONENT Mounting Pedestal DWG NUMBERS 939J710

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
10.1	Mounting pedestal fails to contain drive gas pressure as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Drive gas inlet port breaks b. Pedestal body breaks c. Pedestal to actuator mounting flange breaks d. Pedestal seal surface at P_1 supply port damaged. e. Drive gas inlet connector fitting breaks	Start-up and Steady State	4 4 4 4 4
10.2	Mounting pedestal fails to contain coolant gas pressure, increasing coolant gas consumption.	a. Pedestal to actuator mounting flange breaks b. Pedestal body breaks c. Pedestal interface seals surface damaged d. Shaft lock seal surface damaged e. Pedestal seal weld breaks	Start-up and Steady State	2 2 2 2 2
10.3	Mounting pedestal disengages the pressure vessel, resulting in loss of reactor propellant, and the control drum in the full in position.	a. Pedestal breaks b. Retainer threads break c. Locking device breaks and retainer nut loosens.	Start-up and Steady State	4 4 4

2.1.8 Discussion and Evaluation

The proportional pneumatic rack and pinion actuator concept is the only concept that has been used in the NERVA project. Although the simple single piston design has never been built, its forerunner has been used successfully on the XE program and has accumulated many hours of operating experience under all expected NERVA environments. Past experience together with design effort have resulted in a concept which is the best proportional pneumatic candidate. The redesign effort extensively simplifies the XE design while retaining the basic principles which have been successful.

The servovalve, which is the heart of the pneumatic designs, has been redesigned to remove undesirable features. The redesign improves reliability and performance but maintains the simple principles and features of the original design. The basic torque motor flapper concept is retained. The redesign emphasis is to improve construction. The dynamic pressure feedback bellows of the XE design is removed and a new annular nozzle concept is incorporated without a drastic departure from the original concept.

The concentrically mounted three-deck potentiometer is a departure from the XE configuration but retains the same construction materials. The potentiometer is assembled concentric with the actuator shaft, thus utilizing the same bearings. In this design, the potentiometer track design is longer, giving a greater arc length per degree of shaft rotation and allowing greater linearity or easier manufacture. This increase in track length may allow incorporation of a wire wound potentiometer instead of the plastic composition potentiometer now considered in all designs. The limiting parameter for a wire wound potentiometer is the system resolution which is a function of wire spacing. With a larger diameter potentiometer, more wire turns per degree of arc can be wound on the potentiometer, thus improving resolution.

The single piston proportional pneumatic actuator is compact enough to fit on a 36 drum reactor concept. Its radial width at the control drum centerline is about 6.0 inches. Its height above the pressure vessel mounting boss is about 4-3/4 inches. Clearance required above the actuator for removal is about 2-3/4 inches to clear the output shaft and mounting stud. Its weight is estimated at about 8 pounds.

Coolant requirements for a one hour run at the heating rates estimated for NERVA, about 3 watts per pound, are less than 1/2 pound and can probably be eliminated. Coolant packages have been provided in the event later analysis indicates that they are necessary. Maximum drive gas at 100°R and 215 psia for a one hour run is about 36 pounds. Electrical power is required to supply the amplifier and feedback potentiometers, but it is all in the control range and is considered small enough to be neglected in this study. A preliminary estimate of the concept reliability obtained by calibrating the fault tree is $.9_{586}$.

No problems are anticipated with this design from the standpoint of materials, performance or ability to meet and operate in the prescribed environments. Table 2-7 is a listing of some of the more significant advantages and disadvantages of the single piston, rack and pinion pneumatic actuator.

TABLE 2-7

SINGLE PISTON, RACK AND PINION PNEUMATIC ACTUATOR SUMMARY TABLE

<u>Advantages</u>	<u>Disadvantages</u>
1. Power Media for H_2 is Readily Available from Engine Source.	1. Severe Weight Penalty Exists for the Drive Gas Startup Pneumatic Supply System Weight Required Due to Actuator Consumption of H_2 .
2. Experience and Background of the XE Actuator Program is Directly Applicable.	2. Servovalve Susceptible to Malfunction at Cryogenic Temperatures if H_2 Supply is not Free of Trace Gas Contaminants.
3. Physical Size will Fit up to a 36 Drum NSS Configuration.	3. Vibration Environmental Capabilities Unknown for NERVA Values. No random Vibration Data for Similar Device have been Collected.
4. Possibility Exists for Use of Wire-Wound Feed-back Potentiometer, Thus Improving Potentiometer Reliability	4. Design not Easily Remotely Removable in the 36 Drum Configuration.
5. Highly Probable that No Coolant Gas Flow will be Required.	5. Drum Spring Probably Required to Hold Drum in the Shutdown Condition.
6. Environmental Capabilities are Very Good in Regard to Cryogenic and Radiation Tolerances.	
7. Mechanism Weight is Low.	
8. Maintainability is Considered Excellent Based Upon XE Experience.	

2.2 HELICAL CAM PROPORTIONAL PNEUMATIC CONCEPT

2.2.1 Mechanical Description

The helical cam proportional pneumatic actuator discussed in this section is shown in Figure 2-8.

This actuator is divided into four main categories for discussion purposes.

- 1) Servovalve assembly
- 2) Feedback potentiometer
- 3) Drive train (piston and cam assembly, output shaft, ball and vertical rack)
- 4) Housing enclosure

Basically, the servovalve converts the command signals from the control system into a pressure differential across the piston assembly. This pressure differential causes translation of the piston thereby producing a rotation of the output shaft. The feedback potentiometer which is driven directly by the output shaft produces a signal proportional to the output rotation (i.e., drum position). This electrical signal is fed back to the control system. Any difference between the command and feedback signals results in a rotation of the drums until the feedback signal equals the command signal. The housing enclosure physically contains the other parts and also provides porting for the required fluids.

2.2.1.1 Servovalve Assembly

The servovalve is shown in the actuator schematic in Figure 2-9. The servovalve converts electrical input signals into differential pressures and is the interface between the control system and the required mechanical motion of the control drums. The servovalve can be broken into its major components, the torque motor and valve assembly. The torque motor is a device which changes the electrical input signals to a mechanical output motion of the torque motor armature. The torque motor armature is held in a centered position in a magnetic field by a centering spring. The magnetic field is supplied by four Alnico permanent magnets. The electrical signal inputs to the torque motor coils polarize the armature causing output rotation about the centering spring. Output motion is parallel to the magnetic flux in the air gap.

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Figure 2-8. Proportional Pneumatic Helical Cam Actuator

Figure 2-9. Helical Cam Proportional Pneumatic Actuator

The amount of output motion is determined by the balance of the magnetic force and the spring centering force. When the torque motor is combined with the valve, pressure forces must also be considered in the force balance.

The valve is a single stage, flapper-nozzle, push-pull device operating about a null pressure. It consists of two fixed orifices and two variable orifices. The unique feature of this valve is the use of variable orifices which employ annular nozzles. This concept allows greater flows without the disadvantage of large negative feedback pressure forces. The supply gas to the valve splits and flows two ways through the valve (Figure 2-9). The flow in each side goes through a fixed orifice and a variable orifice in series. Cylinder pressure is the pressure between the two orifices and is a function of the relative areas of the fixed and variable orifice. The null pressure and any pressure bias is established by the mechanical adjustment of the variable nozzles. The differential pressure across the piston is determined by the position of the armature and is continuously variable to about $3/4$ of supply pressure in each direction. As previously explained, electrical inputs to the torque motor cause an output motion which produces the variable feature of the annular nozzles. For example, if an electrical signal caused a clockwise rotation of the armature, the right-hand nozzle discharge area would be reduced while the left-hand nozzle area would be increased. The pressure on the right side of the piston would rise, and the left side pressure would decrease. This differential pressure would cause piston movement to the left. An electrical input of opposite polarity would cause the piston assembly to move to the right.

2.2.1.2 Potentiometer

The potentiometer produces an electrical output that is proportional to the shaft position of the actuator and is, therefore, a measure of drum position. This potentiometer is a three-deck device which provides three-fold redundancy to the position feedback signal. Each deck is electrically independent. The potentiometer is assembled concentrically with the main output shaft of the actuator and uses the main actuator bearings for alignment. This feature produces the simplest assembly and eliminates many parts required in separately mounted potentiometers. The potentiometer is assembled and aligned on the output shaft by the potentiometer manufacturer to eliminate the possibility of error in assembly.

2.2.1.3 Drive Train

The drive train consists of the piston assembly; the output shaft, with the spirally cut groove; output shaft support bearings; the balls; the ball retainer; and the piston cam follower assembly. The servovalve develops a differential pressure across the piston. The two sides of the piston are pneumatically isolated by a piston ring and the piston is held from contacting the liner by a guide ring. The differential pressure across the piston produces a linear motion of the piston assembly. This linear motion is converted to rotary motion by the balls which are trapped in the spiral grooves cut externally in the output shaft and internally in the piston assembly. The pressure force on the piston causes it to move. The side cams keep the piston from rotating; therefore, it moves in a linear fashion. The force is transmitted from the piston through the balls to the shaft which rotates. The rotary motion is transmitted to the load by the output shaft. The output shaft is supported in the housing by the two shaft bearings. The balls are held in proper orientation in the spiral grooves by the retainer. The piston cams ride in a cam slot and keep the piston assembly from rotating in the liner. The operation is very similar to that of a "Yankee screwdriver" mechanism and converts the linear motion of the piston to the rotary motion of the output shaft.

2.2.1.4 Housing Enclosure

The housing ties together all of the functional parts of the actuator. Passages drilled discretely in the housing carry drive gas and coolant gas to the various ports and locations of the actuator. Drive gas pressure is expected to be about 215 psia and coolant gas, which comes from the reactor dome, will vary from zero before reactor startup to about 700 psia at reactor full power. Two external covers form a part of the actuator. They serve as assembly access ports and also maintain the integrity of the working fluids. One cover is the cylinder cover and the other is the servovalve cover.

All electrical power, input command signals and output position signals enter and exit the actuator by way of the electrical connector.

Drive gas enters the actuator across the actuator mounting interface, through the drive gas filter, and is ported directly to the servovalve.

The coolant gas enters the actuator from the reactor dome through the coolant filter which is located just to the side of the output drive shaft. A shaft seal at the bottom of the output shaft isolates high pressure coolant from the internal parts of the actuator. Two small drilled metering holes in the housing allow the correct quantity of coolant to enter the actuator. Coolant flow through one of these holes cools the aft bearing and the potentiometer. Coolant flow through the other hole is ported to the spirally cut groove in the cylinder liner. Output of this groove is collected and ported to the servovalve cavity and is used to cool the torque motor. All drive and coolant gas is combined at the exhaust outlet for disposal or other use. A suggested use is to pressurize the run tank. The actuator will operate with little effect on performance with an externally caused exhaust pressure range of about zero to 50 psia.

2.2.2 System Description

A block diagram of the helical cam proportional pneumatic actuator system is shown in Figure 2-10. This block diagram shows all of the subassemblies that make up the actuator system and their interrelationship with other systems within the NERVA engine system. The components in the diagram that comprise the actuator system are the actuator mechanism, the actuator amplifier (including compensation and associated logic) and the actuator output drive shaft.

The actuator mechanism mounts to a flange on the pressure vessel closure which provides the interface for remote or manual removal and replacement. Drive gas, coolant gas, exhaust gas and output drive shaft cross this interface to perform their respective functions. All electrical wires enter and exit the actuator through a plug mounted directly to the actuator body. This plug also has been designed with remote removal and replacement in mind.

The amplifier, combined with the actuator mechanism and supplied with the proper electrical and pneumatic inputs, constitutes a closed loop drum position control system. This servomechanism positions the actuator output shaft (and therefore changes drum position and reactor reactivity) in accordance with the difference between the commanded drum angle and the measured drum angle. Actuator movement reduces the magnitude of this difference to zero.

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Figure 2-10. Helical Cam Proportional Pneumatic Actuator System Block Diagram

The number of these actuator systems on a reactor is equal to the number of control drums in the reactor and therefore has not been fixed. However, groups of 12, 18, 24, and 36 control drums are now under consideration. This actuator system is suitable for any of these reactor drum combinations up to and including 36.

2.2.3 Radiation Evaluation

Table 2-1 of Section 2.1.3 provides the radiation environment at the proposed actuator location forward of the pressure vessel closure. As those values describe the environment in the absence of perturbation by the actuator itself, they apply equally to all of the actuator concepts at this location. In most instances, the presence of the actuator will reduce the levels, so that the use of the unperturbed numbers is generally conservative.

2.2.4 Thermal Evaluation

The thermal-nuclear environment of the helical cam proportional pneumatic concept is, in general, similar to that of the rack and pinion concept discussed in Section 2.1.4 and the thermal performance is also expected to be similar. It is expected that the actuator structure can be adequately cooled in the low heating rate environment above the pressure vessel dome, although the coolant requirements will vary as a function of the actuator size and its internal heat generation.

The unique thermal design problems on the helical cam actuator design, which may be pointed out, are twofold. First, the end of the drive shaft, balls, and guide must be conductively cooled to the cooled heat sink in the vicinity of the bearings and potentiometer. The balls are conductively cooled through point contact of metal or through stagnant hydrogen ambient environment. This type of coolant may be adequate with the low heat generation rates, however to assure no problem, additional detailed evaluation would be necessary. Second, the long piston, although being low in mass, is somewhat thermally isolated from the major heat sinks to which coolant is supplied. More detailed analyses would be required to evaluate the effect of this "thermal isolation".

In general, the regions of primary thermal analysis interest will include the relatively thick metal sections, such as housing flanges, or the asymmetrical metal sections, where maximum temperature levels or thermal distortions would be expected to occur.

2.2.5 Structural Evaluation

The helical cam proportional pneumatic actuator is similar to the rack and pinion actuator discussed in Section 2.1.5. Structurally, the only difference between the two actuators is the method of converting linear motion to rotary motion. The structural evaluation of the servovalve assembly, feedback potentiometer, and housing enclosure is identical to that of the rack and pinion actuator discussed in Section 2.1.5.

The drive train of the helical cam actuator converts the linear motion of the piston to rotary motion by two balls which are trapped in the spiral grooves cut externally in the output shaft and internally in the piston assembly. The major areas of structural concern are the balls and spiral grooves. The balls which transmit the axial force from the piston to output shaft must be able to roll freely in the grooves. Sliding or rubbing of the balls will cause surface wear to both the balls and grooves, and additional functional resistance will be introduced into the system. Contact stresses in the balls may be high if the maximum pressure drop is applied to the piston. Consideration must be given to material selection and thermal distortion of the balls and grooves.

The drive train of the helical cam actuator is a more complex mechanism and has more potential problem areas than that of the rack and pinion actuator.

2.2.6 Radiation Effects Evaluation

The total expected radiation environment to which this actuator will be subjected is given in Section 2.1.3. To assess the effects of this environment on the actuator, a comparison of known test environments with this expected environment will indicate the sensitivity of any given concept to successful operation in the expected radiation levels. The sensitive components in this concept are the torque motor, the potentiometer, the piston rings and shaft seals, and electrical insulation and potting compounds. All other materials used in the construction of

the actuator are metals. Although detail designs are not available, final material selection will be made from lists of qualified materials or will be separately qualified.

2.2.6.1 Torque Motor

The torque motor contains two items which are considered sensitive to a radiation environment, the permanent magnets and the electrical coil. Changes in magnetic properties are reported after radiation exposures approximating $3 \times 10^{18} \text{ n cm}^{-2}$ (1, 2) This is approximately three orders of magnitude above the expected NERVA level. Other experiments at approximately the same neutron fluence show very little effect. Irradiation of a torque motor, similar to the NERVA design in the GTR facility, to $7 \times 10^{16} \text{ n cm}^{-2}$ produces an anomaly in the torque motor behavior. This anomaly is thought to be caused by the cryogenic rather than the radiation environment. The anomaly does not affect the performance of the torque motor. In addition, a prototype torque motor was operated in the NRX-A6 pneumatic actuator side-by-side test⁽³⁾ to levels approximately two orders of magnitude higher than the expected NERVA levels with no evidence of change. Test results of the Lewis Research Center Program⁽⁴⁾ at the Plum Brook Reactor also show no anomalies.

Electrical coils are part of all the above mentioned torque motor tests and evidence no signs of damage. However, it is planned to take advantage of improvements in the state-of-the-art insulation materials and use the polyimide series for future wire insulation to further improve radiation tolerance and increase coil reliability.

2.2.6.2 Potentiometer

A prototype potentiometer is also included in the tests described in the above section. A reported failure in the Lewis tests⁽⁴⁾ caused some concern until a subsequent post-irradiation examination revealed the failure was caused by a softening and flowing of a potting compound not included in the GTR and NRX-A6 tests. The material that failed was used in very early model potentiometers but has now been removed. Future controls will assure using only those specified materials that will not be subject to property changes under radiation environment.

2.2.6.3 Piston Rings, Shaft Seals, Electrical Insulation and Potting Materials

Although these items and materials are adequate for use in the NERVA environment, it is planned to take advantage of the improvements in the state-of-the-art in insulation materials. Polyimide materials, now used in the piston rings and seals, will be used in wire insulation and potting materials to increase radiation tolerance and reliability.

2.2.7 Reliability and Safety Evaluation

2.2.7.1 Fault Tree Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliability of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale of 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection, assembly and testing the identified component's ability to perform during its useful life installed in the actuator. The number 100 represents the most difficult level and the number 1, the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event identified on the tree, and has assigned a relative weighting number to each failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-11 shows in summary form the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific

Figure 2-11. Helical Cam Pneumatic Actuator

components within the actuator concept that contribute to the main block failure. The numbers in parentheses are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A listing of the failure events is shown in Table 2-8. These failure events are located in the fault tree by their identifying numbers which appear above the blocks on the fault tree. The events are listed in an indented manner which also indicates levels on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the subtotals progress toward the right of the page.

The final total of the weighted numbers (1784) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree have been indicated in parentheses in the blocks of the summary fault tree, Figure 2-11. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

The calibration process (Section 2.1.7.1.1) consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

TABLE 2-8
DETAILED FAULT TREE ANALYSIS

Helical Ball Proportional Pneumatic Actuator Reliability - Fault Tree Analysis 939J471 Estimated Reliability 9₅82. 1784

1.	Actuator Coolant Gas Consumption Rate Exceeds Specified Rate Limits		196
1.1	Interface Seal Joint Fails at Shaft		47
1.1.1	Pressure Vessel Seal Surface Fails to Contain Pressure	AGC	
1.1.2	Actuator Seal Surface Fails to Contain Pressure	1	
1.1.3	Seal Fails to Contain Pressure	30	
1.1.4	Seal Joint Separates	16	
1.1.4.1	Actuator Flange Fractures	1	
1.1.4.2	Pressure Vessel Flange Fractures	AGC	
1.1.4.3	Hold Down Bolts Lose Force	15	
1.1.4.3.1	Bolts Lose Torque	5	
1.1.4.3.2	Belleville Gradient Changes	10	
1.2	Interface Seal Joint Fails		47
1.2.1	Pressure Vessel Seal Surface Fails to Contain Pressure	AGC	
1.2.2	Actuator Seal Surface Fails to Contain Pressure	1	
1.2.3	Seal Fails to Contain Pressure	30	
1.2.4	Seal Joint Separates	16	
1.2.4.1	Actuator Flange Fractures	1	
1.2.4.2	Pressure Vessel Flange Fractures	AGC	

TABLE 2-8 (Continued)

1.2.4.3	Hold Down Bolts Loose Force	15	
1.2.4.3.1	Bolts Lose Torque	5	
1.2.4.3.2	Belleville Loses Gradient	10	
1.3	Actuator Mechanism Fails to Control Coolant		102
1.3.1	Mechanism Seal Surface Fails		1
1.3.2	Lower Shaft Seal Fails		100
1.3.3	Shaft Seal Surface Fails		1
2.	Actuator Fails to Achieve Time/Position Band		1528
2.1	Actuator Piston Pressures are not Correct Values		584
2.1.1	Servo valve Converts Signal Incorrectly		135
2.1.1.1	Torquemotor Characteristics Change	119	
2.1.1.1.1	Coil Fails	60	
2.1.1.1.2	Armature Assembly Fails	25	
2.1.1.1.2.1	Weld Fails	10	
2.1.1.1.2.2	Armature Spring Fails	2	
2.1.1.1.2.3	Frame Fails	3	
2.1.1.1.2.4	Armature Fails	10	
2.1.1.1.3	Field Assembly Fails	4	
2.1.1.1.3.1	Pole Piece Fails	1	
2.1.1.1.3.2	Bottom Shunt Fails	1	
2.1.1.1.3.3	Top Piece Fails	1	

TABLE 2-8 (Continued)

2.1.1.1.3.4	Magnets Fail	1	
2.1.1.1.4	Coil Lead Wires Fail	30	
2.1.1.2	Valve Characteristics Change		16
2.1.1.2.1	Flapper Screw Position Changes	7	
2.1.1.2.1.1	Screw Breaks Mech.	2	
2.1.1.2.1.2	Lock Screw Fails Allowing Flapper Screw to Move	5	
2.1.1.2.2	Nozzle Assembly Fails	4	
2.1.1.2.2.1	Nozzle Core Fails	3	
2.1.1.2.2.2	Manifold Fails	1	
2.1.1.2.3	Fasteners Fail	5	
2.1.2	Actuator System Loses Drive Gas Pressure		449
2.1.2.1	Flow Passages Blocked by Contamination		10
2.1.2.2	Mechanisms Pressures Wrong Value		415
2.1.2.2.1	Clogged Filter Drops Pressure	AGC	
2.1.2.2.2	Housing Assembly Fails	17	
2.1.2.2.2.1	Mechanism Body Fails	1	
2.1.2.2.2.2	Cylinder Liner Fails	1	
2.1.2.2.2.3	Piston Fails	10	
2.1.2.2.2.4	Cylinder Cover Fails	5	
2.1.2.2.3	Internal Seal Joints Fail		398
2.1.2.2.3.1	P-1 Nozzle Seal Joint Fails	67	

TABLE 2-8 (Continued)

2.1.2.2.3.1.1	Bottom Seal Fails	30	
2.1.2.2.3.1.2	Top Seal Fails	30	
2.1.2.2.3.1.3	Nozzle Sealing Surface Fails	1	
2.1.2.2.3.1.4	Port Sealing Surface Fails	1	
2.1.2.2.3.1.5	Fasteners Fail Allowing Joint to Separate	5	
2.1.2.2.3.2	P-2 Nozzle Seal Joint Fails		67
2.1.2.2.3.2.1	Bottom Seal Fails	30	
2.1.2.2.3.2.2	Top Seal Fails	30	
2.1.2.2.3.2.3	Nozzle Sealing Surface Fails	1	
2.1.2.2.3.2.4	Port Sealing Surface Fails	1	
2.1.2.2.3.2.5	Fasteners Fail	5	
2.1.2.2.3.3	Cylinder Liner Housing Seal Joint Fails		2
2.1.2.2.3.3.1	Liner Fails	1	
2.1.2.2.3.3.2	Housing Fails	1	
2.1.2.2.3.4	P-1 Cylinder Cover Seal Joint Fails		11
2.1.2.2.3.4.1	Seals Fail (2)	6	
2.1.2.2.3.4.2	Mechanism Seal Surfaces Fail (2)	1	
2.1.2.2.3.4.3	Cover Seal Surfaces Fail (2)	1	
2.1.2.2.3.4.4	Cover Fasteners Fail Allowing Joint to Separate	3	
2.1.2.2.3.5	P-2 Shaft Seal Joint Fails		130

TABLE 2-8 (Continued)

2.1.2.2.3.5.1	Seal Shaft Surface Fails	10	
2.1.2.2.3.5.2	Housing Seal Surface Fails	20	
2.1.2.2.3.5.3	Seal Fails	100	
2.1.2.2.3.6	P-1 Piston Seal Joint Fails	121	
2.1.2.2.3.6.1	Piston Seal Fails	100	
2.1.2.2.3.6.2	Cylinder Under Seal Surface Fails	20	
2.1.2.2.3.6.3	Piston Seal Surface Fails	1	
2.1.2.3	Mechanism/Pressure Vessel Seal Joint Fails		24
2.1.2.3.1	Pressure Vessel Seal Surface Fails	1	
2.1.2.3.2	Mechanism Seal Surface Fails	1	
2.1.2.3.3	Drive Filter Seal Fails	6	
2.1.2.3.4	Seal Joint Separates	16	
2.1.2.3.4.1	Actuator Flange Fractures	1	
2.1.2.3.4.2	Pressure Vessel Flange Fractures	AGC	
2.1.2.3.4.3	Hold Down Bolts Lose Force	15	
2.1.2.3.4.3.1	Bolts Lose Torque	5	
2.1.2.3.4.3.2	Belleville Gradient Changes	10	
2.1.3	Exhaust Restricted Causing High Back Pressure		AGC
2.1.4	Drive Gas Supply to Mechanism is not Proper Value		AGC
2.2	Actuator Receives Improper Command Signal from Amplifier		249
2.2.1	Amplifier Supply Voltage is not Correct Value		AGC
2.2.2	Amplifier Fails Internally		30

TABLE 2-8 (Continued)

2.2.3	Amplifier Receives Improper Feedback Signal		219
2.2.3.1	Potentiometer Supply Voltage is Wrong Value		30
2.2.3.1.1	Mechanism Wiring Harness Fails	30	
2.2.3.1.2	Voltage Supplied to System is in Error	AGC	
2.2.3.2	Feedback Potentiometer Output Fails		154
2.2.3.2.1	Potentiometer Electrically Fails	101	
2.2.3.2.1.1	Track Resistance Value Changes	10	
2.2.3.2.1.2	Protective Resistor Changes Value	10	
2.2.3.2.1.3	Wiper Resistance Changes Value	1	
2.2.3.2.1.4	Wiper/Track Contact Resistance Changes	80	
2.2.3.2.2	Angular Relationship Pot to Drum Changes	21	
2.2.3.2.2.1	Pot Position Changes Relative to Output Shaft	20	
2.2.3.2.2.3	Output Shaft Changes Relative to Drum	1	
2.2.3.2.3	Potentiometer Mechanically Fails	32	
2.2.3.2.3.1	Potentiometer Shaft Fails	1	
2.2.3.2.3.2	Wiper Spring Gradient Changes	1	
2.2.3.2.3.3	Bearings Fail	10	
2.2.3.2.3.4	Potentiometer Housing Fractures	20	
2.2.3.3	Feedback Signal Transmitted Improperly		35
2.2.3.3.1	Wiring Harness Actuator/Amplifier Fails	AGC	
2.2.3.3.2	Mechanism Wiring Harness Fails	30	
2.2.3.3.3	Electromagnetic Interference Distorts Signal	5	

TABLE 2-8 (Continued)

2.3	Output Shaft Fails to Position Drums		260
2.3.1	Crown Spline Fails		10
2.3.2	Shaft Breaks		20
2.3.3	Transmission Assembly Fails		230
2.3.3.1	Cam Follower Fails (2)	80	
2.3.3.2	Cam Fails (2)	10	
2.3.3.3	Retainer Fails	80	
2.3.3.4	Balls Fail (2)	20	
2.3.3.5	Piston Ball Track Fails	20	
2.3.3.6	Shaft Ball Track Fails	20	
2.4	Actuator Internal Load Changes		435
2.4.1	Potentiometer Load Changes		10
2.4.2	Actuator Drive Train Loads Change		425
2.4.2.1	Cylinder Liner Changes Load Value	80	
2.4.2.2	Bearings Change Load Value	60	
2.4.2.3	Transmission System Load Value Changes	285	
2.4.2.3.1	Piston Head Fails	10	
2.4.2.3.2	Transmission Assembly Fails	230	
2.4.2.3.2.1	Cam Follower Fails (2)	80	
2.4.2.3.2.2	Cam Fails (2)	10	
2.4.2.3.2.3	Retainer Fails	80	
2.4.2.3.2.4	Balls Fail (2)	20	

TABLE 2-8 (Continued)

2.4.2.3.2.5	Piston Ball Track Fails	20	
2.4.2.3.2.6	Shaft Ball Track Fails	20	
2.4.2.3.3	Piston Seal Fails	20	
2.4.2.3.4	Piston Ring Fails	20	
2.4.2.3.5	Piston/Piston Joint Track Fails	5	
2.5	Control Drum Characteristics Change		EC677559
3.	Actuator Electrical Power Consumption Rate Exceeds Limits		60
3.1	Actuator/Amplifier External Cable Short Circuits		AGC
3.2	Actuator Amplifier Short Circuits		20
3.3	Mechanism Short Circuits Internally		40
3.3.1	Potentiometer Short Circuits	10	
3.3.2	Wiring Harness System Short Circuits	20	
3.3.2.1	Wiring Insulation Fails	10	
3.3.2.2	Connector Short Circuits	10	
3.3.3	Torque Motor Short Circuits	10	

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

2.2.7.2 Failure Mode Evaluation

A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts are not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component is analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another.⁽⁹⁾ The total number then indicates the relative reliability of the actuator concept; the lower the number, the more reliable the particular concept is relative to the others. Each concept is compared with the others on the basis of the total relative failure probability number. A failure mode analysis for the helical cam proportional pneumatic actuator is shown in Table 2-9.

2.2.7.3 Safety Evaluation

The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and

TABLE 2-9

COMPONENT FAILURE MODES ANALYSIS

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY KCC COMPONENT Torque Motor DWG NUMBERS 939J465

W59150

Relative Ranking 197

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Torque motor characteristics change to bias its output to the full out or the full in position.	a. Pole piece breaks b. Bottom shunt breaks c. Top field piece breaks d. Magnet loses magnetic properties e. Armature assembly weld breaks f. Armature spring breaks g. Frame breaks h. Armature breaks i. Coil shorts or coils open (full in position failure only) j. Coil lead wire shorts or lead wires open (full in position failure only)	Start-up and Steady State	1 1 1 1 1 1 1 1 6 3
1.2	Torque motor characteristics change as to become unstable.	a. Bottom shunt breaks b. Top field piece breaks c. Armature assembly weld breaks d. Armature spring breaks e. Frame breaks	Start-up and Steady State	Combined with b,c,e,f,&g above.
2.1	Servo valve characteristics change to bias its output to the fullout or the full in position.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle) e. Flapper screw breaks (P_2 flapper or P_1 flapper). f. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	1 1 1 1 1 1
2.2	Servo valve characteristics change to inhibit the operating range.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	Combined with a,b,&f above

TABLE 2-9 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY KCC COMPONENT Servo Valve DWG NUMBERS 939J465

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.3	Servo valve characteristics change to inhibit velocity control capability	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of posi- (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle)	Start-up and Steady State	Combined with a,b,c,&d above.
3.1	Drive train mechanical load increases.	a. Piston head contacts liner and increases friction. b. Piston seal drags and increases friction c. Piston ring drags and increases friction d. Piston/piston track joint cocks and increases friction. e. Piston ball track surface damage increases friction. f. Shaft ball track surface damage increases friction. g. Balls surface damage increases friction h. Ball retainer surface damage increases friction. i. Cam track surface damage increases friction. j. Cam rollers bind and increase friction k. Output shaft bearings bind and increase friction. l. Cylinder liner surface damage increases friction.	Start-up and Steady State	1 1 1 1 1 1 6 1 6 4 6

TABLE 2-9 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY KAC COMPONENT Drive Train DWG NUMBERS 939J465

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.2	Drive train jams in some position between full in and maximum operating range.	a. Piston head breaks and jams mechanism b. Piston seal breaks and jams mechanism c. Piston ring breaks and jams mechanism d. Piston/piston track joint breaks and jams mechanism e. Piston ball track surface damage jams mechanism f. Shaft ball track surface damage jams mechanism g. Balls surface damage jams mechanism h. Ball retainer surface damage jam mechanism. i. Cam track surface damage jams mechanism j. Cam rollers seize and jam mechanism k. Outout shaft bearings seize l. Cylinder liner surface damage jams mechanism.	Start-up and Steady State	1 1 1 1 1 1 1 2 1 2 2 2
3.3	Drive train fails to contain drive gas pressure so as to bias the actuator to the full out position.	a. Piston seal leaks b. Piston seal surface damaged c. Cylinder liner seal surface damaged d. Cylinder liner leaks at seal joint with housing. e. Piston breaks f. Cylinder liner breaks	Steady State and Start up	8 1 2 1 1 1
3.4	Drive train fails to contain drive gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Shaft, upper seal housing seal surface damaged severely. b. Shaft upper seal surface damaged severely c. Cylinder liner breaks d. Cylinder liner joint with cam track housing leaks.	Steady State and Start up	2 1 1 1

TABLE 2-9 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
DATE APPROVED BY *RLC* COMPONENT Drive Train DWG NUMBERS 939J465

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.5	Drive train fails to provide output torque.	a. Transmission helical ball joint breaks b. Output shaft breaks c. Shaft crowned spline joint breaks	Steady State and Start up	10 2 1
3.6	Drive train fails to contain coolant gas pressure, increasing coolant gas consumption.	a. Shaft lower seal housing seal surface damaged. b. Shaft lower seal surface damaged	Steady State and Start up	2 1
4.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open. e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 4 2
4.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	1 2
4.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start-up and Steady State	1
4.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	1 1 8

TABLE 2-9 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY RUC COMPONENT Housing and Covers DWG NUMBERS 939J465

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Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full out position.	a. Housing breaks at P_1 supply port to servo valve. b. Housing seal surface at P_1 nozzle damaged	Start up and Steady State	1 1
5.2	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Housing breaks at P_2 supply port to servo valve. b. Housing seal surface at P_2 nozzle damaged c. Housing flange breaks d. Cylinder cover breaks e. Cylinder cover fasteners break f. Cylinder cover seal surface damaged g. Supply gas filter clogs h. Filter interface seal surface damaged	Start up and Steady State	1 1 1 1 1 2 1
5.3	Housing fails to contain coolant gas pressure, increasing coolant gas consumption.	a. Housing mounting flange breaks b. Interface seal surface damaged c. Housing seal surface for coolant gas filter damaged.	Start up and Steady State	1 1 1
6.1	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full out position.	a. P_1 nozzle bottom seal leaks b. Output shaft upper seal leaks	Start-up and Steady State	3 10
6.2	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Cylinder cover seal leaks b. P_1 nozzle top seal leaks c. P_2 nozzle top seal leaks d. P_2 nozzle bottom seal leaks e. Filter interface seal leaks f. Drive gas supply connector seal leaks	Start-up and Steady State	3 3 3 3 3 3

TABLE 2-9 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY K.C. COMPONENT Seals, Coolant DWG NUMBERS 939J465

459150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
7.1	Coolant seals fail to contain gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range; and to increase coolant gas consumption.	a. Actuator coolant interface seal leaks b. Lower end output shift seals leak c. Coolant filter seal leaks	Start-up and Steady State	3 10 3
8.1	Mounting stud fails to maintain proper clamping force, resulting in increased coolant gas consumption through leakage, and probably inhibiting actuator operating range or actuator going to the full in position.	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action allowing nut to loosen.	Start-up and Steady State	1 1 1
9.1	Electrical wiring harness to torque motor fails to carry proper command signal.	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	1 2
9.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	1 2

criticality ranking for each concept, failure modes are identified. For each of the failure modes listed, mechanisms of obtaining that failure mode are established as they relate to a particular design. Each of these failure mechanisms is given a numerical ranking consistent with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reductions in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.
1	Failures resulting in insignificant effects on chamber temperature/pressure.

By assigning each mechanism of failure to one of the above categories, and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-10 presents a tabulation of the failures, mechanism of failure and criticality ranking of failure for the helical cam pneumatic actuator. Also shown is the total criticality ranking for this concept.

2.2.8 Discussion and Evaluation

The major difference between this helical cam pneumatic actuator concept and the rack and pinion concept is the manner in which the piston motion is translated into rotary output

TABLE 2-10
COMPONENT SAFETY CRITICALITY

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
DATE APPROVED BY KGC COMPONENT Torque Motor DWG NUMBERS 939J465

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Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Torque motor characteristics change to bias its output to the full out or the full in position.	a. Pole piece breaks b. Bottom shunt breaks c. Top field piece breaks d. Magnet loses magnetic properties e. Armature assembly weld breaks f. Armature spring breaks g. Frame breaks h. Armature breaks i. Coil shorts or coils open (full in position failure only) j. Coil lead wire shorts or lead wires open (full in position failure only)	Start-up and Steady State	4 4 4 4 4 4 4 4 4
1.2	Torque motor characteristics change as to become unstable.	a. Bottom shunt breaks b. Top field piece breaks c. Armature assembly weld breaks d. Armature spring breaks e. Frame breaks	Start-up and Steady State	2 2 2 2 2
2.1	Servo valve characteristics change to bias its output to the fullout or the full in position.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle) e. Flapper screw breaks (P_2 flapper or P_1 flapper). f. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	4 4 4 4 4
2.2	Servo valve characteristics change to inhibit the operating range.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	2 2 2

TABLE 2-10 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY KAC COMPONENT Servo Valve DWG NUMBERS 939J465

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Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.3	Servo valve characteristics change to inhibit velocity control capability	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of posi- (P ₂ nozzle or P ₁ nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P ₂ nozzle or P ₁ nozzle)	Start-up and Steady State	1 1 1 1
3.1	Drive train mechanical load increases.	a. Piston head contacts liner and increases friction. b. Piston seal drags and increases friction c. Piston ring drags and increases friction d. Piston/piston track joint cocks and increases friction. e. Piston ball track surface damage increases friction. f. Shaft ball track surface damage increases friction. g. Balls surface damage increases friction h. Ball retainer surface damage increases friction. i. Cam track surface damage increases friction. j. Cam rollers bind and increase friction k. Output shaft bearings bind and increase friction. l. Cylinder liner surface damage increases friction.	Start-up and Steady State	2 2 2 2 2 2 2 2 2 2 2 2

TABLE 2-10 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY KAC COMPONENT Drive Train DWG NUMBERS 939J465

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.2	Drive train jams in some position between full in and maximum operating range.	a. Piston head breaks and jams mechanism b. Piston seal breaks and jams mechanism c. Piston ring breaks and jams mechanism d. Piston/piston track joint breaks and jams mechanism e. Piston ball track surface damage jams mechanism f. Shaft ball track surface damage jams mechanism g. Balls surface damage jams mechanism h. Ball retainer surface damage jam mechanism. i. Cam track surface damage jams mechanism j. Cam rollers seize and jam mechanism k. Outout shaft bearings seize l. Cylinder liner surface damage jams mechanism.	Start-up and Steady State	4 4 4 4 4 4 4 4 4 4 4 4
3.3	Drive train fails to contain drive gas pressure so as to bias the actuator to the full out position.	a. Piston seal, leaks b. Piston seal surface damaged c. Cylinder liner seal surface damaged d. Cylinder liner leaks at seal joint with housing. e. Piston breaks f. Cylinder liner breaks	Steady State and Start up	4 4 4 4 4 4
3.4	Drive train fails to contain drive gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Shaft, upper seal housing seal surface damaged severely. b. Shaft upper seal surface damaged severely c. Cylinder liner breaks d. Cylinder liner joint with cam track housing leaks.	Steady State and Start up	4 4 4 4

TABLE 2-10 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY ME COMPONENT Drive Train DWG NUMBERS 939J465

W5J150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.5	Drive train fails to provide output torque.	a. Transmission helical ball joint breaks b. Output shaft breaks c. Shaft crowned spline joint breaks	Steady State and Start up	4 4 4
3.6	Drive train fails to contain coolant gas pressure, increasing coolant gas consumption.	a. Shaft lower seal housing seal surface damaged. b. Shaft lower seal surface damaged	Steady State and Start up	2 2
4.1	Potentiometers fail to provide feedback signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open. e. Potentiometers housing breaks	Start-up and Steady State	4 4 4 4 4
4.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	4 4
4.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start-up and Steady State	4
4.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	2 2 2

TABLE 2-10 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY RUC COMPONENT Housing and Covers DWG NUMBERS 939J465

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full out position.	a. Housing breaks at P_1 supply port to servo valve. b. Housing seal surface at P_1 nozzle damaged	Start up and Steady State	4 4
5.2	Housing and covers fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Housing breaks at P_2 supply port to servo valve. b. Housing seal surface at P_2 nozzle damaged c. Housing flange breaks d. Cylinder cover breaks e. Cylinder cover fasteners break f. Cylinder cover seal surface damaged g. Supply gas filter clogs h. Filter interface seal surface damaged	Start up and Steady State	4 4 4 4 4 4 4 4
5.3	Housing fails to contain coolant gas pressure, increasing coolant gas consumption.	a. Housing mounting flange breaks b. Interface seal surface damaged c. Housing seal surface for coolant gas filter damaged.	Start up and Steady State	2 2 2
6.1	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full out position.	a. P_1 nozzle bottom seal leaks b. Output shaft upper seal leaks	Start-up and Steady State	4 4
6.2	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Cylinder cover seal leaks b. P_1 nozzle top seal leaks c. P_2 nozzle top seal leaks d. P_2 nozzle bottom seal leaks e. Filter interface seal leaks f. Drive gas supply connector seal leaks	Start-up and Steady State	4 4 4 4 4 4

TABLE 2-10 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY KAC COMPONENT Seals, Coolant DWG NUMBERS 939J465

459150

Code Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Coolant seals fail to contain gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range; and to increase coolant gas consumption.	a. Actuator coolant interface seal leaks b. Lower end output shift seals leak c. Coolant filter seal leaks	Start-up and Steady State	4 4 4
8.1	Mounting stud fails to maintain proper clamping force, resulting in increased coolant gas consumption through leakage, and probably inhibiting actuator operating range or actuator going to the full in position.	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action allowing nut to loosen.	Start-up and Steady State	4 4 4
9.1	Electrical wiring harness to torque motor fails to carry proper command signal.	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	4 4
9.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	4 4

shaft motion. The single piston, piston seal, and piston liner portion of the rack and pinion concept is retained. The feedback potentiometer, servovalve, and control amplifier are the same as those discussed in Section 2.1.8. However, the helical cam concept employs a markedly different drive train which is described in detail in Section 2.2.1.3. This drive train design is a major innovation and as best as can be determined, no actuator of this type is presently available commercially.

The development of this actuator would necessitate a major development program. In comparison, it is felt that at the present state-of-the-art the unit is inferior to the single piston, rack and pinion concept and no desirable advantage is to be gained over the rack and pinion concept through an advancement of the state-of-the-art. The weight, size, and drive and coolant gas consumptions are approximately the same as the single piston rack and pinion concept. The reliability estimate indicates that this concept would not be as reliable as either of the other pneumatic proportional concepts.

The helical cam pneumatic actuator is compact enough to fit on a 36 drum reactor concept. Its radial width at the control drum centerline is about 6.1 inches. Its height above the pressure vessel mounting boss is about 6-1/2 inches. Clearance required above the actuator for removal is approximately 2-3/4 inches to clear the output shaft and mounting studs. The actuator weight is estimated to be about 9-3/4 pounds.

Coolant requirements for a one hour run at the heating rates estimated for NERVA, about 3 watts per pounds, are less than 1/2 pound and can probably be eliminated. Maximum drive gas at 100°R and 215 psia for a one hour run is about 36 pounds. Electrical power is required to supply the amplifier and feedback potentiometer but it is all in the control range and is considered small enough to be neglected for this study. A preliminary estimate of the concept reliability obtained by calibrating the fault tree is .9₅82. Table 2-11 is a listing of some of the more significant advantages and disadvantages of the helical cam pneumatic actuator concept.

TABLE 2-11
HELICAL CAM PNEUMATIC ACTUATOR
SUMMARY TABLE

<u>Advantages</u>	<u>Disadvantages</u>
1. Power media of H ₂ is readily available from engine source.	1. No experience or background in the unique transmission system of this actuator.
2. Possibility exists for use of a wire-wound feedback potentiometer, thus improving potentiometer reliability.	2. Severe weight penalty exists for the drive gas startup pneumatic supply system weight required due to actuator consumption of H ₂ .
3. Some portions of XE actuator experience and background are directly applicable to this actuator design, that is servovalve, hot, etc.	3. Transmission's vibration and shock environmental capabilities are unknown.
4. Mechanism weight is low.	4. Servovalve susceptible to malfunction at cryogenic temperature if H ₂ supply is not free of trace gas contaminants.
5. Physical size applicable up to a 36 drum NSS.	5. Design not easily remotely removed in a 36 drum configuration.
6. Highly probable that no coolant gas will be required.	6. Dynamic shaft seal required at pressure vessel interface.
	7. Drum spring probably required to hold drum in the shutdown condition.

2.3 DYNAVECTOR PROPORTIONAL CONCEPT

2.3.1 Mechanical Description

An existing Dynavector actuator was modified to apply a particular rotary actuator concept to the NERVA reactor. (The Dynavector^{R*} Actuator was developed by the Bendix Corporation.) The primary modification was incorporation of a servovalve and a feedback potentiometer. Some secondary modifications were made to provide coolant flow for the actuator and to adapt for the particular interfaces which required mounting, electrical circuitry, pneumatic drive power, and drive shaft coupling. The following paragraphs explain the basic Dynavector concept and the proposed major modifications to a particular Dynavector actuator. A Dynavector incorporated into a control drum actuator is shown in Figure 2-12.

The pneumatic Dynavector actuator is both an integral high-speed captive vane motor and a high-ratio epicyclic transmission. The major components consist of series of displacement chambers, unique integral epicyclic transmission, and commutation porting. The transmission and motor use elements common to both, resulting in a simple and reliable design.

The power element is a positive displacement, very low inertia, non-rotating vane motor. Its output is a radial force vector which rotates at high speed in either direction of rotation. Displacement chambers, formed by the vanes and the housing, expand and collapse at the same speed as the force vector, but do not rotate. The motor is self-commutating but does not contain a rotating porting plate or spindle. Absence of high-velocity members in the motor significantly reduces the inertia, resulting in high acceleration capability.

Integration of the power element and epicyclic transmission into an integral actuator design results in a servo-actuator with a high torque-to-inertia ratio.

Dynavector actuator operation is illustrated by Figure 2-13. The basic components are the ring gear, the ground gear and housing, the center output gear and shaft, and the vanes. Displacement chambers are formed between the ground gear and the ring gear mesh by the vanes. This gear mesh provides displacement motion without rotation because both gears have exactly the same number of teeth. It may be considered as a loose spline, but it is a true involute gear mesh. The internal portion of the ring gear forms the transmission between the motor and the

* Registered trademark Bendix Corporation.

Figure 2-12. Proportional Actuator Pneumatic Dynavector Concept

Figure 2-13. Dynavector Basic Design and Operation

output shaft, and represents the epicyclic transmission. The ring gear does not rotate but orbits in a small circle and drives the output gear.

A force vector is generated by pressurizing three adjacent displacement chambers while venting the remaining three. The vector is made to rotate by pressurizing a vented chamber adjacent to the original three pressurized chambers while simultaneously venting the diametrically opposite chamber. At that instant, the force vector advances through an angle equal to the arc width of one displacement chamber. If the force vector on the ring gear is located at approximately 90 degrees to the ring and the output gear contact point, the ring gear will move, causing the output gear to turn and the contact point to move. Movement of the ring gear switches the porting, causing the force vector to rotate so that it remains 90 degrees to the contact point; thus, the motion will be continuous and the output shaft will turn continuously, but at a much lower speed than the force vector. The ratio will be determined by the difference in number of teeth between the ring gear and the output gear. The gears in Figure 2-13 have 30 and 32 teeth; thus, the reduction ratio is 15:1.

Available differential pressure, in the form of two motor port pressures, P_1 and P_2 , must be commutated to the proper displacement chambers to produce a rotating force vector in phase with the ring gear motion. To insure that this phase relationship always holds true, the motion or position of the ring gear is used to provide this commutation through a series of ports. Each displacement chamber has a pair of supply ports designated P_1 and P_2 . The P_1 ports are all interconnected in the housing and brought out to a single motor inlet port. All the P_2 ports are likewise interconnected. These ports are in the housing and, therefore, are stationary with respect to the displacement chambers. They are also located under the ring gear face as shown in Figure 2-13. A port connecting the displacement chambers to the ring gear face ports the P_1 or P_2 pressures to the displacement chambers.

By locating these P_1 and P_2 ports as shown in Figure 2-13, the ring gear ports will open P_1 ports to half the displacement chambers and P_2 ports to the remaining half. The resulting pressure force on the ring gear from the displacement chambers connected to P_1 is 180 degrees opposite P_2 and 90 degrees from the output gear contact point. Therefore, pressurizing P_1 and venting P_2 produces rotation in one direction, while interchanging pressure

and return reverses the motor. This also satisfies the desired relationship between force vector and ring gear position. Because this commutation is created by the displacement member or ring gear itself, it will always rotate in phase with the motor, producing maximum efficiency.

A servovalve added to the actuator controls the speed and direction of rotation of the motor. The servovalve converts electrical input signals to differential pressures and is the interface between the control system and the required mechanical motion of the control drums. The major components of the servovalve are the torque motor and valve assembly.

The torque motor changes the electrical input signals to a mechanical output motion of the torque motor armature. The torque motor armature is centered in a magnetic field by a centering spring. The magnetic field is supplied by four Alnico permanent magnets. The electrical signal inputs to the torque motor coils polarize the armature causing output rotation about the centering spring. Output motion is parallel to the magnetic flux in the air gap. The amount of output motion is determined by the balance of the magnetic force and the spring centering force. When the torque motor is combined with the valve, pressure forces must also be considered in the force balance.

The valve is a single stage, flapper-nozzle, push-pull device operating about a null pressure. It consists of two fixed orifices and two variable orifices. The unique feature of this valve is the use of variable orifices which employ annular nozzles. This concept allows greater flows without the disadvantage of large negative feedback pressure force. The supply pressure to the valve splits and flows two ways through the valve (Figure 2-14). Each half flows through a fixed orifice and a variable orifice in series. The pressure between the two orifices, and thus each cylinder pressure, is a function of the relative areas of the fixed and variable orifice. The null pressure and any pressure bias is established by the mechanical adjustment of the variable nozzles. The differential pressure across the ring gear is determined by the position of the armature and is continuously variable to about 3/4 of supply pressure in each direction. As explained, electrical inputs to the torque motor causes an output motion which produces the variable feature of the annular nozzles. For example, if an electrical signal caused a clockwise rotation of the armature, the right-hand nozzle discharge area would be reduced while the left-hand nozzle discharge area would be increased. The pressure in the three P_1 chambers would rise, and the left side pressure P_2 would decrease.

Figure 2-14. Dynavector Actuator Schematic

The proposed design will incorporate a potentiometer. The potentiometer produces an electrical output that is proportional to the shaft position of the actuator and is therefore a measure of drum position. This potentiometer is a three-deck device which provides threefold redundancy to the position feedback signal. Each deck is electrically independent.

2.3.2 System Description

A block diagram of the Dynavector proportional pneumatic actuator system is shown in Figure 2-15. This block diagram shows all of the subassemblies that make up the actuator system and their interrelationship with other systems within the NERVA engine system. The components in the diagram that constitute the actuator system are the actuator mechanism, the actuator amplifier (including compensation and associated logic) and the actuator output drive shaft.

The actuator mechanism mounts to a flange on the pressure vessel closure which provides the interface for remote or manual removal and replacement. Drive gas, coolant gas, exhaust gas and output drive shaft cross this interface to perform their respective functions. All electrical wires enter and exit the actuator through a plug mounted directly to the actuator body. This plug also has been designed with remote removal and replacement in mind.

The amplifier, combined with the actuator mechanism and supplied with the proper electrical and pneumatic inputs, constitute a closed loop drum position control system. This servomechanism positions the actuator output shaft (and therefore changes drum position and reactor reactivity) in accordance with the difference between the commanded drum angle and the measured drum angle. Actuator movement reduces the magnitude of this difference to zero.

2.3.3 Radiation Evaluation

Table 2-1 of Section 2.1.3 provides the radiation environment at the proposed actuator location forward of the pressure vessel closure. As those values describe the environment in the absence of perturbation by the actuator itself, they apply equally to all of the actuator concepts at this location. In most instances the presence of the actuator will reduce the levels, so that the use of the unperturbed numbers is generally conservative.

613129-5B

Figure 2-15. Dynavector Proportional Pneumatic Actuator System Block Diagram

2.3.4 Thermal Evaluation

The thermal-nuclear environment of the Dynavector Proportional concept is, in general, similar to that of the rack and pinion concept discussed in Section 2.1.4 and the thermal performance is also expected to be similar. At the low heating rates in the forward region of the PV closure, it is expected that the actuator structure can be adequately cooled. In fact, it is possible that no coolant will be required. The coolant requirements will vary as a function of the actuator size and its internal heat generation as has been previously discussed.

The Dynavector Proportional concept presents a probable non-symmetric temperature system resulting from the heat source (internal heat generation) and non-symmetric distribution of coolant flow around the output gear and shaft, ring gear, and stationary gear. The non-symmetry of temperature distribution is not expected to cause major design difficulty if the actuator is placed in the low heating rate region forward of the pressure vessel closure. In addition, the continuous drive gas leakage flow over the ring gear end face close clearance flow impedance will provide coolant to the ring gear. This feature, which perhaps leads to more drive gas flow requirement, does, to some extent, use a portion of the drive for actuator pneumatic mechanism coolant.

In general, the regions of primary thermal analysis interest will include the relatively thick metal sections, such as housing flanges, or the asymmetrical metal sections, where maximum temperature levels or thermal distortions would be expected to occur.

2.3.5 Structural Evaluation

The servovalve assembly, feedback potentiometer and housing enclosure for the Dynavector proportional pneumatic actuator are similar to those assemblies of the rack and pinion actuator discussed in Section 2.1.5 and the same structural evaluation can be applied to both designs. In addition, a Marmon clamp is used at the interface flange of the Dynavector actuator housing instead of bolts. The clamping load and stresses in a Marmon clamp are difficult to predict analytically because they are greatly influenced by the friction forces in the mating parts at assembly. Component tests should be performed to determine the loads and stresses in the clamp.

The primary area of structural analysis concern in this actuator is the drive train assembly which is an epicyclic gear arrangement. The major components in this assembly are the ring gear, ground gear and housing, the center output gear, and the vanes. During the detail analysis phase system torques and forces, bending stresses, contact stresses, fatigue life, surface wear, material selection, and thermal stresses and distortions of the gears will be considered if this design is selected from the trade study.

2.3.6 Radiation Effects Evaluation

The total expected radiation environment to which this actuator will be subjected is given in Section 2.1.3. To assess the effects of this environment on the actuator, a comparison of known test environments with this expected environment will indicate the sensitivity of any given concept to successful operation in the expected radiation levels. The sensitive components in this concept are the torque motor, the potentiometer, the shaft seals, and the electrical insulation and potting compounds. All other materials used in the construction of the actuator are metals. Although detail designs are not available, final material selection will be made from lists of qualified materials or will be separately qualified.

2.3.6.1 Torque Motor

The torque motor contains two items which are considered sensitive to a radiation environment, the permanent magnets and the electrical coil. Changes in magnetic properties are reported after radiation exposures approximating $3 \times 10^{18} \text{ n cm}^{-2}$ (1,2). This is approximately three orders of magnitude above the expected NERVA level. Other experiments at approximately the same neutron fluence show very little effect. Irradiation of a torque motor, similar to the NERVA design in the GTR facility, to $7 \times 10^{16} \text{ n cm}^{-2}$ produces an anomaly in the torque motor behavior. This anomaly is thought to be caused by the cryogenic rather than the radiation environment. The anomaly does not affect the performance of the torque motor. In addition, a prototype torque motor was operated in the NRX-A6 pneumatic actuator side-by-side test⁽³⁾ to levels approximately two orders of magnitude higher than the expected NERVA levels with no evidence of change. Test results of the Lewis Research Center Program⁽⁴⁾ at the Plum Brook Reactor also show no anomalies.

Electrical coils are part of all the above mentioned torque motor tests and evidence no signs of damage. However, it is planned to take advantage of improvements in the state-of-the-art in insulation materials and use the polyimide series for future wire insulation to further improve radiation tolerance and increase coil reliability.

2.3.6.2 Potentiometer

A prototype potentiometer is also included in the tests described in the above section. A reported failure in the Lewis tests⁽⁴⁾ caused some concern until a subsequent post-irradiation examination revealed the failure was caused by a softening and flowing of a potting compound not included in the GTR and NRX-A6 tests. The material that failed was used in very early model potentiometers but has now been removed. Future controls will assure using only those specified materials that will not be subject to property changes under radiation environment.

2.3.6.3 Shaft Seals, Electrical Insulation and Potting Materials

Although these items and materials are adequate for use in the NERVA environment, it is planned to take advantage of the improvements in the state-of-the-art in insulation materials. Polyimide materials will be used in wire insulation and potting materials to increase radiation tolerance and reliability.

2.3.7 Reliability and Safety Evaluation

2.3.7.1 Fault Tree Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliability of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale from 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection,

assembly and testing the identified component's ability to perform during its useful life installed in the actuator. The number 100 represents the most difficult level and the number 1, the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event identified on the tree and has assigned a relative weighting number to each failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-16 shows in summary form the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific components within the actuator concept that contribute to the main block failure. The numbers in parentheses are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A tabular listing of the failure events is shown in Table 2-12. These failure events are located in the fault tree by their identifying numbers which appear above the blocks on the fault tree. The events are listed in an indented manner which also indicates levels on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the subtotals progress toward the right of the page.

The final total of the weighted numbers (1721) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree are indicated in parentheses in the blocks of the summary fault tree, Figure 2-16. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

Figure 2-16. Summary Fault Tree, Dynavecator Pneumatic Actuator

TABLE 2-12
DETAILED FAULT TREE ANALYSIS

Dynavec Proportional Pneumatic Actuator Reliability - Fault Tree
Analysis 939J958 Estimated Reliability 9583

				1721
1.	Actuator Coolant Gas Consumption Rate Exceeds Specified Rate Limits			54
1.1	Interface Seal Joint Fails		43	
1.1.1	Pressure Vessel Seal Surface Fails to Contain Pressure		AGC	
1.1.2	Actuator Seal Surface Fails to Contain Pressure		1	
1.1.3	Seal Fails to Contain Pressure		30	
1.1.4	Seal Joint Separates		12	
1.1.4.1	Actuator Flange Fractures		1	
1.1.4.2	Pressure Vessel Flange Fractures		AGC	
1.1.4.3	Clamp Lose Force		11	
1.1.4.3.1	L.H. Bolt Looses Torque	5		
1.1.4.3.2	Clamp Spring Gradient Changes	1		
1.1.4.3.3	R.H. Bolt Looses Torque	5		
1.2	Actuator Mechanism Fails to Control Coolant		11	
1.2.1	Shaft Seal Joint Fails		10	
1.2.2	Orifice Fails		1	
2.	Actuator Fails to Achieve Time/Position Band			1607
2.1	Actuator Chamber Pressures are not Correct Values		584	
2.1.1	Servo valve Converts Signal Incorrectly		135	
2.1.1.1	Torquemotor Characteristics Change		119	
2.1.1.1.1	Coil Fails	60		
2.1.1.1.2	Armature Assembly Fails	25		

TABLE 2-12 (Continued)

2.1.1.1.2.1 Weld Fails	10		
2.1.1.1.2.2 Armature Spring Fails	2		
2.1.1.1.2.3 Frame Fails	3		
2.1.1.1.2.4 Armature Fails	10		
2.1.1.1.3 Field Assembly Fails		4	
2.1.1.1.3.1 Pole Piece Fails	1		
2.1.1.1.3.2 Bottom Shunt Fails	1		
2.1.1.1.3.3 Top Piece Fails	1		
2.1.1.1.3.4 Magnets Fail	1		
2.1.1.1.4 Coil Lead Wires Fail		30	
2.1.1.2 Valve Characteristics Change			16
2.1.1.2.1 Flapper Screw Position Changes		7	
2.1.1.2.1.1 Flapper Screw Fails Mech.	2		
2.1.1.2.1.2 Lock Screw Fails Allowing Flapper Screw to Move	5		
2.1.1.2.2 Nozzle Assembly Fails		4	
2.1.1.2.2.1 Nozzle Core Fails	3		
2.1.1.2.2.2 Manifold Fails	1		
2.1.1.2.3 Fasteners Fail		5	
2.1.2 Actuator Looses Drive Gas Pressure			449
2.1.2.1 Flow Passages are Blocked			10
2.1.2.2 Supply Inlet Seal Joint Fails			14
2.1.2.2.1 Seal Fails Mechanically		5	
2.1.2.2.2 Joint Loses Seating Torque		7	
2.1.2.2.2.1 Fitting Rotates Loose	5		
2.1.2.2.2.2 Fitting Threads Fail	1		

TABLE 2-12 (Continued)

2.1.2.2.2.3 Housing Threads Fail	1	
2.1.2.2.3 Housing Seal Surface Fails		1
2.1.2.2.4 Fitting Seal Surface Fails		1
2.1.2.3 Gas Inlet Fitting Fails		1
2.1.2.4 Servovalve Seal Joint Fails		134
2.1.2.4.1 P-1 Nozzle Seal Joint Fails	67	
2.1.2.4.1.1 Bottom Seal Fails	30	
2.1.2.4.1.2 Top Seal Fails	30	
2.1.2.4.1.3 Nozzle Sealing Surface Fails	1	
2.1.2.4.1.4 Port Sealing Surface Fails	1	
2.1.2.4.1.5 Fasteners Fail Allowing Joint to Separate	5	
2.1.2.4.2 P-2 Nozzle Seal Joint Fails	67	
2.1.2.4.2.1 Bottom Seal Fails	30	
2.1.2.4.2.2 Top Seal Fails	30	
2.1.2.4.2.3 Nozzle Sealing Surface Fails	1	
2.1.2.4.2.4 Port Sealing Surface Fails	1	
2.1.2.4.2.5 Fasteners Fail	5	
2.1.2.5 Ring Gear to Cover Seal Joint Fails		40
2.1.2.5.1 Front Cover Fails	/	10
2.1.2.5.2 Ring Gear Fails		20
2.1.2.5.3 Back Cover Fails		10
2.1.2.6 Metal Seal Joint Fails		66
2.1.2.6.1 Front Cover Seal Fails	30	
2.1.2.6.2 Rear Cover Seal Surface Fails	1	
2.1.2.6.3 Rear Cover Seal Fails	30	
2.1.2.6.4 Front Cover Seal Surface Fails	1	

TABLE 2-12 (Continued)

2.1.2.6.5 Fasteners Fail	2	
2.1.2.6.6 Reaction Gear Seal Surface Fails	2	
2.1.2.7 Vanes Fail (9)		180
2.1.2.8 Actuator Body Fails		4
2.1.2.8.1 Reaction Gear Cracks	1	
2.1.2.8.2 Ring Gear Cracks	1	
2.1.2.8.3 Back Cover Cracks	1	
2.1.2.8.4 Front Cover Cracks	1	
2.2 Actuator Receives Improper Command Signal from Amplifier		249
2.2.1 Amplifier Supply Voltage is not Correct Value		AGC
2.2.2 Amplifier Fails Internally		30
2.2.3 Amplifier Receives Improper Feedback Signal		219
2.2.3.1 Potentiometer Supply Voltage is Wrong Value		30
2.2.3.1.1 Mechanism Wiring Harness Fails	30	
2.2.3.1.2 Voltage Supplied to System is in Error	AGC	
2.2.3.2 Feedback Potentiometer Output Fails		154
2.2.3.2.1 Potentiometer Electrically Fails		101
2.2.3.2.1.1 Track Resistance Value Changes	10	
2.2.3.2.1.2 Protective Resistor Changes Value	10	
2.2.3.2.1.3 Wiper Resistance Changes Value	1	
2.2.3.2.1.4 Wiper/Track Contact Resistance Changes	80	
2.2.3.2.2 Angular Relationship Pot to Drum Changes		21
2.2.3.2.2.1 Pot Position Changes Relative to Output Shaft	20	
2.2.3.2.2.2 Output Shaft Changes Relative to Drum	1	
2.2.3.2.3 Potentiometer Mechanically Fails		32
2.2.3.2.3.1 Potentiometer Shaft Fails	1	

TABLE 2-12 (Continued)

2.2.3.2.3.2 Wiper Spring Gradient Changes	1		
2.2.3.2.3.3 Bearings Fail	10		
2.2.3.2.3.4 Potentiometer Housing Fractures	20		
2.2.3.3 Feedback Signal Transmitted Improperly		35	
2.2.3.3.1 Wiring Harness to Amplifier Fails		AGC	
2.2.3.3.2 Mechanism Wiring Harness Fails		30	
2.2.3.3.3 Electromagnetic Interference Distorts Signal		5	
2.3 Output Shaft Fails to Position Drums			110
2.3.1 Crown Spline Fails		10	
2.3.2 Output Gear/Shaft Spline Joint Fails		80	
2.3.3 Shaft Breaks		20	
2.4 Actuator Internal Load Changes			664
2.4.1 Potentiometer Load Changes		10	
2.4.2 Actuator Drive Train Loads Change		654	
2.4.2.1 Ring Gear/Back Cover Friction Increases		62	
2.4.2.1.1 Reaction Gear Contracts	1		
2.4.2.1.2 Ring Gear Expands or Warps	10		
2.4.2.1.3 Bearings Allow Ring Gear to Skew	30		
2.4.2.1.3.1 Bearing Fails	10		
2.4.2.1.3.2 Cover Fails Allowing Bearing to Move	5		
2.4.2.1.3.3 Bearing Retainer Fails	10		
2.4.2.1.3.4 Output Shaft Fails Allowing Bearing to Move	5		
2.4.2.1.4 Shaft Fails Allowing Ring Gear to Move	1		
2.4.2.1.5 Contaminants Lodge in the Gear Cover Clearance	20		
2.4.2.2 Ring Gear Front Cover Friction Increases		62	
2.4.2.2.1 Reaction Gear Contracts	1		

TABLE 2-12 (Continued)

2.4.2.2.2	Ring Gear Expands or Warps	10	
2.4.2.2.3	Bearings Allow Ring Gear to Skew	30	
2.4.2.2.3.1	Bearing Fails	10	
2.4.2.2.3.2	Cover Fails Allowing Bearing to Move	5	
2.4.2.2.3.3	Bearing Retainer Fails	10	
2.4.2.2.3.4	Output Shaft Fails Allowing Bearing to Move	5	
2.4.2.2.4	Shaft Fails Allowing Ring Gear to Move	1	
2.4.2.2.5	Contaminants Lodge in the Gear Cover Clearance	20	
2.4.2.3	Reaction Gear Ring Gear Loads Increase		20
2.4.2.3.1	Ring Gear Fails	5	
2.4.2.3.2	Reaction Gear Fails	5	
2.4.2.3.3	Cont. Bind Gear Mesh	10	
2.4.2.4	Vane Load Levels Increase		360
2.4.2.4.1	Vanes Fail and Bind Motion	180	
2.4.2.4.2	Ring Gear Vane Sockets Fail	90	
2.4.2.4.3	Reaction Gear Vane Sockets Fail	90	
2.4.2.5	Ring Gear Output Gear Joint Fails		50
2.4.2.5.1	Ring Gear Fails	20	
2.4.2.5.2	Output Gear Fails	20	
2.4.2.5.3	Cont. in Gear Mesh	10	
2.4.2.6	Shaft Seal Fails Causing Friction		100
2.5	Control Drum Characteristics Change		EC 677559
3.0	Actuator Electrical Power Consumption Rate Exceeds Limits		60
3.1	Actuator/Amplifier External Cable Short Circuits		AGC
3.2	Actuator Amplifier Short Circuits		20
3.3	Mechanism Short Circuits Internally		40
3.3.1	Potentiometer Short Circuits	10	
3.3.2	Wiring Harness System Short Circuits	20	
3.3.3	Torque Motor Short Circuits	10	

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

The calibration process (Section 2.1.7.1.1) consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

2.3.7.2 Failure Mode Evaluation

A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts are not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component is analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another.⁽⁹⁾ The total number then indicates the relative reliability of the actuator concept; the lower the number, the more reliable the particular concept is relative to the others. Each concept is compared with the others on the basis of the total relative failure probability number. A failure mode analysis for the Dynavector proportional pneumatic actuator is shown in Table 2-13.

2.3.7.3 Safety Evaluation

The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and criticality ranking for each concept, failure modes are identified. For each of the failure modes listed, mechanisms of obtaining that failure mode are established as they relate to a particular design. Each of these failure mechanisms is given a numerical ranking consistent with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reductions in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.
1	Failures resulting in insignificant effects on chamber temperature/pressure.

TABLE 2-13

COMPONENT FAILURE MODES ANALYSIS

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY *RUC* COMPONENT Torque Motor DWG NUMBERS 939J955

W59150

Relative Ranking 210

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Torque motor characteristics change to bias its output to the full out or the full in position.	a. Pole piece breaks b. Bottom shunt breaks c. Top field piece breaks d. Magnet loses magnetic properties e. Armature assembly weld breaks f. Armature spring breaks g. Frame breaks h. Armature breaks i. Coil shorts or coil open (full in position failure only) j. Coil lead wire shorts or lead wires open (full in position failure only)	Start-up and Steady State	1 1 1 1 1 1 1 1 6 3
1.2	Torque motor characteristics change as to become unstable	a. Bottom shunt breaks b. Top field piece breaks c. Armature assembly weld breaks d. Armature spring breaks e. Frame breaks	Start-up and Steady State	Combined with b,c,e,f and g above.
2.1	Servo valve characteristics change to bias its output to the full out or the full in position.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P ₂ nozzle or P ₁ nozzle) c. Manifold breaks d. Nozzle seal surface damaged (P ₁ nozzle or P ₂ nozzle) e. Flapper screw breaks (P ₂ flapper or P ₁ flapper) f. Flapper lock loosens allowing flapper screw to move. (P ₂ screw lock or P ₁ screw lock)	Start-up and Steady State	1 1 1 1 1 1
2.2	Servo valve characteristics change to inhibit the operating range.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P ₂ nozzle or P ₁ nozzle) c. Flapper lock loosens allowing flapper screw to move. (P ₂ screw lock or P ₁ screw lock)	Start-up and Steady State	Combined with a,b,&f above

TABLE 2-13 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM ActuatorDATE APPROVED BY KCC COMPONENT Servo Valve DWG NUMBERS 939J955

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.3	Servo valve characteristics change to inhibit velocity control capability.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle)	Start-up and Steady State	Combined with a,b,c,&d above
3.1	Drive train mechanical load increases.	a. Shaft seal drags and increases friction b. Ping gear/output gear joint surface damage increases friction. c. Ring gear vane sockets surface damage increases friction. d. Reaction gear vane sockets damage increases friction. e. Vanes bind and increase friction f. Ring gear/reaction gear joint surface damage increases friction. g. Ring gear warps and drags on covers h. Reaction gear contracts and drags on covers i. Output shaft bearings increase friction	Steady State and Start-up	7 3 9 9 9 1 1 1 4

TABLE 2-13 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY KAC COMPONENT Drive Train DWG NUMBERS 939J955

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.2	Drive train jams in some position between full in and maximum operating range.	1. Output shaft breaks and allows bearing to go askew.	Steady State and Start-up	1
		2. Output shaft breaks and allows ring gear to go askew.		1
		3. Bearing retainer breaks		1
		4. Cover breaks allowing bearing to move		1
		a. Shaft seal breaks and jams mechanism		3
		b. Ring gear/output gear joint breaks and jams mechanism.		2
		c. Ring gear vane socket and vane seize, and jams mechanism.		9
		d. Reaction gear vane socket and vane seize, and jams mechanism.		9
		e. Ring gear/reaction gear joint breaks and jams mechanism.		1
		f. Ring gear warps and jams mechanism.		1
		g. Reaction gear contracts and jams mechanism.		1
		h. Output shaft bearings seize		2
		i. Output shaft breaks, allowing mechanism to jam.		1
		j. Bearing retainer breaks, allowing mechanism to jam.		1
3.3	Drive train fails to contain drive gas pressure so as to fail to provide output torque.	h. Bearing seat in cover breaks, allowing mechanism to jam.		1
		a. Ring gear breaks at interface with covers	Steady State and Start-up	1
		b. Vanes break		18
		c. Reaction gear seal surface damaged severely		1
		d. Ring gear breaks		1
		e. Reaction gear breaks		1

TABLE 2-13 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE _____ APPROVED BY R.G.C. COMPONENT Drive Train DWG NUMBERS 939J955

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.4	Drive train fails to provide output torque.	a. Ring gear/output gear joint breaks b. Output shaft breaks c. Shaft crowned spline joint breaks	Steady State and Start-up	8 2 1
4.1	Potentiometers fail to provide feedback signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open.	Start-up and Steady State	1 1 1 4
4.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft. c. Potentiometer mounting fasteners break or loosen. d. Potentiometers housing breaks	Start-up and Steady State	1 2 1 1
4.3	Potentiometers provide a single single constant position signal.	a. Potentiometers coupling with pinion output shaft breaks. b. Potentiometers bearings seize c. Potentiometers shaft breaks	Start-up and Steady State	1 1 1
4.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	1 1 8

TABLE 2-13 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Authority
 DATE APPROVED BY K.G.C. COMPONENT Covers DWG NUMBERS 9390955

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Code Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Covers fail to contain drive gas pressure as to bias the actuator to the full out position.	a. Front cover P_2 port to servo valve cracks and leaks. b. Front cover body breaks and leaks P_2 pressure. c. Back cover body breaks and leaks P_2 pressure.	Steady State and Start-up	1 1 1
5.2	Covers and fitting fail to contain drive gas pressure as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Front cover P_1 port to servo valve cracks and leaks. b. Front cover body breaks and leaks P_1 pressure. c. Back cover body breaks and leaks P_1 pressure. d. Front and back cover seal surfaces damaged. e. Front and back cover fasteners break or loosen. f. Port in front cover for drive gas inlet breaks and leaks. g. Seal surface in front cover for drive gas inlet fitting damages. h. Fitting seal surface damaged. i. Fitting breaks or loosens	Steady State and Start-up	1 1 1 1 1 1 1 1 1
5.3	Covers fail to contain coolant gas, increasing coolant gas consumption.	a. Back cover flange breaks b. Back cover interface seal surface damaged.	Steady State and Start-up	1 1

TABLE 2-13 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY KAC COMPONENT Seals, Working Fluid DWG NUMBERS 939J955

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full out position.	a. P_1 nozzle bottom seal leaks	Start-up and Steady State	3
6.2	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. P_1 nozzle top seal leaks b. P_2 nozzle top seal leaks c. P_2 nozzle bottom seal leaks d. Drive gas supply connector seal leaks e. Body to front cover seal leaks f. Body to back cover seal leaks	Start-up and Steady State	3 3 3 3 3 3
7.1	Coolant seals fail to contain gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range; and to increase coolant gas consumption.	a. Back cover interface seal leaks b. Output shaft seals leak c. Interface port seal leaks	Start-up and Steady State	3 3 1
8.1	V-Band clamp fails to maintain proper clamping force, resulting in increase coolant gas consumption.	a. Left or right hand bolt breaks or loosens b. Clamp loses spring gradient	Start-up and Steady State	1 1
9.1	Electrical wiring harness to torque motor fails to carry proper command signal.	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	1 2
9.2	Electrical wiring harness to potentiometers fail to carry feedback signal or fail to carry proper supply voltage.	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	1 2

By assigning each mechanism of failure to one of the above categories, and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-14 presents a tabulation of the failures, mechanism of failure and criticality ranking of failure for the Dynavector pneumatic actuator. Also shown is the total criticality ranking for this concept.

2.3.8 Discussion and Evaluation

Basically, this proposed NERVA concept utilizes a standard Dynavector actuator modified to accept a feedback potentiometer and a servovalve. The feedback potentiometer is the same as that developed in the XE program, but it could be designed to utilize the concentrically mounted potentiometers of the other pneumatic designs. The potentiometer will be isolated from induced shaft vibration by mounting with a bellows coupling. The potentiometer to be used in this concept is a first redesign of the XE version. The servovalve is the same design as shown in all the proportional pneumatic actuator concepts.

The concept of a pneumatic Dynavector actuator applied to the NERVA environment is, in essence, the crux of the problem. The only information available in regard to performance and capability of the basic unit is at elevated and/or ambient temperatures. No Dynavector has yet been critically subjected to the extreme operational conditions of hydrogen gas at 140°R or lower, or radiation, shock, or vibration.

A rather ambitious development program would be required to evaluate the ability of the Dynavector to withstand NERVA operation and environment. First, the vane-to-housing and vane-to-gear joints are regarded as highly susceptible to wear, binding and leakage. Second, the ability to control the critical clearance between the end caps and reaction gear must be present. This clearance must be controlled at a value of 4 to 6 ten thousandths to minimize drive gas leakage. The question immediately arises as to how well this clearance be maintained over a broad temperature operation as required in the NERVA project.

The present concept is not directly applicable to a 36 drum reactor design. In order to fit the space envelope of a 36 drum design, the concept of a concentric potentiometer, as

TABLE 2-14
COMPONENT SAFETY CRITICALITY

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
DATE APPROVED BY *RUC* COMPONENT Torque Motor DWG NUMBERS 939J955

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Torque motor characteristics change to bias its output to the full out or the full in position.	a. Pole piece breaks b. Bottom shunt breaks c. Top field piece breaks d. Magnet loses magnetic properties e. Armature assembly weld breaks f. Armature spring breaks g. Frame breaks h. Armature breaks i. Coil shorts or coil open (full in position failure only) j. Coil lead wire shorts or lead wires open (full in position failure only)	Start-up and Steady State	4 4 4 4 4 4 4 4 4 4
1.2	Torque motor characteristics change as to become unstable	a. Bottom shunt breaks b. Top field piece breaks c. Armature assembly weld breaks d. Armature spring breaks e. Frame breaks	Start-up and Steady State	2 2 2 2 2

TABLE 2-14 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY RCE COMPONENT Servo Valve DWG NUMBERS 939J955

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.1	Servo valve characteristics change to bias its output to the full out or the full in position.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged (P_1 nozzle or P_2 nozzle) e. Flapper screw breaks (P_2 flapper or P_1 flapper) f. Flapper lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	4 4 4 4 4 4
2.2	Servo valve characteristics change to inhibit the operating range.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Flapper ² lock loosens allowing flapper screw to move. (P_2 screw lock or P_1 screw lock)	Start-up and Steady State	2 2 2
2.3	Servo valve characteristics change to inhibit velocity control capability.	a. Valve mounting fasteners break or loosen b. Nozzle core breaks or moves out of position (P_2 nozzle or P_1 nozzle) c. Manifold breaks d. Nozzle seal surface damaged. (P_1 nozzle or P_2 nozzle)	Start-up and Steady State	1 1 1 1

TABLE 2-14 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator

DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 939J955

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.1	Drive train mechanical load increases.	a. Shaft seal drags and increases friction	Steady State and Start-up	2
		b. Ring gear/output gear joint surface damage increases friction.		2
		c. Ring gear vane sockets surface damage increases friction.		2
		d. Reaction gear vane sockets damage increases friction.		2
		e. Vanes bind and increase friction		2
		f. Ring gear/reaction gear joint surface damage increases friction.		2
		g. Ring gear warps and drags on covers		2
		h. Reaction gear contracts and drags on covers		2
		i. Output shaft bearings increase friction		2
		j. Output shaft breaks and allows bearing to go askew.	Steady State and Start-up	2
		k. Output shaft breaks and allows ring gear to go askew.		2
3.2	Drive train jams in some position between full in and maximum operating range.	l. Bearing retainer breaks		2
		m. Cover breaks allowing bearing to move		2
		a. Shaft seal breaks and jams mechanism	Steady State and Start-up	4
		b. Ring gear/output gear joint breaks and jams mechanism.		4
		c. Ring gear vane socket and vane seize, and jams mechanism.		4
		d. Reaction gear vane socket and vane seize, and jams mechanism.		4
		e. Ring gear/reaction gear joint breaks and jams mechanism.		4
		f. Ring gear warps and jams mechanism.		4

TABLE 2-14 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY K.C.C. COMPONENT Drive Train DWG NUMBERS 939J955

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
		d. Reaction gear contracts and jams mechanism.		4
		h. Output shaft bearings seize		4
		i. Output shaft breaks, allowing mechanism to jam.		4
		j. Bearing retainer breaks, allowing mechanism to jam.		4
		h. Bearing seat in cover breaks, allowing mechanism to jam.		4
3.3	Drive train fails to contain drive gas pressure so as to fail to provide output torque.	a. Ring gear breaks at interface with covers b. Vanes break c. Reaction gear seal surface damaged severely d. Ring gear breaks e. Reaction gear breaks	Steady State and Start-up	4 4 4 4 4
3.4	Drive train fails to provide output torque.	a. Ring gear/output gear joint breaks b. Output shaft breaks c. Shaft crowned spline joint breaks	Steady State and Start-up	4 4 4
4.1	Potentiometers fail to provide feedback signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open.	Start-up and Steady State	4 4 4 4
4.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft. c. Potentiometer mounting fasteners break or loosen. d. Potentiometers housing breaks	Start-up and Steady State	4 4 4 4

TABLE 2-14 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
DATE APPROVED BY KAC COMPONENT Potentiometers DWG NUMBERS 939J955

W59150

Node Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.3	Potentiometers provide a single single constant position signal.	a. Potentiometers coupling with pinion output shaft breaks. b. Potentiometers bearings seize c. Potentiometers shaft breaks	Start-up and Steady State	4 4 4
4.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	2 2 2
5.1	Covers fail to contain drive gas pressure as to bias the actuator to the full out position.	a. Front cover P_2 port to servo valve cracks and leaks. b. Front cover body breaks and leaks P_2 pressure. c. Back cover body breaks and leaks P_2 pressure.	Steady State and Start-up	4 4 4
5.2	Covers and fitting fail to contain drive gas pressure as to bias the actuator to the full in position, or to inhibit the actuator operat- ing range.	a. Front cover P_1 port to servo valve cracks and leaks. b. Front cover body breaks and leaks P_1 pressure. c. Back cover body breaks and leaks P_1 pressure. d. Front and back cover seal surfaces damaged. e. Front and back cover fasteners break or loosen.	Steady State and Start-up	4 4 4 4 4

TABLE 2-14 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY K.G.C. COMPONENT Covers DWG NUMBERS 939J955

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
		f. Port in front cover for drive gas inlet breaks and leaks.		4
		g. Seal surface in front cover for drive gas inlet fitting damages.		4
		h. Fitting seal surface damaged.		4
		i. Fitting breaks or loosens		4
5.3	Covers fail to contain coolant gas, increasing coolant gas consumption.	a. Back cover flange breaks b. Back cover interface seal surface damaged.	Steady State and Start-up	2 2
6.1	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full out position.	a. P_1 nozzle bottom seal leaks	Start-up and Steady State	4
6.2	Working fluid seals fail to contain drive gas pressure as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. P_1 nozzle top seal leaks b. P_2 nozzle top seal leaks c. P_2 nozzle bottom seal leaks d. Drive gas supply connector seal leaks e. Body to front cover seal leaks f. Body to back cover seal leaks	Start-up and Steady State	4 4 4 4 4 4
7.1	Coolant seals fail to contain gas pressure so as to bias the actuator to the full in position or to inhibit the actuator operating range; and to increase coolant gas consumption.	a. Back cover interface seal leaks b. Output shaft seals leak c. Interface port seal leaks	Start-up and Steady State	4 4 4

TABLE 2-14 (Continued)

DATE 8-13-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Actuator
 DATE APPROVED BY Roe COMPONENT Wiring Harness DWG NUMBERS 939J955

*59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
9.1	Electrical wiring harness to torque motor fails to carry proper command signal.	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	4 4
9.2	Electrical wiring harness to potentiometers fail to carry feedback signal or fail to carry proper supply voltage.	a. Harness wires short or open b. Connector pins short or open	Start-up and Steady State	4 4
8.1	V-Band clamp fails to maintain proper clamping force, resulting in increase coolant gas consumption.	a. Left or right hand bolt breaks or loosens b. Clamp loses spring gradient	Start-up and Steady State	4 4

shown in previous actuator concepts, would be utilized. This advances a question about the ability of such a potentiometer to operate with the induced vibratory motion of a Dynavector actuator output shaft.

Reliability estimates indicate that the pneumatic Dynavector actuator is not as reliable as the single piston rack and pinion design and, therefore, would offer no incentive for use. Little or no experience exists on this concept in the NERVA environment, which is to its disadvantage. The Dynavector proportional pneumatic actuator as pictured will fit on a 24 drum reactor concept. Redesign and repackaging may adapt it for a 36 drum concept. Its radial width at the control drum centerline is about 6.1 inches. Its height above the pressure vessel mounting boss is about 7 inches. Clearance required above the actuator for removal is 1.1 inches to clear the output shaft. Its weight is estimated to be about 11.9 pounds.

Coolant requirements for a one hour run at the heating rates estimated for NERVA, about 3 watts per pound, are less than 1/2 pound and can probably be eliminated. Maximum drive gas at 100°R and 215 psia for a one hour run is about 36 pounds. Electrical power is required to supply the amplifier and feedback potentiometer, but it is all in the control range and is considered small enough to be neglected for this study. A preliminary estimate of the concept reliability obtained by calibrating the fault tree is $.9_{5}83$. Table 2-15 lists some of the more significant advantages and disadvantages of the pneumatic Dynavector actuator.

TABLE 2-15

PNEUMATIC DYNAVECTOR ACTUATOR SUMMARY TABLE

<u>Advantages</u>	<u>Disadvantages</u>
1. Servovalve Design of Other Pneumatic Actuators is Directly Applicable.	1. Environmental Capabilities are Unknown.
2. Mechanism Weight is Low.	2. Ability to Seal H_2 Internally with Controlled Clearances Over Temperature Ranges Required and Wearing of Parts is Highly Questionable.
3. Mechanism Readily Remotely Removable.	3. Severe Weight Penalty Exists for the Drive Gas Startup Pneumatic Supply System Weight Required Due to Actuator Consumption of H_2 .
4. Highly Probable that No Coolant Gas Will Be Required.	4. Very Little Experience or Background Exists for this Design Applied to NERVA Environmental Conditions.
	5. Design not Applicable to a 36 Drum NSS. (May Be Redesigned to Fit).
	6. Servovalve Susceptible to Malfunction at Cryogenic Temperatures if H_2 Supply is not Free of Trace Gas Contaminants.
	7. Maintainability Factors are Unknown.
	8. Dynamic Shaft Seal Required at Mounting Pedestal Interface.
	9. Vibration Effects of Orbiting Ring Gear Unknown.

2.4 ELECTRIC STEPPING MOTOR PROPORTIONAL CONCEPT

The stepping motor is an electrical device which, when energized by a discrete, pulsed input signal, produces an output in discrete steps of rotary motion. Its angular displacement is bi-directional and is determined by the sequence in which the stator windings are pulsed.

There are two basic types of stepping motors. The first type operates on the reaction between an electromagnetic field and a permanent magnet rotor and is classified as a permanent magnet stepping motor (PM). The second type operates on the reaction between an electromagnetic field and soft iron rotor, similar to the electric solenoid action, and is classified as a variable reluctance stepping motor (VR).

Electric stepping motor technology has evolved during the past decade due primarily to the development of solid state electronic control devices, such as the SCR and TRIAC and the stringent performance and reliability requirements of the space program and computer software. The electric stepping motor has been used in many applications similar to NERVA. In the space program these motors have been used as positioning devices on the Ranger, Mariner, Surveyor, Lunar Orbiter and the OSO family of satellites, among others. The motors have been used as reactor control drum actuators in the Pratt and Whitney LCRE^(10, 11, 12) and SNAP-50 programs, the Atomics International SNAP-10A,^(13, 14, 15) SNAP-2⁽¹⁶⁾ and SNAP-8^(17, 18) reactors, and the Pewee nuclear studies, core furnace, and ZEPO reactors at LASL.⁽¹⁹⁾ The SNAP-10A SNAPSHOT program utilized PM stepping motors for the control drum actuators. This flight test, the only reactor in space operation ever attempted, was completely successful.⁽²⁰⁾ Succeeding programs such as SNAP-8 will continue to use stepping motors. Table 2-16 shows the NERVA expected radiation environment in comparison to those environments of other space programs.

TABLE 2-16

RADIATION ENVIRONMENT COMPARISON

	<u>NERVA</u>	<u>SNAP-10A</u>	<u>SNAP-8</u>
Operating Time	1 hour	2, 180 hours	12, 000 hours
Total Dose	2.3×10^{14} nvt (E ~ 1.0 Mev)	5.0×10^{18} nvt (E ~ 0.1 Mev)	1.0×10^{20} nvt (E ~ 0.1 Mev)
Gamma	1.8×10^6 R	5.5×10^9 R	3×10^{10} R

As a control drum actuator the electric stepping motor is characterized by its flexibility. It is an open loop mechanism which can be operated as part of a closed loop control system, if desired. Control is digital and exact with the output shaft moving in equal incremental steps. Resolution is less than 0.1 degree and accuracy can be better than ± 3 minutes, non-accumulative. The rate of change of position is variable and simply programmed as long as rated torque values are not exceeded.

The inherent reliability of the stepping motor is perhaps the principle advantage of its application. Relative to other electric motors the stepping motor has fewer moving parts, a simple, solid, lightweight rotor, no electrically functional friction surfaces, no rotor insulation requirements, and all low speed rotating bearing components.

2.4.1 Responsyn Concept

2.4.1.1 Mechanical Description

The Responsyn stepping motor actuator is shown in Figure 2-17. This variable reluctance stepping motor is a special adaptation of the Harmonic drive power transmission system. The motor is manufactured by USM for industrial and commercial application. While this motor has not been used extensively in space and nuclear applications, the Harmonic drive transmission system, the major component of the motor, has been successfully employed in aerospace and nuclear programs.

Figure 2-17. Proposed Electrical Control Drum Actuator, Responsyn Concept

The actuator consists of four subsystems.

- 1) Drive subsystem
- 2) Feedback subsystem
- 3) Coolant subsystem
- 4) Housing enclosure subsystem

2.4.1.1.1 Drive Subsystem. The drive subsystem, functionally depicted in Figure 2-18, employs three basic elements.

- 1) A rigid, internally splined circular spline
- 2) A non-rigid, externally splined flexspline
- 3) A wave generator

The flexspline is smaller than the circular spline and has fewer spline teeth. The wave generator provides a radial deflecting force to the flexspline. In conventional mechanical Harmonic drive, as used in other control drum actuator concepts, the wave generator takes the form of an ellipsoidal cam and is surrounded by an anti-friction bearing which deflects the non-rigid flexspline so that it mates with the circular spline at two equally spaced areas 180 degrees apart on their respective circumferences. In the Responsyn stepping motor, the wave generator takes the form of a discretely rotating magnetic field, created by sequentially energizing eight salient poles in diametrically opposed pairs. The magnetic field attracts the magnetic backing of the flexspline to the energized pole faces, thus deflecting the flexspline and drawing the flexspline and circular spline into engagement in the energized pole areas. The rotating position of the magnetic field causes a corresponding rotation in the mesh of the splines. As the field makes one complete rotation, the flexspline rotates in the opposite direction through a distance equal to the difference between the pitch circumference of the circular spline and that of the flexspline. The flexspline is directly coupled by its end plate to the output shaft of the actuator. The difference between the two pitch circumferences is small, thus the high-speed rotation of the magnetic field is directly converted into a rotary output having greatly reduced speed and increased torque.

Figure 2-18. Responsyn Stepping Motor

2.4.1.1.2 Feedback. Feedback of actuator output shaft position to the control amplifier is accomplished through a three deck potentiometer. This device provides triple redundancy to the position feedback signal. Each deck is electrically independent. The potentiometer is assembled concentrically with the main output shaft of the actuator and uses the main actuator bearings for alignment. This feature produces the simplest assembly and eliminates many parts required in separately mounted potentiometers. The potentiometer is assembled and aligned on the output shaft by the manufacturer to eliminate the possibility of error in assembly.

2.4.1.1.3 Coolant Gas. Coolant gas is taken from the propellant line downstream of the turbopump at approximately 900 psia, passed through the actuator and exhausted into the reactor dome at approximately 700 psia.

2.4.1.1.4 Housing. The housing ties together all of the functional parts of the actuator. All electric power, input command signals and output position signals enter and exit the actuator by way of the electrical connector.

2.4.1.1.5 Variation. A variation of the Responsyn actuator just discussed is shown in Figure 2-19. This actuator utilizes a smaller Responsyn motor and incorporates a single pass planetary gear train to more nearly match the motor's output characteristics to that required by the load. This matching provides a Responsyn concept actuator which meets the required performance characteristics with less input power required than for the direct drive unit.

2.4.1.2 System Description

The Responsyn stepping motor is shown incorporated in the Control Drum Actuator System (CDAS) in Figure 2-20. The motor converts a digital, electrical format into uniform, discrete drum angle positions within the resolution requirements of the CDAS. The digital format is a four-bit cyclic binary code in which two adjacent bits are in the ON state while the other two are in the OFF state. The ON state represents a constant current in a particular phase winding of the Responsyn motor while the OFF state represents no current.

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Figure 2-19. Proportional Electric Control Drum Actuator - Responsyn Concept with an Additional Planetary Reduction

Figure 2-20. Responsyn Electrical Stepping Motor Proportional Actuator System Direct Drive

Table 2-17 is an example of eight consecutive steps coded in such a way as to cause the drum to move four steps in the direction of increasing reactivity and then return to its original position. A code of 1 represents an ON state and a 0 an OFF state.

TABLE 2-17
DRUM POSITIONING CODE

<u>Step Number</u>	<u>Code</u>	<u>Angular Change</u>	<u>Drum Angle</u>
0	1100	0	θ
1	0110	+ 1	$\theta + 1$
2	0011	+ 1	$\theta + 2$
3	1001	+ 1	$\theta + 3$
4	1100	+ 1	$\theta + 4$
5	1001	- 1	$\theta + 3$
6	0011	- 1	$\theta + 2$
7	0110	- 1	$\theta + 1$
8	1100	- 1	θ

The actuator output shaft angular position is measured by an angular position indicator. This device converts angular position into an equivalent electrical signal. The actuator output shaft is coupled to the control drum by means of a drive shaft.

The Responsyn motor receives the digital, electrical currents from a code generator. The code generator is able to change and maintain the binary code in response to a pulsed input signal. The direction of drum angle command change is given by the polarity of the pulses. The magnitude of the commanded change is given by the number of pulses. The rate at which drum angle is commanded to change is determined by the frequency of the pulses.

Because of the precise angular positioning ability of the Responsyn motor the drum bank may be programmed to move to a predetermined angle (drum worth). This can be accomplished by counting the number of pulses delivered to the code generator. In this manner, the Responsyn actuator may be operated as an open loop system since the angular change and the rate of angular change are both controllable. In the open loop system the code generator input

pulses would be in proportion to the temperature or power errors or the derivatives of these errors. The Responsyn actuator may also be operated as a closed loop system where the input pulses are in proportion to the difference between drum position command and position indicator output.

An example of the closed loop control system for a stepping motor is shown in Figure 2-21. In this example the drum position command is in the form of an analog voltage which is proportional to angular position. The command signal is compared with the drum position readout (also an analog voltage) to obtain an error signal. Digital information is taken from the error signal by the sign detector. The relationship between the sign detector input (θ_e) and the output ((+) and (-)) is given in Table 2-18.

TABLE 2-18

SIGN DETECTOR INPUT AND OUTPUT

If	Then
$\theta_e > 1/2 \theta_s$	(+) = 1, (-) = 0
$ \theta_e < 1/2 \theta_s$	(+) = 0, (-) = 0
$\theta_e < -1/2 \theta_s$	(+) = 0, (-) = 1

The term θ_s is the resolution and has a minimum of one step angle. The sign detector outputs are used to control the clock gates. If either (+) or (-) is a 1, a clock gate is opened and pulses from the clock generator are fed into the code generator. The code generator steps the motor in the direction which causes the error to come within the resolution band. Once within the resolution band, both gates are closed and the motor holds its position.

Electrical power is supplied to the actuator controller. Coolant gas is supplied to the actuator and exhausted into the pressure vessel. The coolant gas must be at a higher pressure than the chamber at all times. The coolant gas flow can be regulated to control the temperature of the actuator and, thereby, reduce the effects of thermal expansion and contraction caused by extreme temperature changes.

Estimated electrical power requirements for the Responsyn stepping motor are from the manufacturer's specifications. The direct drive concept motor requires 100 watts and the planetary gear concept requires 30 watts.

Figure 2-21. Closed Loop Stepping Motor, Proportional Actuator System

2.4.1.3 Radiation Evaluation

Table 2-1 of Section 2.1.3 provides the radiation environment at the proposed actuator location forward of the pressure vessel closure. As those values describe the environment in the absence of perturbation by the actuator itself, they apply equally to all of the actuator concepts at this location. In most instances the presence of the actuator will reduce the levels, so that the use of the unperturbed numbers is generally conservative.

2.4.1.4 Thermal Evaluation

The radiation heating environment of the proposed electrical control drum actuator Responsyn concept is similar to that of the other candidate actuators. It is expected that in this low heating rate environment, the actuator structure and components may be adequately cooled. The coolant requirements will vary as the size and weight of the actuator and its internal heat generation rate vary.

The electrical control drum actuator shows pump discharge bleed at 55°R as the H₂ coolant. The thermal transient problems in this instance may be more severe than previous pneumatic actuators which used reactor dome H₂ bleed for coolant.

The electric actuator also has heavy iron or steel masses in the motor rotor and thick stator coils and metal poles which will require adequate cooling. These heavy sections appear to be capable of being designed to assure thermal adequacy in the operating environment.

The Responsyn stepping motor incorporates a flexspline power and gear reduction transmission system. This flexspline would be operating in a cryogenic environment. Care in selection of material used in this component will be required, as it is a component with cycling loads imposed on it at cryogenic conditions in a nuclear radiation field.

The alternate to the flexspline is a planetary gear assembly. A concern one may have in this type of operation is the effect on alignment and gear wear of thermal expansion variation from ambient (or above ambient) temperature to cryogenic temperature at which the planetary gear will be required to operate.

2.4.1.5 Structural Evaluation

The basic difference between the pneumatic actuators and the electric actuators is the method of supplying torque to the drive shaft. The drive gas and servovalve assembly, which are required in the pneumatic actuators, are eliminated in the electric actuator concepts. The Responsyn stepping motor actuator consists of three main assemblies, feedback potentiometer, drive assembly, and housing enclosure.

The feedback potentiometer is primarily an electrical device used to measure drum position and no structural problems are anticipated.

The basic component in the drive assembly of this actuator is the Responsyn stepping motor. The major structural components which actually form the transmission are a rigid, internally splined circular spline, a non-rigid, extremely splined flexspline, and a wave generator which deflects the flexspline. If this design is selected, these structural components will be analyzed in detail and the structural reliability of the complete stepping motor should be determined by component testing. A potential problem area may be in the selection of a suitable material for the cryogenic operation of the flexspline.

In Figure 2-17, the motor output shaft is splined directly to the drive shaft; whereas, in Figure 2-19, the Responsyn actuator incorporates a speed reducer between the motor output shaft and the drive shaft. The speed reducer is a single pass planetary gear train. If the Responsyn actuator in Figure 2-19 is selected, the bending stresses, contact stresses, fatigue life, surface wear, material selection and thermal distortions of the gears will be considered in depth.

The housing enclosure for the Responsyn actuator is in general similar to that of the rack and pinion pneumatic actuator discussed in Section 2.1.5. Cooling gas is supplied to the Responsyn actuator housing directly from the propellant line. The maximum pressure is expected to be 900 psia instead of 700 psia as in the pneumatic actuators. Therefore, the Responsyn actuator housing must be thicker than the rack and pinion actuator housing to contain the increased cooling gas pressure. If the Responsyn actuator is selected, the major areas of structural analysis concern will include mechanical and thermal stresses in the housing enclosure and the flange bolt loads and stresses. Proof tests should be performed on the asymmetrical housing enclosure to confirm the analytical stress analysis.

A Marmon clamp is used at the interface flange of the actuator housing in Figure 2-17 instead of bolts which are used in the Figure 2-19 design. The clamping load and stresses in a Marmon clamp are difficult to analytically predict because they are greatly influenced by the friction forces in the mating parts at assembly. Component tests should be performed to determine the loads and stresses in the clamp.

2.4.1.6 Radiation Effects Evaluation

The total expected radiation environment to which this actuator will be subjected is given in Section 2.1.3. To assess the effects of this environment on the actuator, a comparison of known test environments with this expected environment will indicate the sensitivity of any given concept to successful operation in the expected radiation levels. The sensitive components in this concept are the motor coils, the potentiometer, the shaft seals, and the electrical insulation and potting compounds. All other materials used in the construction of the actuator are metals. Although detail designs are not available, final material selection will be made from lists of qualified materials or will be separately qualified.

2.4.1.6.1 Motor Coils. Although motors have not been directly tested on the NERVA program, tests on other devices give important information concerning the expected performance of motor winding rails in a radiation environment. The electric coils contained in a pneumatic actuator torque motor and in the lock shut-off solenoid are similar to those used in electric motor construction. Tests conducted in a radiation environment at the GTR facility, during the NRX-A6 pneumatic actuator side-by-side test, and tests conducted by the Lewis Research Center at the Plum Brook Reactor all included the electric coils mentioned above. No coil anomalies were reported during any of these tests.⁽⁴⁾ However, it is planned to take advantage of improvements in the state-of-the-art in insulation materials and use the polyimide series for future coil insulations to further improve radiation tolerance and increase coil reliability.

2.4.1.6.2 Potentiometer. A prototype potentiometer was also included in the tests described in the above section. A reported failure in the Lewis tests⁽⁴⁾ caused some concern until a subsequent post-irradiation examination revealed the failure was caused by a softening

and flowing of a potting compound not included in the GTR and NRX-A6 tests. The material that failed was used in very early model potentiometers but has been removed. Future controls will assure using only those specified materials that will not be subject to property changes under radiation environment.

2.4.1.6.3 Shaft Seals, Electrical Insulation and Potting Materials. Although these items and materials are adequate for use in the NERVA environment, it is planned to take advantage of the improvements in the state-of-the-art in insulation materials. Polyimide materials will be used in wire insulation and potting materials to increase radiation tolerance and reliability.

2.4.1.7 Reliability and Safety Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliability of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale from 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection, assembly and testing the identified component's ability to perform during its useful life installed in the actuator. The number 100 represents the most difficult level and the number 1, has the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event identified on the tree and has assigned a relative weighting number to each failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-22 shows in summary form the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific components within the actuator concept that contribute to the main block failure. The numbers in parentheses are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A tabular listing of the failure events is shown in Table 2-19. These failure events are located in the fault tree by their identifying numbers which appear above the blocks on the fault tree. The events are listed in an indented manner which also indicates levels on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the subtotals progress toward the right of the page.

The final total of the weighted numbers (1048) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree are indicated in parentheses in the blocks of the summary fault tree, Figure 2-22. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

The calibration process (Section 2.1.7.1.1) consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability

Figure 2-22. Summary Fault Tree, Responsyn Stepping Motor Electric Actuator

TABLE 2-19
DETAILED FAULT TREE ANALYSIS

Direct Drive Responsyn Stepping Motor Proportional Electric Actuator Reliability
Fault Tree Analysis 939J953 Estimated Reliability 9₅89

1048

1. Actuator Coolant Gas Consumption Exceeds Specified Limits		95
1.1 Actuator Housing Fails to Contain Coolant Gas		55
1.1.1 Cover Fails to Contain Coolant Gas	5	
1.1.2 Cover to Body Interface Joint Fails	9	
1.1.2.1 Seal Fails	6	
1.1.2.2 Cover Fasteners Fail	3	
1.1.3 Housing Body Fails to Contain Coolant Gas	1	
1.1.4 Electrical Connector Fails to Contain Gas	40	
1.1.4.1 Seal Fails	30	
1.1.4.2 Fasteners Lose Clamping Force	5	
1.1.4.3 Connector Body Fails to Contain Gas	5	
1.2 Housing to Pedestal Interface Fails to Contain Gas		40
1.2.1 Interface Inlet Coolant Seal Fails	30	
1.2.2 Fasteners Lose Clamping Force	5	
1.2.3 Interface Exhaust Coolant Passage Seal Fails	5	
2. Actuator Fails to Position Control Drum Within Time Position Band		871
2.1 Actuator Fails to Convert Electrical to Mechanical Power		131
2.1.1 Electrical Connector Fails to Transmit Proper Signal	10	
2.1.1.1 Conductor Fails to Transmit Signal	5	
2.1.1.2 Insulator Fails Permitting Short Circuit	5	

TABLE 2-19 (Continued)

2.1.2	Motor Fails Electrically		86
2.1.2.1	Wiring Failure	80	
2.1.2.2	Pole Pieces Break	1	
2.1.2.3	Flexspline Magnetic Properties Deteriorate	5	
2.1.3	Actuator Internal Wiring Harness Fails		35
2.1.3.1	Conductor Fails	5	
2.1.3.2	Insulation Fails	25	
2.1.3.3	Terminal Mechanically Fails	5	
2.2	Improper Command Received from Amplifier		279
2.2.1	Amplifier Control Voltage Incorrect		AGC
2.2.2	Amplifier Fails Internally		30
2.2.3	Amplifier Feedback Signal Incorrect		249
2.2.3.1	Potentiometer Supply Voltage Wrong Value	30	
2.2.3.1.1	Actuator System Wiring Harness Fails	30	
2.2.3.1.2	Voltage Supplied is in Error	AGC	
2.2.3.2	Feedback Potentiometer Output Fails		154
2.2.3.2.1	Potentiometer Electrically Fails	101	
2.2.3.2.1.1	Track Resistance Value Changes	10	
2.2.3.2.1.2	Protective Resistor Changes Value	10	
2.2.3.2.1.3	Wiper Resistance Value Changes	1	
2.2.3.2.1.4	Wiper to Track Contact Resistance Changes	80	
2.2.3.2.2	Angular Relationship Pot to Drum Changes		21
2.2.3.2.2.1	Pot Position Relative to Shaft Changes	20	
2.2.3.2.2.2	Shaft Relative to Drum Changes	1	

TABLE 2-19 (Continued)

2.2.3.2.3	Potentiometer Mechanically Fails	32	
2.2.3.2.3.1	Potentiometer Shaft Fails	1	
2.2.3.2.3.2	Wiper Spring Gradient Changes	1	
2.2.3.2.3.3	Bearings Fail	10	
2.2.3.2.3.4	Potentiometer Housing Fractures	20	
2.2.3.3	Feedback Signals Transmitted Improperly		65
2.2.3.3.1	Wiring Harness Pedestal to Amplifier Fails	AGC	
2.2.3.3.2	Pedestal Wiring Harness Fails	30	
2.2.3.3.3	Mechanism Wiring Harness Fails	30	
2.2.3.3.4	Electro-Magnetic Interference Distorts Signal	5	
2.3	Actuator External Control Drum Loads Change		EC 677559
2.4	Actuator Internal Loads Change		461
2.4.1	Flexspline Fails to Transmit Sufficient Torque		260
2.4.1.1	Teeth Fail to Transmit Torque		150
2.4.1.1.1	Teeth Break	100	
2.4.1.1.2	Teeth Wear	50	
2.4.1.2	Fastener Interferes with Motion		10
2.4.1.3	Laminations Fail		20
2.4.1.3.1	Laminations Crack or Buckle	10	
2.4.1.3.2	Magnetic Material to Cup Bond Breaks	10	
2.4.1.4	Cup Fails to Transmit Motion		80
2.4.1.4.1	Weld Fails	30	
2.4.1.4.2	Cup Breaks	50	
2.4.2	Motor Fails Mechanically to Provide Sufficient Torque		91
2.4.2.1	Spline Mesh Friction Increases		5
2.4.2.2	Fasteners Interfere with Motion		10

TABLE 2-19 (Continued)

2.4.2.3	Stator Wiring Interferes with Motion	76	
2.4.2.3.1	Actuator Housing Distorts	1	
2.4.2.3.2	Stator Potting Material Deteriorates	10	
2.4.2.3.3	Conductor at I.D. of Motor Breaks	5	
2.4.2.3.4	Pole Pieces Break	60	
2.4.3	Output Shaft-Pot Bearings Friction Level Increases		70
2.4.4	Output Shaft Fails to Transmit Torque		40
2.4.4.1	Teeth Break	10	
2.4.4.2	Shaft Breaks	20	
2.4.4.3	Cup to Shaft Coupling Fails	10	
3.	Actuator Electrical Power Rate Exceeds Specified Limits		82
3.1	Actuator Short Circuits		41
3.1.1	Potentiometer Internal Short Circuit	10	
3.1.2	Stator Wiring Insulation Fails Allowing Short Circuit	10	
3.1.3	Wiring Harness System Short Circuits	21	
3.1.3.1	Interface Connector Short Circuits	10	
3.1.3.2	Wiring Insulation Fails	10	
3.1.3.3	Terminal Fails	1	
3.2	Amplifier Internal Short Circuit		20
3.3	Pedestal Short Circuit Failure		21
3.3.1	Wiring Insulation Fails Permitting Short Circuit	10	
3.3.2	Terminal Mechanical Failure	1	
3.3.3	External Connector Fails Allowing Short Circuit	10	
3.4	Amplifier/Actuator External Cable Short Circuit Failure		AGC

of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

Also included in this section is the fault tree generated for the Responsyn planetary gear concept. The final total of the weighted numbers for this concept (1271) appears at the head of the fault tree listing and summary fault tree for this concept. Figure 2-23 is the summary fault tree for the Responsyn planetary concept and the tabular listing is presented in Table 2-20.

2.4.1.7.1 Failure Mode Evaluation. A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts are not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component is analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another.⁽⁹⁾ The total number then indicates the relative reliability of the actuator concept; the lower the number, the more reliable the particular concept is relative to the others. Each concept is compared with the others on the basis of the total relative failure probability number. The failure mode analysis for the direct drive

Figure 2-23. Summary Fault Tree, Responsyn Electric Stepping Motor - Planetary Drive

TABLE 2-20
DETAILED FAULT TREE ANALYSIS

Responsyn Planetary Drive Stepping Motor Proportional Electric Actuator Reliability
Fault Tree Analysis 939J952 Estimated Reliability 9₅87.

1271

1. Actuator Coolant Gas Consumption Exceeds Specified Limits		123
1.1 Actuator Housing Fails to Contain Coolant Gas		15
1.1.1 Cover Fails to Contain Coolant Gas	5	
1.1.2 Cover to Body Interface Joint Fails	9	
1.1.2.1 Seal Fails	6	
1.1.2.2 Cover Fasteners Fails	3	
1.1.3 Housing Body Fails to Contain Coolant Gas	1	
1.2 Housing to Pedestal Interface Fails to Contain Gas		40
1.2.1 Interface Inlet Coolant Seal Fails	30	
1.2.2 Fasteners Lose Clamping Force	5	
1.2.3 Interface Exhaust Coolant Passage Seal Fails	5	
1.3 Actuator Pedestal Fails to Contain Coolant Gas		68
1.3.1 Weld Fails	15	
1.3.2 Inlet Line Connector Joint Fails to Contain Gas	12	
1.3.2.1 Seal Fails	5	
1.3.2.2 Connector Loosens	7	
1.3.3 Housing Body Ruptures	1	
1.3.4 Electrical Connector Joint Fails to Contain Gas	40	
1.3.4.1 Seal Fails	30	
1.3.4.2 Fasteners Fail	5	
1.3.4.3 Connector Body Fails	5	
2. Actuator Fails to Position Control Drum Within Time Position Band		1066

TABLE 2-20 (Continued)

2.1	Actuator Fails to Convert Electrical to Mechanical Power		131
2.1.1	Electrical Connector Fails to Transmit Proper Signal		10
2.1.1.1	Conductor Fails to Transmit Signal	5	
2.1.1.2	Insulator Fails Permitting Short Circuit	5	
2.1.2	Motor Fails Electrically		86
2.1.2.1	Wiring Failure	80	
2.1.2.2	Pole Pieces Break	1	
2.1.2.3	Flexspline Magnetic Properties Deteriorate	5	
2.1.3	Actuator Internal Wiring Harness Fails		35
2.1.3.1	Conductor Fails	5	
2.1.3.2	Insulation Fails	25	
2.1.3.3	Terminal Mechanically Fails	5	
2.2	Improper Command Received from Amplifier		279
2.2.1	Amplifier Control Voltage Incorrect		AGC
2.2.2	Amplifier Fails Internally		30
2.2.3	Amplifier Feedback Signal Incorrect		249
2.2.3.1	Potentiometer Supply Voltage Wrong Value	30	
2.2.3.1.1	Actuator System Wiring Harness Fails	30	
2.2.3.1.2	Voltage Supplied is in Error	AGC	
2.2.3.2	Feedback Potentiometer Output Fails	154	
2.2.3.2.1	Potentiometer Electrically Fails	101	
2.2.3.2.1.1	Track Resistance Value Changes	10	
2.2.3.2.1.2	Protective Resistor Changes Value	10	
2.2.3.2.1.3	Wiper Resistance Value Changes	1	
2.2.3.2.1.4	Wiper to Track Contact Resistance Changes	80	
2.2.3.2.2	Angular Relationship Pot to Drum Changes	21	

TABLE 2-20 (Continued)

2.2.3.2.2.1	Pot Position Relative to Shaft Changes	20		
2.2.3.2.2.2	Shaft Relative to Drum Changes	1		
2.2.3.2.3	Potentiometer Mechanically Fails	32		
2.2.3.2.3.1	Potentiometer Shaft Fails	1		
2.2.3.2.3.2	Wiper Spring Gradient Changes	1		
2.2.3.2.3.3	Bearings Fail	10		
2.2.3.2.3.4	Potentiometer Housing Fractures	20		
2.2.3.3	Feedback Signals Transmitted Improperly		65	
2.2.3.3.1	Wiring Harness Actuator to Amplifier Fails	AGC		
2.2.3.3.3	Mechanism Wiring Harness Fails	30		
2.2.3.3.4	Electro-Magnetic Interference Distorts Signal	5		
2.2.3.3.2	Pedestal Wiring Harness Fails	30		
2.3	Actuator External Control Drum Loads Change			EC
2.4	Actuator Internal Loads Change			656
2.4.1	Flexspline Fails to Transmit Sufficient Torque		275	
2.4.1.1	Teeth Fail to Transmit Torque		150	
2.4.1.1.1	Teeth Break	100		
2.4.1.1.2	Teeth Wear	50		
2.4.1.2	Fastener Interferes with Motion		10	
2.4.1.3	Magnetic Material Characteristics Change		20	
2.4.1.3.1	Laminations Crack or Buckle	10		
2.4.1.3.2	Magnetic Material to Cup Bond Breaks	10		
2.4.1.4	Cup Fails to Transmit Motion		80	
2.4.1.4.1	Weld Fails	30		
2.4.1.4.2	Cup Breaks	50		
2.4.2	Motor Fails Mechanically		91	
2.4.2.1	Spline Mesh Friction Increases		5	

TABLE 2-20 (Continued)

2.4.2.2	Fasteners Interfere with Motion	10	
2.4.2.3	Stator Wiring Interferes with Motion	76	
2.4.2.3.1	Actuator Housing Distorts	1	
2.4.2.3.2	Stator Potting Material Deteriorates	10	
2.4.2.3.3	Conductor at I.D. of Motor Breaks	5	
2.4.2.3.4	Pole Pieces Break	60	
2.4.3	Output Shaft-Pot Bearings Friction Level Increases		70
2.4.4	Output Shaft Fails to Transmit Torque		30
2.4.4.1	Teeth Break	10	
2.4.4.2	Shaft Breaks	20	
2.4.5	Motor to Transmission Coupling Fails		80
2.4.5.1	Bearing Fails	50	
2.4.5.2	Coupling Gear Teeth Fail/Wear	10	
2.4.5.3	Fastener Loses Clamping Force	20	
2.4.6	Power Transmission Fails		125
2.4.6.1	Spider Fails	20	
2.4.6.2	Bearing Retainer Fails	5	
2.4.6.3	Driver Gear Teeth Wear/Fail	5	
2.4.6.4	Fastener Loses Clamping Force	5	
2.4.6.5	Bearing Fails	60	
2.4.6.6	Planet Gear Teeth Wear/Fail	30	
3.	Actuator Electrical Power Rate Exceeds Specified Limits		82
3.1	Actuator Short Circuits		41
3.1.1	Potentiometer Internal Short Circuit	10	
3.1.2	Stator Wiring Insulation Fails Allowing Short Circuit	10	
3.1.3	Wiring Harness System Short Circuits	21	

TABLE 2-20 (Continued)

3.1.3.1 Interface Connector Short Circuits	10	
3.1.3.2 Wiring Insulation Fails	10	
3.1.3.3 Terminal Fails	1	
3.2 Amplifier Internal Short Circuit		20
3.3 Pedestal Short Circuit Failure		21
3.3.1 Wiring Insulation Fails	10	
3.3.2 Terminal Mechanical Failure	1	
3.3.3 External Connector Short Circuit	10	
3.4 Amplifier/Actuator External Cable Short Circuit Failure		AGC

Responsyn actuator is shown in Table 2-21. A similar failure mode analysis for the Responsyn planetary drive actuator is shown in Table 2-22.

2.4.1.7.2 Safety Evaluation. The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and criticality ranking for each concept, failure modes have been identified. For each of the failure modes listed, mechanisms of obtaining that failure mode are established as they relate to a particular design and each of these failure mechanisms is given a numerical ranking consistent with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reduction in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.
1	Failures resulting in insignificant effects on chamber temperature/pressure.

By assigning each mechanism of failure to one of the above categories, and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-23 presents a tabulation of the failures, mechanism of failure and criticality ranking of failure for the Responsyn direct drive

TABLE 2-21

COMPONENT FAILURE MODES ANALYSIS

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE APPROVED BY RUC COMPONENT Reposyn Motor DWG NUMBERS 939J461
(Direct Drive)

W59150

Relative Ranking 122

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Motor fails electrically so as to produce no output torque.	a. Coil wiring opens or shorts b. Pole pieces break c. Permanent magnet material bond to flex cup breaks d. Loss of permanent magnet properties.	Steady State and Start up	8 1 2 1
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Pole pieces break and jam motor b. Potting compound fails, allowing coils to jam between stator and rotor. c. Stator coil at inside diameter breaks and jams between stator and rotor. d. Flexspline gear teeth bind or break e. Flex cup breaks	Steady State and Start up	6 1 1 10 8
2.1	Drive train mechanical load increases	a. Output shaft bearings bind and increase friction.	Steady State	6
2.2	Drive train jams in some position between full in and the maximum operating range.	a. Output shaft bearings seize	Steady State and Start up	2
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Crown spline breaks c. Joint between output shaft and flex cup breaks.	Steady State and Start up	2 1 1

TABLE 2-21 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act
 DATE APPROVED BY RAC COMPONENT Potentiometers DWG NUMBERS 9391461

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Potentiometers fail to provide feedback signal.	a. All potentiometer tracks short out or open. b. All potentiometer wipers short out or open. c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start up and Steady State	1 1 1 4 2
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start up and Steady State	1 2
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start up and Steady State	1 1 8
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen	Steady State and Start up	1 1 1 1 1

TABLE 2-21 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY RCC COMPONENT Seals, Coolant DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks	Steady	3
		b. Coolant passage interface seal leaks	State	3
		c. Housing to cover seal leaks	and	3
		d. Electrical receptical seals leaks	Start	6
		e. Coolant supply connector seal leaks	up	3

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY RCC COMPONENT V-Band Clamp DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	V-Band clamp fails to maintain proper clamping force.	a. Left or right hand bolt breaks or loosens	Steady	1
		b. Clamp loses spring gradient	State and Start up	1

TABLE 2-21 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State	4 3
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start up	3 5
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Steady State and Start up	2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT Mounting Pedestal DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
8.1	Pedestal fails to contain coolant gas pressure.	a. Pedestal body breaks b. Pedestal interface seals surface damaged c. Electrical receptacle seals surfaces damaged. d. Seal weld breaks e. Coolant supply connector breaks or loosens	Steady State and Start up	1 1 1 1 1

TABLE 2-22
COMPONENT FAILURE MODES ANALYSIS

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE _____ APPROVED BY RAC COMPONENT Responsyn Motor DWG NUMBERS 939J562
(Planetary Drive)

W59150

Relative Ranking 135

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Motor fails electrically so as to produce no output torque.	a. Coil wiring opens or shorts b. Pole pieces break c. Permanent magnet material bond to flex cup, breaks d. Loss of permanent magnet properties	Steady State and Start-up	8 1 2 1
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces break and jams motor c. Flexspline gear teeth bind or break d. Potting compound fails, allowing coils to jam between stator and rotor e. Stator coil at inside diameter breaks and jams between stator and rotor. f. Flex cup breaks	Steady State and Start-up	6 6 10 1 1 8

TABLE 2-22 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.1	Drive train mechanical load increases.	a. Output shaft bearings bind and increase friction. b. Driving gear teeth surface damage increases friction. c. Planet gears teeth surface damage increases friction. d. Ring gear teeth surface damage increases friction. e. Needle bearing binds and increases friction f. Planet gears thrust washers bind and increase friction. g. Bearing retainer fails h. Retainer fasteners break or loosen i. Output shaft gear flanges break	Steady State and Start-up	6 1 1 1 3 1 1 1 2
2.2	Drive train jams in some position between full in and the maximum operating range.	a. Output shaft bearings seize b. Driving gear to planet gears teeth jam c. Ring gear to planet gears teeth jam d. Needle bearing seizes e. Planet gears thrust washers seize f. Bearing retainer breaks g. Output shaft gear flanges break and jam	Steady State and Start-up	2 1 1 1 1 1 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti / DEPARTMENT Reliability SUBSYSTEM Control Drum ActDATE _____ APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Shaft spline breaks c. Coupling, between motor shaft and gear, breaks.	Steady State and Start-up	2 1 2

TABLE 2-22 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY *RAE* COMPONENT Potentiometers DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 4 2
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	1 2
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start-up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	1 1 8

TABLE 2-22 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Housing and Cover DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged. c. Cover breaks d. Cover seal surface damaged. e. Cover fasteners break or loosen	Steady State and Start-up	1 1 1 1 1

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Seals, Coolant DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	1 3 1 3 3

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Mounting Bolts DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	Mounting bolts fail to maintain proper clamping force.	a. Bolt breaks or loosens	Start-up and Steady State	1

TABLE 2-22 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.

DATE _____ APPROVED BY RAC COMPONENT Wiring Harness DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	4 2
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	3 4
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Steady State and Start-up	1 1

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act

DATE _____ APPROVED BY RAC COMPONENT Mounting Pedestal DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
8.1	Pedestal fails to contain coolant gas pressure.	a. Pedestal body breaks b. Pedestal interface seals surfaces damaged c. Electrical receptacle seal surface damaged d. Seal weld breaks e. Coolant supply connector breaks or loosens	Steady State and Start-up	1 1 1 1 1

TABLE 2-23

COMPONENT SAFETY CRITICALITY

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT Reponsyn Motor DWG NUMBERS 939J461
(Direct Drive)

W59150

Total Criticality Ranking 120

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Motor fails electrically so as to produce no output torque.	a. Coil wiring opens or shorts b. Pole pieces break c. Permanent magnet material bond to flex cup breaks d. Loss of permanent magnet properties.	Steady State and Start up	4 4 4 4
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Pole pieces break and jam motor b. Potting compound fails, allowing coils to jam between stator and rotor. c. Stator coil at inside diameter breaks and jams between stator and rotor. d. Flexspline gear teeth bind or break e. Flex cup breaks	Steady State and Start up	4 4 4 4 4

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act
 DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.1	Drive train mechanical load increases	a. Output shaft bearings bind and increase friction.	Steady State	2
2.2	Drive train jams in some position between full in and the maximum operating range.	a. Output shaft bearings seize	Steady State and Start up	2
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Crown spline breaks c. Joint between output shaft and flex cup breaks.	Steady State and Start up	4 4 4

TABLE 2-23 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Acc.
 DATE APPROVED BY RAC COMPONENT Potentiometers DWG NUMBERS 939,1461

W52150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open. b. All potentiometer wipers short out or open. c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start up and Steady State	1 1 1 1 1
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start up and Steady State	1 1
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start up and Steady State	2 2 2

TABLE 2-23 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Housing and Cover DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen	Steady State and Start up	2 2 2 2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act
 DATE _____ APPROVED BY RAC COMPONENT Seals, Coolant DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seals leaks e. Coolant supply connector seal leaks	Steady State and Start up	2 2 2 2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act
 DATE _____ APPROVED BY RAC COMPONENT V-Band Clamp DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
6.1	V-Band clamp fails to maintain proper clamping force.	a. Left or right hand bolt breaks or loosens b. Clamp loses spring gradient	Steady State and Start up	4 4

TABLE 2-23 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State	4 4
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start up	1 1
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Steady State and Start up	2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT Mounting Pedestal DWG NUMBERS 939J461

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
8.1	Pedestal fails to contain coolant gas pressure.	a. Pedestal body breaks b. Pedestal interface seals surface damaged c. Electrical receptacle seals surfaces damaged. d. Seal weld breaks e. Coolant supply connector breaks or loosens	Steady State and Start up	2 2 2 2 2

electric actuator. Also shown is the total criticality ranking for this concept. Table 2-24 gives the same information for the Responsyn planetary drive electric actuator.

2.4.1.8 Discussion and Evaluation

The high reliability of the direct drive Responsyn actuator in comparison to other electrical actuator concepts is due primarily to its fewer parts, its simple internal transmission and its all low-speed bearings. Drive component alignment is not critical and there is little change in performance with temperature. Its advantages in common with other stepping motor concepts are low inertia with resultant fast response, inherent braking and fast reversibility.

Relatively higher power requirements and the large envelope diameter required limit application of the direct drive Responsyn concept to an 18 or fewer drum configuration with high power supply system capacity. The Responsyn requires continuous power to hold position.

An industrial model Responsyn stepping motor (Model HDUM-30-100-04) was procured and tested at WANL under the scope of test documents TS:85DA-182-0 and TS:85DA-186-0. Primary testing was performed to establish frequency response, transient response, linearity, resolution and power requirements as well as loss of power failure modes. Test procedure and results are reported in WANL-TME-1921. The test results indicate that the Responsyn direct drive, while having a very high reliability potential and excellent operating characteristics, would require a good deal more power and a larger envelope than the other electrical stepping motor actuator candidates being considered for NERVA application. The use of a smaller Responsyn by adding a single stage planetary reduction to more nearly match the Responsyn to the load reduces the power requirements at the expense of reliability.

The Responsyn direct drive proportional electric actuator as shown will only fit up to an 18 drum reactor concept. Its radial width at the control drum centerline is about 6.9 inches. Its height above the pressure vessel mounting boss is also about 6.9 inches. Clearance required above the actuator for removal is about 1-3/4 inches to clear the output shaft. The direct drive Responsyn actuator is estimated to weigh about 17 pounds.

TABLE 2-24
COMPONENT SAFETY CRITICALITY

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE _____ APPROVED BY RAC COMPONENT Responsyn Motor DWG NUMBERS 939J562
(Planetary Drive)

W59150

Total Criticality Ranking 160

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Motor fails electrically so as to produce no output torque.	a. Coil wiring opens or shorts b. Pole pieces break c. Permanent magnet material bond to flex cup, breaks d. Loss of permanent magnet properties	Steady State and Start-up	4 4 4 4
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces break and jams motor c. Flexspline gear teeth bind or break d. Potting compound fails, allowing coils to jam between stator and rotor e. Stator coil at inside diameter breaks and jams between stator and rotor. f. Flex cup breaks	Steady State and Start-up	4 4 4 4 4 4

TABLE 2-24 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.1	Drive train mechanical load increases.	a. Output shaft bearings bind and increase friction. b. Driving gear teeth surface damage increases friction. c. Planet gears teeth surface damage increases friction. d. Ring gear teeth surface damage increases friction. e. Needle bearing binds and increases friction f. Planet gears thrust washers bind and increase friction. g. Bearing retainer fails h. Retainer fasteners break or loosen i. Output shaft gear flanges break	Steady State and Start-up	2 2 2 2 2 2 2 2 2
2.2	Drive train jams in some position between full in and the maximum operating range.	a. Output shaft bearings seize b. Driving gear to planet gears teeth jam c. Ring gear to planet gears teeth jam d. Needle bearing seizes e. Planet gears thrust washers seize f. Bearing retainer breaks g. Output shaft gear flanges break and jam	Steady State and Start-up	4 4 4 4 4 4 4
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Shaft spline breaks c. Coupling, between motor shaft and gear, breaks.	Steady State and Start-up	4 4 4

TABLE 2-24 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY [Signature] COMPONENT Potentiometers DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 1 1
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	1 1
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start-up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	2 2 2

TABLE 2-24 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Housing and Cover DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged. c. Cover breaks d. Cover seal surface damaged. e. Cover fasteners break or loosen	Steady State and Start-up	2 2 2 2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Seals, Coolant DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	2 2 2 2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Mounting Bolts DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
6.1	Mounting bolts fail to maintain proper clamping force.	a. Bolt breaks or loosens	Start-up and Steady State	4

TABLE 2-24 (Continued)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.

DATE APPROVED BY RAC COMPONENT Wiring Harness DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	4 4
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	1 1
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Steady State and Start-up	2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.

DATE APPROVED BY RAC COMPONENT Mounting Pedestal DWG NUMBERS 939J462

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
8.1	Pedestal fails to contain coolant gas pressure.	a. Pedestal body breaks b. Pedestal interface seals surfaces damaged c. Electrical receptacle seal surface damaged d. Seal weld breaks e. Coolant supply connector breaks or loosens	Steady State and Start-up	2 2 2 2 2

Coolant requirements for a one-hour run at the heating rates estimated for NERVA, about 3 watts per pound, are less than 1 pound and in all likelihood can be neglected. The main electrical power required is on the order of 100 watts with a reduced power of 50 watts assumed to provide a holding torque when the actuator is not moving. Signal level power to supply the feedback potentiometers and control amplifier are small and have been neglected for this comparative study. A preliminary estimate of the concept reliability obtained by calibrating the fault tree is $.9_{5}89$. Table 2-25 is a listing of some of the more significant advantages and disadvantages of the direct drive Responsyn concept.

To reduce the power requirements and more nearly match the load, a smaller Responsyn with an additional planetary gear stage instead of direct drive high reliability was considered. The Responsyn planetary proportional electric actuator will fit on up to a 36 drum reactor concept. Its width at the control drum centerline is about 6.5 inches. Its height above the pressure vessel mounting boss is about 5.1 inches. Clearance required above the actuator for removal is about 3.9 inches to clear the output shaft and planetary gear reduction which has been recessed into the pressure vessel. The planetary drive Responsyn actuator is estimated to weigh about 9.8 pounds.

Coolant requirements for a one hour run at the heating rates estimated for NERVA, about 3 watts per pound, are less than $1/2$ pound and can probably be neglected. The main electrical power required is on the order of 30 watts with a reduced power to 15 watts assumed to provide a holding torque when the actuator is not moving. Signal level power to supply the feedback potentiometers and control amplifier is small and has been neglected for this comparative study. A preliminary estimate of the concept reliability obtained by calibrating the fault tree is $.9_{5}87$. Table 2-26 is a listing of some of the significant advantages and disadvantages of the Responsyn planetary concept.

TABLE 2-25
DIRECT DRIVE RESPONSYN
CDAS CONCEPT

SUMMARY TABLE

<u>Advantages</u>	<u>Disadvantages</u>
1. Few Moving Parts.	1. High Power Consumption.
2. Low Speed Bearings	2. Low Efficiency.
3. Velocity Programmable.	3. High Current.
4. Inherent Braking.	4. Mechanism Weight is High.
5. Excellent Response Time.	5. Size Limits Applicability to 18 Drum Configuration.
6. High Resolution.	6. A Bias Spring or Zero Position Lock May Be Required.
	7. Must be Energized Continuously to Hold Position.

TABLE 2-26
PLANETARY / RESPONSYN
CDAS CONCEPT

SUMMARY TABLE

<u>Advantages</u>	<u>Disadvantages</u>
1. Low Speed Bearings.	1. High Power Consumption.
2. Velocity Programmable.	2. Low Efficiency.
3. Inherent Braking.	3. High Current.
4. Excellent Response Time.	4. Mechanism Weight is Relatively High.
5. High Resolution.	5. A Bias Spring or Zero Position Lock May be Required.
	6. Must be Energized Continuously to Hold Position.

2.4.2 Slo-Syn Concept

2.4.2.1 Mechanical Description

The Slo-Syn stepping motor actuator discussed in this section is shown in Figure 2-24. This actuator consists of five subsystems.

- 1) Motor Subsystem
- 2) Transmission Subsystem
- 3) Feedback Subsystem
- 4) Coolant Subsystem
- 5) Housing Enclosure Subsystem

2.4.2.1.1 Motor. The motor is a modified Slo-Syn unit, manufactured by Superior Electric Company. It is a permanent magnet rotor precision stepping motor, analogous in operation to a synchronous inductor motor. Figure 2-25 shows a simplified layout of the motor. The stator has a two-phase, eight-salient pole winding configuration. The rotor contains a cylindrical permanent magnet which is magnetized axially. The rotor is divided into two sections forming north and south magnetic poles. Each section has projecting teeth at its circumference which serve to localize the magnetic poles. The two rotor sections are off-set by $1/2$ of a rotor tooth pitch.

If the rotor is aligned such that a south magnetic pole is centered about stator salient poles N1 and N5, then a south magnetic pole will be $1/4$ of a tooth pitch from stator salient poles N2 and N6. South magnetic pole rotor teeth will also be $1/4$ of a tooth pitch from salient poles S4 and S8 and $1/2$ of a tooth pitch from salient poles S3 and S7.

North magnetic rotor teeth are centered about salient poles S3 and S7. They are also $1/4$ of a rotor tooth pitch from salient poles N2, N6, S4, S8 and $1/2$ of a rotor tooth pitch from salient poles N1 and N5.

If phase 1 is energized such that salient poles N1 and N5 form north magnetic poles and salient poles S3 and S7 form south magnetic poles, the rotor will be aligned as shown. Energizing phase 2, such that salient poles N2 and N6 form north magnetic poles and salient poles S4 and S8 form south magnetic poles, will cause the rotor to move clockwise $1/4$ of a rotor tooth pitch. Now south magnetic pole rotor teeth are in alignment with salient poles

Figure 2-24. Proportional Control Drum Actuator
Slo-Syn Electric Stepping Motor Concept

613129-8B

Figure 2-25. Layout of a Simplified Slo-Syn Motor

N2 and N6. The north magnetic pole rotor teeth are in alignment with salient poles S4 and S8. Energizing phase 1 again, such that salient poles N1 and N5 form south magnetic poles and salient poles S3 and S7 form north magnetic poles, the rotor will move clockwise $1/4$ of a tooth pitch where south magnetic pole rotor teeth become aligned with salient poles S3 and S7. Continuous sequential energizing of phase 1 and phase 2 with alternate reversing of phase polarity drives the rotor shaft at $1/50$ of synchronous speed.

2.4.2.1.2 Transmission Subsystem. The transmission subsystem, functionally depicted in Figure 2-26, employs three basic elements.

- 1) A wave generator
- 2) A non-rigid, externally splined flexspline
- 3) A rigid, internally splined circular spline

The wave generator is a two-lobe, elliptoidal cam, surrounded by an anti-friction bearing which deflects the non-rigid flexspline so that it mates with the circular spline at two equally spaced areas 180 degrees apart on their respective circumferences. The wave generator functions as the transmission input element and is directly coupled to the stepping motor. Rotation of the wave generator causes a progressive rotation of the elliptoidal shape in the flexspline, resulting in a continuous and progressive inter-engagement between flexspline and circular spline teeth. There are fewer teeth on the flexspline than on the circular spline, and a slow mechanically-reduced relative motion between these two elements is thus generated. As the wave generator makes one complete rotation, the flexspline rotates in the opposite direction through a distance equal to the difference between the pitch circumference of the circular spline and that of the flexspline. The flexspline is directly coupled by its closed-end plate to the output shaft of the actuator. The difference between the two pitch circumferences is small, thus the high-speed rotation of the wave generator is directly converted into a rotary output having greatly reduced speed and increased torque.

This transmission, the Harmonic drive, is manufactured by the USM Corporation and has found wide application throughout industry and the aerospace program.

Figure 2-26. Harmonic Drive Transmission

Used in the LOX valve actuator of the Centaur rocket engine propellant utilization system, the mechanism has been subjected to extremes of temperature and shock approaching the NERVA environment.

Several nuclear reactors have utilized Harmonic drive transmissions, along with electric stepping motors, in reflector drive systems. The Pratt and Whitney LCRE program and SNAP-50 program both carried development of the Harmonic drive system through irradiation testing of components before termination of the program.

2.4.2.1.3 Feedback. Feedback of actuator output shaft position to the control amplifier is accomplished through a three deck potentiometer. This device provides triple redundancy to the position feedback signal. Each deck is electrically independent. The potentiometer is assembled concentrically with the main output shaft of the actuator and uses the main actuator bearings for alignment. This feature produces the simplest assembly and eliminates many parts required in separately mounted potentiometers. The potentiometer is assembled and aligned on the output shaft by the manufacturer to eliminate the possibility of error in assembly.

2.4.2.1.4 Coolant Gas. Coolant gas is taken from the propellant line down stream of the turbopump at approximately 900 psia, passed through the actuator and exhausted into the reactor dome at approximately 700 psia.

2.4.2.1.5 Housing. The housing ties together all of the functional parts of the actuator. All electric power, input command signals and output position signals enter and exit the actuator by way of the electrical connector.

2.4.2.2 System Description

The Slo-Syn stepping motor is shown incorporated in the Control Drum Actuator System (CDAS) in Figure 2-27. The motor converts a digital, electrical format into uniform, discrete drum angle positions within the resolution requirements of the CDAS. The digital format is a four-bit cyclic binary code in which two adjacent bits are in the ON state while the other two are in the OFF state. The ON state represents a constant current in a particular phase winding of the Slo-Syn motor while the OFF state represents no current.

Figure 2-27. Slo-Syn Electrical Stepping Motor Proportional Actuator System

Table 2-27 is an example of eight consecutive steps coded in such a manner as to cause the drum to move four steps in the direction of increasing reactivity and then return to its original position. A code of 1 represents an ON state and a 0 an OFF state.

TABLE 2-27

DRUM POSITIONING CODE

<u>Step Number</u>	<u>Code</u>	<u>Angular Change</u>	<u>Drum Angle</u>
0	1100	0	θ
1	0110	+ 1	$\theta + 1$
2	0011	+ 1	$\theta + 2$
3	1001	+ 1	$\theta + 3$
4	1100	+ 1	$\theta + 4$
5	1001	- 1	$\theta + 3$
6	0011	- 1	$\theta + 2$
7	0110	- 1	$\theta + 1$
8	1100	- 1	θ

The actuator output shaft angular position is measured by an angular position indicator. This device converts angular position into an equivalent electrical signal. The actuator output shaft is coupled to the control drum by means of a drive shaft.

The Slo-Syn motor receives the digital, electrical currents from a code generator. The code generator is able to change and maintain the binary code in response to a pulsed input signal. The direction of drum angle command change is given by the polarity of the pulses. The magnitude of the commanded change is given by the number of pulses. The rate at which drum angle is commanded to change is determined by the frequency of the pulses.

Because of the precise angular positioning ability of the Slo-Syn motor the drum bank may be programmed to move to a predetermined angle (drum worth). This can be accomplished by counting the number of pulses delivered to the code generator. In this manner the Slo-Syn actuator may be operated as an open loop system since the angular change and the rate of

angular change are both controllable. In the open loop system the code generator input pulses would be in proportion to the temperature or power errors or the derivatives of these errors. The Slo-Syn actuator may also be operated as a closed loop system where the input pulses are in proportion to the difference between drum position command and position indicator output.

An example of the closed loop control system for a stepping motor is shown in Figure 2-28. In this example the drum position command is in the form of an analog voltage which is proportional to angular position. The command signal is compared with the drum position readout (also an analog voltage) to obtain an error signal. Digital information is taken from the error signal by the sign detector. The relationship between the sign detector input (θ_e) and the output ((+) and (-)) is given in the following table.

TABLE 2-28
SIGN DETECTOR INPUT AND OUTPUT

<u>If</u>	<u>Then</u>
$\theta_e > 1/2 \theta_s$	(+) = 1, (-) = 0
$ \theta_e < 1/2 \theta_s$	(+) = 0, (-) = 0
$\theta_e < -1/2 \theta_s$	(+) = 0, (-) = 1

The term θ_s is the resolution and has a minimum of one step angle. The sign detector outputs are used to control the clock gates. If either (+) or (-) is a 1, a clock gate is opened and pulses from the clock generator are fed into the code generator. The code generator steps the motor in the direction which causes the error to come within the resolution band. Once within the resolution band, both gates are closed and the motor holds its position.

Electrical power is supplied to the actuator controller. Coolant gas is supplied to the actuator and exhausted into the pressure vessel. The coolant gas must be at a higher pressure than the chamber at all times. The coolant gas flow can be regulated to control the temperature of the actuator and, thereby, reduce the effects of thermal expansion and contraction caused by extreme temperature changes.

Figure 2-28. Closed Loop Stepping Motor Proportional Actuator System

Estimated electrical power requirements for the Slo-Syn stepping motor concept are taken from the manufacturer's specifications. The standard commercial grade Slo-Syn stepping motor requires 24 watts.

2.4.2.3 Radiation Evaluation

Table 2-1 of Section 2.13 provides the radiation environment at the proposed actuator location forward of the pressure vessel closure. As those values describe the environment in the absence of perturbation by the actuator itself, they apply equally to all of the actuator concepts at this location. In most instances the presence of the actuator will reduce the levels, so that the use of the unperturbed numbers is generally conservative.

2.4.2.4 Thermal Evaluation

The radiation environment of the Slo-Syn concept is generally similar to the Responsyn concept with low heating rates and pump discharge cryogenic coolant available. The problems associated with adequate cooling of the electrical motor rotor and stator are also similar. The flexible-spline drive would require close detailed analysis to assure its thermal and structural adequacy in the operating environment. Thus, the Slo-Syn type stepping motor is judged to be thermally very similar to the Responsyn stepping motor.

2.4.2.5 Structural Evaluation

Structurally, the Slo-Syn stepping motor actuator is similar to the Responsyn stepping motor discussed in Section 2.4.1.5. The basic difference between the two designs is the type of electric stepping motor used to generate torque.

The Responsyn motor is a variable reluctance motor with an integral transmission (the rotating magnetic field surrounds the rigid spline, flexspline and output shaft). The Slo-Syn motor is a permanent magnet rotor stepping motor connected to a separate transmission. The rotating magnetic field in the Slo-Syn motor drives the rotor shaft which is connected to the transmission. The transmission consists of a rigid, internally splined circular spline, a non-rigid, externally splined flexspline, and a wave generator which are similar to those in the Responsyn motor. If the Slo-Syn actuator is selected from this trade study, the structural reliability of the Slo-Syn unit should be verified by analysis and/or component tests.

The structural evaluation of the transmission, feedback potentiometer and housing enclosure for this actuator is identical to that of the Responsyn actuator discussed in Section 2.4.1.5.

2.4.2.6 Radiation Effects Evaluation

The total expected radiation environment to which this actuator will be subjected is given in Section 2.1.3. To assess the effects of this environment on the actuator, a comparison of known test environments with this expected environment will indicate the sensitivity of any given concept to successful operation in the expected radiation levels. The sensitive components in this concept are the motor coils, the potentiometer, the shaft seals, and the electrical insulation and potting compounds. All other materials used in the construction of the actuator are metals. Although detail designs are not available, final material selection will be made from lists of qualified materials or will be separately qualified.

2.4.2.6.1 Motor Coils. Although motors have not been directly tested on the NERVA program, tests on other devices give important information concerning the expected performance of motor winding rails in a radiation environment. The electric coils contained in a pneumatic actuator torque motor and in the lock shut-off solenoid are similar to those used in electric motor construction. Tests conducted in a radiation environment at the GTR facility, during the NRX-A6 pneumatic actuator side-by-side test, and tests conducted by the Lewis Research Center at the Plum Brook Reactor all included the electric coils mentioned above. No coil anomalies were reported during any of these tests.⁽⁴⁾ However, it is planned to take advantage of improvements in the state-of-the-art in insulation materials and use the polyimide series for future coil insulations to further improve radiation tolerance and increase coil reliability.

2.4.2.6.2 Potentiometer. A prototype potentiometer was also included in the tests described in the above section. A reported failure in the Lewis tests⁽⁴⁾ caused some concern until a subsequent post-irradiation examination revealed the failure was caused by a softening and flowing of a potting compound not included in the GTR and NRX-A6 tests. The material that failed was used in very early model potentiometers but has now been removed. Future

controls will assure using only those specified materials that will not be subject to property changes under radiation environments.

2.4.2.6.3 Shaft Seals, Electrical Insulation and Potting Materials. Although these items and materials are adequate for use in the NERVA environment, it is planned to take advantage of the improvements in the state-of-the-art in insulation materials. Polyimide materials will be used in wire insulation and potting materials to increase radiation tolerance and reliability.

2.4.2.7 Reliability and Safety Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliability of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale from 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection, assembly and testing the identified component's ability to perform during its useful life installed in the actuator. The number 100 represents the most difficult level and the number 1 the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event identified on the tree and has assigned a relative weighting number to each failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-29 shows in summary from the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific components within the actuator concept that contribute to the main block failure. The numbers in parenthesis are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A tabular listing of the failure events is shown in Table 2-29. These failure events are located in the fault tree by their identifying numbers which appear above the blocks on the fault tree. The events are listed in an indented manner which also indicates levels on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the subtotals progress toward the right of the page. The final total of the weighted numbers (1282) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree are indicated in parenthesis in the blocks of the summary fault tree, Figure 2-29. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

The calibration process (Section 2.17.1.1) consists of selecting a failure event which is amendable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

Figure 2-29. Summary Fault Tree, Harmonic Drive/Slo-Syn Stepping Motor

TABLE 2-29
DESIGN FAULT TREE ANALYSIS

Slosyn Stepping Motor/Harmonic Drive Motor Proportional Electric Actuator Reliability
Fault Tree Analysis 939J957 Estimated Reliability 9587

1282

1. Actuator Coolant Gas Consumption Exceeds Specified Limits		95
1.1 Actuator Housing Fails to Contain Coolant Gas		55
1.1.1 Cover Fails to Contain Coolant Gas	5	
1.1.2 Cover to Body Interface Joint Fails	9	
1.1.2.1 Seal Fails	6	
1.1.2.2 Cover Fasteners Fail	3	
1.1.3 Housing Body Fails to Contain Coolant Gas	1	
1.1.4 Electrical Connector Fails to Contain Gas	40	
1.1.4.1 Seal Fails	30	
1.1.4.2 Fasteners Lose Clamping Force	5	
1.1.4.3 Connector Body Fails to Contain Gas	5	
1.2 Housing to Pedestal Interface Fails to Contain Gas		40
1.2.1 Interface Inlet Coolant Seal Fails	30	
1.2.2 Fasteners Lose Clamping Force	5	
1.2.3 Interface Exhaust Coolant Passage Seal Fails	5	
2. Actuator Fails to Position Control Drum Within Time Position Band		1126
2.1 Actuator Fails to Convert Electrical to Mechanical Power		141
2.1.1 Electrical Connector Fails to Transmit Proper Signal	10	
2.1.1.1 Conductor Fails to Transmit Signal	5	
2.1.1.2 Insulator Fails Permitting Short Circuit	5	

TABLE 2-29 (Continued)

2.1.2 Motor Fails Electrically		96
2.1.2.1 Wiring Failure		80
2.1.2.2 Pole Pieces Break		1
2.1.2.3 Loss of Permanent Magnet Bond to Shaft		5
2.1.2.4 Loss of Rotor Permanent Magnet Properties		10
2.1.3 Actuator Internal Wiring Harness Fails		35
2.1.3.1 Conductor Fails		5
2.1.3.2 Insulation Fails		25
2.1.3.3 Terminal Mechanically Fails		5
2.2 Improper Command Received from Amplifier		249
2.2.1 Amplifier Control Voltage Incorrect		AGC
2.2.2 Amplifier Fails Internally		30
2.2.3 Amplifier Feedback Signal Incorrect		219
2.2.3.1 Potentiometer Supply Voltage Wrong Value		30
2.2.3.1.1 Actuator System Wiring Harness Fails	30	
2.2.3.1.2 Voltage Supplied is in Error	AGC	
2.2.3.2 Feedback Potentiometer Output Fails		154
2.2.3.2.1 Potentiometer Electrically Fails	101	
2.2.3.2.1.1 Track Resistance Value Changes	10	
2.2.3.2.1.2 Protective Resistor Changes Value	10	
2.2.3.2.1.3 Wiper Resistance Value Changes	1	
2.2.3.2.1.4 Wiper to Track Contact Resistance Changes	80	
2.2.3.2.2 Angular Relationship Pot to Drum Changes	21	
2.2.3.2.2.1 Pot Position Relative to Shaft Changes	20	
2.2.3.2.2.2 Shaft Relative to Drum Changes	1	

TABLE 2-29 (Continued)

2.2.3.2.3	Potentiometer Mechanically Fails	32	
2.2.3.2.3.1	Potentiometer Shaft Fails	1	
2.2.3.2.3.2	Wiper Spring Gradient Changes	1	
2.2.3.2.3.3	Bearings Fail	10	
2.2.3.2.3.4	Potentiometer Housing Fractures	20	
2.2.3.3	Feedback Signals Transmitted Improperly		35
2.2.3.3.1	Wiring Harness Actuator to Amplifier Fails	AGC	
2.2.3.3.2	Mechanism Wiring Harness Fails	30	
2.2.3.3.3	Electro-Magnetic Interference Distorts Signal	5	
2.3	Actuator External Control Drum Loads Change		EC
2.4	Actuator Internal Loads Change		736
2.4.1	Harmonic Drive Torque Output Low		260
2.4.1.1	Teeth Fail to Transmit Torque		15
2.4.1.1.1	Teeth Break	10	
2.4.1.1.2	Teeth Wear	5	
2.4.1.2	Fastener Interferes with Motion		10
2.4.1.3	Wave Generator Rotation Fails		155
2.4.1.3.1	Bearing Friction Increases	130	
2.4.1.3.2	Eliptoidal Cam Breaks	5	
2.4.1.3.3	Flexible Outer	20	
2.4.1.4	Cup Fails to Transmit Motion		80
2.4.1.4.1	Weld Fails	30	
2.4.1.4.2	Cup Breaks	50	
2.4.2	Motor Fails Mechanically		366
2.4.2.1	Bearing Friction Increases	280	
2.4.2.2	Fasteners Interfere with Motion	10	

TABLE 2-29 (Continued)

2.4.2.3 Stator Wiring Interferes with Motion	76	
2.4.2.3.1 Actuator Housing Distorts	1	
2.4.2.3.2 Stator Porting Material Deteriorates	10	
2.4.2.3.3 Conductor at I.D. of Motor Breaks	5	
2.4.2.3.4 Pole Pieces Break	60	
2.4.3 Output Shaft-Pot Bearings Friction Level Increases		70
2.4.4 Output Shaft Fails to Transmit Torque		40
2.4.4.1 Teeth Break	10	
2.4.4.2 Shaft Breaks	20	
2.4.4.3 Cup to Shaft Coupling Fails	10	
3. Actuator Electrical Power Rate Exceeds Specified Limits		61
3.1 Actuator Short Circuits		41
3.1.1 Potentiometer Internal Short Circuit	10	
3.1.2 Stator Wiring Insulation Fails Allowing Short Circuit	10	
3.1.3 Wiring Harness System Short Circuits	21	
3.1.3.1 Interface Connector Short Circuits	10	
3.1.3.2 Wiring Insulation Fails	10	
3.1.3.3 Terminal Fails	1	
3.2 Amplifier Internal Short Circuit		20
3.3 Amplifier/Actuator External Cable Short Circuit Failure		AGC

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

2.4.2.7.1 Failure Mode Evaluation. A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts were not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component is analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another.⁽⁹⁾ The total number then indicates the relative reliability of the actuator concept; the lower the number the more reliable the particular concept is relative to the others. Each concept was compared with the others on the basis of the total relative failure probability number. The failure mode analysis for the Slo-Syn stepping motor concept is shown in Table 2-30.

2.4.2.7.2 Safety Evaluation. The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and criticality ranking for each concept, failure modes have been identified. For each of the failure modes listed, mechanisms of obtaining that failure mode

TABLE 2-30
COMPONENT FAILURE MODES ANALYSIS

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE _____ APPROVED BY RAC COMPONENT Slo-Syn Motor DWG NUMBERS 100E148

W59150				Relative Ranking 136	
Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating	
1.1	Motor fails electrically so as to produce no output torque.	a. Coil wiring opens or shorts b. Pole pieces break c. Permanent magnet material bond to rotor shaft breaks d. Loss of rotor permanent magnet properties	Steady State and Start-up	8 1 1 1	
1.2	Motor fails mechanically so as to produce no output torque and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces break and jams motor c. Potting compound fails, allowing coils to jam between stator and rotor. d. Stator coil at inside diameter breaks and jams between stator and rotor.	Steady State and Start-up	20 6 1 1	

TABLE 2-30 (Continued)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.

DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 100E148

W57150

Mode Ident. No	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.1	Drive train mechanical load increases.	<ul style="list-style-type: none"> a. Flexspline gear teeth surface damage increases friction. b. Elliptical bearing binds and increases friction. c. Elliptoidal cam breaks d. Flexible outer race breaks e. Output shaft bearings bind and increase friction. 	Steady State and Start-up	<ul style="list-style-type: none"> 1 10 1 2 6
2.2	Drive train jams in some position between full in and the maximum operating range.	<ul style="list-style-type: none"> a. Flexspline gear teeth break and jam the mechanism. b. Elliptical bearing seizes c. Output shaft bearings seize d. Bearing housing fasteners break or loosen and jam mechanism. 	Steady State and Start-up	<ul style="list-style-type: none"> 1 3 2 1
2.3	Drive train fails so as to not transmit motor output torque.	<ul style="list-style-type: none"> a. Output shaft breaks b. Shaft crowned spline breaks c. Flexible cup breaks d. Flexspline gear teeth break e. Keyed joint between motor shaft and elliptoidal cam, breaks f. Coupling between flexible cup and output shaft, breaks. 	Steady State and Start-up	<ul style="list-style-type: none"> 1 1 8 1 1 2

TABLE 2-30 (Continued)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Potentiometers DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 4 2
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft	Start-up and Steady State	1 2
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks	Start-up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	1 1 8

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Housing and Cover DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
4.1	Housing and cover fail to contain cool- and gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen f. Coolant supply connector breaks or loosens	Steady State and Start-up	1 1 1 1 1 1

TABLE 2-30 (Continued)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Seals, Coolant DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	1 3 1 3 3

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Mounting Studs DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	Mounting stud fails to maintain proper clamping force.	a. Stub breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action.	Steady State and Start-up	1 1 1

TABLE 2-30 (Continued)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act
 DATE APPROVED BY RGE COMPONENT Wiring Harness DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	3 2
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	2 4
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Steady State and Start-up	1 1

are established as they relate to a particular design and each of these failure mechanisms has been given a numerical ranking consistent with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reductions in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.
1	Failures resulting in insignificant effects on chamber temperature/pressure.

By assigning each mechanism of failure to one of the above categories, and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-31 presents a tabulation of the failures, mechanism of failure and criticality ranking of failure for the Slo-Syn stepper motor electric actuator. Also shown is the total criticality ranking for this concept.

2.4.2.8 Discussion and Evaluation

The permanent magnet character of the Slo-Syn rotor produces certain major advantages peculiar to designs of this type. The magnetic detenting inherent in this concept and

TABLE 2-31
COMPONENT SAFETY CRITICALITY

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RCC COMPONENT Slo-Syn Motor DWG NUMBERS 100E148

W59150

Total Criticality Ranking 138

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Motor fails electrically so as to produce no output torque.	a. Coil wiring opens or shorts b. Pole pieces break c. Permanent magnet material bond to rotor shaft breaks d. Loss of rotor permanent magnet properties	Steady State and Start-up	4 4 4 4
1.2	Motor fails mechanically so as to produce no output torque and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces break and jams motor c. Potting compound fails, allowing coils to jam between stator and rotor. d. Stator coil at inside diameter breaks and jams between stator and rotor.	Steady State and Start-up	4 4 4 4

TABLE 2-31 (Continued)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 100E148

WS9150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.1	Drive train mechanical load increases.	a. Flexspline gear teeth surface damage increases friction. b. Elliptical bearing binds and increases friction. c. Elliptoidal cam breaks d. Flexible outer race breaks e. Output shaft bearings bind and increase friction.	Steady State and Start-up	4 4 4 4 4
2.2	Drive train jams in some position between full in and the maximum operating range.	a. Flexspline gear teeth break and jam the mechanism. b. Elliptical bearing seizes c. Output shaft bearings seize d. Bearing housing fasteners break or loosen and jam mechanism.	Steady State and Start-up	4 4 4 4
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Shaft crowned spline breaks c. Flexible cup breaks d. Flexspline gear teeth break e. Keyed joint between motor shaft and elliptoidal cam, breaks f. Coupling between flexible cup and output shaft, breaks.	Steady State and Start-up	4 4 4 4 4 4

TABLE 2-31 (Continued)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE APPROVED BY LAC COMPONENT Potentiometers DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 1 1
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft	Start-up and Steady State	1 1
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks	Start-up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	2 2 2

TABLE 2-31 (Continued)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Housing and Cover DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Housing and cover fail to contain cool- and gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen f. Coolant supply connector breaks or loosens	Steady State and Start-up	2 2 2 2 2 2

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Seals, Coolant DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	2 2 2 2 2

TABLE 2-31 (Continued)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Mounting Studs DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
6.1	Mounting stud fails to maintain proper clamping force.	a. Stub breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action.	Steady State and Start-up	2 2 2

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Wiring Harness DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	4 4
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	1 1
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Steady State and Start-up	2 2

the high-speed reduction ratio of the Harmonic drive transmission result in a "fail in place" mode of failure without incorporating additional components into the mechanism. Exact position definition and low power requirements also recommend this concept relative to the other electric actuators.

Permanent magnet rotor electric stepper actuator concepts are nearly identical in operation and configuration; the only significant differences are the number of stator poles and the rotor mechanical construction. The Slo-Syn motor has eight stator poles and maintains the air gap between similar magnetic materials with the permanent magnet pieces magnetizing the rotor discs by intimate surface contact.

The Slo-Syn configuration allows the maintenance of the air gap dimension throughout the operating temperature range.

Emphasis in the development of the Slo-Syn actuator will be upon design of the wave generator bearing and a satisfactory material for the flexspline. Other areas common to most electric actuator concepts requiring substantial development effort are the concentric potentiometer, wiring insulation and motor coil encapsulant.

The Slo-Syn configuration stepping motor has been manufactured by Superior Electric Company for a number of years and has been used extensively in industrial, military and space applications. Special versions of this motor were used in the SNAP-50 and SNAP-10A programs, in applications similar to those in NERVA. Although SNAP-50 was never built, prototype actuators were built and evaluated, including radiation testing, for use on this program. The SNAP-10A reactor was operated successfully for 43 days in space during the 1965 SNAPSHOT program.

The Harmonic drive transmission has also been used successfully in various SNAP programs. Operation in all of these programs was at elevated temperature and low temperature operation requirements will necessitate extensive development work.

Two industrial model Slo-Syn stepping motors (Model H550L) were procured and tested at WANL to establish dynamic operating characteristics and verify analytical design parameters. Primary testing was performed to determine frequency response, transient response, linearity, resolution and power requirements as well as loss of power failure modes. All

parameters of concern met the specification requirements. A DRM presenting these test results is being prepared. Additional testing, with the motor immersed in LN_2 , was conducted to investigate the change in operating characteristics during temperature transient to cryogenic conditions. It was determined that the Slo-Syn rotor configuration permits operation at cryogenic temperature with negligible loss of output torque due to dimension change across the air gap.

The Slo-Syn proportional electric actuator as shown will fit on up to a 36 drum reactor concept. Its radial width at the control drum centerline is about 4.8 inches. Its height above the pressure vessel mounting boss is about 4.4 inches. Clearance required above the actuator for removal is about 4.3 inches to clear the output shaft and transmission which are recessed into the pressure vessel. The Slo-Syn actuator is estimated to weigh about 7.4 pounds.

Coolant requirements for a one hour run at the heating rates estimated for NERVA, about 3 watts per pound, are less than 1/2 pound per actuator and can probably be neglected. The main electrical power required is on the order of 24 watts with a reduced power to 10 watts assumed to provide a holding torque when the actuator is not moving. Signal level power to supply the feedback potentiometers and control amplifiers is small and has been neglected for this comparative study. A preliminary estimate of the concept reliability obtained by calibrating the fault tree is .9₅⁸⁷. Table 2-32 is a listing of some of the significant advantages and disadvantages of the Slo-Syn/Harmonic Drive Concept.

2.4.3 Dynavector Concept

2.4.3.1 Mechanical Description

The Dynavector stepping motor actuator discussed in this section is shown in Figure 2-30. This actuator utilizes a stepping motor under development by Bendix Research Laboratories. The motor is essentially an adaptation of the epicyclic (planetary) transmission, producing a high-speed reduction and torque increase at the actuator output shaft.

TABLE 2-32
SLO-SYN/HARMONIC DRIVE
CDA CONCEPTS
SUMMARY TABLE

<u>Advantages</u>	<u>Disadvantages</u>
1. Low Weight.	1. Moderately High Speed Bearing.
2. Magnetic Detenting at a Low Value is Available.	2. Rotor Construction is More Complex than Other Similar Devices.
3. Velocity Programmable by the Frequency of the Input Pulses.	
4. Small Overall Size so as to Fit on a 36 Drum Reactor Concept.	
5. Inherent Braking Due to P.M. Rotor and Stator Attractions.	
6. Few Moving Parts.	
7. High Resolution Obtained by Small Step Angle.	
8. Relatively Low Power Required with a Reduced Power while Holding.

Figure 2-30. Proportional Control Drum Actuator Electric Dynavector Concept

The actuator consists of four subsystems.

- 1) Drive subsystem
- 2) Feedback subsystem
- 3) Coolant subsystem
- 4) Housing enclosure subsystem

2.4.3.1.1 Drive Subsystem. The drive subsystem, functionally depicted in Figure 2-31, consists of four major components.

- 1) Stationary (ground) gear
- 2) Ring gear
- 3) Output gear
- 4) Electric motor

A rotating radial magnetic force vector is imposed upon the ring gear, Figure 2-31, by the sequential energizing of the motor stator poles. The reaction of the rotating force vector on the armature piece, which is rigidly fastened to the ring gear, produces an orbiting motion of the ring gear. The ground gear and ring gear mesh provide displacement with slow rotation because the gears have nearly the same number of teeth. The internal portion of the ring gear forms the transmission between the motor and the output shaft and represents the epicyclic transmission. The ring gear rotates very slowly, but orbits rapidly about a small radius and drives the output gear.

The motor stator consists of eight physical poles electrically connected to establish four effective flux poles distributed at 90 degree intervals around the stator circumference. Two flux poles are energized at all times and attract the armature toward the stator at that point. The armature being rigidly attached to the ring gear draws the ring gear outer teeth into mesh with the stationary ground gear. As the ring gear is drawn into engagement by the magnetic force vector, the teeth on the internal circumference of the ring gear are engaged with the teeth of the output gear at a point 90 degrees away from the force vector. Upon rotation of the force vector, under control of the control amplifier, the ring gear moves to maintain mesh with the ground gear normal to the force vector. The ring gear rotates very

Figure 2-31. Dynavector Drive Subsystem

slowly, but orbits rapidly about a small radius and drives the output gear. As the force vector rotates, the output shaft turns continuously, but at a much slower speed than the force vector. Thus, the high-speed rotation of the magnetic field is directly converted into a rotary output having greatly reduced speed and increased torque.

2.4.3.1.2 Feedback. Actuator output shaft position feedback to the control amplifier is accomplished through a three deck potentiometer. This device provides threefold redundancy to the position feedback signal. The potentiometer configuration is that developed for the XE pneumatic actuators and utilizes a bellows coupling for transmission of output shaft rotation to the potentiometer shaft, thus isolating the potentiometer wipers from core vibration and minimizing alignment requirements.

2.4.3.1.3 Coolant Gas. Coolant gas enters the actuator through the coolant filter which is located in the housing cover. The coolant is taken from the propellant line after the turbopump at approximately 900 psia, passed through the actuator and exhausted into the reactor dome at approximately 700 psia.

2.4.3.1.4 Housing. The housing ties together all of the functional parts of the actuator. All electric power, input command signals and output position signals enter and exit the actuator by way of the electrical connector.

2.4.3.2 System Description

The Dynavector stepping motor is shown incorporated in the Control Drum Actuator System (CDAS) in Figure 2-32. The motor converts a digital, electrical format into uniform, discrete drum angle positions within the resolution requirements of the CDAS. The digital format is a four-bit cyclic binary code in which two adjacent bits are in the ON state while the other two are in the OFF state. The ON state represents a constant current in a particular phase winding of the Dynavector motor while the OFF state represents no current.

Table 2-33 is an example of eight consecutive steps coded in such a manner as to cause the drum to move four steps in the direction of increasing reactivity and then return to its original position. A code of 1 represents an ON state and a 0 an OFF state.

$$11 \times 10^{-5} \text{ lb/sec.}$$

TABLE 2-33
DRUM POSITIONING CODE

<u>Step Number</u>	<u>Code</u>	<u>Angular Change</u>	<u>Drum Angle</u>
0	1100	0	θ
1	0110	+ 1	$\theta + 1$
2	0011	+ 1	$\theta + 2$
3	1001	+ 1	$\theta + 3$
4	1100	+ 1	$\theta + 4$
5	1001	- 1	$\theta + 3$
6	0011	- 1	$\theta + 2$
7	0110	- 1	$\theta + 1$
8	1100	- 1	θ

The actuator output shaft angular position is measured by an angular position indicator. This device converts angular position into an equivalent electrical signal. The actuator output shaft is coupled to the control drum by means of a drive shaft.

The Dynavector motor receives the digital, electrical currents from a code generator. The code generator is able to change and maintain the binary code in response to a pulsed input signal. The direction of drum angle command change is given by the polarity of the pulses. The magnitude of the commanded change is given by the number of pulses. The rate at which drum angle is commanded to change is determined by the frequency of the pulses.

Because of the precise angular positioning ability of the Dynavector motor the drum bank may be programmed to move to a predetermined angle (drum worth). This can be accomplished by counting the number of pulses delivered to the code generator. In this manner the Dynavector actuator may be operated as an open loop system since the angular change and the rate of angular change are both controllable. In the open loop system the code generator input pulses would be in proportion to the temperature or power errors or the derivatives of these errors. The Dynavector actuator may also be operated as a closed loop system where the

input pulses are in proportion to the difference between drum position command and position indicator output.

An example of the closed loop control system for a stepping motor is shown in Figure 2-33. In this example the drum position command is in the form of an analog voltage which is proportional to angular position. The command signal is compared with the drum position readout (also an analog voltage) to obtain an error signal. Digital information is taken from the error signal by the sign detector. The relationship between the sign detector input (θ_e) and the output ((+) and (-)) is given in the following table.

TABLE 2-34
SIGN DETECTOR INPUT AND OUTPUT

<u>If</u>	<u>Then</u>
$\theta_e > 1/2 \theta_s$	(+) = 1, (-) = 0
$ \theta_e < 1/2 \theta_s$	(+) = 0, (-) = 0
$\theta_e < -1/2 \theta_s$	(+) = 0, (-) = 1

The term θ_s is the resolution and has a minimum of one step angle. The sign detector outputs are used to control the clock gates. If either (+) or (-) is a 1, a clock gate is opened and pulses from the clock generator are fed into the code generator. The code generator steps the motor in the direction which causes the error to come within the resolution band. Once within the resolution band, both gates are closed and the motor holds its position.

Electrical power is supplied to the actuator controller. Coolant gas is supplied to the actuator and exhausted into the pressure vessel. The coolant gas flow can be regulated to control the temperature of the actuator and, thereby, reduce the effects of thermal expansion and contraction caused by extreme temperature changes.

Estimated electrical power requirements for the Bendix Dynavector stepping motor are taken from the manufacturer's initial component test data. The Dynavector stepping motor requires 44 watts.

Figure 2-33. Closed Loop Stepping Motor Proportional Actuator System

2.4.3.3 Radiation Evaluation

Table 2-1 of Section 2.1.3 provides the radiation environment at the proposed actuator location forward of the pressure vessel closure. As those values describe the environment in the absence of perturbation by the actuator itself, they apply equally to all of the actuator concepts at this location. In most instances the presence of the actuator will reduce the levels, so that the use of the unperturbed numbers is generally conservative.

2.4.3.4 Thermal Evaluation

The thermal-nuclear environment of the Dynavector electric stepping motor concept is, in general, similar to that of prior actuators and the thermal performance is also expected to be similar to that of other stepping motor designs. It is expected that the actuator structure can be adequately cooled although the coolant requirements may vary as a function of the actuator size and its internal heat generation. Internal coolant passages will have to be incorporated into the motor mechanism housing structure so as not to interfere with its electrical function. Regions of primary thermal analysis interest will include the relatively thick wall sections, such as housing flanges, or the asymmetrical metal sections, where maximum temperature levels or thermal distortions would be expected to occur. Further design and analyses would be required to fully identify such regions.

2.4.3.5 Structural Evaluation

The Dynavector stepping motor actuator is an electrical adaptation to the Dynavector pneumatic actuator. The three main assemblies in the Dynavector electric actuator are the drive system assembly, feedback potentiometer and housing enclosure. The feedback potentiometer and housing enclosure are similar to those assemblies of the Responsyn actuator discussed in Section 2.4.1.5 and the same structural evaluation applies to both designs.

Structurally, the drive system of this actuator is similar to that of the Dynavector pneumatic actuator discussed in Section 2.3.5. Both designs have a unique epicyclic gear transmission consisting of a stationary gear, ring gear and output gear. The basic difference between the two concepts is the method of producing the rotating radial force vector. In the

Dynavector pneumatic actuator the radial force vector is produced pneumatically by sequentially pressurizing the displacement chambers, and the radial force vector is produced magnetically in the Dynavector electric by sequentially energizing the motor stator poles. If this actuator is selected from the trade study, system torques and forces, bending stresses, contact stresses, fatigue life, surface wear, material selection, and thermal stresses and distortions of the gears will be considered in detail. The structural reliability of this actuator drive system should be verified by component tests.

2.4.3.6 Radiation Effects Evaluation

The total expected radiation environment to which this actuator will be subjected is given in Section 2.1.3. To assess the effects of this environment on the actuator, a comparison of known test environments with this expected environment will indicate the sensitivity of any given concept to successful operation in the expected radiation levels. The sensitive components in this concept are the motor coils, the potentiometer, the shaft seals, and the electrical insulation and potting compounds. All other materials used in the construction of the actuator are metals. Although detail designs are not available, final material selection will be made from lists of qualified materials or will be separately qualified.

2.4.3.6.1 Motor Coils. Although motors have not been directly tested on the NERVA program, tests on other devices give important information concerning the expected performance of motor winding rails in a radiation environment. The electric coils contained in a pneumatic actuator torque motor and in the lock shut-off solenoid are similar to those used in electric motor construction. Tests conducted in a radiation environment at the GTR facility, during the NRX-A6 pneumatic actuator side-by-side test, and tests conducted by the Lewis Research Center at the Plum Brook Reactor all included the electric coils mentioned above. No coil anomalies were reported during any of these tests.⁽⁴⁾ However, it is planned to take advantage of improvements in the state-of-the-art in insulation materials and use the polyimide series for future coil insulations to further improve radiation tolerance and increase coil reliability.

2.4.3.6.2 Potentiometer. A prototype potentiometer is also included in the tests described in the above section. A report failure in the Lewis tests⁽⁴⁾ caused some concern until a subsequent post-irradiation examination revealed the failure was caused by a softening and flowing of a porting compound not included in the GTR and NRX-A6 tests. The material that failed was included in very early potentiometers but has since been abandoned. Future controls will assure using only those specified materials that will not be subject to property changes under radiation environment.

2.4.3.6.3 Shaft Seals, Electrical Insulation and Potting Materials. Although these items and materials are adequate for use in the NERVA environment, it is planned to take advantage of the improvements in the state-of-the-art in insulation materials. Polyimide materials will be used in wire insulation and potting materials to increase radiation tolerance and reliability.

2.4.3.7 Reliability and Safety Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliability of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale from 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection, assembly and testing the identified component's ability to perform during its useful life installed in the actuator. The number 100 represents the most difficult level and the number 1 the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event identified on the tree and has assigned a relative weighting number to each failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with

the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-34 shows in summary form the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific components within the actuator concept that contribute to the main block failure. The numbers in parentheses are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A listing of the failure events is shown in Table 2-35. These failure events are located in the fault tree by means of their identifying numbers which appear above the blocks on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the subtotals progress toward the right of the page.

The final total of the weighted numbers (1137) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree are indicated in parentheses in the blocks of the summary fault tree, Figure 2-34. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

The calibration process (Section 2.1.7.1.1) consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the

Figure 2-34. Summary Fault Tree, Dynavector Stepping Motor Electrical Actuator

TABLE 2-35
DETAILED FAULT TREE ANALYSIS

Dynavecator Stepping Motor - Proportional Electric Actuator Reliability
Fault Tree Analysis 939J961 Estimated Reliability .9589

1137

1.0 Actuator Coolant Gas Consumption Exceeds Specified Limits		85
1.1 Cover Fails to Contain Coolant Gas	1	
1.2 Cover to Body Interface Joint Fails to Contain Coolant Gas	11	
1.2.1 Seal Fails to Contain Coolant Gas (2)	6	
1.2.2 Cover Fasteners Lose Clamping Force	5	
1.3 Pot Housing to Cover Interface Joint Fails to Contain Coolant Gas	10	
1.3.1 Seal Fails to Contain Coolant Gas	6	
1.3.2 Pot Housing Fasteners Lose Clamping Force	4	
1.4 Housing Body Fails to Contain Coolant Gas	1	
1.5 Pedestal/Housing Interface Joint Fails to Contain Gas	11	
1.5.1 Seal Fails to Contain Coolant Gas	6	
1.5.2 Fasteners Lose Clamping Force	5	
1.6 Electrical Connector Joint Fails to Contain Gas	40	
1.6.1 Seal Fails to Contain Gas	30	
1.6.2 Fasteners Lose Clamping Force	5	
1.6.3 Connector Body Fails to Contain Gas	5	
1.7 Inlet Line Connector Joint Fails to Contain Gas	12	
1.7.1 Seal Fails to Contain Coolant Gas	5	
1.7.2 Connector Loosens	6	
2.0 Actuator Fails to Position Control Drum Within Time Position Band		991
2.1 Actuator Fails to Convert Elec. Power to Mech. Power	126	
2.1.1 Electric Connector Fails to Transmit Proper Signal	10	
2.1.1.1 Conductor Fails to Transmit Signal	5	
2.1.1.2 Insulator Fails Allowing Short Circuit	5	

TABLE 2-35 (Continued)			
2.1.2	Motor Fails Electrically		81
2.1.2.1	Wiring Failure	80	
2.1.2.2	Pole Piece Failure	1	
2.1.3	Actuator Internal Wiring Harness Fails		35
2.1.3.1	Conductor Fails to Transmit Signal	5	
2.1.3.2	Insulation Fails	25	
2.1.3.3	Terminal Fails	5	
2.2	Actuator External Control Drum Load Changes		EC 677559
2.3	Amplifier Receives Improper Feedback Signal		219
2.3.1	Potentiometer Supply Voltage is Wrong Value		30
2.3.1.1	Actuator System Wiring Harness Fails	30	
2.3.1.2	Voltage Supplied to System is in Error	AGC	
2.3.2	Feedback Potentiometer Output Fails		154
2.3.2.1	Potentiometer Electrically Fails	101	
2.3.2.1.1	Track Resistance Value Changes	10	
2.3.2.1.2	Protective Resistor Value Changes	10	
2.3.2.1.3	Wiper Resistance Value Changes	1	
2.3.2.1.4	Wiper to Track Contact Resistance Value Changes	80	
2.3.2.2	Angular Relationship Pot To Drum Changes	21	
2.3.2.3	Potentiometer Mechanically Fails	32	
2.3.2.3.1	Potentiometer Shaft Fails	1	
2.3.2.3.2	Wiper Spring Gradient Changes	1	
2.3.2.3.3	Bearings Fail	10	
2.3.2.3.4	Potentiometer Housing Fractures	20	
2.3.3	Feedback Signals Transmitted Improperly		35
2.3.3.1	Wiring Harness Actuator to Amplifier Fails	AGC	
2.3.3.2	Mechanism Wiring Harness Fails	30	
2.3.3.3	Electro-Magnetic Int. Distorts Signal	5	

TABLE 2-35 (Continued)

2.4	Output Shaft Fails to Position Drum		110
2.4.1	Crown Spline Teeth Fail		10
2.4.2	Shaft Breaks		20
2.4.3	Output Gear/Shaft Spline Joint Fails		80
2.5	Actuator Internal Load Changes		506
2.5.1	Potentiometer Loads Change		10
2.5.1.1	Bearings Fail	4	
2.5.1.2	Housing Fails	2	
2.5.1.3	Shaft Fails	2	
2.5.1.4	Coupling Fails	2	
2.5.2	Actuator Drive Train Load Changes Value		390
2.5.2.1	Ring Gear/Housing Bearing Fraction Increases	140	
2.5.2.1.1	Upper Ring Gear Bearing Surface Fails	40	
2.5.2.1.2	Lower Ring Gear Bearing Surface Fails	40	
2.5.2.1.3	Upper Housing Bearing Surface Fails	30	
2.5.2.1.4	Lower Housing Bearing Surface Fails	30	
2.5.2.2	Upper Output Shaft Bearing Fails	30	
2.5.2.3	Lower Output Shaft Bearing Fails	30	
2.5.2.4	Upper Ground Gear/Ring Gear Loads Increase	70	
2.5.2.4.1	Ring Gear Fails	30	
2.5.2.4.2	Ground Gear Fails	30	
2.5.2.4.3	Contaminants in Gear Mesh	10	
2.5.2.5	Lower Ground Gear/Ring Gear Loads Increase	70	
2.5.2.5.1	Ring Gear Fails	30	
2.5.2.5.2	Ground Gear Fails	30	
2.5.2.5.3	Contaminants in Mesh	10	

TABLE 2-35 (Continued)

2.5.2.6	Ring Gear/Output Gear Loads Increase	50	
2.5.2.6.1	Ring Gear Fails	20	
2.5.2.6.2	Ground Gear Fails	20	
2.5.2.6.3	Contaminants in Mesh	10	
2.5.3	Motor Fails Mechanically to Provide Torque		106
2.5.3.1	Fasteners Interfere with Rotating Parts	10	
2.5.3.2	Ring Gear Body Fails	30	
2.5.3.3	Stator Wiring Interferes with Parts	66	
2.5.3.3.1	Actuator Housing Distorts	1	
2.5.3.3.2	Stator Potting Deteriorates	10	
2.5.3.3.3	Conductor at O.D. of Motor Breaks	5	
2.5.3.3.4	Pole Piece Breaks	50	
2.6	Actuator Receives Improper Command		30
2.6.1	Power Supplies Fail		AGC
2.6.2	Amplifier Fails Internally		30
3.0	Actuator Electrical Power Rate Exceeds Specified Limit		61
3.1	Actuator Short Circuits		41
3.1.1	Pot Internal Short Circuit Failure		10
3.1.2	Stator Wiring Insulation Fails		10
3.1.3	Wiring Harness Short Circuits		21
3.1.3.1	Electrical Connector Short Circuits	10	
3.1.3.2	Wiring Insulation Fails/Short Circuits	10	
3.1.3.3	Terminal Short Circuits	1	
3.2	Amplifier Internal Short Circuit		20
3.3	Amplifier/Actuator External Cable Short Circuit		AGC

reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

2.4.3.7.1 Failure Mode Evaluation. A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts are not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component is analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another.⁽⁹⁾ The total number then indicates the relative reliability of the actuator concept; the lower the number the more reliable the particular concept is relative to the others. Each concept was compared with the others on the basis of the total relative failure probability number. The failure mode analyses for the electric Dynavector concept is shown in Table 2-36.

TABLE 2-36
COMPONENT FAILURE MODES ANALYSIS

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE _____ APPROVED BY RGC COMPONENT Dynavector Motor DWG NUMBERS 100E147

W59150

Relative Ranking 125

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Motor fails electrically so as to produce no output torque.	a. Coil wiring opens or shorts b. Pole pieces break and jams motor	Steady State	8 1
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Pole pieces break b. Potting compound fails, allowing coils to jam between stator and rotating gear. c. Stator coil at inside diameter breaks and jams between stator and rotating gear.	Steady State and Start-up	6 1 1

TABLE 2-36 (Continued)

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 100F147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.1	Drive train mechanical load increases.	a. Output shaft bearings increase friction. b. Ring gear to housing contact surface damaged. c. Ring gear to top cover contact surface damaged. d. Ring gear/reaction gear lower gear joint surface damage increases friction. e. Ring gear/reaction gear upper gear joint surface damage increases friction. f. Ring gear/output shaft gear joint surface damage increases friction.	Steady State and Start-up	6 4 4 6 6 4
2.2	Drive train jams in some position between full in and maximum operating position.	a. Output shaft bearings seize b. Ring gear to housing contact surface jams mechanism. c. Ring gear to top cover contact surface jams mechanism. d. Ring gear/reaction gear lower gear joint breaks and jams mechanism. e. Ring gear/reaction gear upper gear joint breaks and jams mechanism f. Ring gear/output shaft gear joint breaks and jams mechanism.	Steady State and Start-up	2 1 1 2 2 2
2.3	Drive train fails to transmit torque output.	a. Output shaft breaks b. Crowned spline breaks c. Ring gear/output shaft gear joint breaks	Steady State and Start-up	2 1 8

TABLE 2-36 (Continued)

DATE 8-25-69 PREPARED BY I. R. Snezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY ACE COMPONENT Potentiometers DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 4 2
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	1 2
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start-up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	1 1 8

TABLE 2-36 (Continued)

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY LAC COMPONENT Housing and Covers DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
4.1	Housing and covers fail to contain coolant gas pressure, increasing coolant gas consumption.	a. Housing breaks b. Housing interface seal surfaces damaged c. Housing to top cover interface seal surface damaged. d. Cover breaks e. Cover fasteners break or loosen f. Cover seal surfaces damaged g. Potentiometer cover breaks h. Potentiometer cover fasteners break or loosen. i. Potentiometer cover seal surfaces damaged j. Coolant gas connector seal surface damaged k. Coolant gas connector breaks or loosens	Steady State and Start-up	1 1 1 1 1 1 1 1 1 1 1

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY LAC COMPONENT Seals, Coolant DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Coolant seals fail to contain coolant gas, increasing coolant gas consumption.	a. Housing interface seals leak b. Cover to housing interface seal leaks c. Cover to potentiometer cover seals leak d. Electrical connector seal leaks e. Coolant gas connector seal leaks	Steady State and Start-up	1 1 1 3 1

TABLE 2-36 (Continued)

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE _____ APPROVED BY RGC COMPONENT Mounting Bolts DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	Mounting bolts fail to maintain clamping force.	a. Bolt breaks or loosens	Steady State and Start-up	1

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE _____ APPROVED BY RGC COMPONENT Wiring Harness DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
7.1	Electrical wiring harness to motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State	3 2
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	4 2
7.3	Electrical connector fails to contain coolant gas, increasing coolant gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen c. Connector seal surface damaged.	Steady State and Start-up	1 1 1

2.4.3.7.2 Safety Evaluation. The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and criticality ranking for each concept, failure modes have been identified. For each of the failure modes listed, mechanisms of obtaining that failure mode are established as they relate to a particular design and each of these failure mechanisms has been given a numerical ranking consistent with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reductions in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.
1	Failures resulting in insignificant effects on chamber temperature/pressure.

By assigning each mechanism of failure to one of the above categories, and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-37 presents a tabulation of the failures, mechanism of failure and criticality ranking of failure for the Dynavector electric actuator. Also shown is the total criticality ranking for this concept.

TABLE 2-37
COMPONENT SAFETY CRITICALITY

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE _____ APPROVED BY R.G.C. COMPONENT Dynavector Motor DWG NUMBERS 100E147

W59150

Total Criticality Ranking 134

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Motor fails electrically so as to produce no output torque.	a. Coil wiring opens or shorts b. Pole pieces break and jams motor	Steady State	4 4
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Pole pieces break b. Potting compound fails, allowing coils to jam between stator and rotating gear. c. Stator coil at inside diameter breaks and jams between stator and rotating gear.	Steady State and Start-up	4 4 4

TABLE 2-37 (Continued)

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY R.R.C. COMPONENT Drive Train DWG NUMBERS 100F147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.1	Drive train mechanical load increases.	a. Output shaft bearings increase friction. b. Ring gear to housing contact surface damaged. c. Ring gear to top cover contact surface damaged. d. Ring gear/reaction gear lower gear joint surface damage increases friction. e. Ring gear/reaction gear upper gear joint surface damage increases friction. f. Ring gear/output shaft gear joint surface damage increases friction.	Steady State and Start-up	2 2 2 2 2 2
2.2	Drive train jams in some position between full in and maximum operating position.	a. Output shaft bearings seize b. Ring gear to housing contact surface jams mechanism. c. Ring gear to top cover contact surface jams mechanism. d. Ring gear/reaction gear lower gear joint breaks and jams mechanism. e. Ring gear/reaction gear upper gear joint breaks and jams mechanism f. Ring gear/output shaft gear joint breaks and jams mechanism.	Steady State and Start-up	4 4 4 4 4 4
2.3	Drive train fails to transmit torque output.	a. Output shaft breaks b. Crowned spline breaks c. Ring gear/output shaft gear joint breaks	Steady State and Start-up	4 4 4

TABLE 2-37 (Continued)

DATE 8-25-69 PREPARED BY I. R. Shezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY *ICC* COMPONENT Potentiometers DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 1 1
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	1 1
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start-up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	2 2 2

TABLE 2-37 (Continued)

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY *RAC* COMPONENT Housing and Covers DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Housing and covers fail to contain coolant gas pressure, increasing coolant gas consumption.	a. Housing breaks	Steady State and Start-up	2
		b. Housing interface seal surfaces damaged		2
		c. Housing to top cover interface seal surface damaged.		2
		d. Cover breaks		2
		e. Cover fasteners break or loosen		2
		f. Cover seal surfaces damaged		2
		g. Potentiometer cover breaks		2
		h. Potentiometer cover fasteners break or loosen.		2
		i. Potentiometer cover seal surfaces damaged		2
		j. Coolant gas connector seal surface damaged		2
		k. Coolant gas connector breaks or loosens		2

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY *RAC* COMPONENT Seals, Coolant DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Coolant seals fail to contain coolant gas, increasing coolant gas consumption.	a. Housing interface seals leak	Steady State and Start-up	2
		b. Cover to housing interface seal leaks		2
		c. Cover to potentiometer cover seals leak		2
		d. Electrical connector seal leaks		2
		e. Coolant gas connector seal leaks		2

TABLE 2-37 (Continued)

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RGC COMPONENT Mounting Bolts DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
6.1	Mounting bolts fail to maintain clamping force.	a. Bolt breaks or loosens	Steady State and Start-up	4

DATE 8-25-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RGC COMPONENT Wiring Harness DWG NUMBERS 100E147

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Electrical wiring harness to motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State	4 4
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	1 1
7.3	Electrical connector fails to contain coolant gas, increasing coolant gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen c. Connector seal surface damaged.	Steady State and Start-up	2 2 2

2.4.3.8 Discussion and Evaluation

The electric Dynavector actuator is based upon the pneumatic Dynavector technology developed by Bendix Research Laboratory. Bendix has successfully adapted the Dynavector concept to a single, small electric actuator and has completed a study for the government applying the electric Dynavector to missile fin control. Development of an electric Dynavector CDA will require a major development effort in the areas of bearing surfaces, ring gear mesh tolerances, and restraining the ring gear when de-energized. The end-mounted potentiometer is adaptable from the XE pneumatic configuration and requires little development.

The Dynavector proportional electric actuator as shown will fit onto a 36 drum reactor concept. Its radial width at the control drum centerline is about 4.6 inches. Its height above the pressure vessel mounting boss is about 5.7 inches. Clearance required above the actuator for removal is about 1.0 inches to clear the output shaft. The Dynavector actuator is estimated to weigh about 6.8 pounds.

Coolant requirements for a one hour run, at the heating rates estimated for NERVA, about 3 watts per pound, are less than 1/2 pound and can probably be neglected. The main electrical power required is about 44 watts with a reduced power of 22 watts assumed to provide a holding torque when the actuator is not moving. Signal level power to supply the feedback potentiometer and actuator amplifier are small and have been neglected for this comparative study. A preliminary estimate of the concept reliability obtained by calibrating the fault tree is $.95^{89}$. Table 2-38 is a listing of some of the more significant advantages and disadvantages of the electric Dynavector/direct drive concept.

TABLE 2-38
DYNAVECTOR/DIRECT DRIVE CDA CONCEPT SUMMARY TABLE

<u>Advantages</u>	<u>Disadvantages</u>
1. Low Speed Bearings	1. An estimated high development cost
2. Small Overall Size	2. High Friction Components
3. Velocity Programmable	3. Information is Based on a Single Prototype
	4. High Power Consumption
	5. Low Efficiency
	6. Power Required Continuously to Hold Position Against a Bias Spacing.

2.4.4 Permanent Magnet Rotor Electric Stepper Motor Concept

2.4.4.1 Mechanical Description

The permanent magnet rotor stepping motor actuator discussed in this section is shown in Figure 2-35. The Sigma Instruments, Inc., motor upon which this concept is based is representative of a type of stepping motor built by a number of manufacturers, among them IMC, A. W. Haydon, CDC, and Aeroflex. This type of stepping motor has been used extensively as a servomotor in space applications such as Surveyor, Mariner, Lunar Orbiter, and reactor applications such as SNAP and LCRE.

The actuator consists of five subsystems.

- 1) Motor subsystem
- 2) Transmission subsystem
- 3) Feedback subsystem
- 4) Coolant subsystem
- 5) Housing enclosure subsystem

2.4.4.1.1 Motor Subsystem. The motor is a permanent magnet rotor precision stepping motor. Its operation is analogous to that of a synchronous inductor motor. Figure 2-36 shows a simplified functional layout of the stepping sequence of the motor. The rotor is a cylindrical permanent magnet, which is magnetized radially to establish alternating north and south polarized magnetic poles at the projecting teeth on its circumference. The stator is of the salient pole winding configuration, with twice the number of electromagnetic poles as the number of permanent magnetic poles in the rotor. The stator poles are evenly distributed around the circumference in four alternating winding configurations A, $\bar{A}$, B and $\bar{B}$, thus presenting a five wire system to the control system logic circuitry.

Figure 2-36 depicts the four sequential modes of stepping operation of the motor. The large solid arrow indicates rotor position at the start of the step pulse and the dotted arrow indicates the position upon completion of the pulse. Stator pole polarities shown are those impressed upon the motor during the control pulse. The small arrows indicate the direction of the local force vector imposed upon the rotor by the interaction of the magnetic fields.

Figure 2-35. Proportional Control Drum Actuator Wright Permanent Magnet Rotor Electric Stepping Motor Concept

613129-6B

Figure 2-36. Stepping Sequence (Sheet 1)

613129-7B

Figure 2-36. Stepping Sequence (Sheet 2)

Rotation of the simplified motor shown is in the clockwise direction at an increment of 22.5 degrees per step pulse.

2.4.4.1.2 Transmission Subsystem. The transmission subsystem, functionally depicted in Figure 2-37, employs three basic elements.

- a) A wave generator
- b) A non-rigid, externally splined flexspline
- c) A rigid, internally splined circular spline

The wave generator is a two lobe, ellipoidal cam surrounded by an anti-friction braking which deflects the non-rigid flexspline so that it mates with the circular spline at two equally spaced areas 180 degrees apart on their respective circumferences. The wave generator functions as the transmission input element and is directly coupled to the stepping motor. Rotation of the wave generator causes a progressive rotation of the ellipoidal shape in the flexspline, resulting in a continuous and progressive inter-engagement between flexspline and circular spline teeth. There are fewer teeth on the flexspline than on the circular spline, and a slow mechanically-reduced relative motion between these two elements is thus generated. As the wave generator makes one complete rotation, the flexspline will rotate in the opposite direction through a distance equal to the difference between the pitch circumference of the circular spline and that of the flexspline. The flexspline is directly coupled, by means of its closed end plate, to the output shaft of the actuator. The difference between the two pitch circumferences is small, thus the high-speed rotation of the wave generator is directly converted into a rotary output having greatly reduced speed and increased torque.

2.4.4.1.3 Feedback. Feedback of actuator output shaft position to the control amplifier is accomplished through a three deck potentiometer. This device provides triple redundancy to the position feedback signal. Each deck is electrically independent. The potentiometer is assembled concentrically with the main output shaft of the actuator and uses the main actuator bearings for alignment. This feature produces the simplest assembly and eliminates many parts required in separately mounted potentiometers. The potentiometer is assembled and aligned on the output shaft by the manufacturer to eliminate the possibility of error in assembly.

(a) Transmission Elements

(b) Simplified Transmission Assembly

Figure 2-37. Harmonic Drive Transmission

2.4.4.1.4 Coolant Gas. Coolant gas is taken from the propellant line after the turbo-pump at approximately 900 psia, passed through the actuator and exhausted into the reactor dome at approximately 700 psia.

2.4.4.1.5 Housing. The housing ties together all of the functional parts of the actuator. All electric power, input command signals and output position signals enter and exit the actuator by way of the electrical connector.

2.4.4.2 System Description

The permanent magnet rotor stepping motor is shown incorporated in the Control Drum Actuator System (CDAS) in Figure 2-38. The stepping motor converts a digital, electrical format into uniform, discrete drum angle positions within the resolution requirements of the CDAS. The digital format is a four bit cyclic binary code in which two adjacent bits are in the ON state while the other two are in the OFF state. The ON state represents a constant current in a particular phase winding of the motor stator while the OFF state represents no current.

Table 2-39 is an example of eight consecutive steps coded in such a manner as to cause the drum to move four steps in the direction of increasing reactivity and then return to its original position. A code of 1 represents an ON state and a 0 an OFF state.

TABLE 2-39
DRUM POSITIONING CODE

<u>Step Number</u>	<u>Code</u>	<u>Angular Change</u>	<u>Drum Angle</u>
0	1100	0	θ
1	0110	+ 1	$\theta + 1$
2	0011	+ 1	$\theta + 2$
3	1001	+ 1	$\theta + 3$
4	1100	+ 1	$\theta + 4$
5	1001	- 1	$\theta + 3$
6	0011	- 1	$\theta + 2$
7	0110	- 1	$\theta + 1$
8	1100	- 1	θ

Figure 2-38. Permanent Magnet Rotor Electrical Stepping Motor Proportional Actuator System

The actuator output shaft angular position is measured by an angular position indicator. This device converts angular position into an equivalent electrical signal. The actuator output shaft is coupled to the control drum by means of a drive shaft.

The stepping motor receives the digital, electrical currents from a code generator. The code generator is able to change and maintain the binary code in response to a pulsed input signal. The direction of drum angle command change is given by the polarity of the input pulses. The magnitude of the commanded change is given by the number of input pulses. The rate at which drum angle is commanded to change is determined by the frequency of the pulses.

Because of the precise angular positioning ability of the stepping motor the drum bank may be programmed to move to a predetermined angle (drum worth). This can be accomplished by counting the number of pulses delivered to the code generator. The actuator may be operated as an open loop system since both angular change and the rate of angular change are controllable. In the open loop system the code generator input pulses would be in proportion to the temperature or power errors or the derivatives of these errors. The actuator may also be operated as a closed loop system where the input pulses are in proportion to the difference between drum position command and position indicator output.

An example of the closed loop control system for a stepping motor is shown in Figure 2-39. In this example the drum position command is in the form of an analog voltage which is proportional to angular position. The commanded signal is compared with the drum position readout (also an analog voltage) to obtain an error signal. Digital information is taken from the error signal by the sign detector. The relationship between the sign detector input (θ_e) and its output ((+) and (-)) is given in Table 2-40.

TABLE 2-40

SIGN DETECTOR INPUT AND OUTPUT

<u>If</u>	<u>Then</u>
$\theta_e > 1/2 \theta_s$	(+) = 1, (-) = 0
$1/2 \theta_s > \theta_e > -1/2 \theta_s$	(+) = 0, (-) = 0
$\theta_e < -1/2 \theta_s$	(+) = 0, (-) = 1

Figure 2-39. Closed Loop Permanent Magnet Rotor Stepping Motor Proportional Actuator System

The term θ_s is the resolution and has a minimum of one step angle. The sign detector outputs are used to control the clock gates. If either (+) or (-) is a 1, a clock gate is opened and pulses from the clock generator are fed into the code generator. The code generator steps the motor in the direction which causes the error to come within the resolution band. Once within the resolution band, both gates are closed and the motor holds its position.

Electrical power is supplied to the actuator controller. Estimated electrical power requirements for the permanent magnet rotor stepping motor are 32 watts when moving. Coolant gas if required is supplied to the actuator and exhausted into the pressure vessel. The coolant gas must be at a higher pressure than the chamber at all times. The coolant gas flow can be regulated to control the temperature of the actuator and, thereby, reduce the effects of thermal expansion and contraction caused by extreme temperature changes.

2.4.4.3 Radiation Evaluation

Table 2-1 of Section 2.1.3 provides the radiation environment at the proposed actuator location forward of the pressure vessel closure. As those values describe the environment in the absence of perturbation by the actuator itself, they apply equally to all of the actuator concepts at this location. In most instances, the presence of the actuator will reduce the levels, so that the use of the unperturbed numbers is generally conservative.

2.4.4.4 Thermal Evaluation

The thermal-nuclear environment of the permanent magnet rotor electric stepping motor concept is, in general, similar to that of prior actuators and its thermal performance is also expected to be similar to that of other stepping motor designs. It is expected that the actuator structure can be adequately cooled although the coolant requirements will vary as a function of the actuator size and its internal heat generation. Internal coolant passages will have to be incorporated into the motor mechanism housing structure so as not to interfere with its electrical function. Regions of primary thermal analysis interest will include the relatively thick wall sections, such as housing flanges, or the asymmetrical metal sections, where maximum temperature levels or thermal distortions would be expected to occur. Further design and analyses would be required to fully identify such regions.

2.4.4.5 Structural Evaluation

Structurally, permanent magnet rotor stepping motor actuator is similar to the Responsyn actuator discussed in Section 2.4.1.5 and the Slo-Syn actuator discussed in Section 2.4.2.5. The motor is a permanent magnet rotor precision stepping motor with a separate transmission. The transmission which surrounds the rotor and stator consists of a rigid, internally splined circular spline, a non-rigid, externally splined flexspline, and a wave generator. If the permanent magnet rotor actuator is selected, the structural reliability of the unit will be verified by analysis and/or component tests.

The structural evaluation of the transmission, feedback potentiometer, and housing enclosure for this actuator is identical to that of the Responsyn actuator discussed in Section 2.4.1.5.

2.4.4.6 Radiation Effects Evaluation

The total expected radiation environment to which this actuator will be subjected is given in Section 2.1.3. To assess the effects of this environment on the actuator, a comparison of known test environments with this expected environment will indicate the sensitivity of any given concept to successful operation in the expected radiation levels. The sensitive components in this concept are the motor coils, the potentiometer, the shaft seals, and the electrical insulation and potting compounds. All other materials used in the construction of the actuator are metals. Although detail designs are not available, final material selection will be made from lists of qualified materials or will be separately qualified.

2.4.4.6.1 Motor Coils. Although motors have not been directly tested on the NERVA program, tests on other devices give important information concerning the expected performance of motor winding rails in a radiation environment. The electric coils contained in a pneumatic actuator torque motor and in the lock shut-off solenoid are similar to those used in electric motor construction. Tests conducted in a radiation environment at the GTR facility, during the NRX-A6 pneumatic actuator side-by-side test, and tests conducted by the Lewis Research Center at the Plum Brook Reactor all included the electric coils mentioned above. No coil anomalies were reported during any of these tests.⁽⁴⁾ However, it is planned

to take advantage of improvements in the state-of-the-art in insulation materials and use the polyimide series for future coil insulations to further improve radiation tolerance and increase coil reliability.

2.4.4.6.2 Potentiometer. A prototype potentiometer was also included in the tests described in the above section. A reported failure in the Lewis tests⁽⁴⁾ caused some concern until a subsequent post-irradiation examination revealed the failure was caused by a softening and flowing of a potting compound not included in the GTR and NRX-A6 side-by-side tests. Future controls will assure using only those specified materials that will not be subject to property changes under radiation environment.

2.4.4.6.3 Shaft Seals, Electrical Insulation and Potting Materials. Although these items and materials are adequate for use in the NERVA environment, it is planned to take advantage of the improvements in the state-of-the-art in insulation materials. Polyimide materials will be used in wire insulation and potting materials to increase radiation tolerance and reliability.

2.4.4.7 Reliability and Safety Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliability of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale from 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection, assembly and testing the identified component's ability to perform during its useful life installed in the actuator. The number 100 represents the most difficult level and the number 1, the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-40 shows in summary form the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific components within the actuator concept that contribute to the main block failure. The numbers in parentheses are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A tabular listing of the failure events is shown in Table 2-41. These failure events are located in the fault tree by means of their identifying numbers which appear above the blocks on the fault tree. The events are listed in an indented manner which also indicates levels on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the subtotals progress toward the right of the page.

The final total of the weighted numbers (1363) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree are indicated in parentheses in the blocks of the summary fault tree, Figure 2-40. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

Figure 2-40. Summary Fault Tree Permanent Magnet Rotor Stepping Motor

TABLE 2-41

DETAILED FAULT TREE ANALYSIS

Permanent Magnet Rotor Concept - Stepping Motor Proportional Electric
Actuator Reliability Fault Tree Analysis 939J966 Estimated Reliability $.9586$,

1. Actuator Coolant Gas Consumption Exceeds Specified Limits		95
1.1 Actuator Housing Fails to Contain Coolant Gas		55
1.1.1 Cover Fails to Contain Coolant Gas	5	
1.1.2 Cover to Body Interface Joint Fails	9	
1.1.2.1 Seal Fails	6	
1.1.2.2 Cover Fasteners Fail	3	
1.1.3 Housing Body Fails to Contain Coolant Gas	1	
1.1.4 Electrical Connector Fails to Contain Gas	40	
1.1.4.1 Seal Fails	30	
1.1.4.2 Fasteners Lose Clamping Force	5	
1.1.4.3 Connector Body Fails to Contain Gas	5	
1.2 Housing to Pedestal Interface Fails to Contain Gas		40
1.2.1 Interface Inlet Coolant Seal Fails	30	
1.2.2 Fasteners Lose Clamping Force	5	
1.2.3 Interface Exhaust Coolant Passage Seal Fails	5	
2. Actuator Fails to Position Control Drum Within Time Position Band		1207
2.1 Actuator Fails to Convert Electrical to Mechanical Power		138
2.1.1 Electrical Connector Fails to Transmit Proper Signal	10	
2.1.1.1 Conductor Fails to Transmit Proper Signal	5	
2.1.1.2 Insulator Fails Permitting Short Circuit	5	
2.1.2 Motor Fails Electrically	93	

TABLE 2-41 (CONTINUED)

2.1.2.1	Wiring Failure	80	
2.1.2.2	Loss of Permanent Magnet Bonding to Shaft	2	
2.1.2.3	Pole Pieces Break	1	
2.1.2.4	Loss of Rotor Permanent Magnet Properties	10	
2.1.3	Actuator Internal Wiring Harness Fails		35
2.1.3.1	Conductor Fails	5	
2.1.3.2	Insulation Fails	25	
2.1.3.3	Terminal Mechanically Fails	5	
2.2	Improper Command Received from Amplifier		249
2.2.1	Amplifier Supply Voltage Incorrect Value		AGC
2.2.2	Amplifier Fails Internally		30
2.2.3	Amplifier Feedback Signal Incorrect		219
2.2.3.1	Potentiometer Supply Voltage Wrong Value	30	
2.2.3.1.1	Actuator Wiring Harness Fails	30	
2.2.3.1.2	Voltage Supplied is in Error	AGC	
2.2.3.2	Feedback Potentiometer Output Fails		154
2.2.3.2.1	Potentiometer Electrically Fails	101	
2.2.3.2.1.1	Track Resistance Value Changes	10	
2.2.3.2.1.2	Protective Resistor Changes Value	10	
2.2.3.2.1.3	Wiper Resistance Value Changes	1	
2.2.3.2.1.4	Wiper to Track Contact Resistance Changes	80	
2.2.3.2.2	Angular Relationship Pot to Drum Changes	21	
2.2.3.2.2.1	Pot Position Relative to Shaft Changes	20	
2.2.3.2.2.2	Shaft Relative to Drum Changes	1	
2.2.3.2.3	Potentiometer Mechanically Fails	32	

TABLE 2-41 (CONTINUED)

2.2.3.2.3.1 Potentiometer Shaft Fails	1		
2.2.3.2.3.2 Wiper Spring Gradient Changes	1		
2.2.3.2.3.3 Bearings Fail	10		
2.2.3.2.3.4 Potentiometer Housing Fractures	20		
2.2.3.3 Feedback Signals Transmitted Improperly		35	
2.2.3.3.1 Wiring Harness Actuator to Amplifier Fails	AGC		
2.2.3.3.2 Mechanism Wiring Harness Fails	30		
2.2.3.3.3 Electro-Magnetic Interference Distorts Signal	5		
2.3 Actuator External Control Drum Loads Change			EC
2.4 Actuator Internal Loads Change			820
2.4.1 Harmonic Drive Fails to Transmit Sufficient Torque		260	
2.4.1.1 Teeth Fail to Transmit Torque		15	
2.4.1.1.1 Teeth Break	10		
2.4.1.1.2 Teeth Wear	5		
2.4.1.2 Fastener Interferes with Motion		10	
2.4.1.3 Wave Generator Rotation Impaired		155	
2.4.1.3.1 Bearing Friction Increases	130		
2.4.1.3.2 Eliptoidal Cam Breaks	5		
2.4.1.3.3 Flexible Outer Race Breaks	20		
2.4.1.4 Cup Fails to Transmit Motion		80	
2.4.1.4.1 Weld Fails	30		
2.4.1.4.2 Cup Breaks	50		
2.4.2 Motor Fails Mechanically		450	
2.4.2.1 Bearing Friction Increases		280	
2.4.2.2 Fasteners Interfere with Motion		10	
2.4.2.3 Stator Wiring Interferes with Motion		160	

TABLE 2-41 (CONTINUED)

2.4.2.3.1 Actuator Housing Distorts	1		
2.4.2.3.2 Stator Potting Material Deteriorates	10		
2.4.2.3.3 Conductor at I.D. Of Motor Breaks	5		
2.4.2.3.4 Pole Pieces Break	144		
2.4.3 Output Shaft-Pot Bearings Friction Level Increases		70	
2.4.4 Output Shaft Fails to Transmit Torque		40	
2.4.4.1 Teeth Break	10		
2.4.4.2 Shaft Breaks	20		
2.4.4.3 Cup to Shaft Coupling Fails	10		
3. Actuator Electrical Power Rate Exceeds Specified Limits			61
3.1 Actuator Short Circuit Failure		41	
3.1.1 Potentiometer Internal Short Circuit		10	
3.1.2 Stator Wiring Insulation Fails Allowing Short Circuit		10	
3.1.3 Wiring Harness System Short Circuits		21	
3.1.3.1 Connector Short Circuits	10		
3.1.3.2 Wiring Insulation Fails	10		
3.1.3.3 Terminal Fails	1		
3.2 Amplifier Internal Short Circuit		20	
3.3 Amplifier/Actuator External Cable Short Circuit Failure		AGC	

The calibration process (Section 2.1.7.1.1) consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

2.4.4.7.1 Failure Mode Evaluation. A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts are not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component is analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another.⁽¹⁹⁾ The total number then indicates the relative reliability of the actuator concept; the lower the number the more reliable the particular concept is relative to the others. Each concept is compared with the others on the basis of the

total relative failure probability number. The failure mode analysis for the permanent magnet rotor proportional electric stepper motor concept is shown in Table 2-42.

2.4.4.7.2 Safety Evaluation. The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and criticality ranking for each concept, failure modes have been identified. For each of the failure modes listed, mechanisms of obtaining that failure mode are established as they relate to a particular design and each of these failure mechanisms is given a numerical ranking consistent with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reductions in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.
1	Failures resulting in insignificant effects on chamber temperature/pressure.

By assigning each mechanism of failure to one of the above categories, and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-43 presents a tabulation of the

TABLE 2-42

COMPONENT FAILURE MODES ANALYSIS

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Actuator
DATE APPROVED BY RGC COMPONENT P. M. Motor DWG NUMBERS 100E145

W59150

Relative Ranking 137

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Motor fails electrically so as to produce no output torque	a. Coil wiring opens or shorts b. Pole pieces break c. Permanent magnet material bond to rotor shaft breaks d. Loss or rotor permanent magnet properties	Steady State and Start-up	8 1 1 1
1.2	Motor fails mechanically so as to produce no output torque and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces breaks and jams motor c. Potting compound fails, allowing coils to jam between stator and rotor. d. Stator coil at inside diameter breaks and jams between stator and rotor.	Steady State and Start-up	20 10 1 1

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
DATE APPROVED BY RGC COMPONENT Drive Train DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.1	Drive train mechanical load increases	a. Flexspline gear teeth surface damage increases friction. b. Elliptical bearing binds and increases friction. c. Elliptical cam breaks d. Flexible outer race breaks e. Output shaft bearings bind and increase friction.	Steady State and Start-up	1 10 1 2 6

TABLE 2-42 (CONTINUED)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Actuator
 DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.2	Drive train jams in some position between full in and the maximum operating range.	a. Flexspline gear teeth break and jam the mechanism. b. Elliptical bearing seizes c. Output shaft bearings seize d. Bearing housing fasteners break or loosen and jam mechanism.	Steady State and Start-up	1 3 2 1
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Shaft crowned spline breaks c. Flexible cup breaks d. Flexspline gear teeth break	Steady State and Start-up	1 1 8 1

TABLE 2-42 (CONTINUED)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RCC COMPONENT Potentiometers DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 4 2
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft	Start-up and Steady State	1 2
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks	Start-up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Startup and Steady State	1 1 8

TABLE 2-42 (CONTINUED)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Actuator
 DATE _____ APPROVED BY RAC COMPONENT Housing and Cover DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen f. Coolant supply connector breaks or loosens	Steady State and Start-up	1 1 1 1 1 1

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Actuator
 DATE _____ APPROVED BY RAC COMPONENT Seals, Coolant DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	1 3 1 3 3

TABLE 2-42 (CONTINUED)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum ActuatorDATE APPROVED BY RQC COMPONENT Mounting Studs DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	Mounting stud fails to maintain proper clamping force.	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action.	Steady State and Start-up	1 1 1

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum ActuatorDATE APPROVED BY RQC COMPONENT P. M. Motor DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	3 2
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Start-up and Steady State	2 4
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Start-up and Steady State	1 1

TABLE 2-43

COMPONENT SAFETY CRITICALITY

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum ActuatorDATE APPROVED BY RGC COMPONENT P. M. Motor DWG NUMBERS 100E145

W59150

Total Criticality Ranking 134

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Motor fails electrically so as to produce no output torque	a. Coil wiring opens or shorts b. Pole pieces break c. Permanent magnet material bond to rotor shaft breaks d. Loss or rotor permanent magnet properties	Steady State and Start-up	4 4 4 4
1.2	Motor fails mechanically so as to produce no output torque and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces breaks and jams motor c. Potting compound fails, allowing coils to jam between stator and rotor. d. Stator coil at inside diameter breaks and jams between stator and rotor.	Steady State and Start-up	4 4 4 4

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RGC COMPONENT Drive Train DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.1	Drive train mechanical load increases	a. Flexspline gear teeth surface damage increases friction. b. Elliptical bearing binds and increases friction. c. Elliptical cam breaks d. Flexible outer race breaks e. Output shaft bearings bind and increase friction.	Steady State and Start-up	2 2 2 2 2

TABLE 2-43 (CONTINUED)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum ActuatorDATE _____ APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.2	Drive train jams in some position between full in and the maximum operating range.	a. Flexspline gear teeth break and jam the mechanism. b. Elliptical bearing seizes c. Output shaft bearings seize d. Bearing housing fasteners break or loosen and jam mechanism.	Steady State and Start-up	4 4 4 4
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Shaft crowned spline breaks c. Flexible cup breaks d. Flexspline gear teeth break	Steady State and Start-up	4 4 4 4

TABLE 2-43 (CONTINUED)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Actuator
 DATE _____ APPROVED BY RUC COMPONENT Potentiometers DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.1	Potentiometers fail to provide feedback signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 1 1
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft	Start-up and Steady State	1 1
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks	Start-up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Startup and Steady State	2 2 2

TABLE 2-43 (CONTINUED)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum ActuatorDATE _____ APPROVED BY RCC COMPONENT Housing and Cover DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen f. Coolant supply connector breaks or loosens	Steady State and Start-up	2 2 2 2 2 2

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum ActuatorDATE _____ APPROVED BY RCC COMPONENT Seals, Coolant DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	2 2 2 2 2

TABLE 2-43 (CONTINUED)

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Actuator
 DATE APPROVED BY RAC COMPONENT Mounting Studs DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
6.1	Mounting stud fails to maintain proper clamping force.	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action.	Steady State and Start-up	2 2 2

DATE 8-21-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Actuator
 DATE APPROVED BY RAC COMPONENT P. M. Motor DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	4 4
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Start-up and Steady State	1 1
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Start-up and Steady State	2 2

failures, mechanism of failure and criticality ranking of failure for the permanent magnet rotor electric actuator. Also shown is the total criticality ranking for this concept.

2.4.4.8 Discussion and Evaluation

The permanent magnet rotor actuator concept is nearly identical in operation and configuration to other permanent magnet rotor actuator concepts, the only significant differences are the number of stator poles and the rotor mechanical construction. This motor has 24 stator poles and maintains the air gap between magnetic pole pieces and a full permanent magnet material disc.

The motor has a relatively high flux density and thus, in general, requires less input power to attain a given torque output. However, the dissimilar materials bounding the air gap may present operating difficulties in change of air gap dimension or interference during temperature transients, and warrants a detailed analysis and development tests.

Other areas, common to most actuator concepts, requiring development effort are the concentric potentiometer, wiring insulation and motor coil encapsulant.

The permanent magnet rotor motor upon which this concept is based is representative of a type of stepping motor built by a number of manufacturers, among them IMC, A. W. Haydon, CDC, Aeroflex, and Sigma Instruments, Inc. This type of stepping motor has been used extensively as a servomotor in space applications such as Surveyor, Mariner, Lunar Orbiter and reactor applications such as SNAP and LCRE.

The Harmonic drive transmission has also been used successfully in various SNAP programs. Operation in all of these programs was at elevated temperature, however, and low temperature operation requirements will necessitate additional analysis and development tests.

The permanent magnet rotor proportional electric actuator as shown will fit on up to a 36 drum reactor concept. Its radial width at the control drum centerline is about 4.9 inches. Its height above the pressure vessel mounting boss is about 4.5 inches. Clearance required above the actuator for removal is about 2.5 inches to clear the output shaft. The permanent magnet rotor stepping motor is estimated to weigh about 6.7 pounds.

Coolant requirements for a one hour run at the heating rates estimated for NERVA, about 3 watts per pound, are less than 1/2 pound and can probably be neglected. The main electrical power required is about 32 watts with no power required during non-moving phases of reactor operating time because of the high detent torque available. Signal level power to supply the feedback potentiometers and control amplifier is small and has been neglected for the comparative study. A preliminary estimate of the concept reliability obtained by calibrating the fault tree is $.9586$. Table 2-44 is a listing of some of the more significant advantages and disadvantages of the permanent magnet rotor concept.

2.5 AC SERVOMOTOR PROPORTIONAL CONCEPT

The AC servomotor actuator is a two phase, 400 Hz motor and high ratio Harmonic drive speed-reducing transmission configuration, similar in transmission, housing and feedback potentiometer to the permanent magnet stepping motor concepts. The motor is based upon that used in the optimized electric control drum actuator developed for WANL by Westinghouse Research in 1963.

2.5.1 Mechanical Description

The AC servomotor actuator discussed in this section is shown in Figure 2-41.

The actuator consists of five subsystems.

- 1) Motor subsystem
- 2) Transmission subsystem
- 3) Feedback subsystem
- 4) Coolant subsystem
- 5) Housing enclosure subsystem

2.5.1.1 Motor Subsystem

The motor is a modified two-phase 400 Hz induction motor utilizing a small diameter, high resistance rotor. Operation is as in the standard polyphase induction motor, producing moderate torque at very high speed. The motor output is handled by a high ratio, speed reducing transmission which develops the operating characteristics required.

TABLE 2-44

PERMANENT MAGNET STEPPER/HARMONIC DRIVE
CDA CONCEPT SUMMARY TABLE

<u>Advantages</u>	<u>Disadvantages</u>
1. Low weight	1. Moderately high speed bearing
2. High magnetic detent forces are available to hold position without power	2. Moderately high gear reduction
3. High resolution	
4. Small overall size	
5. Inherent braking	
6. Few moving parts	
7. Programmable velocity	
8. Can be operated without feedback potentiometers in the control loop	
9. Control transistors can be operated in a switching mode for highest reliability.

Figure 2-41. Proportional Control Drum Actuator A. C. Motor Electric Concept

2.5.1.2 Transmission Subsystem

The transmission subsystem, functionally depicted in Figure 2-42 employs three basic elements.

- 1) A wave generator
- 2) A non-rigid, externally splined flexspline
- 3) A rigid, internally splined circular spline

The wave generator is a two-lobe, elliptoidal cam surrounded by an anti-friction bearing which deflects the non-rigid flexspline so that it mates with the circular spline at two equally spaced areas 180 degrees apart on their respective circumferences. The wave generator functions as the transmission input element and is directly coupled to the stepping motor. Rotation of the wave generator causes a progressive rotation of the elliptoidal shape in the flexspline, resulting in a continuous and progressive engagement between flexspline and circular spline teeth. There are fewer teeth on the flexspline than on the circular spline, and a slow mechanically-reduced relative motion between these two elements is thus generated. As the wave generator makes one complete rotation, the flexspline rotates in the opposite direction through a distance equal to the difference between the pitch circumference of the circular spline and that of the flexspline. The flexspline is directly coupled, by its closed end plate, to the output shaft of the actuator. The difference between the two pitch circumferences is small, thus the high-speed rotation of the wave generator is directly converted into a rotary output having greatly reduced speed and increased torque.

2.5.1.3 Feedback

Feedback of actuator output shaft position to the control amplifier is accomplished through a three-deck potentiometer. This device provides triple redundancy to the position feedback signal. Each deck is electrically independent of the other two. The potentiometer is assembled concentrically with the main output shaft of the actuator and uses the main actuator bearings for alignment. This feature produces the simplest assembly and eliminates many parts required in separately mounted potentiometers. The potentiometer is assembled and aligned on the output shaft by the manufacturer to eliminate the possibility of error in assembly.

Figure 2-42. Harmonic Drive Transmission

2.5.1.4 Coolant Gas

Coolant gas is taken from the propellant line after the turbopump at approximately 900 psia. It is passed through the actuator and then is exhausted into the reactor dome at approximately 700 psia.

2.5.1.5 Housing

The housing ties together all of the functional parts of the actuator. All electric power, input command signals and output position signals enter and exit the actuator by way of the electrical connector.

2.5.2 System Description

The ac servomotor actuator system block diagram is shown in Figure 2-43. The system uses a two-phase high-speed induction motor. The fixed phase is excited by a constant ac current. The control phase is excited by a variable amplitude ac current which is displaced from the fixed phase by ± 90 degrees.

The output of the motor is coupled to the actuator output shaft by a gear arrangement which reduces speed and increases torque to meet the control drum requirements. The actuator output shaft is coupled to the control drum by a drive shaft. An angular position indicator is provided to measure the actuator output shaft angle for both control and diagnostic purposes.

The ac current for the control phase of the servomotor is generated by the actuator amplifier which contains the necessary compensation and modulation to control the servomotor. The amplifier is driven by an error signal which is the difference between the drum position command and the output position indicator signals.

Electrical power is supplied to the actuator amplifier. The required power is in the form of both ac and dc currents. Hydrogen coolant is supplied to the actuator and exhausted into the pressure vessel. The coolant gas must be at a pressure greater than that of the chamber at all times.

Figure 2-43. A. C. Servomotor Proportional Control Drum Concept

2.5.3 Radiation Evaluation

Table 2-1 of Section 2.1.3 provides the radiation environment at the proposed actuator location forward of the pressure vessel closure. As those values describe the environment in the absence of perturbation by the actuator itself, they apply equally to all of the actuator concepts at this location. In most instances, the presence of the actuator will reduce the levels, so that the use of the unperturbed numbers is generally conservative.

2.5.4 Thermal Evaluation

The thermal-nuclear environment of the ac servomotor proportional concept is, in general, similar to that of Section 2.1.4 and the thermal performance is also expected to be similar. It is expected that the actuator structure can be adequately cooled, although the coolant requirements will vary as a function of the actuator size and its internal heat generation. Internal coolant passages will have to be incorporated into the motor mechanism housing structure so as not to interfere with its electrical function. Regions of primary thermal analysis interest will include the relatively thick wall sections, such as housing flanges, or the asymmetrical metal sections, where maximum temperature levels or thermal distortions would be expected to occur.

2.5.5 Structural Evaluation

The structural evaluation of the ac servomotor actuator is identical to that of the Slo-syn actuator discussed in Section 2.4.2.5. The only difference between these two designs is the substitution of an ac motor for an electric stepping motor. If this actuator is selected from the trade study, the structural reliability of the ac will be verified by analysis and/or component tests.

2.5.6 Radiation Effects Evaluation

The total expected radiation environment to which this actuator will be subjected is given in Section 2.1.3. To assess the effects of this environment on the actuator, a comparison of known test environments with this expected environment will indicate the sensitivity of any given concept to successful operation in the expected radiation levels. The sensitive components in this concept are the motor coils, the potentiometer, the shaft seals,

and the electrical insulation and potting compounds. All other materials used in the construction of the actuator are metals. Although detail designs are not available, final material selection will be made from lists of qualified materials or will be separately qualified.

2.5.6.1 Motor Coils

Although motors have not been directly tested on the NERVA program, tests on other devices give important information concerning the expected performance of motor winding rails in a radiation environment. The electric coils contained in a pneumatic actuator torque motor and in the lock shut-off solenoid are similar to those used in electric motor construction. Tests conducted in a radiation environment at the GTR facility, during the NRX-A6 pneumatic actuator side-by-side test, and tests conducted by the Lewis Research Center at the Plum Brook Reactor all included the electric coils mentioned above. No coil anomalies were reported during any of these tests.⁽⁴⁾ However, it is planned to take advantage of improvements in the state-of-the-art in insulation materials and use the polyimide series for future coil insulations to further improve radiation tolerance and increase coil reliability.

2.5.6.2 Potentiometer

A prototype potentiometer was also included in the tests described in the above section. A reported failure in the Lewis tests⁽⁴⁾ caused some concern until a subsequent post-irradiation examination revealed the failure was caused by a softening and flowing of a potting compound not included in the GTR and NRX-A6 side-by-side tests. Future controls will assure using only those specified materials that will not be subject to property changes under radiation environment.

2.5.6.3 Shaft Seals, Electrical Insulation and Potting Materials

Although these items and materials are adequate for use in the NERVA environment, it is planned to take advantage of the improvements in the state-of-the-art in insulation materials. Polyimide materials will be used in wire insulation and potting materials to increase radiation tolerance and reliability.

2.5.7 Reliability and Safety Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliabilities of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale from 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection, assembly and testing the identified component's ability to perform during its useful life installed in the actuator. The number 100 represents the most difficult level and the number 1 the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event identified on the tree and has assigned a relative weighting number to each failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-44 shows in summary form the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific components within the actuator concept that contribute to the main block failure. The numbers in parentheses are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A tabular listing of the failure events is shown in Table 2-45. These failure events are located in the fault tree by means of their identifying numbers which appear above

Figure 2-44. Summary Fault Tree AC Motor Harmonic Drive Concept

TABLE 2-45
DETAILED FAULT TREE ANALYSIS

A.C. Motor Harmonic Drive Proportional Electric Actuator Reliability
Fault Tree Analysis 939J956 Estimated Reliability .9585

1498

1. Actuator Coolant Gas Consumption Exceeds Specified Limits		95
1.1 Actuator Housing Fails to Contain Coolant Gas		55
1.1.1 Cover Fails to Contain Coolant Gas	5	
1.1.2 Cover to Body Interface Joint Fails	9	
1.1.2.1 Seal Fails	6	
1.1.2.2 Cover Fasteners Fail	3	
1.1.3 Housing Body Fails to Contain Coolant Gas	1	
1.1.4 Electrical Connector Fails to Contain Gas	40	
1.1.4.1 Seal Fails	30	
1.1.4.2 Fasteners Lose Clamping Force	5	
1.1.4.3 Connector Body Fails to Contain Gas	5	
1.2 Housing to Pedestal Interface Fails to Contain Gas		40
1.2.1 Interface Inlet Coolant Seal Fails	30	
1.2.2 Fasteners Lose Clamping Force	5	
1.2.3 Interface Exhaust Coolant Passage Seal Fails	5	
2. Actuator Fails to Position Control Drum Within Time Position Band		1262
2.1 Actuator Fails to Convert Electrical to Mechanical Power		201
2.1.1 Electrical Connector Fails to Transmit Proper Signal	10	
2.1.1.1 Conductor Fails to Transmit Signal	5	
2.1.1.2 Insulator Fails Permitting Short Circuit	5	

TABLE 2-45 (CONTINUED)

2.1.2 Motor Fails Electrically		121
2.1.2.1 Wiring Failure in Stator Winding	40	
2.1.2.2 Pole Pieces Break	1	
2.1.2.3 Wiring Failure in Rotor Winding	80	
2.1.3 Actuator Internal Wiring Harness Fails		35
2.1.3.1 Conductor Fails	5	
2.1.3.2 Insulation Fails	25	
2.1.3.3 Terminal Mechanically Fails	5	
2.1.4 Pedestal Wiring Harness Fails to Transmit Signal		35
2.1.4.1 Conductor Fails to Transmit Signal	5	
2.1.4.2 Insulation Fails Allowing Short Circuit	25	
2.1.4.3 Terminal Mechanical Failure	5	
2.2 Improper Command Received from Amplifier		249
2.2.1 Amplifier Control Voltage Incorrect		AGC
2.2.2 Amplifier Fails Internally		30
2.2.3 Amplifier Feedback Signal Incorrect		219
2.2.3.1 Potentiometer Supply Voltage Wrong Value	30	
2.2.3.1.1 Actuator System Wiring Harness Fails	30	
2.2.3.1.2 Voltage Supplied is in Error	AGC	
2.2.3.2 Feedback Potentiometer Output Fails	154	
2.2.3.2.1 Potentiometer Electrically Fails	101	
2.2.3.2.1.1 Track Resistance Value Changes	10	
2.2.3.2.1.2 Protective Resistor Changes Value	10	
2.2.3.2.1.3 Wiper Resistance Value Changes	1	
2.2.3.2.1.4 Wiper to Track Contact Resistance Changes	80	

TABLE 2-45 (CONTINUED)

2.2.3.2.2 Angular Relationship Pot to Drum Changes	21	
2.2.3.2.2.1 Pot Position Relative to Shaft Changes	20	
2.2.3.2.2.2 Shaft Relative to Drum Changes	1	
2.2.3.2.3 Potentiometer Mechanically Fails	32	
2.2.3.2.3.1 Potentiometer Shaft Fails	1	
2.2.3.2.3.2 Wiper Spring Gradient Changes	1	
2.2.3.2.3.3 Bearings Fail	10	
2.2.3.2.3.4 Potentiometer Housing Fractures	20	
2.2.3.3 Feedback Signals Transmitted Improperly		35
2.2.3.3.1 Wiring Harness Actuator to Amplifier Fails	AGC	
2.2.3.3.2 Mechanism Wiring Harness Fails	30	
2.2.3.3.3 Electro-Magnetic Interference Distorts Signal	5	
2.3 Actuator External Loads Change		EC
2.4 Actuator Internal Loads Change		812
2.4.1 Flexspline Torque Output Low		260
2.4.1.1 Teeth Fail to Transmit Torque		15
2.4.1.1.1 Teeth Break	10	
2.4.1.1.2 Teeth Wear		
2.4.1.2 Fastener Interfers with Motion		10
2.4.1.3 Wave Generator Rotation Fails		155
2.4.1.3.1 Bearing Friction Increases	130	
2.4.1.3.2 Eliptoidal Cam Breaks	5	
2.4.1.3.3 Flexible Outer Race Breaks	20	
2.4.1.4 Cup Fails to Transmit Motion		80
2.4.1.4.1 Weld Fails	30	
2.4.1.4.2 Cup Breaks	50	

TABLE 2-45 (CONTINUED)

2.4.2	Motor Fails Mechanically		442
2.4.2.1	Bearing Friction Increases	280	
2.4.2.2	Fasteners Interfere with Motion	10	
2.4.2.3	Stator Wiring Interferes with Motion	76	
2.4.2.3.1	Actuator Housing Distorts	1	
2.4.2.3.2	Stator Porting Material Deteriorates	10	
2.4.2.3.3	Conductor at I.D. of Motor Breaks	5	
2.4.2.3.4	Pole Pieces Break	60	
2.4.2.4	Rotor Wiring Interferes with Rotation	76	
2.4.2.4.1	Actuator Housing Distorts	1	
2.4.2.4.2	Rotor Porting Material Deteriorates	10	
2.4.2.4.3	Conductor at Circumference of Rotor Breaks	5	
2.4.2.4.4	Pole Pieces Break	60	
2.4.3	Output Shaft-Pot Bearings Friction Level Increases		70
2.4.4	Output Shaft Fails to Transmit Torque		40
2.4.4.1	Teeth Break	10	
2.4.4.2	Shaft Breaks	20	
2.4.4.3	Cup to Shaft Coupling Fails	10	
3.	Actuator Electrical Power Rate Exceeds Specified Limits		141
3.1	Actuator Short Circuits		121
3.1.1	Potentiometer Internal Short Circuit	10	
3.1.2	Stator Wiring Insulation Fails Allowing Short Circuit	10	
3.1.3	Wiring Harness System Short Circuits	21	
3.1.3.1	Interface Connector Short Circuits	10	
3.1.3.2	Wiring Insulation Fails	10	
3.1.3.3	Terminal Fails	1	

TABLE 2-45 (CONTINUED)

3.1.4 Rotor Wiring Insulation Fails	80	
3.2 Amplifier Internal Short Circuit		20
3.3 Amplifier/Actuator External Cable Short Circuit Failure		AGC

the blocks on the fault tree. The events are listed in an indented manner which also indicates levels on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the subtotals progress toward the right of the page.

The final total of the weighted numbers (1498) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree are indicated in parentheses in the blocks of the summary fault tree, Figure 2-44. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

The calibration process (Section 2.1.7.1.1) consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

2.5.7.1 Failure Mode Evaluation

A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts are not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component is analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another.⁽⁹⁾ The total number then indicates the relative reliability of the actuator concept; the lower the number the more reliable the particular concept is relative to the others. Each concept is compared with the others on the basis of the total relative failure probability number. A failure mode analysis for the ac motor proportional electric actuator is shown in Table 2-46.

2.5.7.2 Safety Evaluation

The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and criticality ranking for each concept, failure modes have been identified. For each of the failure modes listed, mechanisms of obtaining that failure mode are established as they relate to a particular design and each of these failure mechanisms has been given a numerical ranking

TABLE 2-46

COMPONENT FAILURE MODES ANALYSIS

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT AC-Motor DWG NUMBERS 100E148

W59150

Relative Ranking 147

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Motor fails electrically so as to produce no output torque	a. Stator wiring opens or shorts b. Pole pieces break c. Rotor wiring opens or shorts	Steady State and Start-up	4 1 8
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces break and jam motor c. Stator potting compound fails, allowing coils to jam between stator and rotor d. Stator coil at inside diameter, breaks and jams between stator and rotor e. Rotor potting compound fails, allowing coils to jam between stator and rotor f. Rotor coil, at outside diameter, breaks and jams between stator and rotor g. Rotor pole pieces break and jam motor.	Steady State and Start-up	20 6 1 1 1 1 6

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.1	Drive train mechanical load increases.	a. Flexspline gear teeth surface damage increases friction b. Elliptical bearing binds and increases friction c. Elliptoidal cam breaks d. Flexible outer race breaks e. Output shaft bearings bind and increase friction	Steady State and Start-up	1 10 1 2 6

TABLE 2-46 (CONTINUED)

DATE 8-22-68 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.2	Drive train jams in some position between full in and the maximum operating range.	a. Flexspline gear teeth break and jam the mechanism b. Elliptical bearing seizes c. Output shaft bearings seize d. Bearing housing fasteners break or loosen and jam mechanism	Steady State and Start-up	1 3 2 1
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Shaft crowned spline breaks c. Flexible cup breaks d. Flexspline gear teeth break e. Keyed joint, between motor shaft and elliptoidal cam, breaks f. Coupling between flexible cup and output shaft, breaks	Steady State and Start-up	1 1 8 1 1 2

TABLE 2-46 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT Potentiometers DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Potentiometers fail to provide feedback signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 4 2
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	1 2
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks	Start-up and Steady	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	State Startup and Steady State	1 1 8

2-311

TABLE 2-46 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.

DATE APPROVED BY RAC COMPONENT Housing and Cover DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen f. Coolant supply connector breaks or loosens	Steady State and Start-up	1 1 1 1 1 1

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act

DATE APPROVED BY RAC COMPONENT Seals, Coolant DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	1 3 1 3 3

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.

DATE APPROVED BY RAC COMPONENT Mounting Studs DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	Mounting stud fails to maintain proper clamping force.	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action	Steady State and Start-up	1 1 1

consistent with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reductions in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.
1	Failures resulting in insignificant effects on chamber temperature/pressure.

By assigning each mechanism of failure to one of the above categories, and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-47 presents a tabulation of the failures, mechanism of failure and criticality ranking of failure for the ac motor electric actuator. Also shown is the total criticality ranking for this concept.

2.5.8 Discussion and Evaluation of Concept

Requirements for 400 Hz, two phase power, high speed bearings and stopping circuitry in the form of a capacitor shorting system or mechanical brake severely limit the adaptability of an ac motor to the CDA application. All of the development work necessary in building

TABLE 2-47

COMPONENT SAFETY CRITICALITY

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT AC-Motor DWG NUMBERS 100E148

W59150

Total Criticality Ranking 166

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Motor fails electrically so as to produce no output torque	a. Stator wiring opens or shorts b. Pole pieces break c. Rotor wiring opens or shorts	Steady State and Start-up	4 4 4
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces break and jam motor c. Stator potting compound fails, allowing coils to jam between stator and rotor d. Stator coil at inside diameter, breaks and jams between stator and rotor e. Rotor potting compound fails, allowing coils to jam between stator and rotor f. Rotor coil, at outside diameter, breaks and jams between stator and rotor g. Rotor pole pieces break and jam motor	Steady State and Start-up	4 4 4 4 4 4 4

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.1	Drive train mechanical load increases.	a. Flexspline gear teeth surface damage increases friction b. Elliptical bearing binds and increases friction c. Elliptoidal cam breaks d. Flexible outer race breaks e. Output shaft bearings bind and increase friction	Steady State and Start-up	2 2 2 2 2

TABLE 2-47 (CONTINUED)

DATE 8-22-68 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Drive Train DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.2	Drive train jams in some position between full in and the maximum operating range.	a. Flexspline gear teeth break and jam the mechanism b. Elliptical bearing seizes c. Output shaft bearings seize d. Bearing housing fasteners break or loosen and jam mechanism	Steady State and Start-up	4 4 4 4
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Shaft crowned spline breaks c. Flexible cup breaks d. Flexspline gear teeth break e. Keyed joint, between motor shaft and elliptoidal cam, breaks f. Coupling between flexible cup and output	Steady State and Start-up	4 4 4 4 4 4

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RAC COMPONENT Potentiometers DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.1	Potentiometers fail to provide feedback signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open e. Potentiometers housing breaks	Start-up and Steady State	4 4 4 4 4
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative toinion output shaft.	Start-up and Steady State	2 2

TABLE 2-47 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Potentiometers DWG NUMBERS 100E145

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks	Start-up and Steady	4
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation	a. All potentiometer wipers change in resistance b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance	State Startup and Steady State	2 2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RAC COMPONENT Housing and Cover DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen f. Coolant supply connector breaks or loosens	Steady State and Start-up	2 2 2 2 2 2

TABLE 2-47 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT Seals, Coolant DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	2 2 2 2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RAC COMPONENT Mounting Studs DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
6.1	Mounting stud fails to maintain proper clamping force.	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action	Steady State and Start-up	2 2 2

TABLE 2-47 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY R.R.C. COMPONENT Wiring Harness DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	4 4
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	1 1
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks. b. Connector fasteners break or loosen	Steady State and Start-up	2 2

a stepping motor actuator must also be accomplished for the ac motor actuator in addition to the items noted above. An optimized ac motor actuator will be the heaviest of the electric concepts as well as the most difficult to stabilize and control. Stabilization networks in ac motors are notably more complex than equivalent dc systems. Temperature changes in ac motor windings directly affect stability and the use of passive elements for stability require use of elaborate modulating and demodulating schemes.

The ac proportional electric actuator, as shown, will fit on up to a 36 drum reactor concept. Its radial width at the control drum centerline is about 4.8 inches. Its height above the pressure vessel mounting boss is about 4.4 inches. Clearance required above the actuator for removal is about 4.3 inches to clear the output shaft. The ac motor actuator concept is estimated to weigh about 7.9 pounds. Coolant requirements for a one hour run at the heating rates estimated for NERVA, about 3 watts per pound, are less than 1/2 pound and can probably be neglected. The main electrical power required is about 45 watts with a reduced power of 30 watts required to hold the actuator in position when it is not moving. Signal level power to supply the feedback potentiometer and control amplifier is small and has been neglected for this comparative study. A preliminary estimate of the concept reliability, obtained by calibrating the fault tree, is $.9_{585}$. Table 2-48 is a listing of some of the more significant advantages and disadvantages of the ac servomotor concept.

2.6 DC MOTOR PROPORTIONAL CONCEPT

The dc motor actuator is adapted from the dc motors developed for use in aircraft control surface actuation. These motors have been refined to the point where they are very efficient, have excellent response time, low weight and small overall size relative to other electric motors. Most dc motors used in spare applications are limited to short duration or to binary ON-OFF service.

2.6.1 Mechanical Description

The dc servomotor actuator discussed in this section is shown in Figure 2-45.

TABLE 2-48

AC SERVO MOTOR/HARMONIC DRIVE
CDA CONCEPT SUMMARY TABLE

Advantages

1. No obvious advantages.

Disadvantages

1. High speed bearings tend to reduce reliability
2. AC power required
3. Low efficiency
4. Capacitor shorting to stop
5. Requires convection cooling
6. Heavy
7. A brake or continuous power required to hold position against bias spring
8. May be difficult to stabilize over temperature range

Figure 2-45. Proportional Control Drum Actuator D. C. Motor Electric Concept

The actuator consists of five subsystems.

- 1) Motor subsystem
- 2) Transmission subsystem
- 3) Feedback subsystem
- 4) Coolant subsystem
- 5) Housing enclosure subsystem

2.6.1.1 Motor

The motor is a modified split-series dc servomotor utilizing a small diameter, high resistance rotor. Operation is as in the standard brush commutated split-series dc motor, producing moderate torque at very high speed. The motor output is transformed by a high ratio, speed reducing transmission which develops the operating characteristics required.

2.6.1.2 Transmission Subsystem

The transmission subsystem, functionally depicted in Figure 2-46 employs three basic elements.

- 1) A wave generator
- 2) A non-rigid, externally splined flexspline
- 3) A rigid, internally splined circular spline

The wave generator is a two-lobe, elliptoidal cam surrounded by an anti-friction bearing which deflects the non-rigid flexspline so that it mates with the circular spline at two equally spaced areas 180 degrees apart on their respective circumferences. The wave generator functions as the transmission input element and is directly coupled to the stepping motor. Rotation of the wave generator causes a progressive rotation of the elliptoidal shape in the flexspline, resulting in a continuous and progressive engagement between flexspline and circular spline teeth. There are fewer teeth on the flexspline than on the circular spline, and a slow mechanically-reduced relative motion between these two elements is thus generated.

(a) Transmission Elements

(b) Simplified Transmission Assembly

Figure 2-46. Harmonic Drive Transmission

As the wave generator makes one complete rotation, the flexspline rotates in the opposite direction through a distance equal to the difference between the pitch circumference of the circular spline and that of the flexspline. The flexspline is directly coupled, by its closed end plate, to the output shaft of the actuator. The difference between the two pitch circumferences is small, thus the high-speed rotation of the wave generator is directly converted into a rotary output having greatly reduced speed and increased torque. In this dc motor concept, it is doubtful if a single stage of gear reduction is adequate to match the high speed dc motor output to the drum requirements.

2.6.1.3 Feedback

Feedback of actuator output shaft position to the control amplifier is accomplished through a three-deck potentiometer. This device provides triple redundancy to the position feedback signal. Each deck is electrically independent. The potentiometer is assembled concentrically with the main output shaft of the actuator and uses the main actuator bearings for alignment. This feature produces the simplest assembly and eliminates many parts required in separately mounted potentiometers. The potentiometer is assembled and aligned on the output shaft by the manufacturer to eliminate the possibility of error in assembly.

2.6.1.4 Coolant Gas

Coolant gas is taken from the propellant line after the turbopump at approximately 900 psia. It is passed through the actuator and then exhausted into the reactor dome at approximately 700 psia.

2.6.1.5 Housing

The housing ties together all of the functional parts of the actuator. All electric power, input command signals and output position signals enter and exit the actuator by way of the electrical connector.

2.6.2 System Description

The dc servomotor actuator system block diagram is shown in Figure 2-47. The system uses a series wound stator dc motor. The motor produces an output torque in proportion to a dc current input.

Figure 2-47. D. C. Servomotor Proportional Control Drum Concept

The output of the motor is coupled to the actuator output shaft by a gear arrangement which reduces speed and increases torque to meet the control drum requirements. The actuator output shaft is coupled to the control drum by means of a drive shaft. An angular position indicator is provided to measure the actuator output shaft angle for both control and diagnostic purposes.

The dc current which controls the motor is generated by the actuator amplifier which contains the necessary compensation to stabilize the closed loop control system. The amplifier is driven by an error signal which is the difference between the drum position command and the output position indicator signals.

Electrical power is supplied to the actuator amplifier. Hydrogen coolant gas is supplied to the actuator and exhausted into the pressure vessel. The coolant gas must be at a pressure greater than that of the chamber at all times. An additional function of the coolant gas is to quench the arc generated by the brushes of the dc motor. The coolant gas must provide a minimum pressure in the actuator anytime the motor is in operation.

2.6.3 Radiation Evaluation

Table 2-1 of Section 2.1.3 provides the radiation environment at the proposed actuator location forward of the pressure vessel closure. As those values describe the environment in the absence of perturbation by the actuator itself, they apply equally to all of the actuator concepts at this location. In most instances, the presence of the actuator will reduce the levels, so that the use of the unperturbed numbers is generally conservative.

2.6.4 Thermal Evaluation

The thermal-nuclear environment of the dc proportional concept is, in general, similar to that of section 2.1.4 and the thermal performance is also expected to be similar. It is expected that the actuator structure can be adequately cooled although the coolant requirements will vary as a function of the actuator size and its internal heat generation. Internal coolant passages will have to be incorporated into the motor mechanism housing structure so as not to interfere with its electrical function. Regions of primary thermal analysis interest will include the relatively thick wall sections, such as housing flanges, or the asymmetrical

metal sections, where maximum temperature levels or thermal distortions would be expected to occur. Rotor heating due to electrical power dissipation will have to be evaluated.

2.6.5 Structural Evaluation

The structural evaluation of the dc servomotor actuator is identical to that of the Slo-syn actuator discussed in Section 2.4.2.5. The only difference between these two designs is the substitution of a dc motor for an electric stepping motor. If this actuator is selected from the trade study, the structural reliability of the dc motor will be verified by analysis and/or component tests.

2.6.6 Radiation Effects Evaluation

The total expected radiation environment to which this actuator will be subjected is given in Section 2.1.3. To assess the effects of this environment on the actuator, a comparison of known test environments with this expected environment will indicate the sensitivity of any given concept to successful operation in the expected radiation levels. The sensitive components in this concept are the motor coils, the potentiometer, the shaft seals, and the electrical insulation and potting compounds. All other materials used in the construction of the actuator are metals. Although detail designs are not available, final material selection will be made from lists of qualified materials or will be separately qualified.

2.6.6.1 Motor Coils

Although motors have not been directly tested on the NERVA program, tests on other devices give important information concerning the expected performance of motor winding rails in a radiation environment. The electric coils contained in a pneumatic actuator torque motor and in the lock shut-off solenoid are similar to those used in electric motor construction. Tests conducted in a radiation environment at the GTR facility, during the NRX-A6 pneumatic actuator side-by-side test, and tests conducted by the Lewis Research Center at the Plum Brook Reactor all included the electric coils mentioned above. No coil anomalies were reported during any of these tests.⁽⁴⁾ However, it is planned to take advantage of improvements in the

state-of-the-art in insulation materials and use the polyimide series for future coil insulations to further improve radiation tolerance and increase coil reliability.

2.6.6.2 Potentiometer

A prototype potentiometer is also included in the tests described in the above section. A reported failure in the Lewis tests⁽⁴⁾ caused some concern until a subsequent post-irradiation examination revealed the failure was caused by a softening and flowing of a potting compound not included in the GTR and NRX-A6 side-by-side test. The material that failed was used in very early model potentiometers but has now been removed. Future controls will assure using only those specified materials that will not be subject to property changes under radiation environment.

2.6.6.3 Shaft Seals, Electrical Insulation and Potting Materials

Although these items and materials are adequate for use in the NERVA environment, it is planned to take advantage of the improvements in the state-of-the-art in insulation materials. Polyimide materials will be used in wire insulation and potting materials to increase radiation tolerance and reliability.

2.6.7 Reliability and Safety Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliability of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale from 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection, assembly and testing the identified component's ability to perform during its useful life installed

in the actuator. The number 100 represents the most difficult level and the number 1, the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event identified on the tree and has assigned a relative weighting number to each failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-48 shows in summary form the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific components within the actuator concept that contribute to the main block failure. The numbers in parentheses are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A tabular listing of the failure events is shown in Table 2-49. These failure events are located in the fault tree by their identifying numbers which appear above the blocks on the fault tree. The events are listed in an indented manner which also indicates levels on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the subtotals progress toward the right of the page.

The final total of the weighted numbers (1688) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree are indicated in parentheses in the blocks of the summary fault tree, Figure 2-48. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

Figure 2-48. Summary Fault Tree DC Motor Proportional Electric Actuator

TABLE 2-49

DETAILED FAULT TREE ANALYSIS

D.C. Motor Proportional Electric Actuator Reliability
 Fault Tree Analysis 939J957 Estimated Reliability .9583

1688

1.0	Actuator Coolant Gas Consumption Exceeds Specified Lim'ts		95
1.1	Actuator Housing Fails to Contain Coolant Gas		55
1.1.1	Cover Fails to Contain Coolant Gas	5	
1.1.2	Cover to Body Interface Joint Fails	9	
1.1.2.1	Seal Fails	6	
1.1.2.2	Cover Fasteners Fail	3	
1.1.3	Housing Body Fails to Contain Coolant Gas	1	
1.1.4	Electrical Connector Fails to Contain Gas	40	
1.1.4.1	Seal Fails	30	
1.1.4.2	Fasteners Lose Clamping Force	5	
1.1.4.3	Connector Body Fails to Contain Gas	5	
1.2	Housing to Pedestal Interface Fails to Contain Gas		40
1.2.1	Interface Inlet Coolant Seal Fails	30	
1.2.2	Fasteners Lose Clamping Force	5	
1.2.3	Interface Exhaust Coolant Passage Seal Fails	5	
2.0	Actuator Fails to Position Control Drum Within Time Position Band		1462
2.1	Actuator Fails to Convert Electrical to Mechanical Power		401
2.1.1	Electrical Connector Fails to Transmit Proper Signal	10	
2.1.1.1	Conductor Fails to Transmit Signal	5	
2.1.1.2	Insulator Fails Permitting Short Circuit	5	
2.1.2	Actuator Internal Wiring Harness Fails	35	

TABLE 2-49 (CONTINUED)

2.1.2.1	Conductor Fails	5	
2.1.2.2	Insulation Fails	25	
2.1.2.3	Terminal Mechanically Fails	5	
2.1.3	Motor Fails Electrically		356
2.1.3.1	Wiring Failure in Rotor Winding	80	
2.1.3.2	Wiring Failure in Stator Winding	40	
2.1.3.3	Pole Pieces Break	1	
2.1.3.4	Commutation Failure	235	
2.1.3.4.1	Brush Holder/Spring Failure	15	
2.1.3.4.1.1	Fastener Failure	5	
2.1.3.4.1.2	Brush Holder Fails	5	
2.1.3.4.1.3	Loss of Spring Gradient	5	
2.1.3.4.2	Brush Failure	100	
2.1.3.4.2.1	Material Deterioration	60	
2.1.3.4.2.2	Material Mechanical Failure	40	
2.1.3.4.3	Wiring Failure	50	
2.1.3.4.3.1	Conductor Fails	10	
2.1.3.4.3.2	Insulation Fails	40	
2.1.3.4.4	Slip Ring Failure	70	
2.1.3.4.4.1	Mechanical Failure	30	
2.1.3.4.4.2	Electrical Failure	40	
2.2	Improper Command Received from Amplifier		249
2.2.1	Amplifier Control Voltage Incorrect		AGC
2.2.2	Amplifier Fails Internally		30
2.2.3	Amplifier Feedback Signal Incorrect		219

TABLE 2-49 (CONTINUED)

2.2.3.1	Potentiometer Supply Voltage Wrong Value		30	
2.2.3.1.1	Actuator System Wiring Harness Fails		30	
2.2.3.1.2	Voltage Supplied is in Error	AGC		
2.2.3.2	Feedback Potentiometer Output Fails		154	
2.2.3.2.1	Potentiometer Electrical Fails		101	
2.2.3.2.1.1	Track Resistance Value Changes	10		
2.2.3.2.1.2	Protective Resistor Changes Value	10		
2.2.3.2.1.3	Wiper Resistance Value Changes	1		
2.2.3.2.1.4	Wiper to Track Contact Resistance Changes	80		
2.2.3.2.2	Angular Relationship Pot to Drum Changes		21	
2.2.3.2.2.1	Pot Position Relative to Shaft Changes	20		
2.2.3.2.2.2	Shaft Relative to Drum Changes	1		
2.2.3.2.3	Potentiometer Mechanically Fails		32	
2.2.3.2.3.1	Potentiometer Shaft Fails	1		
2.2.3.2.3.2	Wiper Spring Gradient Changes	1		
2.2.3.2.3.3	Bearings Fail	10		
2.2.3.2.3.4	Potentiometer Housing Fractures	20		
2.2.3.3	Feedback Signals Transmitted Improperly		35	
2.2.3.3.1	Wiring Harness Actuator to Amplifier Fails	AGC		
2.2.3.3.2	Mechanism Wiring Harness Fails	30		
2.2.3.3.3	Electro-Magnetic Interference Distorts Signal	5		
2.3	Actuator External Control Drum Loads Change			EC
2.4	Actuator Internal Loads Change			812
2.4.1	Flexspline Torque Output Low		260	
2.4.1.1	Teeth Fail to Transmit Torque		15	

TABLE 2-49 (CONTINUED)

2.4.1.1.1 Teeth Break	10	
2.4.1.1.2 Teeth Wear	5	
2.4.1.2 Fastener Interferes with Motion		10
2.4.1.3 Wave Generator Rotation Fails		155
2.4.1.3.1 Bearing Friction Increases	130	
2.4.1.3.2 Eliptoidal Cam Breaks	5	
2.4.1.3.3 Flexible Outer Race Breaks	20	
2.4.1.4 Cup Fails to Transmit Motion		80
2.4.1.4.1 Weld Fails	30	
2.4.1.4.2 Cup Breaks	50	
2.4.2 Motor Fails Mechanically		442
2.4.2.1 Bearing Friction Increases		280
2.4.2.2 Fasteners Interfere with Motion		10
2.4.2.3 Stator Wiring Interferes with Motion		76
2.4.2.3.1 Actuator Housing Distorts	1	
2.4.2.3.2 Stator Porting Material Deteriorates	10	
2.4.2.3.3 Conductor at I.D. of Motor Breaks	5	
2.4.2.3.4 Pole Pieces Break	60	
2.4.2.4 Rotor Wiring Interferes with Rotation		76
2.4.2.4.1 Actuator Housing Distorts	1	
2.4.2.4.2 Rotor Porting Material Deteriorates	10	
2.4.2.4.3 Conductor at Circumference of Rotor Breaks	5	
2.4.2.4.4 Pole Pieces Break	60	
2.4.3 Output Shaft-Pot Bearings Friction Level Increases		70
2.4.4 Output Shaft Fails to Transmit Torque		40
2.4.4.1 Teeth Break		10

TABLE 2-49 (CONTINUED)

2.4.4.2 Shaft Breaks	20	
2.4.4.3 Cup to Shaft Coupling Fails	10	
3.0 Actuator Electrical Power Rate Exceeds Specified Limits		131
3.1 Actuator Short Circuits		111
3.1.1 Potentiometer Internal Short Circuit	10	
3.1.2 Stator Wiring Insulation Fails Allowing Short Circuit	10	
3.1.3 Wiring Harness System Short Circuits	21	
3.1.3.1 Interface Connector Short Circuits	10	
3.1.3.2 Wiring Insulation Fails	10	
3.1.3.3 Terminal Fails	1	
3.1.4 Rotor Wiring Insulation Fails	70	
3.2 Amplifier Internal Short Circuit		20
3.3 Amplifier/Actuator External Cable Short Circuit Failure		AGC

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

The calibration process (Section 2.1.7.1.1) consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

2.6.7.1 Failure Mode Evaluation

A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts were not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component is analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another.⁽⁹⁾ The total number then indicates the relative reliability of the actuator concept; the lower the number, the more reliable the particular concept is relative to the others. Each concept is compared with the others on the basis of the total relative failure probability number. A failure mode analysis for the self commutating dc motor concept is shown in Table 2-50.

2.6.7.2 Safety Evaluation

The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and criticality ranking for each concept, failure modes have been identified. For each of the failure modes listed, mechanisms of obtaining that failure mode are established as they relate to a particular design and each of these failure mechanisms is given a numerical ranking consistent with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reductions in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.

TABLE 2-50

COMPONENT FAILURE MODES ANALYSIS

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RUC COMPONENT DC Motor DWG NUMBERS 100E148

W59150

Relative Ranking 171

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Motor fails electrically so as to produce no output torque	a. Stator wiring opens or shorts b. Pole pieces break c. Rotor wiring opens or shorts d. Brush holder breaks e. Brush spring loses spring gradient f. Brush breaks or deteriorates g. Commutator wiring shorts or opens h. Slip ring breaks	Steady State and Start-up	4 1 8 1 1 10 5 8
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces break and jam motor c. Stator potting compound fails, allowing coils to jam between stator and rotor d. Stator coil, at inside diameter, breaks and jams between stator and rotor e. Rotor potting compound fails, allowing coils to jam between stator and rotor. f. Rotor coils, at outside diameter, breaks and jams between stator and rotor. g. Rotor pole pieces break and jam motor	Steady State and Start-up	20 6 1 1 1 1 6

TABLE 2-50 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RGC COMPONENT Drive Train DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.1	Drive train mechanical load increases.	a. Flexspline gear teeth surface damage increases friction. b. Elliptical bearing binds and increased friction. c. Elliptoidal cam breaks d. Flexible outer race breaks e. Outout shaft bearings bind and increase friction.	Steady State and Start-up	1 10 1 2 6
2.2	Drive train jams in some position between full in and the maximum op-	a. Flexspline gear teeth break and jam the mechanism. b. Elliptical bearing seizes c. Outout shaft bearings seize d. Bearing housing fasteners break or loosen and jam mechanism	Steady State and Start-up	1 3 2 1
2.3	Drive train fails so as to not transmit motor output torque.	a. Outout shaft breaks b. Shaft crowned spline breaks c. Flexible cup breaks d. Flexspline gear teeth break e. Keyed joint, between motor shaft and elliptoidal cam, breaks f. Coupling between flexible cup and output shaft, breaks	Steady State and Start-up	1 1 8 1 1 2

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TABLE 2-50 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act,
 DATE _____ APPROVED BY RAC COMPONENT Potentiometers DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Potentiometers fail to provide feedback signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open. e. Potentiometers housing breaks	Start-up and Steady State	1 1 1 4 2
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	1 2
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start-up and Steady State	1
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	1 1 8

TABLE 2-50 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY RGC COMPONENT Housing and Cover DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen f. Supply convector breaks or loosens	Steady State and Start-up	1 1 1 1 1 1

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY RGC COMPONENT Seals, Coolant DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	1 3 1 3 3

TABLE 2-50 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.

DATE APPROVED BY RGC COMPONENT Mounting Studs DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
6.1	Mounting stud fails to maintain proper clamping force.	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action.	Steady State and Start-up	1 1 1

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.

DATE APPROVED BY RGC COMPONENT Wiring Harness DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	3 2
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Short out or open	Steady State and Start-up	2 4
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Steady State and Start-up	1 1

Failures resulting in insignificant effects on chamber temperature/pressure.

By assigning each mechanism of failure to one of the above categories, and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-51 presents a tabulation of the failures, mechanism of failure and criticality ranking of failure for the dc motor electric actuator. Also shown is the total criticality ranking for this concept.

2.6.8 Discussion and Evaluation

The dc motor has a small envelope and is relatively lightweight compared to some of the other electric concepts. Response time is excellent; however, an armature shorting technique will probably be utilized to stop the motor at position without excessive coasting.

A major problem exists in developing a reliable commutation system. Aside from the problems affecting all dc motors, brush failure, spring gradient loss, film deposition, etc., the development effort must also solve the problem of corona discharge and arc quenching in the four torr atmosphere the actuator will face on startup. Other areas, common to most electric actuator concepts, requiring substantial development effort are the concentric potentiometer, wiring insulation, high-speed bearings and motor coil encapsulant.

Velocity limits are a requirement placed on the control drum actuator by NSS control and safety. To achieve these limits with a dc motor, a tachometer or the derivative of position is required. It is questionable whether the signal to noise ratio of the position derivative could be made low enough to be used as an input to the motor, particularly with the large gear reduction required between the motor output and the potentiometer shaft. A tachometer built integrally with the motor shaft appears to be the best solution.

The self-commutating dc proportional electric actuator, as shown, will fit on up to a 36 drum reactor concept. Its radial width at the control drum centerline is about 4.8 inches. Its height above the pressure vessel mounting boss is about 4.4 inches. Clearance required

TABLE 2-51

COMPONENT SAFETY CRITICALITY

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY RGC COMPONENT DC Motor DWG NUMBERS 100E148

W59150

Total Criticality Ranking 194

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Motor fails electrically so as to produce no output torque	a. Stator wiring opens or shorts b. Pole pieces break c. Rotor wiring opens or shorts d. Brush holder breaks e. Brush spring loses spring gradient f. Brush breaks or deteriorates g. Commutator wiring shorts or opens h. Slip ring breaks	Steady State and Start-up	4 4 4 4 4 4 4 4
1.2	Motor fails mechanically so as to produce no output torque, and/or result in excessive electrical power consumption.	a. Motor bearings bind b. Pole pieces break and jam motor c. Stator potting compound fails, allowing coils to jam between stator and rotor d. Stator coil, at inside diameter, breaks and jams between stator and rotor e. Rotor potting compound fails, allowing coils to jam between stator and rotor. f. Rotor coils, at outside diameter, breaks and jams between stator and rotor. g. Rotor pole pieces break and jam motor	Steady State and Start-up	4 4 4 4 4 4 4

TABLE 2-51 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RGC COMPONENT Drive Train DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.1	Drive train mechanical load increases.	a. Flexspline gear teeth surface damage increases friction. b. Elliptical bearing binds and increased friction. c. Elliptoidal cam breaks d. Flexible outer race breaks e. Output shaft bearings bind and increase friction.	Steady State and Start-up	2 2 2 2 2
2.2	Drive train jams in some position between full in and the maximum op-	a. Flexspline gear teeth break and jam the mechanism. b. Elliptical bearing seizes c. Output shaft bearings seize d. Bearing housing fasteners break or loosen and jam mechanism	Steady State and Start-up	4 4 4 4
2.3	Drive train fails so as to not transmit motor output torque.	a. Output shaft breaks b. Shaft crowned spline breaks c. Flexible cup breaks d. Flexspline gear teeth break e. Keyed joint, between motor shaft and elliptoidal cam, breaks f. Coupling between flexible cup and output shaft, breaks	Steady State and Start-up	4 4 4 4 4 4

2-345

TABLE 2-51 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act,
 DATE APPROVED BY RAC COMPONENT Potentiometers DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.1	Potentiometers fail to provide feed-back signal.	a. All potentiometer tracks short out or open b. All potentiometer wipers short out or open c. All protective resistors open d. All potentiometer wiper to track contacts open. e. Potentiometers housing breaks	Start-up and Steady State	4 4 4 4 4
3.2	Potentiometers provide error signal calling for greater or less angular position than demanded.	a. All potentiometer tracks change linearity b. All potentiometers change position relative to pinion output shaft.	Start-up and Steady State	4 4
3.3	Potentiometers provide a single constant position signal.	a. Potentiometers bonded joint with pinion output shaft breaks.	Start-up and Steady State	4
3.4	Potentiometers change characteristics as to change the gain and cause instability or sluggish operation.	a. All potentiometer wipers change in resistance. b. All protective resistors change in resistance. c. All potentiometer wiper to track contacts change in resistance.	Start-up and Steady State	2 2 2

TABLE 2-51 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RCC COMPONENT Housing and Cover DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Housing and cover fail to contain coolant gas pressure.	a. Housing body breaks b. Housing interface seals surfaces damaged c. Cover breaks d. Cover seal surface damaged e. Cover fasteners break or loosen f. Supply convector breaks or loosens	Steady State and Start-up	2 2 2 2 2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY RCC COMPONENT Seals, Coolant DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Coolant seals fail to contain coolant gas pressure, increasing gas consumption.	a. Housing interface seals leaks b. Coolant passage interface seal leaks c. Housing to cover seal leaks d. Electrical receptical seal leaks e. Coolant supply connector seal leaks	Steady State and Start-up	2 2 2 2 2

TABLE 2-51 (CONTINUED)

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RGC COMPONENT Mounting Studs DWG NUMBERS 100E148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
6.1	Mounting stud fails to maintain proper clamping force.	a. Stud breaks b. Belleville washer loses spring gradient c. Locking device loses crimping action.	Steady State and Start-up	2 2 2

DATE 8-22-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY RGC COMPONENT Wiring Harness DWG NUMBERS 100F148

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
7.1	Electrical wiring harness to the motor fails to carry proper command signal.	a. Harness wires short out or open b. Connector pins short out or open	Steady State and Start-up	4 4
7.2	Electrical wiring harness to potentiometers fail to carry proper feedback signal or fail to carry proper supply voltage.	a. Harness wires short out or open b. Short out or open	Steady State and Start-up	1 1
7.3	Electrical connector fails to contain coolant gas pressure, increasing gas consumption.	a. Connector body leaks b. Connector fasteners break or loosen	Steady State and Start-up	2 2

above the actuator for removal is about 4.3 inches. The self-commutating dc motor concept is estimated to weight about 7.1 pounds. Coolant requirements for a one hour run at the heating rates estimated for NERVA, about 3 watts per pound, are less than 1/2 pound and can probably be neglected. The main electrical power required is about 20 watts with a reduced power of about 5 watts and is assumed to provide a holding torque against the bias spring when the actuator is not moving. Signal level power to supply the feedback potentiometers and actuator control amplifier is small and has been neglected for this comparative study. A preliminary estimate of the concept reliability, obtained by calibrating the fault tree, is 0.9583. Table 2-52 is a listing of some of the more significant advantages and disadvantages of the dc servo-motor concept.

2.7 DRUM MOUNTED VANE BINARY CONCEPT

2.7.1 Mechanical Description

The pneumatic vane binary actuator concept is shown mounted within the pressure vessel below a control drum in Figure 2-49. The actuator consists of a body which houses the vanes and serves as a pressure cylinder. The actuator body is rigidly mounted on the control drum support structure. The internal diameter of the body cylinder has two stationary vanes spaced 180 degrees apart. Inside the cylinder is a drive shaft with two rotary vanes also spaced 180 degrees apart. The drive shaft is held within the body cylinder by two bearings and adapter bearing housings.

Between the stationary vanes and the drive shaft are seals which are held in slots in the stationary vanes and pressed against the drive shaft by seal springs. Baffle plates seal the upper and lower ends of the stationary vanes. In like manner, the rotary vanes contain seals which fill the space between the rotary vanes and the cylinder wall and baffle plates. The rotary vane seals are loaded both axially and radially by seal springs. The spaces between the drive shaft and the baffle plates are sealed by piston rings. All seals are fibre graphite and oriented to minimize stress and wear. Seal springs are of the phosphor bronze ribbon type.

2-350

Figure 2-49. Two-Position Control Drum Actuator Pneumatic Vane Concept

TABLE 2-52

DC SERVO MOTOR/HARMONIC DRIVE
CDA CONCEPT SUMMARY TABLE

<u>Advantages</u>	<u>Disadvantages</u>
1. Low weight.	1. High speed bearings.
2. Probably requires less power than other concepts.	2. Brush commutation.
3. High short time stall torque due to high gear reduction.	3. Armature shorting to stop.
4. Small overall size.	4. Very high currents at increased loads. Possible to burn out motor armature.
	5. Requires convection cooling.
	6. Probably requires tachometer for stabilization and velocity limits.
	7. Probably requires a brake or zero position lock.
	8. Low torque at the motor output shaft.

Pneumatic drive pressure enters the actuator and travels axially down a stationary vane and then enters the chamber between a stationary vane and a rotary vane. The pressure is also commuted through the drive shaft and into the space between the other stationary vane and its rotary vane. The spaces in the pressure cylinder which are not given drive pressure are allowed to vent into the reactor pressure vessel.

The difference between the drive gas pressure and the reactor pressure generates a torque between the stationary and rotary vanes. This torque faces the rotary vane and the drive shaft to move.

The drive shaft is connected to a torque tube through an involute spline coupling. The torque tube is connected to the forward end of the control drum. Inside the torque tube is a torsion bar return spring which is affixed to the torque tube at the involute spline coupling and to the reflector structure at the forward end of the drum.

The torque generated by the actuator tends to move the torque tube and the control drum against the torque of the torsion bar return spring. If not stopped the actuator drive shaft will rotate until the rotary vanes hit the opposite stationary vanes. This contact could cause high stress due to the high angular velocity at contact. To alleviate this problem a hard stop is machined into the torque tube above the involute spline coupling. Before the vanes can come into contact, the hard stop cam strikes the actuator stationary support and stops the actuator's motion. The inertia of the control drum causes it to twist the torque tube and dissipate its energy as dampened oscillation about the hard stop position.

When the drive gas pressure is removed, the return spring forces the drum and actuator to return to the inward position. The hard stop prevents the vanes from making contact. The hard stop is adjusted to provide 140 degrees of drum rotation. The quiescent drum position is at 20 degrees and its full out position is at 160 degrees. This provides the maximum change in reactivity control for the 140 degrees of total drum rotation.

Coolant gas enters the actuator at the lower bearing, travels outward on the lower baffle plate, through the actuator body, along the upper baffle plate and through the upper bearing. The coolant can also travel through the drive shaft and up the torsion bar and torque tube.

2.7.2 System Description

The pneumatic vane binary actuator system is shown in Figure 2-50. To operate a drum an electric pulse is generated by the reactor controller and switched electronically to the selected control drum actuator valve. This valve is a bi-stable "H" valve consisting of four solenoid valves. The solenoid valves are connected pneumatically on the four legs of an H. This arrangement is more reliable than a single solenoid valve.

The four solenoid valves are energized or de-energized simultaneously. As bi-stable devices, they require an excitation pulse of short duration. Then they retain their state after the pulse has subsided. The "H" valves control drive gas to their respective vane actuators.

The drive gas for the "H" valves comes from a pressure selector valve. The pressure selector valve selects either the accumulator or the turbopump for the source of drive gas. The greatest pressure is the one that is selected. Before the bootstrap operation the turbopump is operative and the drive gas must be supplied by the accumulator. Once the reactor is in operation the turbopump pressure is greater than the reactor chamber pressure and the actuator drive gas is taken from the turbopump outlet. The accumulator also recharges from the turbopump.

Coolant gas for the actuator comes from the reflector inlet plenum. The gas is diverted to travel through the actuator housing and thence to the control drums. A second flow path is up the central drive shaft of the actuator to cool the torque tube and the torsion bar return spring.

2.7.3 Radiation Evaluation

The calculated nominal radiation environment at the proposed location on the aft end of the reflector, selected for this actuator concept only, is summarized in Table 2-53. The basis for this table is the same as for the data given in Section 2.1.3. The radiation levels at the aft location are much higher than those quoted for the other concepts, because no shielding material is present between the actuator and the core.

Figure 2-50. Pneumatic Vane Actuator System

TABLE 2-53

NOMINAL RADIATION ENVIRONMENT FOR A CONTROL DRUM
ACTUATOR LOCATED AFT OF THE REFLECTOR⁽¹⁾

Item	Radiation Level at 1575 Mw ⁽²⁾	Time-integrated Fluence or Dose in 60 Minutes
1) Total Neutron Flux	$2.3 \times 10^{14} \text{ n/cm}^2\text{-sec}$	$8.3 \times 10^{17} \text{ n/cm}^2$
2) Fast Neutron Flux ($E > 1.0 \text{ Mev}$)	$3.9 \times 10^{13} \text{ n/cm}^2\text{-sec}$	$1.4 \times 10^{17} \text{ n/cm}^2$
3) Thermal Neutron Flux	$4.9 \times 10^{13} \text{ n/cm}^2\text{-sec}$	$1.8 \times 10^{17} \text{ n/cm}^2$
4) Gamma Ray Dose	$3.2 \times 10^8 \text{ rads-C/hr}$	$3.2 \times 10^8 \text{ rads-C}$
5) Heating Rate, Stainless Steel	$3.8 \times 10^2 \text{ watt/lb}$ $= 0.84 \text{ watt/gm}$ $= 1.3 \times 10^3 \text{ Btu/hr-lb}$ $= 3.7 \times 10^2 \text{ Btu/hr-in}^3$	
6) Heating Rate, Aluminum	$3.7 \times 10^2 \text{ watt/lb}$ $= 0.81 \text{ watt/gm}$ $= 1.3 \times 10^3 \text{ Btu/hr-lb}$ $= 1.2 \times 10^2 \text{ Btu/hr-in}^3$	

(1) An uncertainty factor of three (1σ) is associated with these values. The location assumed is at reactor coordinates $R = 23.4 \text{ in.}$, $Z = 55.0 \text{ in.}$ (Station zero is at dome end of core.)

(2) Calculated at end of 60 minute full power run.

As in the forward location, an uncertainty factor of three should be attached to these numbers, as a preliminary estimate. In this case, this indicates the possibility of heating rates in excess of 2 watts per gram in structural materials, implying a potential heat removal problem.

2.7.4 Thermal Evaluation

A preliminary thermal evaluation of a two-position pneumatic control drum actuator has been performed and is reported in DRM-1070.

These analyses are based on heating rates obtained from DRM-1009 and three dimensional TAP-A models of a typical 90 degree sector of the actuator. It is conservatively assumed that the actuators are cooled only on the exterior surface by the nozzle exit gas, neglecting internal cooling by the pneumatic fluid. The calculation is performed for three different actuator materials and for two actuator configurations, a one bearing design and a three-bearing design shown on Figure 2-49. A summary of the results is given in Table 2-54.

TABLE 2-54

SUMMARY OF NOMINAL STEADY STATE TEMPERATURES IN ACTUATOR STRUCTURE

Material	Configuration				Material Temperature Limit
	One Bearing T avg	T max	Three Bearing T avg	T max	
Aluminum	240°R	310°R	250°R	345°R	710°R
Titanium	1215		1860		1010
Stainless Steel	1490		2105		1260

Based on the calculated temperatures and the indicated material temperature limits, aluminum is the only material that is thermally adequate.

The pressure head which is available in the hot bleed cycle NSS and which drives the actuator pneumatic fluid is shown in Figures 2-51 and 2-52.

Figure 2-51. Pressure Drop From Pump Discharge to Reflector Exit Plenum
(Applicable to Hot Bleed Cycle Only)

Figure 2-52. Pressure Drop From Pump Discharge to Dome End Plenum
(Applicable to Hot Bleed Cycle Only)

2.7.5 Structural Evaluation

The drum-mounted actuator is completely different from the pneumatic and electric actuator concepts which were previously discussed. This pneumatic, two-position actuator is mounted on the aft end of the control drum. It does not have a feedback potentiometer or servovalve assembly, but it uses both a drive gas and cooling gas. The drive gas is supplied from the propellant line at about 900 psia, and the actuator is cooled by the nozzle exit gas. Basically, the drive gas provides the torque to rotate the control drum to its "full out" position, and the drum return spring provides the torque to rotate the drum to its "full in" position.

The major components in this actuator are two concentric torsion bar springs, a double-vaned cylinder, a housing structure and graphite seals. The two concentric torsion springs, which go through the center of the control drum, connect the double-vaned cylinder to the forward end of the control drum. The outer hollow torsion bar functions as a drive shaft and hard stop spring. The inner solid torsion bar is the drum return spring. A potential problem area may be in the design of a torsion bar return spring that will have an adequate preload torque, have a low spring rate, fit into the available space and satisfy all the stress requirements. The housing structure contains the functional parts of the drive system (double-vaned cylinder and graphite seals) and provides the flow passages. The maximum pressure drop across this housing is expected to be about 215 psia instead of the 900 psi drop across the housings of the electric actuators.

If the drum-mounted, vane actuator is selected from this trade study, the major areas of structural analysis will include the mechanical and thermal stresses in the housing structure, torsional springs, vane, graphite seals and mounting bolts. The structural reliability of this actuator will be verified by component tests.

2.7.6 Radiation Effects Evaluation

All the materials selected for the two-position down mounted pneumatic actuators are metals or graphite. No inorganics are planned for this actuator; therefore, the radiation effects are expected to be limited to those dictated by a need for adequate cooling.

2.7.7 Reliability and Safety Evaluation

A fault tree is generated for each actuator concept. The fault tree defines those actuator system failures which result in failure of the nuclear subsystem. Each failure is evaluated to determine which components of the actuator could cause the identified system failure. Several components affect the mission success in more than one failure. This factor is taken into account in establishing the fault trees. The fault tree is used to obtain a relative evaluation of the reliability of the various actuator concepts.

The reliability evaluation of each actuator concept is accomplished by assigning a relative weighting number to all failure events identified at the lowest level in the fault tree analysis. The relative weighting number assigned is based on an arbitrary scale from 1 to 100. Each number is an estimated measure of the difficulties of design, manufacture, inspection, assembly and testing the identified component's ability to perform during its useful life installed in the actuator. The number 100 represents the most difficult level and the number 1, the least difficult.

A group of engineers has reviewed each fault tree, has estimated the difficulty of the design task for each specific failure event identified on the tree and has assigned a relative weighting number to each failure event. A total number is derived from each fault tree and this number measures the relative probability of failure of each alternate design concept with the others. The total number is obtained by adding the numbers assigned through the progression identified in the logic displayed by the fault tree.

Figure 2-53 shows in summary form the main contributors to the failure of each actuator concept. The second level of blocks are those actuator failure events that cause NSS failure. The third level of blocks which "OR" into the main failure blocks relate to the specific components within the actuator concept that contribute to the main block failure. The numbers in parentheses are the logic totals of all the lower level blocks feeding into any given block. The identifying numbers outside of each block are the same as the appropriate block on the fault tree diagram. A tabular listing of the failure events is shown in Table 2-55. These failure events are located in the fault tree by their identifying numbers which appear above the

Figure 2-53. Summary Fault Tree Drum Mounted-Two Position Pneumatic Vane Actuator

TABLE 2-55

DETAILED FAULT TREE ANALYSIS

Drum Mounted Pneumatic Two-Position Binary Vane
Actuator Reliability
Fault Tree Analysis 939J959 Estimated Reliability $.9_{612}$

878

1.0	Actuator Fails to Achieve Commanded Time/Position Band	868
1.1	Actuator Chamber Pressures not Correct Value	415
1.1.1	Drive Gas Supply to Mechanism is Improper	AGC
1.1.2	Control Solenoid Fails to Develop Proper Pressure	50
1.1.3	Solenoid Valve to Actuator Supply Line Fails	20
1.1.4	Stationary Vane Seal Fails (2)	100
1.1.5	Fasteners Lose Clamping Force	5
1.1.6	Rotor Vane Seal Fails (2)	100
1.1.7	Shaft Seal Fails (2)	100
1.1.8	Vane Spring Failure (4)	40
1.2	Control Solenoid Fails to Receive Proper Command From Control System	EC
1.3	Actuator Internal Load Changes	225
1.3.1	Drive Transmission Load Changes	45
1.3.1.1	Internal Shaft Fails	10
1.3.1.2	Coolant Screen Fails Allowing Contamination	10
1.3.1.3	Forward Bearing Fails	10
1.3.1.4	Aft Bearing Fails	10

TABLE 2-55 (CONTINUED)

1.3.1.5	Wave Washer Fails	5	
1.3.2	Rotor Assembly Load Changes		105
1.3.2.1	Stationary Vane Fails (2)	10	
1.3.2.2	Rotor Vane Fails (2)	10	
1.3.2.3	Vane Seal Fails (4)	40	
1.3.2.4	Shaft Seal Fails	40	
1.3.2.5	Vane Spring Fails	5	
1.3.3	Chamber Assembly Fails		60
1.3.3.1	Cylindrical Liner Fails	5	
1.3.3.2	Plate Liner Fails (2)	10	
1.3.3.3	Stationary Vane Seal Fails (2)	40	
1.3.3.4	Stationary Vane Spring Fails (2)	5	
1.3.4	Housing Fails		15
1.3.4.1	Aft Bell Housing Fails	5	
1.3.4.2	Fastener Failure	5	
1.3.4.3	Forward Bell Housing Fails	5	
1.4	Drive Shaft Fails to Position Drum		228
1.4.1	Drive Shaft Fails		85
1.4.1.1	Forward Spline Teeth Fail	30	
1.4.1.2	Actuator Output Spline Teeth Fail	30	

TABLE 2-55 (CONTINUED)

1.4.1.3	Shaft Shears	25	
1.4.2	Return Spring Fails		111
1.4.2.1	Return Spring Coupling to Ground Fails	31	
1.4.2.1.1	Forward Spline Teeth Fail	30	
1.4.2.1.2	Retaining Nut Fails	1	
1.4.2.2	Return Spring Shaft Shears	50	
1.4.2.3	Drive Shaft to Return Spring Spline Teeth Fail	30	
1.4.3	Drive Shaft to Ground Assembly Fails	32	
1.4.3.1	Forward Housing Fails	1	
1.4.3.2	Return Spring to Ground Spline Teeth Fail	30	
1.4.3.3	Large Retaining Nut/Lock Fails	1	
1.5	Control Drum Load Characteristics Change		EC
2.0	Actuator Power Consumption Rates Exceed Rate Limits		10
2.1	Solenoid Short Circuited in Control Valve		10

blocks on the fault tree. The events are listed in an indented manner which also indicates levels on the fault tree. The weighting numbers assigned to the events are listed on the right side of the page and are similarly indented. Therefore, weighting numbers which are indented closest to the center of the page are failure events which are the lowest level on the fault tree. As these are logically combined to produce the combined relative probabilities of failure, the subtotals progress toward the right of the page.

The final total of the weighted numbers (878) appears at the head of the list on the right-hand side of the page. The totals for the higher level events of the fault tree are indicated in parentheses in the blocks of the summary fault tree, Figure 2-53. Through use of the block identifying numbers, the source of the relative failure probability weighting number in each block can be identified to the reliability evaluation list and also to the fault tree drawing.

The relative probability of failure number is used to compare actuator concepts, but it has no significance as a quantitative measure of the probability of failure. The calibration process, which immediately follows the reliability evaluation list, is used to convert the results obtained to a quantitative reliability estimate for the particular concept.

The calibration process (Section 2.1.7.1.1) consists of selecting a failure event which is amenable to analysis by the stress/strength overlap method, computing the probability of failure for this event, and comparing the result with the weighting number arrived at in the reliability evaluation list for the same event. By adjusting the computed probability of failure in the ratio of the weighting number for that single failure event to the relative probability of failure number total obtained from the reliability evaluation list, a quantitative estimate of the true probability of failure for the actuator system is obtained.

To increase the degree of confidence, the calibration process is repeated (Section 2.1.7.1.2) using a second selected failure event. The most conservative estimate obtained is used as the quantitative estimate of the true probability of failure.

2.7.7.1 Failure Mode Evaluation

A failure mode analysis is prepared for each control drum actuator concept under consideration. As the actuator concepts are not completely detailed designs, the failure mode analyses are studies of arbitrarily selected groups of parts that form basic components within each actuator rather than studies of individual parts. In generating the failure mode analyses, each component was analyzed for possible modes of failure. These failure modes are identified and listed. Then, each failure mode is analyzed and the component failure mechanisms which cause the particular failure mode are identified and listed.

A reliability comparison of each actuator concept is accomplished by using a rating technique which utilizes a relative failure probability number based on a scale ranging from 1 to 10. The relative failure probability number is assigned to each component failure mechanism and represents an estimated probability of failure due to the particular failure mechanism. On the scale, 1 represents the lowest probability of failure and 10 represents the highest.

Engineering judgement is used in estimating the relative failure probability number for each failure mechanism. A total number is calculated by adding the relative probability numbers. This technique is considered acceptable since the failure modes listed are independent and mutually exclusive of one another⁽⁹⁾. The total number then indicates the relative reliability of the actuator concept; the lower the number the more reliable the particular concept is relative to the others. Each concept is compared with the others on the basis of the total relative failure probability number. A failure mode analysis for the down mounted two-position pneumatic vane actuator is shown in Table 2-56.

2.7.7.2 Safety Evaluation

The inherent safety and criticality of any failure is an important parameter to be considered in making a selection of a recommended concept. To determine a relative safety and criticality ranking for each concept, failure modes have been identified. For each of the failure modes listed, mechanisms of obtaining that failure mode are established as they relate to a particular design and each of these failure mechanisms is given a numerical ranking consistent with its effect on the NSS and engine mission. Four categories of criticality are used to determine the safety rating of each concept as follows:

TABLE 2-56

COMPONENT FAILURE MODES ANALYSIS

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY KAC COMPONENT Drive Train DWG NUMBERS 711J760

W59150

Relative Ranking 111

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.1	Drive train mechanical load increases.	a. Rotor shaft bearings bind and increases friction. b. Cylinder liner surface damage increases friction. c. Plate liner surface damage increases friction.	Steady State and Start-up	2 1 1
1.2	Drive train jams in some position between full in and maximum operating position.	a. Rotor shaft bearings seize b. Cylinder liner surface damage jam mechanism. c. Plate liner surface damage jams mechanism	Steady State and Start-up	1 1 1
1.3	Drive train fails to provide output torque.	a. Rotor vane breaks b. Rotor output shaft breaks c. Rotor/drive shaft joint breaks d. Drive shaft/drum joint breaks e. Drive shaft breaks	Steady State and Start-up	1 1 3 3 2

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TABLE 2-56 (CONTINUED)

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY K.C.E. COMPONENT Drive Train DWG NUMBERS 711J760

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
1.4	Drive train fails to return drum to in position.	a. Drive shaft/return spring joint breaks b. Return spring breaks c. Return spring/belleville housing joint breaks. d. Belleville housing breaks	Steady State and Start-up	3 5 3 1
1.5	Drive train fails to contain drive gas pressure so as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Plate liner seal surfaces damaged b. Rotor vane seal surfaces damaged c. Rotor shaft seal surfaces damaged	Steady State and Start-up	1 1 1

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act
 DATE APPROVED BY K.C.E. COMPONENT Housing and Covers DWG NUMBERS 711J760

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
2.1	Housing and covers fails to contain drive gas pressure so as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Housing body breaks b. Stationary vane breaks c. End covers break d. Stationary vane sealing surface damaged	Steady State and Start-up	1 1 1 1

TABLE 2-56 (CONTINUED)

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE APPROVED BY LAC COMPONENT Seals, Working Fluid DWG NUMBERS 711J760

A59150

Mode ident. no.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
3.1	Working fluid seals fail to contain drive gas pressure so as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Stationary vane seals leaks b. Vane seal spring loses spring gradient c. Rotor vane seals leaks d. Rotor vane seal spring loses spring gradient. e. Rotor shaft seals leak	Steady State and Start-up	10 2 10 2 10
3.2	Working fluid seals fail so as to increase frictional load.	a. Stationary vane seal drags and increases friction. b. Rotor vane seal drags and increases friction. c. Rotor shaft seals drag and increase friction.	Steady State and Start-up	3 3 3
3.3	Working fluid seals fail so as to jam the actuator between full in and maximum operating position.	a. Stationary vane seal breaks and jams mechanism. b. Rotor vane seal breaks and jams mechanism c. Rotor shaft seals break and jam mechanism	Steady State and Start-up	1 1 1

TABLE 2-56 (CONTINUED)

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY R.G.C. COMPONENT Mounting Bolts DWG NUMBERS 711J760

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
4.1	Mounting bolts lose clamping force.	a. Bolt breaks b. Locking cup loses crimping action, allowing bolt to loosen.	Steady State and Start-up	1 1

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE _____ APPROVED BY R.G.C. COMPONENT Control Solenoid DWG NUMBERS 711J760

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Failure Probability Rating
5.1	Control Solenoid characteristics change so as to bias the actuator to the full out position.	a. Solenoid seals leak b. Solenoid seal surfaces damaged c. Solenoid return springs loses spring gradient. d. Plungers surface damaged and jams in open	Steady State and Start-up	10 1 1 1
5.2	Control solenoid characteristics change so as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Solenoid coils short or open b. Coil lead wires short or open c. Plungers surface damaged and jams in closed position. d. Valve bodies break and leak e. Body to manifold joints break and leak	Steady State and Start-up	2 1 1 1 2
5.3	Solenoid to actuator supply line fails so as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Line joints break b. Seals leak c. Seal surfaces damaged	Steady State and Start-up	3 3 1

<u>Ranking</u>	<u>Description</u>
4	Failures resulting in gross core failure or possibly affecting structural integrity; crew safety jeopardized; African window safety in question.
3	Failures requiring corrective action resulting in reductions in chamber pressure/temperature below the emergency recovery mode level.
2	Failures requiring corrective action resulting in reduction in chamber temperature/pressure but not below emergency recovery mode level; completion of mission in question.
1	Failures resulting in insignificant effects on chamber temperature/pressure.

By assigning each mechanism of failure to one of the above categories, and finally obtaining a sum of all of the failure mechanisms, a total relative criticality ranking is obtained for each concept. The lower the total number estimate for a concept, the safer that concept is in relationship to the other concepts considered. Table 2-57 presents a tabulation of the failures, mechanism of failure and criticality ranking of failure for the two position pneumatic actuator. Also shown is the total criticality ranking for this concept.

2.7.8 Discussion and Evaluation

The two-position actuator is the simplest of those included in this study. However, because of its nature, two positions for operation full-in and full-out, it is not directly comparable to the other actuators discussed. Although control systems studies indicate that two-position control drums adversely affect core life and, therefore, a two-position actuator is not recommended, this concept does show that an actuator can be physically mounted inside the pressure vessel and can be adequately cooled for proper operation. This concept probably

TABLE 2-57

COMPONENT SAFETY CRITICALITY

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.

DATE APPROVED BY KAC COMPONENT Drive Train DWG NUMBERS 711J760

W59150

Total Criticality Ranking 176

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.1	Drive train mechanical load increases.	a. Rotor shaft bearings bind and increases friction. b. Cylinder liner surface damage increases friction. c. Plate liner surface damage increases friction.	Steady State and Start-up	2 2 2
1.2	Drive train jams in some position between full in and maximum operating position.	a. Rotor shaft bearings seize b. Cylinder liner surface damage jam mechanism. c. Plate liner surface damage jams mechanism	Steady State and Start-up	4 4 4
1.3	Drive train fails to provide output torque.	a. Rotor vane breaks b. Rotor output shaft breaks c. Rotor/drive shaft joint breaks d. Drive shaft/drum joint breaks e. Drive shaft breaks	Steady State and Start-up	4 4 4 4 4

TABLE 2-57 (CONTINUED)

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY KAC COMPONENT Drive Train DWG NUMBERS 711J760

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
1.4	Drive train fails to return drum to in position.	a. Drive shaft/return spring joint breaks b. Return spring breaks c. Return spring/belleville housing joint breaks. d. Belleville housing breaks	Steady State and Start-up	4 4 4 4
1.5	Drive train fails to contain drive gas pressure so as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Plate liner seal surfaces damaged b. Rotor vane seal surfaces damaged c. Rotor shaft seal surfaces damaged	Steady State and Start-up	4 4 4

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY KAC COMPONENT Housing and Covers DWG NUMBERS 711J760

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
2.1	Housing and covers fails to contain drive gas pressure so as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Housing body breaks b. Stationary vane breaks c. End covers break d. Stationary vane sealing surface damaged	Steady State and Start-up	4 4 4 4

TABLE 2-57 (CONTINUED)

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY R.G.C. COMPONENT Seals, Working Fluid DWG NUMBERS 711J760

A59150

Code Ident. no.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
3.1	Working fluid seals fail to contain drive gas pressure so as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Stationary vane seals leaks b. Vane seal spring loses spring gradient c. Rotor vane seals leaks d. Rotor vane seal spring loses spring gradient. e. Rotor shaft seals leak	Steady State and Start-up	4 4 4 4 4
3.2	Working fluid seals fail so as to increase frictional load.	a. Stationary vane seal drags and increases friction. b. Rotor vane seal drags and increases friction. c. Rotor shaft seals drag and increase friction.	Steady State and Start-up	2 2 2
3.3	Working fluid seals fail so as to jam the actuator between full in and maximum operating position.	a. Stationary vane seal breaks and jams mechanism. b. Rotor vane seal breaks and jams mechanism c. Rotor shaft seals break and jam mechanism	Steady State and Start-up	4 4 4

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.DATE APPROVED BY R.G.C. COMPONENT Mounting Bolts DWG NUMBERS 711J760

A59150

Code Ident. no.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
4.1	Mounting bolts lose clamping force.	a. Bolt breaks b. Locking cup loses crimping action, allowing bolt to loosen.	Steady State and Start-up	4 4

TABLE 2-57 (CONTINUED)

DATE 8-20-69 PREPARED BY I. R. Spezialetti DEPARTMENT Reliability SUBSYSTEM Control Drum Act.
 DATE _____ APPROVED BY K.A.E. COMPONENT Control Solenoid DWG NUMBERS 711J760

W59150

Mode Ident. No.	Component Failure Mode of Failure	Component Mechanism of Failure	Mission Phase	Safety Criticality Rating
5.1	Control Solenoid characteristics change so as to bias the actuator to the full out position.	a. Solenoid seals leak b. Solenoid seal surfaces damaged c. Solenoid return springs loses spring gradient. d. Plungers surface damaged and jams in open	Steady State and Start-up	4 4 4 4
5.2	Control solenoid characteristics change so as to bias the actuator to the full in position, or to inhibit the actuator operating range.	a. Solenoid coils short or open b. Coil lead wires short or open c. Plungers surface damaged and jams in closed position. d. Valve bodies break and leak e. Body to manifold joints break and leak	Steady State and Start-up	4 4 4 4 4
5.3	Solenoid to actuator supply line fails so as to bias the actuator to the full in position or to inhibit the actuator operating range.	a. Line joints break b. Seals leak c. Seal surfaces damaged	Steady State and Start-up	4 4 4

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violates the maintainability requirement because the nozzle must be removed for repair or replacement. However, because of the inherent actuator simplicity and high estimated reliability, the simplifying effects on the NSS, particularly the shield design, does make this concept attractive. The concept can be mounted on the dome with some redesign.

The two-position actuator as shown will fit on up to a 36 drum reactor concept. Its radial width at the control drum centerline is about 4.3 inches and its height below the drum is about 4.6 inches. Removal clearance is about 1.3 inches to clear the output shaft. This two-position pneumatic concept is estimated to weigh 5.5 pounds. Coolant is reflector flow and therefore is not considered in the evaluation. Drive gas is not considered a penalty if it can always come from the pump outlet. However, the pump to reflector inlet pressure drop is very low during startup and may not be sufficient to drive the drums. In that event, a startup supply with its attendant penalties must be assessed against the two-position actuator. Electrical power to supply the drive solenoids is considered to be in the control range and is neglected in this comparative study. A preliminary estimate of the concept reliability, obtained by calibrating the fault tree, is $.9_{612}$.

3.0 COMPARISON MATRIX OF DESIGN APPROACHES

The parameter value estimate matrix, Table 3-1, is generated to arrive at a meaningful method of evaluating the various actuator concepts based on common criteria. The first step is to specify pertinent actuator performance criteria. Other criteria are also specified which are generally not considered as performance factors. In addition to specifying various individual actuator parameters, certain system parameters are specified. This is necessary because the various actuators require different amounts of input power, thereby imposing significantly different power supply weight penalties.

After defining the pertinent parameters, the next step is to determine the capability of each actuator considering each performance parameter specified.

Realizing that it is difficult to make a realistic comparison between electric and pneumatic actuators regarding certain parameters such as power requirements, the weighting factor method of evaluation is chosen. A weighting factor is assigned to each performance parameter based upon a judgement of its relative importance. Likewise, for each performance parameter, the individual actuator concepts are assigned a rating based upon their performance capability. A final figure of merit is then computed by multiplying the weighting factor assigned to a parameter column by the particular actuator rating for that parameter and summing the figures obtained for each performance parameter column.

Listed across the top are the various parameters that have been considered for each concept and the alternates are listed down the left side. The first four columns, respectively, are the study layout drawing number, the fault tree drawing number, the maximum number that can be physically mounted on a reactor, and the type of main power required.

The transient power column lists the power required when the actuator is moving and supplying design torque, while the holding power is an estimate of the power required to hold a drum position against the zero bias spring. The system integrated power for a one hour run is based on an 18 drum reactor so that all alternates can be evaluated on a common base. Furthermore, a duty cycle where the actuator is assumed to be moving 25 percent of the time and holding 75 percent of the time is used in making this integrated power calculation. Using the total integrated power and a power supply specific weight of 0.1 pounds per watt-hour a system power supply weight penalty is calculated for each electric concept. A

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TABLE 3-1
CONTROL DRUM ACTUATOR STUDY-PARAMETER VALUE ESTIMATE MATRIX

		Concept Study Layout Dwg. No.	Fault Tree Dwg. No.	Maximum Drum Complement	Drive Power Requirements				System Coolant Requirements (1 Hr. Full Power Run; 3.0 w/lb Heating Rate)	Method of Gas Recovery	Actuator Weight	18 Drum Total System Related Weight	Applicable Developmental Test Experience		Number of Items	Relative Reliability		Remote Maintainability	Stress	Thermal	Radiation Tolerance	Stall Torque (in-lb)	Band Width (Hz)	Resolution (+ degrees)	Velocity o/sec	Acceleration a/sec ²	Safety Rating	Figure of Merit	Comments
					Type	Transient	Holding	18 Drum Reactor System (Integrated Power (60 Min. Run) Assuming 25% Duty Cycle)					18 Drum Reactor Power Supply Wt. (Assumes 10.1 lb/whr.)	WANL		Other	Fault Tree												
Specification Value →					Pneumatic or Electric			Should be minimized													100	1	0.2 Max	+ 10	+ 20				
Actuator Type ↓																													
ANALOG ELECTRIC	Direct Drive Responsyn	939J461	939J953	18	D.C.	100 W	50 W	1134 whr	113 lb	17 lb	419 lb	Prototype lab tests (TME-1921), pot component development tests.	60	9048	122	V-band clamp	No detail designs are available, but no significant structural problems are anticipated. Harmonic drives, where used, must be carefully analyzed to assure proper reliability at cryogenic temperatures.	Operation will generally be at room temperature or below and internal temperature gradients are expected to be small.	No material degradation problems are anticipated in shielded environment of dome mounting. Electromagnet coils, potentiometer resistance tracks, organic seals and coolant distribution porting must be re-evaluated if actuators are relocated to more hostile environment below shield.	200	1	0.10	10	20	120	.636	Flexible laminated magnetic rotor requires special attention to potential wear and stress problems.		
	Planetary Transmission Responsyn	939J462	939J952	36	D.C.	30 W	15 W	333 whr	33 lb	7 lb	9.8 lb	212 lb	Similar to direct drive Responsyn.	70	1271	13				Nuts, lock cups and electrical connector	100	1	0.045	10	20	160	.569	Above comment applies; potential problems amplified by higher speeds and more bearings.	
	Permanent Magnet Stepper	100E145	939J962	36	D.C.	32 W	0 W	144 whr	14 lb	4 lb	6.7 lb	135 lb	Similar to Slo-Syn in concept, pot tests applicable.	65	1363	137				Nuts, lock cups and electrical connector	300	1	0.075	10	20	134	.769	If permanent magnet material other than Alnico V is used, susceptibility to radiation damage must be evaluated.	
	Slo-Syn Stepper	100E148	939J954	36	D.C.	24 W	10 W	243 whr	24 lb	5 lb	7.4 lb	157 lb	Prototype lab tests (TME-1921); potentiometer component tests.	75	1282	136				Nuts, lock cups and electrical connector	150	1	0.025	10	20	138	.780	Relatively wide application of Slo-Syn and Harmonic drive components lends confidence to this design concept. Matching speed torque to drum req. may be difficult.	
	Dynavector	100E147	939J961	36	D.C.	44 W	22 W	486 whr	49 lb	7 lb	6.8 lb	172 lb	Potentiometer component development tests only.	70	1137	.2*				Nuts, lock cups and electrical connector	140	1	0.045	10	20	134	.553	Only one unit ever built and tested. Large development effort required.	
	2 θ A.C. Servo	100E148	939J956	36	400 Hz A.C.	45 W	30 W	594 whr	59 lb	8 lb	7.9 lb	201 lb	Potentiometer component tests only.	80	1496	147				Nuts, lock cups and electrical connector	110	1	0.1	10	20	166	.581	Relatively high speed rotor bearings require special attention to potential wear problems.	
	Self Commutating D.C. Servo	100E148	939J957	36	D.C.	20 W	5 W	162 whr	16 lb	5 lb	7.1 lb	144 lb	Potentiometer component tests only.	75	1688	171				Nuts, lock cups and electrical connector	140	1	0.1	10	20	194	.652	Potential problem areas include high speed rotor bearings and excessive brush and commutator wear. Short time torques may be much higher than listed.	
ANALOG PNEUMATIC	2-Piston Rack and Pinion	939J170	939J173	18	GH ₂ at 215 psia	Consumption rate is .01 lb/sec at 140°R, 215 psia or .004 lb/sec at 520°R, 215 psia	Drive Gas Wt. (Based on 500°R Gas Temp.)	18 Drum Reactor Drive Gas Storage System Wt. (Assumes 44 lb/lb drive gas at 500°R for one startup)	257 lb	220 lb	7 lb	14.6 lb	483 lb	Extensive XE-1 & 2, A6 side-by-side, Plum Brook, 44 actuators total.	113	1892	22	V-band clamp	No detail designs available, but no significant wear or structural problems are anticipated.	Preliminary irradiation heating information indicates that no high temperature material limits are exceeded in shielded location. Operation will generally be at room temperature or below and internal temperature gradients are expected to be small.	No material degradation problems are anticipated in shielded environment of dome mounting. Electromagnet coils, potentiometer resistance tracks, organic seals and coolant distribution porting must be re-evaluated if actuators are relocated to more hostile environment below shield.	300	1	0.1	10	20	364	.534	Extensive developmental experience on XE actuators lends credence to the applicability of this design.
	1-Piston Rack and Pinion	939J470	939J471	36							4 lb	8.1 lb	366 lb	Similar to two-position concept but only component tests directly applicable.	75	1431	171	Nuts, lock cups and electrical connector				250	1	0.1	10	20	346	.591	XE experience largely applicable to this design concept, plus its relative simplicity, indicate good probability of meeting program requirements.
	1-Piston Helical Cam	939J465	939J473	36							4 lb	9.8 lb	396 lb	Potentiometer Servovalve piston ring component tests only.	70	1784	197	Nuts, lock cups and electrical connector				200	1	0.1	10	20	364	.414	Unproven ball cage design may be source of excessive friction or wear.
	Dynavector	Similar to 939J955	939J958	24							5 lb	11.9 lb	434 lb	Potentiometer & Servovalve component tests only.	150	1721	210	V-band clamp				100	1	0.1	10	20	.352	.372	Differential expansion attending thermal environment could result in troublesome seal leakage problems.
BINARY PNEUMATIC	Vane Actuator with Solenoid Control Valve	939J760	939J959	36	GH ₂	Consumption rate is .002 lb/sec at 140°R, 215 psia	Drive flow exhausted to reflector inlet	110 lb	Shares reflector coolant flow	Exhaust to nozzle reflector interface	5.5 lb	209 lb	Bearings only.	50	878	111	Access to vane bolts requires removing nozzle valve access outside P.V.	Graphite seals require special attention	No problem anticipated	No problem anticipated	400	N.A.	N.A.	N.A.	N.A.	176	.739	Relative simplicity of NSS attending this concept must be weighed against limited maintenance access.	

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pneumatic supply system penalty is assessed against the pneumatic concepts by calculating the torque motor flow for a one minute startup and a storage system specific weight of 44 pounds per pound of supply gas required.

The required coolant is calculated to remove both electrical heat and gamma heat but the coolant requirements are not assessed against the concepts because none are assumed to be dumped overboard.

The actuator weight is an estimate based on the concept size and the materials of construction and does not represent a detail piece by piece calculation. All are done on the same basis and the number is therefore assumed to be good for comparative purposes.

The total system related weight is the weight of 18 actuators plus the supply system weight assessed against each concept. The applicable experience column is an attempt to list WANL experience as well as other nuclear or related space experience. In some cases, only component experience is listed.

The number of items is a number giving the relative complexity of the concept. It is not an exact part count because each screw, washer, etc., is not included, but it does represent the sum of the items or groups of similar items. The numbers under the relative reliability columns are taken directly from the fault trees and failure modes. They represent the comparative reliability of each concept with the lower numbers being the more reliable in each case.

The next four columns, remote maintainability, stress, thermal and radiation tolerance, are self explanatory. Five performance parameters are listed under the next five columns. Each actuator concept is designed to meet these requirements as a minimum. An added benefit of some of the designs is a greater than required stall torque which is felt to be of some benefit in the event of a malfunction in the drum system. The velocity of each concept is assumed to be electronically limited and does not represent the maximum capability of the concept. For instance, the pneumatic devices are capable of very high velocities ($1000^{\circ}/\text{sec}$ or greater) in the event of a failure of the velocity clamp. Likewise, the dc and ac motors have very high velocities in the event of rate loop or limiter failure. The velocity of the stepper motor would be somewhat higher (on the order of 2 to 3 times) but maximum speed capability is inherently lower in these designs.

The safety rating is taken directly from the safety and criticality ranking for each concept and the figure of merit is taken directly from the summary evaluation matrix of Section 4.0. The comments about each concept are self explanatory.

4.0 SELECTION OF DESIGN APPROACH

The final selection of a recommended design approach should be the result of this trade study. However, after completing the evaluation of the various alternates, it becomes evident that other important factors of a systems nature are in a position to swing the study one way or another. The comparison matrix is used to select one candidate from each functional group, that is, one proportional electric, one proportional pneumatic and the two-position. Results of other systems studies then can select between groups. The comparison matrix, Table 4-1, shows the five weighting factors across the top as Reliability, Related System Weight, Related Experience, Performance (Stall Torque) and Safety with weightings of .40, .25, .20, .05, and .10 respectively. The actuator candidates are shown at the left of the table. All columns have a relative merit number which has been normalized around the best candidate in that column. The highest number represents the best concept for each column. The weighted merit number then is the product of the relative merit and the weighting factor. The figure of merit is the sum of all the weighted merit numbers for each concept.

A single reliability number is obtained by normalizing the numbers obtained from the fault trees, normalizing the numbers obtained from the failure mode analysis, and averaging the two to obtain the relative merit number shown in Table 4-1.

The related system weight relative merit is obtained by normalizing the related system weight from Table 3-1. The related experience relative merit is based on engineering judgement with the XE actuator experience as the basis for the judgement.

Since all actuators are designed to meet the minimum performance requirements, normalization was based on stall torque, a side benefit of the particular design concept. The highest stall is assigned a relative merit of 1.00. The safety relative merit is obtained by normalizing the numbers from the safety criticality table for each concept.

4.1 SELECTION OF TWO-POSITION CONCEPT

The selection of a two-position concept is relatively easy because a pneumatic vane actuator can be mounted inside the pressure vessel directly to the aft end of the drum. Materials contained in this actuator will withstand the environment to which it is subjected. With drum mounting, the drive shaft and pedestal are eliminated with the attendant removal

TABLE 4-1
~~STRUCTURAL SUPPORT COOLANT VALVE ACTUATOR~~
TRADE STUDY-SUMMARY EVALUATION MATRIX

Weighted Relative Merit		Reliability	Related System Weight	Related Experience	Performance	Safety	(Totalized Weighted Merit) Figure of Merit
Weighting Factor		.40	.25	.20	.05	.10	
ANALOG ELECTRIC	Direct Drive Responsyn	.350 .874	.081 .322	.080 .4	.025 .50	.100 1.00	.636
	Plan. Trans. Responsyn	.303 .757	.159 .637	.040 .2	.012 .25	.075 .750	.589
	Perm. Mag. Stepper	.291 .728	.250 1.00	.120 .6	.038 .75	.090 .895	.789
	Slo-Syn Stepper	.300 .750	.215 .860	.160 .8	.018 .37	.087 .870	.780
	Electric Dynavector	.322 .829	.194 .785	.020 .1	.017 .35	.090 .895	.653
	2 Ø A.C. Servo	.268 .670	.168 .672	.060 .3	.013 .27	.072 .723	.581
	Commutated D.C. Servo	.234 .584	.234 .937	.080 .4	.042 .85	.062 .618	.652
ANALOG PNEUMATIC	2 Piston R & P	.194 .484	.070 .280	.200 1.0	.037 .75	.033 .330	.534
	1 Piston R & P	.252 .631	.092 .369	.180 .9	.032 .62	.035 .347	.591
	1 Piston Heli-Cam	.211 .527	.085 .341	.060 .3	.025 .50	.033 .330	.414
	Pneumatic Dynavector	.208 .519	.078 .311	.040 .2	.012 .25	.034 .341	.372
FLUIDIC	Digital Diverter	.400 1.00	.161 .645	.060 .3	.050 1.00	.063 .683	.739

BINARY PNEUMATIC
VALVE ACTUATORS
WITH VALVE

of the holes through the shield and support plate. The actuator controller is reduced to a simple redundant array of solenoid valves. These valves would be of the pulse operated type that would remain in the position commanded by the last signal applied. Additional complexity may have to be built into the reactor control system to properly program the correct drums IN and/or OUT. This concept requires no fluids for operation which can not also be used as propellant. The operating fluid is exhausted from the actuator into the pressure vessel plenum where it is mixed with the main propellant stream. This drum mounted, two-position concept, represents the simplest of all actuator concepts from an actuation system standpoint. Although the preliminary reliability estimate did not predict that this concept will be several orders of magnitude greater than the analog concepts, it is felt that the development problem areas associated with this concept are simpler than with any other concept. Although it may appear that drum mounting does not meet the NPRD requirements for remote removal and reassembly prior to NSS operation, it is felt that the simplicity and other benefits of this scheme warrant serious consideration. Removal can be accomplished through the aft end. Specific design may or may not require nozzle removal to effect the desired maintenance.

If it is felt that internal mounting requires too much compromise of program requirements, dome mounting can be accomplished with the additional complexity of drive shaft, etc., as mentioned above. The other serious consideration is whether or not the two-position concept can be incorporated into the overall control system concept when core thermal and stress restrictions are imposed. If the system considerations recommend a two-position control concept then the recommended actuator design is the drum mounted, two-position concept actuated by a redundant array of solenoid valves.

4.2 SELECTION OF AN ANALOG CONCEPT

The final selection of an analog actuator is strongly influenced by system considerations such as electric power supply specific weights, pneumatic supply system specific weights, recovery of pneumatic actuator working fluids and number of reactor control drums. Electric actuators, particularly electric stepping motors, are potentially the best candidates for this application.

4.2.1 Selection of an Analog Electric Actuator

Of the electric candidates considered, the permanent magnet rotor types have several advantages over the other concepts. Experience on the SNAP program in a reactor environment similar to NERVA environment in addition of the other inherent advantages of the permanent magnet stepper motor make the Slo-syn concept one of the best concepts of the electric stepper motor actuators. The other permanent magnet type, is smaller and lighter, and contains more poles. Its larger design step makes it more readily adaptable to the CDA applications. Inherent high detent torque also recommends the PM rotor concept. The dc motor concept appears desirable from a power utilization standpoint, but the inherent problems connected with mechanical brush commutation required velocity limit tachometer and mandatory analog electronics eliminate it as the selected design. Therefore, based on the results of this trade study, the permanent magnet rotor concept is selected as the best electrical proportional control drum actuator.

4.2.2 Selection of an Analog Pneumatic Actuator

Of the pneumatic candidates considered, all past NERVA technology experience has been with the basic rack and pinion design. All pneumatic concepts considered have employed the same servovalve and feedback device. The only difference in the pneumatic concepts is the means employed to change the pneumatic pressure to output rotary motion. Because the concepts considered do not appear to have any obvious advantage in reliability, machinability, or performance over the basic rack and pinion concept, no reason exists to abandon the rack and pinion concept which has been so successful on the technology program. An extensive redesign effort has been accomplished to simplify the basic XE design and to increase the reliability and reduce the weight and size.

4.3 FINAL ACTUATOR SELECTION

To make a final selection from the drum mounted, two-position pneumatic actuator, the proportional permanent magnet rotor electric actuator, and the proportional rack and pinion single piston pneumatic actuator requires further study and evaluation from a system standpoint. It is believed that the actuator development program submitted in

response to Government Technical Directive 69-13 will result in an actuator of any of the above selections that will meet the program requirements. Overriding systems parameters mentioned previously must be accurately considered in order to assure the lightest and best actuator system for the NERVA program. The results of an AGC electric vs pneumatic supply system will strongly influence the final selection.

5.0 METHODS OF IMPROVING RELIABILITY OF SELECTED, RECOMMENDED ACTUATOR DESIGN APPROACHES

5.1 INVESTIGATIONS OF SYNCHROS VS. POTENTIOMETERS

Substitution of electromagnetic transducers of the synchro type to increase control system reliability has been suggested as an alternative to drum position feedback, a function now performed by potentiometers in the drum actuators. The "weak link" in the potentiometer that has prompted consideration of the synchro is the junction between wiper and resistance track. Due to wear and contamination susceptibilities, this sliding contact causes some lack of confidence concerning its ability to meet the stringent reliability objectives. By eliminating this point of friction, a synchro apparently offers a potential reliability improvement while also providing the possibility of reduced sensitivity to electromagnetic interferences, because of the frequency discrimination possibilities attendant with ac operation.

However, examination of various synchro configurations which are applicable as feedback devices do not reveal any competitive candidate justifying immediate selection. Those devices promising adequate performance characteristics are generally attended by electronic excitation and demodulation networks which by their very nature have a degree of complexity required to perform their relatively sophisticated function. While no single component of such a system can likely be regarded as having poor reliability, the series array of components may be so large that no net reliability improvement is gained. In addition, the relatively large size of synchros implies either reduced redundancy, or increased actuator size, weight and coolant consumption. Tests involving potentiometers such as the XE series, the NRX-A6 pneumatic actuator side-by-side, GTR, Plum Brook, Pneumatic Actuator Qualification Test (WANL-TME-1954) and the actuator extended life tests where potentiometers were run under all expected operating conditions for up to 3000 hours without failure lend confidence to the use of potentiometers as the feedback device. Also, as discussed under the stepper motor sections, potentiometers may only be required for diagnostic purposes. Therefore, WANL recommends that potentiometers continue to be used as feedback devices in the CDA and SSCVA.

5.2 COMBINATION BINARY/ANALOG DRUM ACTUATOR

More or less conventional mechanisms of moderate complexity have been addressed to the task of control drum actuation during the current concept study. In the case of analog actuators particularly, this complexity has incited doubts about whether such a mechanism might credibly attain its allotted reliability goal; an objective so stringent as to be generally unsatisfied by devices comprised of more than one part, as evidenced by the Farada Data.

A major contributor to these reservations is the system failure mode involving large registration disparity between members of the drum bank. Preference is accorded the binary actuator concept with respect to this failure mode, due to its relative simpler construction. However, the potential system reliability is compromised when binary actuators are employed as independently controlled units to implement reactivity shimming, rather than acting in unison as a monolithic bank. This is because the redundancy applicable to a master control solenoid valve could well be prohibitive when applied to 36 individually controlled actuators. Further, in addition to being more probable, an actuator position at variance with command could introduce more severely injurious effects since the resultant core thermal stresses are superimposed on those already inherent in independent binary control.

In response to these problems, it has been suggested that the binary actuator be employed in the banked configuration in combination with small displacement analog actuators assigned to shimming function. This concept is visualized as using a pneumatic vane binary actuator having an angular travel in the neighborhood of 130 degrees with an analog shim actuator, either pneumatic or electric, effecting a vernier modulation of the "out" drum position limited in range to about ± 10 degrees. The configuration of this hybrid actuator could take either of two forms; the binary and analog actuators could be differentially coupled to the drum via a gear transmission, or, alternatively, the vernier actuator could be carried "piggyback" on the vane rotor. The latter case would, of course, necessitate commutation of electrical and/or pneumatic signals to the vernier actuator.

While the hybrid actuator concept evidences relative freedom from serious consequences resulting from a single actuator failure, this advantage must be evaluated against the obvious penalties of additional system weight, complexity, and development costs.

In light of these considerable penalties, it would seem appropriate that further efforts on the hybrid actuator be deferred and the concept be consigned to a standby, last resort status until such time as the current trade study of more conventional systems might indicate more substantial evidence that the reliability objectives are likely to prove unattainable by these means.

5.3 ELEMENTARY ANALYSIS OF DRUM ACTUATOR SYSTEM

As an alternative to potentiometer feedback to achieve closed loop position gaging, it is proposed to equip the drums with closely matched torsion springs biased toward zero. The torque of these springs would be balanced against that produced by pneumatic vane or piston actuators equally pressurized from a common servovalve.

System Advantages

1. Eliminates dependency on precision feedback potentiometers
2. Individual actuators would not contain a servovalve.
3. Absence of the above two items would probably permit mounting relatively simple actuators inside pressure vessel similar to two-position drum/actuator concept.
4. System weight would be considerably reduced.

System Disadvantages

1. It is unlikely that any scheme could be devised to permit automatic redundancy of the servovalve; therefore, the valve reliability requirement would be quite high.
2. The valve loading imposed by the bank of actuators would prohibit utilizing a single-stage valve of the design currently developed. A two-stage spool valve would be required of a degree of increased complexity to warrant concern as to the ability to meet the extreme reliability required of this device.
3. It is required that actuator cylinder pressures be matched both statically and dynamically to obtain drum position registry. Because variations between actuators in piston or vane seal leakage are inevitable, the distribution manifold communicating from the valve to the actuators would require both low and matched line impedance to each actuator. That is individual large lines of equal length.

4. The combination of drum inertia and drive gas compliance would result in a relatively low frequency system resonance. The static friction associated with the piston seals acts to excite drum oscillation at this resonant frequency. The high value of friction provides good damping of this oscillation, but experience has indicated that the drum motion attendant to this type of operation consists of a series of relatively large amplitude lurches.

5. Piston seal friction comparable to that experience on the XE actuators would result in a static resolution limitation of approximately ± 3.7 percent which is probably unsatisfactory.

This resolution is based upon the following:

Assume XE actuator sizing, static friction torque on the XE piston seals measures;

$$T_f \cong \pm .1 \Delta P \text{ in-lbs/psi; drive torque; } T = 2.2 \Delta P \text{ in-lbs/psi.}$$

Let Initial drum spring torque

$$T_{\text{init}} = 20 \text{ in-lbs}$$

Drum travel

$$\Delta \theta = 150^\circ$$

Drive supply pressure

$$P_s = 200 \text{ psig}$$

Cylinder pressure (assume two-stage valve) $0 \leq \Delta P \leq P_s$

Maximum drive torque

$$T_{\text{max}} = 2.2 P_s - T_f = (2.2 - .1) P_s = 420 \text{ in-lb}$$

Drum spring gradient

$$G_s = \frac{T_{\text{max}} - T_{\text{init}}}{\Delta \theta} = \frac{420 - 20}{150} = 2.66 \text{ in-lbs/o}$$

At 90° position

$$P \approx 100 \text{ psig}, T_f = \pm .1 \Delta P = 10 \text{ in-lbs.}$$

Resolution

$$R = T_f / G_s = \frac{\pm 10 \text{ in-lbs}}{2.66 \text{ in-lbs/o}} = \pm 3.7^\circ$$

Attempts to reduce this value, by increasing the drive pressure or piston size to permit a corresponding increase in spring gradient, would result in an increase in piston seal friction in approximately the same proportion, so that the resolution is nearly independent of actuator parameter sizing over a large range of values. There appears to be no obvious solution to the problem.

6.0 REFERENCES

1. A. Boltax, "Behavior of Semiconductors and Magnetic Materials in Radiation Environment," *Elect. Mfg.*, Vol. 63, No. 92, March 1969.
2. F. Kucher and R. E. Bowman, "Effects of Radiation on Materials and Components," Reinhold Pub.
3. "NRX-A6 Final Report," Westinghouse Astronuclear Laboratory, WANL-TNR-224, January 1969.
4. D. J. Robinson, J. T. Mayer and R. R. Wyer, "NERVA Control Drum Actuator Irradiation Test Program," NASA TND-5347, July 1969.
5. J. E. Shipley, *Machine Design*, McGraw Hill Book Co., Inc. N.Y., 1956.
6. Table IV, Nitralloy 135MOD, Room Temperature Average Yield Strength, Nitralloy Corporation, 1954.
7. R. Shollenberger, Telephone conversation, 3 June 1969.
8. D. K. Lloyd and M. Lipow, "Reliability Management, Methods and Mathematics," pg. 77, May 1964.
9. D. J. DeSalvo, "Structural Reliability Analysis Techniques and Reflector Example, October 1968
10. "Final Report on LCRE Control Drum Drive Development," PWAC-403.
11. "Final Report on Irradiation and Thermal Testing of LCRE Control Drum Electrical Components," PWAC-493.
12. "Control Drive Mechanism Development," PWAC - 492.
13. "SNAP-10A Flight System Prototype (FSM-1) Performance," NAA-SR-10735
14. "Irradiation of SNAP-10A Control Drum Drive Actuators and Position Sensors," NAA-SR-10717.
15. "SNAP-10A Component Development Summary," NAA-SR-9898.
16. "The Development Philosophy for SNAP Mechanisms, O. P. Steel, A. I., Third Aerospace Mechanisms Symposium, NASA.
17. "S8DR Actuator Interim Report," NAA-SR-12605.

REFERENCES (CONTINUED)

18. "S8DR Actuator Second Interim Report, " AI-AEC-12779.
19. B. G. Strait, "Nuclear Reactor Control with Stepping Motor Actuators, " LASL, AIAA Paper Number 66-557.
20. "Final SNAPSHOT Performance Report, " NAA-SR-11934.

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ABSTRACT This trade study was conducted to select one control drum actuator candidate for development to meet program requirements. Four pneumatic-type proportional actuator candidates, seven electrical-type proportional actuators, and one pneumatic-type binary two-position actuator were considered. The comparison was made on five basic parameters: Reliability, related system weight, related experience, performance, and safety. The selected concepts are: Pneumatic, Single Piston Rack and Pinion; Electric, Permanent Magnet Rotor Electric Stepper Motor, and Pneumatic, Two Positions.		
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