**Westinghouse
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DATA ITEM S-54

**CONTROL DRUM ACTUATOR
DESIGN CONCEPTS (U)**

TRADE STUDY NO.764

MASTER

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ABSTRACT

This report presents a trade study of design concepts for the Control Drum Actuator System, a component of the NERVA Nuclear Subsystem (NSS). The purpose of this study is to evaluate and select the most logical and reasonable approach for continued detailed design and development of this component, consistent with the programmatic and technical requirements for the ten-hour full-flow cycle engine as defined in the NERVA Program Requirements Document.

The functional and technical requirements were identified by the December, 1969, Systems Engineering draft issued of the component specification, EC 677585.

The alternate design concepts evaluated are:

Motor

- Series DC Motor
- Permanent Magnet Stepping Motor
- Brushless DC Motor

Transmission

- Conventional Spur Gear Train
- Epicyclic
- Worm Gear
- Harmonic
- Wobble
- Planetary/Harmonic
- Planetary/Wobble

Actuator Malfunction Override Device (AMOD)

- Clock Spring
- Torsion Spring
- Drive Shaft Center Spring
- Pyrotechnic Devices

Selection of the recommended design concept in each of these areas is based upon the construction of a comparison matrix. Each alternate is evaluated on the basis of performance, physical characteristics, and reliability, with particular emphasis upon the severe environmental requirements.

The permanent magnet stepping motor design, incorporating the epicyclic transmission and drive shaft center spring AMOD configuration, is the concept selected and recommended for continued detail design and development. The major factors leading to this selection are described.

INTRODUCTION

This study supplements the much broader Control Drum Actuator Trade Study No. 754 (TME-1984, January 1970) which developed the electric motor approach for the NERVA application, and considers only the two best concepts as determined by that trade study.

The key component in the actuator design is the motor. The selection of the motor type essentially controls the character of the remainder of the design and determines the possible approaches to development of the actuator system.

The most significant parameter in this trade study, the one which exerts the greatest influence on selection of a design approach, is the unprecedented system reliability requirement. The motor concepts considered, DC series motor and permanent magnet stepping motor, represent a number of distinct contrasting characteristics. The actuator systems dictated by these characteristics differ significantly, and the study essentially reduces to the evaluation of the effect of these differences upon system reliability.

Discussions on the categorization of nuclear subsystem components in November 1969, and subsequent SNPO direction by means of SNP-1, TD-70-11 and NP-1, TD-70-6, resulted in the agreement that this component was in Category B: "One for which further trading of concepts was needed, but with selection of one design needed prior to PDR". Therefore, this report constitutes the necessary S-54 Trade Study work supporting the concept selection for which detail design and development will proceed leading to NSS PDR and subsequently to hardware release.

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1.0 REQUIREMENTS

The function of the NERVA control drum actuators is to rotate the reactor control drums in response to a position demand signal during engine operation. The duty cycle consists of short, intermittent periods of dynamic operation separated by long periods of inactive coast. Single mission operations will total approximately 10 hours over a period of from one week to several years in the space environment.

The most important design requirements are given in this section. The complete specifications can be found in Specification No. EC-677585, "Performance/Design and Qualification Requirements; Control Drum Drive Assembly for Nuclear Subsystem CP-677555".

1.1 FUNCTIONAL REQUIREMENTS

1.1.1 Primary Performance Requirements

1.1.1.1 Load Torque

The maximum load torque totally resulting from drum bearing friction is 5 in.-lbs.

The drum incorporates a spring, biased toward the zero position, which develops a load of 16 in.-lbs at the zero degree drum position with a gradient of 0.061 in.-lb/degree.

The total maximum load torque is, therefore, 32 in.-lbs. With derating and safety factors considered, a design load torque of 100 in.-lbs is assigned.

Load inertia is approximately 0.25 in.-lb-sec.²

1.1.1.2 Angular Velocity

Rotation is bi-directional and at a rate continuously variable from 0 to 10 degrees/sec. Under no circumstances will the rate of change of angular position exceed 12 degree/sec.

1.1.2 Secondary Performance Requirements

1.1.2.1 Hold Position

If failure of the electrical power system or removal of motor drive power occur, the actuator will maintain the position at failure with a positive holding torque.

1.1.2.2 Malfunction Override

Upon command of the engine programmer, the control drum shall be disengaged from the actuator drive shaft and rotated to the "Orifice Angle" (preselected position), where it will be held in position with a positive holding torque.

1.1.2.3 Resolution

The system static resolution shall be 0.2 degrees maximum at the actuator output shaft.

1.1.2.4 Accuracy

The system static output shaft accuracy shall be 1 degree throughout the working range.

1.2 ENVIRONMENTAL REQUIREMENTS

1.2.1 Primary Environmental Requirements

The non-operating induced environments, which the control drum actuator shall be designed to withstand, are defined in WANL-CP-677555, "The NERVA Nuclear Subsystem Specification". In addition, the control drum actuator will be required to operate to all requirements while subjected to an operating environment resulting from the NSS operation. This environment will be as delineated in NERVA Interface Control Drawing ICD-1134275 and the NERVA Nuclear Subsystem Specification No. 677555. The controller portion of the control drum actuator system shall be tolerant to the environment as specified in AGC-CP-91055, Engineering Critical Component, "Electronics, Components, Instrumentation and Control", during NSS operation.

1.2.1.1 Radiation

The control drum actuator shall be subjected to the following radiation environment (integrated dose for 10 hour life).

Neutron Fluence - Shielded

$$1.4 \times 10^{15} \text{ n/cm}^2 \quad E > 1.0 \text{ Mev}$$

$$2.7 \times 10^{15} \text{ n/cm}^2 \quad 0.4 \text{ ev} < E < 1.0 \text{ Mev}$$

$$7.9 \times 10^{13} \text{ n/cm}^2 \quad E < 0.4 \text{ ev}$$

Gamma Dose - Shielded

$$2.9 \times 10^9 \text{ ergs/gm(C)}$$

1.2.1.2 Temperature

40°R to 540°R.

1.2.1.3 Pressure

The actuator internal pressure will vary from a minimum of 10^{-3} torr during coast periods to a maximum of 750 psia during full power operation. External housing pressure will be that of the space environment.

1.2.1.4 Reliability

The reliability design requirements for the control drum actuator system shall be a 0.999786 probability of success in meeting the primary performance characteristics.

1.2.1.5 Maintainability

No scheduled maintenance is required. The actuator shall be compatible with remote removal equipment.

2.0 DESCRIPTION OF DESIGN APPROACHES

2.1 ALTERNATE 1 - SERIES DC MOTOR

2.1.1 General Description

Series DC motors, by nature, are the most efficient and powerful practical electrical machines, because power is applied directly to the rotor to interact with the stator field in exactly the correct orientation for torque generation.

The rotating member (armature) consists of wire coils wound on a steel core, with each coil terminating at two commutator bars. The armature coils are lap wound, permitting a large number of commutator bars which reduces AC ripple and radio-frequency interference. The field flux is created by coils that are electrically in series with the armature. Current is carried to the armature coils by a brush pair which communicate with the commutator bars through a sliding surface contact. Armature coil switching logic is determined by the dimensional relationship between the commutator bars, coil winding pattern, and field location. When the motor starts, the current is at a maximum. Consequently, the magnetic-field density is greatest, which produces high torque. As the motor speeds up and the current reduces, so does the field flux, until the point is reached where the load torque requirements limit the speed of the motor.

Torque is developed by the action of a magnetic field on current-carrying conductors distributed around the periphery of the armature. The conductors, arranged as coils, are fixed so that the flux density in the air gap is normal to the length of the conductor. The individual coils are interconnected to form a completely closed winding. The ends of the coils are connected in an orderly fashion to the separate contact points of the commutator.

During rotation, the commutator behaves like a multi-position switch whose poles are the brushes connecting to the external circuit. Rotation causes a switching action which continually connects the coils so that all the armature conductors lying under the north pole carry currents flowing in one direction, while those lying under the south pole carry currents in the opposite direction. The commutator reverses the current in each armature coil at the instant it passes through the neutral axis, or when it leaves the influence of the north pole field and enters the influence of the south pole field, or vice versa.

Bi-directional operation requirements dictate that the motor be of the split-series configuration rather than the straight-series configuration. In the split-series motor, the stator comprises two oppositely wound fields, and the motor direction is reversed simply by switching the applied voltage from one field to the other. This ease of reversibility is obtained at the cost of a slight loss in efficiency.

The problems associated with the commutation of DC motors are by far the most difficult to contend with in motor design. The theory of commutation is not nearly as well developed as is the remainder of motor design, and most of the unpredictability in the performance of DC motors relates to this area. The problem has been emphasized in aircraft servomotors, where the high-altitude rarefied atmosphere interferes with the switching action.

Arc suppression and timing problems are accentuated in low pressure environments such as that which NERVA will experience. Two types of special windings will be incorporated in the stator to improve commutation and motor performance: interpole windings to assist commutation, and compensating windings to cancel out the deleterious effects of armature reactions.

When a motor is under load, the armature generates a magnetomotive force which influences the magnitude and distribution of the resultant field flux. The armature magnetomotive force causes a displacement of the neutral zone in the direction opposite to rotation.

This disturbs the commutating action, as the neutral axis is perpendicular to the pole axis only at no load. To obtain improved commutation, interpoles are used to produce the necessary commutating field. The interpole axis is perpendicular to the pole axis while the interpole field opposes the armature field and completely cancels it out in the neutral zone.

Interpoles cancel the armature cross flux only in the commutation zone, and do not affect the non-uniform distribution of flux in the poles. Complete suppression of the armature field is possible only by using a winding distributed over the whole pole surface. Therefore, the compensating winding is placed in the pole face as near the surface as possible. The armature and compensating windings must be connected in series so that conductors of each lying within the same pole pitch carry the same current in opposing directions. The compensating winding will suppress the magnetomotive force of those armature conductors that lie under the pole faces.

2.1.2 Characteristics of the Series DC Motor

To take advantage of the high efficiency of the series DC motor, the overall system must be optimized to operate in the peak efficiency region of the motor. This requires operating at high speed with a torque output matched to the expected load requirements. Figure 2-1 depicts a motor optimized for the NERVA CDA application. Speed at maximum velocity will be approximately 6000 rpm, requiring a transmission reduction ratio of $\sim 3600:1$. Starting torque, with a rigid gear system utilizing dry film lubricant, is expected to be between 5 and 10 oz-in.

The dynamic duty cycle is expected to be 5 percent of the engine operating time maximum. During steady state position demand, the brake will be engaged and power to both the brake and motor removed. The motor is capable of holding position during steady state demand against the very small reflected load spring torque, with a very little power dissipation of 0 to 5 watts. But, because the brake is available and dissipates power in the disengaged mode, it will be used to hold position.

2.1.3 Previous Application

Because of its relatively high efficiency, compact size and torque-speed characteristics, the DC motor has taken predominance over AC systems in aircraft, missile and some space applications.

The ability to operate from storage batteries and deliver a high output in a small frame size has established the split-series DC motor as the basic electrical power unit in aircraft backup actuator systems. Sealed units and motors operating in a controlled atmosphere are used in some primary control systems and power actuator systems, such as autopilot, flap, and trim tab systems. Components, particularly brushes, have had to be developed to assure a reasonable degree of reliability in the low pressure environment of high altitude flight. (Refer to Appendix A-7.2.)

Unidirectional-series DC motors have been utilized in conjunction with magnetic particle clutch brakes to position rocket motor nozzle thrust control vanes and aerodynamic and hydrodynamic control surfaces in missiles and torpedos. These units have been optimized to operate in very severe environments for mission lifetimes of only a few minutes.

28 VDC
2.0" DIA. x 3.3" LG.
20 OZ WEIGHT

Figure 2-1. Series DC Motor Characteristics

Space application has been primarily in the sphere of slow-speed torque motor systems utilizing direct load drive. They have been used in solar array and antenna de-spin mechanisms and some positioning systems in the OAO, OSO, communications, and other satellites. (Refer to Appendix A-7.23.) The DC torque motor is suited to these applications because of its high torque-to-inertia ratio, light weight, and direct drive capability.

Instrument-type DC motors have limited application in space due to their high speed characteristics and precise commutation requirements. There are some unique applications of this motor, however, among them the soil bearing load test of the Surveyor III lunar probe. Four DC motors were used to operate the surface sampler, and an approximation of the forces exerted in digging trenches in the lunar surface, compacting the soil, etc., was made by noting the current drawn by each motor.

Larger unidirectional DC servomotors were used in the Apollo service module engine gimbal actuator. (Appendix A-7.4; A-7.5.) In this application, extensive use of redundancy in the power train was utilized to achieve reliability. (Appendix A-7.22.)

In general, the DC motor has been used in space applications where the unit was sealed and the internal atmosphere effectively controlled, or in very short, limited life, and "one-shot" applications.

2.1.4 Effect Upon Remainder of System

The selection of the type of motor to be used in the NERVA control drum actuator system effectively establishes the requirements and limitations for the remainder of the actuator system. The speed-torque characteristics, control mode, and mechanical configuration, among other motor parameters, directly affect the selection and design of the other major components in the actuator system. The effect upon the major components by the selection of the DC series motor is considered in the following paragraphs.

2.1.4.1 Transmission

A number of transmission types are adaptable for development and incorporation into the NERVA control drum actuator. A number of the more suitable types are described, and the restrictions and limitations imposed by selection of the series DC motor noted.

Selection of the series DC motor of Section 2.1.2 requires a transmission ratio of 3600:1 and an input speed of 6000 rpm.

The motor's high speed means that at least the initial pass of the transmission must incorporate high speed bearings to alleviate the attendant lubricating and noise problems.

2.1.4.1.1 Conventional Gearhead. The conventional multistage gearhead is a widely-used type of transmission. It is relatively simple and easily fabricated. The simplest multistage gearhead to construct would be one using spur gears. Spur gears, however, are noisy when operated at the high input speeds of the DC motor concept.

Helical gears produce less noise and have a greater load capability than equivalent pitch spur gears, but they produce an axial thrust load on their bearings. By using double helical gears, the high speed and load advantages are retained while the axial thrust load is eliminated.

A six-pass gearhead utilizing 12 bearings is required to achieve the 3600:1 reduction ratio. This configuration requiring a large envelope would be quite large and complex relative to other transmissions.

2.1.4.1.2 Epicyclic Transmissions. A double compound planetary gear arrangement can be used with the DC motor concept. The planetary gear offers an advantage over the multistage gearhead in that the input pinion and the output shaft do not have a radial loading. A major disadvantage of the planetary transmission is that the planet gears are loaded radially and have a series failure path so that one faulty planet can freeze the transmission. This configuration places significant loading upon the many small planet bearings which operate at high speed in the first pass and compromise reliability.

A modified form of the compound planetary gear, the epicyclic gear, can be utilized with the DC motor. To attain the high reduction ratio required with the DC motor, certain modifications in the design of the transmission must be made. A stub tooth profile will be used, along with a change in addendum, and the face width of the teeth increased substantially to handle the higher loading of the DC motor. Because of the high speed eccentric input to the transmissions, a high radial load will be placed on the bearings of the motor. This load can be tolerated by the low-speed stepper motor, but careful inertia com-

pensation and counterbalancing of the transmissions input shaft will have to be made to make this transmission feasible for the DC motor.

2.1.4.1.3 Worm Gear Transmission. A two-pass worm gear transmission is a possibility for use with the DC motor and offers certain unique advantages, but it is not feasible from the configuration and efficiency standpoint. A low lead angle worm gear cannot be driven backward, and such an actuator would not require a brake to meet the fail-in-place requirement. However, low lead angle means high friction losses and poor efficiency requiring more power from the motor. The use of sliding contact surfaces in the mesh for power transmissions entails a severe lubrication problem and compromises reliability. The geometry of the two-pass worm gear transmission results in an actuator much larger and more awkward than any of the other actuator transmission concepts.

2.1.4.1.4 Planetary/Harmonic Transmission. The harmonic drive transmission offers unique advantages, particularly in the areas of high gear accuracy, low backlash, and compact configuration. (Appendix A-7.1; A-7.23.) Because of ratio limitations and input speed limitations, neither the one-pass harmonic drive alone nor the compound harmonic drive unit can be used.

A combination of the planetary and harmonic drive transmission types, which minimizes the limitations of each, would consist of a compound planetary gearhead as the pre-stage reduction to a harmonic drive wave generator (Figure 2-2.)

The first pass uses either herringbone or double helical gearing to produce the smooth, continuous action (due to the gradual overlapping engagement of the teeth) essential in a high speed system. The pre-stage ratio would be approximately 30:1 and the harmonic drive ratio 120:1. Input to the harmonic drive would be 200 rpm; a favorable speed for wear considerations.

Certain disadvantages and developmental problems are inherent in this transmission, however. The high-speed planet bearing and radial loading problems are still present as well as the flexing spline lubrication problem. This transmission appears to be one of the most likely candidates for the DC motor concept. Significant developmental problems will be present, but not insurmountable.

Figure 2-2. DC Motor, Planetary Gearhead, Harmonic Drive Transmission Concept

2.1.4.1.5 Wobble Gear Transmission. The wobble gear transmission, described in Section 2.2.4.1.5, cannot be applied directly in the DC motor actuator due to reduction ratio limitations. To attain the required ratio of 3600:1, a pre-stage reduction of 30:1 must be incorporated ahead of the wobble transmission. A compound planetary gear head similar to that of the planetary/harmonic drive transmission can be used to better advantage than a multiple pass spur gear system.

A two-pass wobble gear transmission may also be used in this actuator. In this configuration, the transmission would be composed of a series orientation of two complete wobble gear transmissions, most probably of equal 60:1 ratios.

2.1.4.1.6 Comparison of Transmissions. The comparison matrix technique used is based upon the comparison of the transmissions considered for use with the DC motor on a one-parameter-at-a-time basis. For each parameter considered, a ranking is assigned each transmission indicating its superiority or inferiority with respect to the other five transmissions. The best transmission is assigned a 1, the second best 2, and so on to 6 for the poorest transmission, regardless of the degree of superiority of one over the other. (See Table 2-1.)

At completion of the matrix, the total of the rankings for the six transmissions indicate their relative merit. The transmission with the lowest total is the superior transmission.

2.1.4.2 Position Sensing Device

Selection of the motor type will have negligible effect upon the type of position-sensing device chosen. An infinite-resolution plastic film track potentiometer appears to be the best candidate on the basis of reliability and simplicity of supporting components. This potentiometer is very similar to the one in the XE actuator. A number of construction modifications will be made in the XE unit to meet the more severe environmental requirements, but functionally, the potentiometer will be identical to that of the XE unit.

A recent government directive to AGC requires that the engine programmer use digital techniques rather than the analog techniques of the XE technology program. This necessitates incorporation of an analog-to-digital converter for interface of the potentiometer signal with the engine programmer, or the use of a digital-type shaft position transducer. The

TABLE 2-1

TRANSMISSION COMPARISON MATRIX - DC MOTOR CONCEPT

Parameter	Rating	Planetary/Harmonic	Rating	Planetary/Wobble	Rating	Compound Wobble	Rating	Conventional	Rating	Epicyclic	Rating	Worm
1. Number of Meshes	6	Eleven.	5	Ten.	2	Two.	4	Six.	2	Two.	2	Two.
2. Mesh Nature	1.5	Rolling Contact. Negligible Sliding.	3.5	Rolling Contact. Some Sliding.	5	Rolling Contact. Moderate Sliding.	1.5	Rolling Contact. Negligible Sliding.	3.5	Primarily Rolling. Some Sliding.	6	Pure Sliding Contact
3. Tooth Loading	3	Moderate Loading.	3	Moderate Loading.	3	Moderate Loading.	6	Concentrated and Severe Loading.	3	Good Distribution. Moderate Loading.	3	Moderate Loading.
4. Tooth Pitch	5.5	Fine.	4	Planetary - Coarse. Wobble - Fine.	5.5	Fine.	1.5	Coarse.	3	Moderate.	1.5	Coarse.
5. Number of Bearings	4	Four.	4	Four.	1.5	Two.	6	Twelve.	1.5	Two.	4	Four.
6. Nature of Bearing Loading	3	Primarily Radial.	4	Planetary - Radial. Wobble - Compound.	5	Alignment Tolerances Critical. Compound Loading.	1.5	All Radial.	1.5	All Radial.	6	Severe Compound.
7. Compatibility with Solid Lubricants	6	Planetary - Good. Harmonic - Poor.	3	Planetary - Good. Wobble - Fair.	4.5	Fair.	1.5	Good.	1.5	Good.	4.5	Fair.
8. Efficiency	1.5	Approx. 90%.	4	Approx. 85%.	5	Approx. 80%.	3	Approx. 88%.	1.5	Approx. 90%.	6	Approx. 70%.
9. Contamination Susceptibility	5.5	High	4	Moderate.	2	Negligible.	5.5	High.	2	Negligible.	2	Negligible.
10. Envelope	1.5	Small.	3.5	Moderate.	3.5	Moderate.	5.5	Large.	1.5	Small.	5.5	Large.
11. Weight	2	Moderate.	5	Heavy.	2	Moderate.	5	Heavy.	2	Moderate.	5	Heavy.
12. Number of Components	3.5	Sixteen.	3.5	Sixteen.	2	Eight.	6	Nineteen.	1	Seven.	5	Eleven.
13. Fabrication Difficulty	3	Moderate.	5.5	Severe.	3	Moderate.	3	Moderate.	5.5	Severe.	1	Simple.
14. Ease of Assembly	5.5	Difficult.	5.5	Difficult.	3	Moderately Easy.	1	Simple	3	Moderately Easy.	3	Moderately Easy.
15. Reliability	3.5	Fair.	3.5	Fair.	1.5	Good.	5.5	Poor.	1.5	Good.	5.5	Poor.
16. Thermal Adequacy	1.5	Good.	3.5	Fair.	1.5	Good.	5.5	Poor.	5.5	Poor.	3.5	Fair.
17. Structural Adequacy	2	Fair.	4.5	Poor.	4.5	Poor.	4.5	Poor.	1	Good.	4.5	Poor.
18. Quality Assurance Adequacy	5	Poor.	5	Poor.	5	Poor.	3	Fair.	1.5	Good.	1.5	Good.
TOTAL	63.5		69.5		59.5		69.5		42.0		69.5	

use of a digital shaft position transducer with the stepping motor concept would eliminate the need for an A/D converter. Use of a digital shaft position transducer with the DC motor concept requires the use of a digital-to-analog converter to interface with the analog actuator controller.

2.1.4.3 Additional Components

Tachometer - Control system stability requirements necessitate the incorporation of a brush-commutated DC tachometer on the motor shaft of the DC motor. Integration of the actuator output shaft position signal is not practical in a high reduction ratio system such as this; the compensation problems thus introduced would be difficult to solve and the solutions would be marginal. The addition of a tachometer means an additional reliability consideration.

Position Holding Mechanism - Upon failure of electrical power, the actuator must hold its position until diagnostic measures are taken and the situation corrected, the malfunction override device engaged, or the failure position remain in hold indefinitely. Fulfillment of these requirements with the DC motor will necessitate that a mechanical brake be engaged upon loss of power. The very high reduction ratio will enable a small force of only a few oz-in. to hold the load. However, internal friction in the bearings and the brushes of the DC motor are variable parameters and cannot be depended upon to provide sufficient holding force under all conditions.

Zero Position Lock - The actuators must be positively locked at the zero position during periods when the engine is not in operation, including launch. The mechanical brake engaged upon loss of electrical power will serve this purpose as well as that described above. (Appendix A-7.20.)

2.1.4.4 Cooling

In the normal reactor startup sequence of operation, the drums will be moved out to approximately 110 degrees under a no-propellant flow condition. The normal supply of coolant gas, propellant drawn from the dome, will not be available for cooling the actuator.

Heat generated in the stator windings can be dissipated efficiently by conduction through the actuator housing to the reactor dome.

Heat generated in the rotor will have only an intermittent line contact through the shaft bearings for heat conduction, which will be ineffective in cooling the rotor windings. There does not appear to be an acceptable solution to this cooling problem other than oversizing the rotor conductors to withstand the heat generated. Convection cooling, even that which could be provided by a bottle supply, may not be acceptable due to reactor startup dynamics considerations. Radiant cooling is a possible approach but will not be sufficient in itself to hold down "hot spot" temperatures in the rotor. The cooling of this actuator is analyzed further in Appendix A-3, "Thermal Analysis".

2.1.4.5 Direct Current Motor Actuator Control System

The DC motor control system shown in Figure 2-3 is a conventional positioning actuator control system with velocity limiting and safety features added. The position error is obtained by subtracting the actuator position signal from the command signal. This error signal is clamped by the velocity limiter. The mixer takes the difference between the limited error signal and the motor velocity signal to obtain a signal which is converted into a current and delivered to the motor. The motor is required to operate from a control current rather than a control voltage because of the change in motor resistance due to temperature changes.

The current to the motor generates a torque which accelerates the load until the tachometer generates enough voltage to cancel the error signal and maintain a constant speed. The feedback potentiometer, mounted on the drive shaft, moves until the position cancels that of the command and the actuator stops.

The redundant feedback potentiometers are fed through an auctioneering device which increases the reliability of the system by rejecting signals caused by malfunctioning potentiometers. The power required to excite the potentiometers must also be monitored because loss of this power will open the high gain loop of the system.

A digital/analog converter section must be incorporated in the actuator controller to interface with the engine digital control system. A recent government directive to AGC specifies that the engine control system use digital techniques as opposed to the analog techniques of the XE technology program.

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Figure 2-3. DC Motor Actuator Controller

2.1.4.6 Power

Because the DC motor develops only enough power to meet the load demands, its efficiency is very high, approaching 65 percent at rated conditions. Speed requirements dictate a high ratio transmission between motor and drum load. Thus the actual load of the drum, some 32 in.-lbs, places very little power demand on the motor. Nearly all of the load on the motor will result from transmission losses estimated to be approximately 5 oz-in. Maximum power required will be approximately 37 watts. Minimum power to hold position is approximately 2 watts.

2.2 ALTERNATE 2 - PERMANENT MAGNET STEPPING MOTOR

2.2.1 General Description

The electrical stepping motor is a 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 windings are pulsed.

There are two basic types of electric stepping motors. The first 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 a soft iron rotor, similar to the electric solenoid action, and is classified as a variable reluctance stepping motor (VR).

The permanent magnet type motor has been selected for the NERVA application because of the advantages offered by its magnetic detent torque characteristics. The inherent magnetic property of the rotor produces a constant torque which opposes mechanical rotational forces imposed upon the motor shaft. This detent torque effects a valuable safety factor in the NERVA concept. Failure of electrical power will result in the actuator holding its position at the time of failure, one of the requirements of the CDA specification. Requirements are for the actuator to exert a holding torque upon loss of power of 50 in.-lbs. When reflected through the 120:1 transmission, this requires about 5.5 oz-in. of detent torque. This is only 15 percent of the detent torque available in a PM stepper optimized for the NERVA application.

The operation of the PM stepping motor is functionally depicted in Figure 2-4; its characteristics are shown in Figure 2-5. The rotor is a cylindrical permanent magnet magnetized radially to establish 12 alternating north and south polarized magnetic poles at the projecting teeth on its circumference. The stator is of the salient pole bifilar 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, B, $\bar{A}$ and $\bar{B}$; thus presenting a five wire system to the stepper motor driver section of the actuator controller.

The four sequential modes of stepping operation are functionally depicted in Figure 2-4. The large solid arrow indicates rotor position at the start of the step pulse and the dotted arrow, 15 degrees away, indicates the position upon completion of the pulse. Stator pole polarities shown are those impressed upon the motor during the control pulse.

The stepping motor translates through a precise angular increment in response to a digital electrical format signal. A series of pulses will cause the motor to move through an equal number of uniform incremental steps at the same rate as that of the command signal. 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.

The following table is an example of 10 consecutive steps coded in such a manner as to cause the drum to move five 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 to "OFF" state.

2.2.2 Characteristics of the Permanent Magnet Stepping Motor

The stepper motor responds only to a pulse of sufficient current to cause rotor displacement. In the time between pulses and when a static position is commanded, no power is required to hold position. Thus the total power consumption over the 10-hour operating life of the engine is relatively small. While the motor is functioning, the power consumption is essentially independent of the load and directly proportional to the pulse rate commanded.

EXAMPLE: STEPPING MOTOR LOGIC SEQUENCING

Assume an initial drum position of 90.0 degrees and a 150:1 transmission ratio.

<u>Step Number</u>	<u>Code</u>				<u>Angular Change</u> <u>Degree</u>	<u>Drum</u> <u>Position</u> <u>Degree</u>
	A	B	$\bar{A}$	$\bar{B}$		
Initial Position	1	0	0	1	0	90.0
1	1	1	0	0	<u>+ 0.1</u>	90.1
2	0	1	1	0	<u>+ 0.1</u>	90.2
3	0	0	1	1	<u>+ 0.1</u>	90.3
4	1	0	0	1	<u>+ 0.1</u>	90.4
5	1	1	0	0	<u>+ 0.1</u>	90.5
6	1	0	0	1	- 0.1	90.4
7	0	0	1	1	- 0.1	90.3
8	0	1	1	0	- 0.1	90.2
9	1	1	0	0	- 0.1	90.1
10	1	0	0	1	- 0.1	90.0

The torque developed is a function of running speed. Only a portion of the torque developed in a single step is dissipated in the load. The remainder is dissipated in oscillations, damped by the magnetic detent torque of the permanent magnet rotor.

The total power consumption can be reduced by programming only sufficient current to perform a step, and to monitor the motor for compliance with the step command. Upon failure to step, the current would be increased to full value permitting completion of the step with significant current margin.

2.2.3 Previous Application

Reliability considerations, incremental motion, non-accumulative positional error and the open loop control ability of the stepping motor have been the primary reasons for the increasing application of the stepping motor to spacecraft and nuclear reactor control. (Appendix A-7.6.)

Figure 2-4. Functional Diagram of Stepping Motor
(Sheet 1 of 2)

CODE
AB $\bar{A}$ $\bar{B}$
0011

STEP 3

CODE
AB $\bar{A}$ $\bar{B}$
1001

STEP 4

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Figure 2-4. Functional Diagram of Stepping Motor
(Sheet 2 of 2)

SIGMA 19-2519-D24

28 VDC

64 WATTS INPUT

15° STEP ANGLE

20 Ω /PHASE

1.5 LBS WEIGHT

2.5" DIA. x 2.0"

Figure 2-5. PM Rotor Stepping Motor Characteristics

The development of solid-state switching circuits, an outgrowth of computer software technology over the past decade, has resulted in widespread use of the stepping motor. In applications similar to that of NERVA, the motor has been used in a number of spacecraft and nuclear reactors.

In space probes and satellites, the stepper has been used in positioning devices such as solar panel arrays, and antenna and camera-positioning systems. The Surveyor series of lunar probes used the stepping motor for solar panel orientation, and the critical television camera orientation and optics control systems. Among planetary probes, the Mariner Mars vehicle used stepping motor actuators to orient the solar pressure vanes and solar energy collector panels.

A number of nuclear reactors have considered or used stepping motors for control drum rotation, beginning with the Pratt and Whitney lithium-cooled reactor (Appendix A-7.13) of the early 1960's through the SNAP-8 developmental reactor. (Appendixes A-7.9; A-7.10.) LASL has utilized the stepping motor for control drum drive of the Phoebus-2 ZEPO critical assembly and the PEWEE I reactor. (Appendixes A-7.12; A-7.14.)

In an application very much like NERVA, the SNAP-10A reactor used three permanent magnet stepping motors for control drum drive. (Appendix A-7.11.) This reactor was launched and operated successfully in the space environment, under hard radiation and at high temperature. (Appendixes A-7.7; A-7.8.) The manufacturer, Atomics International, while satisfied with the SNAP-10A actuator performance, will use a variable reluctance stepping motor in later SNAP reactors instead of the permanent magnet stepping motor. (Appendix A-7.20.) This change is being made because of the higher temperatures to be encountered in later reactors. The NERVA will operate at very low temperatures.

2.2.4 Effect Upon Remainder of System

The selection of the type of motor to be used in the NERVA control drum actuator system effectively establishes the requirements and limitations for the remainder of the actuator system. The speed-torque characteristics, control mode, and mechanical configuration, among other motor parameters, directly affect the selection and design of the other

major components in the actuator system. The effect upon the major components by the selection of the permanent magnet stepping motor is considered in the following paragraphs.

2.2.4.1 Transmission

A number of transmissions are adaptable to development and incorporation into the NERVA control drum actuator. In this section, a number of the more suitable types are described and the restrictions and limitations imposed by selection of the permanent magnet stepping motor noted.

The selection of the permanent magnet stepping motor of Paragraph 2.2.2 requires a transmission ratio of 150:1 and input speed of 250 rpm.

2.2.4.1.1 Conventional Gearhead. The conventional multistage gearhead, simple and easily fabricated, has found wide applications. (Appendix A-7.11.) The simplest multistage gearhead would be one using spur gears. The ratio of 150:1 will require a three-pass system involving six bearings as depicted in Figure 2-6. This results in a relatively complex and large configuration transmission.

2.2.4.1.2 Epicyclic Transmissions. A compound planetary gear arrangement can be used with the permanent magnet stepping motor concept. The planetary gear offers an advantage over the multistage gearhead in that the input pinion and the output shaft do not have a radial loading. The major disadvantage of the planetary system is that the planet gears are loaded radially and have a series failure path so that one failed planet can freeze the transmissions.

A modified form of the compound planetary gear, the epicyclic gear shown in the concept of Figure 2-7, can be used with advantages in the number of bearings required, complexity, size and load-carrying capability. The epicyclic transmission has no sun gear and only one planet for each pass (total of two), driven by an eccentric input. Overall, this transmission has fewer moving parts and lower pitch line velocities than the planetary transmission. The eccentric input shaft has the disadvantage of a high radial load on the motor bearings. However, this load can be tolerated because of the low output speed of the stepping motor. (Appendix A-7.24.)

Figure 2-6. Permanent Magnet Stepping Motor Conventional Gear Train Concept

Figure 2-7. Permanent Magnet Stepping Motor Epicyclic Transmission Concept

2.2.4.1.3 Worm Gear Transmission. A single-pass worm gear transmission is a possibility for use with the stepping motor, and offers the advantage of a few bearings. It is not feasible from the configuration and efficiency standpoint, because it results in an actuator larger and more awkward than any of the other actuator transmission concepts. The use of sliding contact surfaces in the mesh for power transmission entails a severe lubrication problem and compromises reliability. Figure 2-8 depicts the one-pass worm gear transmission with a ratio of 120:1, the minimum ratio which satisfies system requirements, chosen to establish the most conservative envelope possible.

2.2.4.1.4 Harmonic Drive. The harmonic drive transmission, Figure 2-9, is adaptable to the stepping motor concept and offers the advantage of few moving parts, light weight, and a compact envelope. The transmission would be of one-pass with a ratio of 150:1. Because of the large number of spline teeth in mesh at any position, high gear accuracy and low backlash are obtained. The thin flexing spline, however, is susceptible to wear and fatigue and presents a difficult lubrication problem. The wave generator is also a complex mechanism incorporating flexible bearing races. The induced environmental requirements, the low temperature and pressure requirements in particular, will necessitate an extensive and comprehensive development program. A major concern is the high starting torque of the directly driven harmonic drive. This torque value is high in conventional oil-lubricated units, however, in the NERVA environment with dry film lubricants, it may be unacceptable. (Appendixes A-7.21; A-7.23.)

2.2.4.1.5 Wobble Gear Transmission. The Wobble gear transmission, Figure 2-10, is suitable for the stepping motor concept in a single-pass with a ratio of 120:1, the minimum ratio that will satisfy the system requirements. The design of this transmission is based upon the use of a pair of specially cut Wobble gears. Action of the bearing carrier and tilted bearing produces a non-rotating conical nutating (wobble) motion of the driving gear at the end of the bellows. This motion causes rotation of the output gear and shaft by sequential engagement of a limited number of gear teeth.

Figure 2-8. Permanent Magnet Stepping Motor Worm Gear Transmission Concept

Figure 2-9. Permanent Magnet Stepping Motor Harmonic Drive Transmission Concept (AMOD)

Figure 2-10. Permanent Magnet Stepping Motor, Wobble Gear Transmission Concept

2.2.4.1.6 Comparison of Transmissions. The comparison matrix technique, Table 2-2 is based upon the comparison of the transmissions considered for use with the permanent magnet stepping motor on a one-parameter-at-a-time basis. For each parameter considered a ranking is assigned each transmission indicating its superiority or inferiority with respect to the other five transmissions. The best transmission is assigned a 1, the second best a 2, and so on to 5 for the poorest transmission, regardless of the degree of superiority of one over the other.

In the completed matrix, the total of the rankings for the five transmissions indicate their relative merit. The transmission with the lowest total is the superior transmission.

2.2.4.3 Additional Components

The inherent magnetic detent torque characteristic and the open loop control technique of the permanent magnet stepping motor actuator facilitate fulfillment of the NERVA requirements without the use of a tachometer, brake, motor shaft monitoring device, or critical need of an output shaft potentiometer.

2.2.4.4 Cooling

Heat dissipated in the motor stator will be removed by conduction through intimate contact with the actuator housing. Negligible electrical energy is dissipated as heat in the rotor of the actuator. Some heat will be generated in this component by gamma heating and will be removed by convection cooling. Coolant gas will be present during engine power operation when the gamma heating rate will be significant. The cooling of this actuator is analyzed further in Appendix A-3, Thermal Analysis.

2.2.4.5 Stepping Motor Actuator Control System

The stepping motor actuator control system, shown in Figure 2-11, is a digital positioning actuator control system. (Appendix A-7.12.) The digital logic format of the engine controller position command signal is directly utilized by the actuator controller. The stepping motor, operating through a 150:1 ratio transmission, requires 1400 pulses to traverse the full 175 degrees of rotary drum motion. Eleven bits are required to contain up to 1400 discrete binary numbers.

TABLE 2-2

TRANSMISSION COMPARISON MATRIX - PM STEPPING MOTOR CONCEPT

Parameter	Rating	Conventional	Rating	Epicyclic	Rating	Worm	Rating	Harmonic	Rating	Wabble
1. Number of Meshes	5	Three.	3	Two.	3	Two.	3	Two	1	One.
2. Mesh Nature	1.5	Rolling Contact. Negligible Sliding.	3	Primarily Rolling. Some Sliding.	5	Pure Sliding Contact.	1.5	Rolling Contact. Negligible Sliding.	4	Rolling Contact. Moderate Sliding.
3. Tooth Loading	5	Severe.	2.5	Moderate.	2.5	Moderate.	2.5	Moderate.	2.5	Moderate.
4. Tooth Pitch	1.5	Coarse.	3	Moderate.	1.5	Coarse.	4.5	Fine.	4.5	Fine.
5. Number of Bearings	5	Six.	3	Two.	4	Three.	1.5	One.	1.5	One.
6. Nature of Bearing Loading	1.5	All Radial.	1.5	All Radial.	5	Severe. Compound.	3	Primarily Radial. Negligible Axial.	4	Compound.
7. Compatibility with Solid Lubricants	1.5	Good.	1.5	Good.	3.5	Fair.	5	Poor.	3.5	Fair.
8. Efficiency	2	Approx. 94%.	3	Approx. 92%.	5	Approx. 80%.	1	Approx. 95%.	4	Approx. 90%.
9. Contamination Susceptibility	4.5	High.	2	Negligible.	2	Negligible.	4.5	High.	2	Negligible.
10. Envelope	4	Moderately Large.	1.5	Small	5	Large.	1.5	Small.	3	Moderate.
11. Weight	3.5	Moderately Heavy.	2	Moderate.	5	Heavy.	1	Light.	3.5	Moderately Heavy.
12. Number of Components	4.5	Six.	2.5	Five.	4.5	Six.	1	Three	2.5	Five.
13. Fabrication Difficulty	3	Moderate.	5	Severe.	1	Simple.	3	Moderate.	3	Moderate.
14. Ease of Assembly	1	Simple.	2.5	Moderately Easy.	2.5	Moderately Easy	4.5	Difficult	4.5	Difficult.
15. Reliability	4.5	Poor.	1	Good.	4.5	Poor	2.5	Fair.	2.5	Fair.
16. Thermal Adequacy	4.5	Poor.	4.5	Poor.	3	Fair.	1.5	Good.	1.5	Good.
17. Structural Adequacy	4	Poor.	1	Good.	4	Poor.	2	Fair.	4	Poor.
18. Quality Assurance Adequacy	3	Fair.	1.5	Good.	1.5	Good.	4.5	Poor.	4.5	Poor.
TOTAL	59.5		44.0		62.5		48.0		56.0

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Figure 2-11. Stepping Motor Actuator Controller

The difference detector is an 11 bit parallel binary subtractor which detects a final carry to determine the sign of the difference. The sign of the difference is used to gate the step motor logic to drive the motor either clockwise or counterclockwise.

The step motor has a two-phase bifilar wound stator and a permanent magnet rotor. The bifilar windings give the motor four discrete phases (A, B, $\bar{A}$, $\bar{B}$). For greatest efficiency and maximum information utilization, two phases are energized at any time. To perform a step, one phase is reversed by energizing its opposite bifilar winding (1100 to 0110) while the other phase remains constant.

By one of a number of techniques, such as detection of the rise time of a newly energized phase or detection of the induced signal in an unenergized coil of a bifilar winding, an indication of rotor motion can be obtained. If the rotor moves one step in response to its command, the step is detected and the up-down counter records the step as being performed.

The output of the up-down counter is then compared with the command input to determine if another step need be performed. The system continues to step the motor until the step motor and its counter have reached the command input. An additional input can also be fed into the counter which, operating from the position potentiometer, is used to align an out-of-place actuator with the average drum bank registry.

2.2.4.6 A Power Reducing Stepping Motor Controller

The system shown in Figure 2-12 is used to reduce the power required for stepping motors. In usual practice, a stepping motor is operated by connecting the stepper logic output flip-flops directly to power amplifiers and thence to the motor windings. When the stepping motor is not stepping (standing still), two of its phases are drawing current and the motor is delivering no useful work.

To reduce this wasted power, a logic system is introduced between the stepper logic flip-flops and the power drivers. In the quiescent state, flip-flop 3 (FF_3) is in the same states as FF_1 , and FF_4 is the same as FF_2 . The outputs of $AND_{5,6,7,8}$ are all 0 preventing the outputs of FF_1 and FF_2 from turning on the power drivers. When a step is commanded by

Figure 2-12. Power Reducing Stepping Motor Control

a change in state of FF_1 or FF_2 the states of FF_4 and FF_3 are not changed due to a lack of a clock pulse. One of the outputs of $AND_{1,2,3}$ or 4 will be a 1 which, going through OR1, will open gates $AND_{5,6,7}$ and 8 allowing the paths between FF_1 and FF_2 and PA 1, 2, 3 and 4 to be completed. The respective phases of the step motor will be energized enabling the motor to step.

The output of OR1 is delayed in time and then fed into the clock input of FF_3 and FF_4 which causes them to attain the state of FF_1 and FF_2 . When FF_3 and FF_4 are equal to FF_1 and FF_2 , gates $AND_{5,6,7}$ and 8 are shut off and power to the motor is again turned off.

The delay time must be adjusted so that the motor is able to settle down to its new step position because once de-energized the motor relies upon its magnetic detent torque to hold it in place.

2.2.4.7 Power

The permanent magnet stepping motor consumes power only during dynamic operation. The power conserving section of the controller removes the excitation from the stator windings between steps. Power consumption at the velocity limit will be approximately 42 watts.

As stated in Section 2.2.2, it may be possible to reduce power consumption by careful programming of the step command current level and monitoring of the motor response.

2.3 ALTERNATE 3 - BRUSHLESS DC MOTOR

2.3.1 In the early 1960's, NASA initiated an effort to develop a motor for use in space which would overcome the barrier of brush life in a vacuum environment. (Appendix A-5.23.) Secondary problems to be overcome in the new concept were brush friction, arcing, electromagnetic interference and brush wear contaminant generation.

Attempts to develop a reliable brushless DC motor were undertaken as early as 30 years ago. All of these early attempts fell victim to the shortcomings of vacuum-tube technology and relay switching techniques. The development of semi-conductors and solid state switching technology have made the brushless DC motor feasible.

Two basic methods of brushless armature commutation have been developed under NASA sponsorship; optical commutation and reluctance switch commutation. Both of these motors are of the stationary armature rotating field (permanent magnet rotor) configuration and approximate brush commutated permanent magnet DC motor-operating characteristics.

The brushless DC motor offers a solution to the problems inherent in the brush commutated motor and, for that reason, is considered here as an alternative to the application of the brush commutated series DC motor to the NERVA control drum actuator system.

Some desirable traits, such as very high starting torque, are given up in the compromise for the better reliability that accompanies application of the brushless DC motor in place of the brush commutated DC motor.

2.3.2 Optical Commutation

Goddard Space Flight Center, in conjunction with Sperry Rand, has developed the optically commutated DC motor. (Appendix A-7.16.) The motor has been built in two principal configurations and both of these have been used in spacecraft applications. An instrument type motor was used in a bearing and wear tester device, aboard a satellite, (Appendix A-7.15) and a torquer has been used to drive a reaction wheel attitude control system. (Appendix A-7.17.)

The photo-optical commutator consists of a tungsten filament lamp, around which rotates a cylindrical sleeve with a slit producing a directional beam. Arranged radially around the rotating sleeve are six photodiodes which conduct electrical current when illuminated. Power transistors apply the source voltage to the appropriate winding terminations when the related photodiode is illuminated. This tends to keep the imposed field perpendicular to that of the permanent magnet rotor field and produces near maximum torque at all times.

The commutation electronics are composed of two sections. The rotor position sensing section, Figure 2-13, is composed of the six photodiodes and must be located in an intimate relationship with the rotor shaft. The commutating section of the electronics consists of switching transistors, capacitors, resistors, etc., (Figure 2-14), and can be packaged as a unit and located at a remote position away from the severe environment of the NSS.

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Figure 2-13. Optical Commutation - Functional Diagram

613233-12B

Figure 2-14. Commutation Functional Schematic Optically Commutated DC Motor

2.3.2.1 Optical Commutation Characteristics

The operating characteristics of an optically commutated DC motor sized for the NERVA CDA application are depicted in Figure 2-15. Controller configuration would be similar to that presented for the series DC motor. The brake component of the actuator would be eliminated and the magnetic detent torque of the motor used to hold position upon loss of electrical power.

The limiting factor in this concept is the inability of the photodiodes to survive the radiation environment of the actuator. Photodiodes are damaged at approximately 1×10^{13} n/cm² fast and 1×10^{11} rads gamma. However, these devices are subject to severe noise generation and false triggering effects at much lower levels of radiation. This arises from the inability of the photosensitive element to distinguish between gamma, neutron and photon radiation. An extensive development effort must be carried out to qualify a tungsten filament light source for the NERVA environment.

2.3.3 Reluctance Switch Commutation

Goddard Space Flight Center has sponsored the development of a brushless DC motor by Westinghouse using reluctance switching techniques for commutation. (Appendix A-7.18.) Two motors were built in a torquer configuration which, due to their relatively slow speed, could be coupled through one pass of one harmonic drive and applied to the NERVA CDA requirement.

This motor uses a permanent magnet rotor for field excitation and a slotted stator with a conventional three-phase induction motor winding for the armature field. The current in the armature is switched by a solid state three-phase bridge switching network. Switching logic and rotor position sensing for the commutation process is accomplished by a reluctance switch. Drive power for the reluctance switch is obtained from an oscillator which is powered from a constant 28 volt DC source. A second reluctance switch is provided for reverse rotation.

The reluctance switch commutation requires a second rotor, of soft iron, rigidly attached to the main shaft. The rotor teeth provide a flux path for the generation of a

28 VDC
 SEPERATE MOTOR
 AND ELECTRONICS
 MOTOR 3.0" DIA. x 4.5"
 ELECTRONICS 2.5" x 3.5" x 1.8"
 4.0 LBS TOTAL WEIGHT

Figure 2-15. Optically-Commutated DC Motor Characteristics

voltage in the stationary secondary winding aligned with the teeth. The voltage output of the reluctance switch is sensed by a triggering circuit which is amplitude sensitive and controls the power switching transistors supplying current to the armature winding.

2.3.3.1 Reluctance Switch Commutation Characteristics

The operating characteristics of a reluctance switch commutated DC motor, Figure 2-16, sized for the NERVA CDA application are depicted in Figure 2-17. Controller configuration would be similar to that presented for the series DC motor. The brake component of the actuator would be eliminated and the magnetic detent torque of the motor used to hold position upon loss of electrical power.

The characteristics of low efficiency and relatively larger size weigh against the concept.

A parameter of concern in this configuration motor is the ripple torque due to switching angle variations. Because of manufacturing variations, there are differences in the output voltages of the reluctance switch sensing windings. There are four firing periods for each switch in one revolution. Thus, the output voltage is subject to variation because the particular sensing winding voltage is influenced by four different positions of the rotor with consequent variation in the magnetic circuit.

The effect of the variation in switching angle is to increase ripple and to lower average torque. This occurs because the PM field is farther than 15 electrical degrees away from its maximum torque position, in relation to the armature field, when the related switching period begins or ends.

2.3.4 Brushless DC Motor Candidate Selected

Of the various brushless DC motor concepts which have been developed under NASA sponsorship, including the two presented in this trade study, the optically commutated system appears to be the most promising for space application. The Goddard Space Flight Center has developed this concept to the point where it has been applied successfully to the space program. This concept cannot be applied unconditionally to the NERVA requirement because

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Figure 2-16. Reluctance Switch Commutated Brushless DC Motor

30 VDC
 SEPARATE MOTOR
 AND ELECTRONICS
 MOTOR 3.5" DIA. x 4.0" LG.
 MOTOR WEIGHT 3.4 LBS
 ELECTRONICS 4.2" x 4.3" x 2.2"
 ELECTRONICS WEIGHT 1.4 LBS

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Figure 2-17. Reluctance Switch Commutated DC Motor Characteristics

of the vulnerability of the photodiode components to radiation. The optically commutated brushless DC motor is included in the comparison matrix (Section 3) with the knowledge that use of this design would require an extensive development program to solve the radiation problem, or incorporation of a massive shield with the present concept.

3.0 COMPARISON OF SYSTEM DESIGN APPROACHES

In this section, the different principles of the design approaches in three areas are contrasted.

3.1 FUNCTIONAL CHARACTERISTICS

The system components in each design approach have been optimized for the NERVA application. Each concept fully meets the functional requirements of the application. However, the basic difference in operating principle between the DC motor and PM motor results in significant differences in the functional characteristics of the designs.

3.1.1 Torque

PM - The rotor of the PM motor is driven through an incremental angle by changes in electromagnetic field location resulting from the switching of energized stator poles. The dynamic torque generated during this step is not constant; as the rotor is displaced through the incremental angle the torque of the unit approaches a sine wave peaking midway between static positions. There is no dynamic torque when the rotor is in alignment with the stator field. Upon reaching the alignment position, the kinetic energy of the rotor is dissipated by rotor reaction with the energized magnetic field, eddy currents and hysteresis loss, resulting in a quickly damped oscillating motion.

The time required for the motor to take one step and come to a complete stop is very short in the NERVA application, making it practical, even at the velocity limit, to de-energize the motor coils between steps and conserve power. The power reducing step-ping motor control of Paragraph 2.2.4.5 and Figure 2-12, accomplishes this function.

Because the PM motor requires only a pulse of sufficient magnitude to develop enough flux to move the rotor, its functioning is independent of small variations in pulse magnitude and duration, and voltage regulators, ripple voltage, noise, etc.

DC - The DC motor develops only enough torque to meet the requirements of the load. In the NERVA CDA application the motor, a high speed device, will transmit power through a high reduction ratio transmission, which reflects a negligible load of only

0.5 oz-in. to the motor. The loading on the motor will result primarily from the transmission and motor internal losses that are expected to total approximately 5 oz-in. under normal conditions.

The transmission and internal motor bearings will be dry film lubricated and when combined with the temperature, radiation and dry coolant gas conditions, may be subject to a wide variation in transmission, internal bearings and brush frictions. For this reason, the motor is sized to have a significant stall torque reserve as well as to operate near peak efficiency under the normal load.

The DC motor will not rotate until the internal friction losses have been overcome. These losses, estimated to be approximately 2.5 oz-in., require 2 watts of power, and the control system permits the motor to sit at a fixed position and dissipate up to this amount of power without producing motion under normal conditions.

Incorporation of a clutch brake for the purpose of holding position upon loss of actuator electrical power, can also be used to hold position without power dissipation during static position commands.

3.1.2 Accuracy

PM - The accuracy of the PM motor actuator is established by the manufacturing tolerances of the mechanical components of the motor. The linearity of the system is independent of drum position through the rotational range of the drum, but it depends upon the relative precision of the stepping increments in a full revolution of the motor. Accuracy in motor position is approximately ± 5 percent. Assuming no loss of accuracy in the transmission, this will result in an accuracy of $\pm 0.03^\circ$, non-accumulative.

DC - The accuracy of the DC motor actuator is strictly dependent upon potentiometer linearity and will vary over the range of drum rotation. Accuracy in such a closed loop is affected by variations in potentiometer power supplies and degradation of controller components. Accuracy will be approximately 0.5 degrees.

3.1.3 Resolution

PM - The resolution of the PM motor actuator is established by the mechanical design of the motor and is essentially the step angle. The step angle of 15° reflected through the transmission results in a drum angle resolution of 0.125° , which is inherently fixed throughout the range of travel of the drum.

DC - The resolution of the DEC motor actuator is dependent upon both the characteristics of the potentiometer and the motor control circuitry which, operating through a 3600:1 transmission, must be capable of stopping within two revolutions to meet the system requirements.

3.1.4 Holding Torque

PM - The magnetic detent torque, inherent to the PM stepping motor, is used to provide the torque necessary to hold the drum in position under the conditions of a static position command, loss of electrical power in a system malfunction, and maintenance of the zero position during inactive engine periods. The strength of this parameter can be varied by designing the stator laminations from near zero to a high percentage of the rated output torque of the motor. This value is anticipated to be optimized at 20 to 30 percent of rated output torque.

This magnetic detent torque is dependent only upon the magnetic properties of the PM rotor and takes effect immediately upon the rotor attaining an alignment position.

DC - Brush and bearing friction supply approximately 3 oz-in. of holding torque on the motor shaft, and when reflected through the transmission, produce more than enough holding torque at the drum. However, the friction level of the brushes and to some extent of the bearings is a variable and can conceivably change to near zero. Mechanisms which rely entirely upon friction to hold position are generally discouraged and are not in keeping with good design practice.

A positive holding force is required and is supplied by the clutch brake mechanism. The brake is disengaged when energized and failure of electrical power will permit an internal spring to drive the brake into engagement. During operation of the actuator, the brake must

be energized to permit the motor to move. This will require approximately 15 watts that must be dissipated continuously while the actuator is in dynamic operation.

3.1.5 Controller

PM - The digital open loop nature of this controller combined with the relatively lenient control requirements of the PM motor results in an easily stabilized system.

The only malfunction mode of concern with the stepper motor is the resonance condition which occurs when too high a stepping rate is impressed upon the motor for the output torque demanded. This phenomenon, which does not allow the motor to move, occurs at a rate well above that required to drive the actuator at the velocity limit.

DC - The analog DC motor actuator controller will be essentially of the configuration developed for the XE actuator. The potentiometer is a very critical component in this closed loop system, as is the tachometer. The control loop is therefore susceptible to power supply variations and feedback component degradation as well as the influence of radio frequency interference (RFI).

3.2 PHYSICAL CHARACTERISTICS

3.2.1 Envelope

PM - Actuator = $7\frac{1}{4}$ inches x $4\frac{3}{4}$ inches diameter

DC - Actuator = $11\frac{1}{2}$ inches x $5\frac{1}{4}$ inches diameter

The difference in envelope configuration relative to that of the PM actuator is due to inclusion of brake and tachometer components and the longer but narrower configuration of the motor itself. Enclosing the commutation mechanism with the motor case requires a 65 percent increase in the DC motor case length.

3.2.2 Power

PM - Motor power dissipation is 42 watts when operating at the velocity limit. This may be reduced by a current programming technique.

DC - Motor power dissipation is 37 watts when operating at the velocity limit at

rated torque. The brake must be energized during motor operation at the cost of 15 watts. Total dissipation is 52 watts.

3.2.3 Weight

ITEM		LBS
PM -	Actuator	= 6.3 Total
	Motor	= 1.5
	Housing	= 1.5
	Pot. Assy.	= 0.8
	AMOD Trig.	= 1.0
	Transmission	= 1.5
DC -	Actuator	= 10.1 Total
	Motor	= 1.3
	Housing	= 2.0
	AMOD Trig.	= 1.0
	Pot Assy.	= 0.8
	Transmission	= 3.3
	Tachometer	= 0.7
	Brake	= 1.1

3.2.4 Cooling

The startup operation requires that after engine cooldown, the actuator will be energized and drive the drum to the 110° position without coolant gas available. Thus, convection cooling of the actuator will be ineffective.

PM - Stator winding heat is dissipated by conduction through the motor housing to engine dome. The rotor does not generate heat and does not require cooling during this mode of operation. Once engine propellant flow is initiated, the actuator is cooled by convection.

DC - Stator winding heat is dissipated by conduction through the motor housing to engine ground. Significant heat is generated in the rotor winding during startup and must be absorbed by the heat sink inherent to the conductors and motor shaft. The capacity of this inherent heat sink is limited and, therefore, the length of operating time without coolant flow must be controlled.

3.2.5 Bearings

Angular contact bearings have been selected for use throughout the actuator because of their clear-cut superiority in satisfying the requirements of the application. The severe environment requires that the bearings be lightly loaded, exhibit low friction in starting at full load, be suited for intermittent duty, and designed for minimum sliding friction.

The most significant effect of the selection of either the DC motor or stepping motor upon the actuator bearings is the great difference in speed of the bearings, particularly in the motor and first pass of the transmission, inherent in this selection. The bearing load capacity, friction torque, and lubricant wear life all degrade with increasing speed as indicated in Figure 3-1. As shown in Figure 3-1.1 load capacity is improved significantly if the speed is held to less than approximately 1000 rpm. The bearings of the PM stepping motor, operating at less than 250 rpm, have a load capacity of up to four times that of the same bearings in the DC motor, and thus can be designed with a greater safety margin than those of the DC motor.

Friction torque decreases, Figure 3-1.2 from a high value at start to a minimum at less than 1000 rpm. The stepping motor bearings will operate at near the minimum friction torque point at the actuator velocity limits. The DC motor bearings will pass through this point and operate with a higher friction torque when the actuator is moving at the velocity limit.

The environmental conditions of the NERVA application dictate that solid lubricants be used in the actuator bearings. Generally, the wear life of solid lubricants is shorter than the service life of hydrodynamic lubricants. Solid lubricants will not dissipate heat generated within the bearing and so require the convection cooling

afforded by the H_2 coolant flow. Although coefficients of friction of solid lubricants are low, they are still many times higher than those in hydrodynamic lubrication. Figure 3-1.3 depicts the relationship between speed and the wear life of MoS_2 , a prime candidate for the NERVA actuator. (Appendix A-7.6) The effectiveness of a solid lubricant, as a separating film between rolling and sliding contacting surfaces, is inversely proportional to the bearing speed and will, therefore, be more effective in the low speed PM stepping motor actuator than it would be in the high speed DC motor.

With all parameters considered, it is evident that the reliability of the bearings is dependent upon actuator motor speed. The high speed DC motor bearings will be less reliable than the low speed PM stepping motor bearings.

3.2.6 Commutation

PM - Commutation is performed without regard to rotor position. The field established by the 24 fixed armature poles is switched and the rotor with its fixed PM field assumes a new position in alignment with the new armature field position, rotating through 15 degrees as it does so.

Speed must be limited to allow the rotor sufficient time to reach the next position and settle out. If the speed should exceed this limit, approximately 250 pulses per second, the motor will go into unidirectional operation. The pulse rate must be reduced to below 250 pulses per second to regain bi-directional operation. This characteristic, a drawback to most stepper applications, is off set in the NERVA application by the velocity limit requirement. In meeting the velocity limit requirement, the pulse rate is limited to 100 pulses per second by the controller pulse generator, which is well below that of the transition pulse rate.

DC - Optimization of performance requires the use of compensation and interpole windings in the stator. This adds to the complexity of the stator structure.

The most severe shortcoming of the self-commutated motor is the brush problem. Because of the very low pressure the motor will be required to operate in, possibly as low as 10^{-3} torr, the radiation environment, temperature environment and dry hydrogen

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Figure 3-1. Effect of Speed on Bearings

environment at full engine power, a special brush material will have to be developed. No qualified material is presently available. The best brushes available, NbSe_2 , sacrifice wear rate for structural integrity. These brushes and similar materials produce a wear product in the form of an electrically conductive dust which must be kept from contaminating the feedback potentiometer. (Appendix A-7.2; A-7.3)

The mechanism of the commutation assembly involves a flexible conductor and spring; both are subject to the high frequency vibration setup by the brushes crossing the commutator bars.

Wear is accelerated by the erosive effect of commutator arcing. Arcing also presents the problem of facilitating developmental testing. A significant amount of system testing time will be spent with hydrogen coolant flow at LN_2 temperatures. Under these conditions, as evidenced in XE testing, liquid oxygen is condensed from the atmosphere and presents a real fire hazard. The addition of an arc producing test item accentuates this hazard.

3.2.7 Additional Components

PM - The permanent magnet stepper requires no components in addition to those used to produce motive force. The only material unique to this concept is the permanent magnet material of the rotor.

Because of the open loop nature of the control loop, the feedback potentiometer is not required. It is retained for the purpose of monitoring shaft position as a part of the diagnostic and safety monitoring system.

DC - The DC motor requires a velocity control loop and a tachometer. A signal taken from the position feedback potentiometer at the output shaft is not reliable due to transmission compliance, backlash, response and resolution requirements.

To meet the requirement for a positive position holding device, the brake is used. This is essentially a low powered solenoid device with the reliability problems inherent in solenoid designs.

3.3 ENVIRONMENTAL CHARACTERISTICS

Performance of the actuator concepts in the NERVA environment is difficult to determine without detailed design and extensive development testing of prototype components and subsystems.

The concepts being considered differ significantly in materials and configuration, particularly in the areas of rotor construction and commutation. This section of the trade study is essentially a resolution of the problem areas and general nature of the problems anticipated in each concept.

3.3.1 Radiation Effects

PM - Stator construction will require radiation qualified insulation and encapsulant. Polyimides appear to be the most likely candidates. Rotor material will be Alnico V or possibly samarium-cobalt. Alnico was used in the SNAP 10A actuator and sustained negligible degradation due to the total gamma dose. Samarium-cobalt, a recent development, offers better performance characteristics but its susceptibility to radiation has not as yet been established.

DC - The rotor is a of a wound multiple coil configuration. Both insulation and encapsulant are required. The insulation will probably be a polyimide. However, requirements to function under the dynamic forces of the rotor are expected to limit the selection of an encapsulant and require developmental testing.

Most of the specialized brush materials in use will survive a hard radiation environment with negligible degradation in performance. However, the material to be used for the NERVA application must meet the severe requirements of the low pressure and dry hydrogen environments. A material will have to be qualified to meet first, these requirements, and then, the radiation requirement. Until such a material is found, the effects of radiation upon the brushes is unknown.

Common Areas - Stator configuration and wiring requirements are similar for both the PM and DC actuators. Both an insulation and encapsulation material must be selected. Polyimides are the most likely candidates.

The potentiometer is the component expected to be most vulnerable to radiation, based upon XE experience. (Appendix A-7.24) Construction of the potentiometer encompasses most of the materials and techniques used elsewhere in the actuator as well as several which are peculiar to the potentiometer. The "plastic-film" nature of the track will have to be qualified for the radiation levels of the 10-hour engine as well as the internal electrical connection techniques of the potentiometer construction. While the potentiometer is common to both the permanent magnet stepping motor and DC motor actuator concepts, it is a critical element of the closed loop control system of the DC motor actuator, and of only secondary importance in the open loop permanent magnet stepping motor actuator.

3.3.2 Temperature Effects

PM - The difference in material of rotor and stator will result in a change of air gap length in making the transition from 530°R (Earth room temperature) to the minimum operating temperature of 40°R. Dimensional changes will be controlled and allowed for in the design of the actuator. Because all of the operating life in the engine will be over a relatively short cryogenic range, the design will be optimized for operation in that temperature range.

DC - Air gap length change will be negligible in this actuator due to the similarity of construction and materials in the stator and rotor. Dimensional changes in the commutation mechanism, tachometer and brake will be controlled and compensated for in the design of the actuator.

Common Areas - Insulation and encapsulant materials must retain their integrity and functional characteristics throughout the full temperature range. This will have to be established by developmental testing.

Transmission dimensional change problems are common to all transmissions considered with both actuator concepts. The problem is more severe in the DC concept however, simply because there is a more complex structure involved in obtaining a higher reduction ratio. Tolerance control will be the primary method of compensating for this problem in all transmission configurations.

Transmission effects upon the potentiometer construction are a problem once again, and as in radiation effects, more important in the closed loop DC actuator than in the open loop PM actuator.

3.3.3 Low Pressure Effects

PM - The long coast period and initial operation in the low pressure environment, 10^{-3} torr, will not significantly affect actuator performance. Some concessions will have to be made in the performance of bearings, transmission efficiency, insulation quality, etc., to qualify components to meet the outgassing and lubricant limitation requirements of the application.

DC - Lubrication of the brushes in the low pressure and dry hydrogen high pressure environments is a serious problem. A material will have to be qualified to meet these conditions as well as the radiation, temperature and vibration environments. Initial studies indicate that a very high wear rate will have to be tolerated, producing a conductive dust product which, in turn, will have to be filtered and trapped within the upper housing actuator, or diverted from the potentiometer by selected cooling techniques.

3.3.4 Vibration Effects

PM - Due primarily to the rugged uniform construction of the rotor and relatively slow speed characteristics of the motor, vibration will have a negligible effect upon this concept. The potentiometer is expected to be the component most vulnerable to vibration but is not of critical importance to the operation of the actuator system.

DC - The complex nature of the rotor requires that particular attention be paid to the integration of encapsulant, wiring, commutator bars and fastenings into a rugged package capable of withstanding the shock and vibration requirements. To develop a suitable rotor configuration, some compromises in size, weight and thermal efficiency will have to be made.

3.4 COMPARISON MATRIX

The comparison matrix technique (see Tables 3-1 through 3-7) used to establish the best control drum actuator design concept is based upon the evaluation of the candidate concepts against the requirements of the specification in six areas: Reliability, Safety, Actuator System, Performance, Envelope, and Development considerations.

The major requirement is making this trade study has been system reliability, and therefore, it effects a proportionally greater influence in determining the best design concept, than do the remaining requirements. The relative importance attached to the matrix areas of consideration are reflected in the weighting values incorporated in making the concept selection. The following weighting values are given the requirement areas:

<u>Requirement</u>	<u>Weighting Value</u>
Reliability	30
Safety	20
Actuator System	15
Performance	15
Development	10
Envelope	10

Within each of the requirement areas, a number of parameters are evaluated to establish the relative merits of the candidate concepts to satisfy the system requirements.

A vertical weighting, or assessment of importance, is apportioned among the parameters of each requirement area. This value, called the parameter rating, establishes the degree of importance of each parameter in effecting compliance with the requirement. For example, in the requirement area of safety, the parameter of "velocity control technique" has a rating of 25 indicating that it has an estimated effect 1.7 times greater than that of the parameter of "fail in place technique", with a rating of 15, on the safety of the actuator system.

A horizontal weighting is apportioned among the three concepts for each of the 31 parameters considered in the comparison matrix. This value, called the emphasis factor, represents the relative merit of each of the concepts with respect to the particular parameter being considered. For example, in comparing the parameter of "velocity control technique", in the requirement area of safety, the PM stepping motor concept is estimated to be better than the DC motor concept by a ratio of 0.50 to 0.25. Moreover, it is estimated to be better than the brushless DC motor concept by a ratio of 0.50 to 0.25, while the DC motor concept is estimated to be equal to the brushless DC motor by a ratio of 0.25 to 0.25. In developing the Figure of Merit for each concept in a particular requirement area, parameter final values are generated for each concept by taking the product of the parameter rating and the emphasis factor for each parameter considered. All of the parameter final values for a concept within the particular requirement area are averaged, and the result is considered to be the Figure of Merit of the concept for that requirement area.

The sum of the six requirement area Figures of Merit establishes the overall Figure of Merit for a particular concept and determine the selected concept.

RELIABILITY CONSIDERATIONS PARAMETER: WEIGHTING FACTOR = 30			Emphasis Factor	Parameter Final Value	Emphasis Factor	Parameter Final Value	Emphasis Factor	Parameter Final Value
			<u>D. C. MOTOR</u>		<u>P. M. STEPPING MOTOR</u>		<u>BRUSHLESS D.C. MOTOR</u>	
1. <u>Reliability Figure of Merit:</u> Rating = 30								
Assessment of the probability of malfunction occurring in the manner described by the failure mode analysis and the severity of effect upon the NSS. The analysis is made of the differences among motor concepts.	0.10	3.0	0.018		0.65	19.5	0.943	0.25 7.5 0.039
FIGURE OF MERIT FOR RELIABILITY		3.0				19.5		7.5
(AVERAGE OF PARAMETER FINAL VALUES)								

TABLE 3-2

SAFETY CONSIDERATIONS PARAMETER:
WEIGHTING VALUE = 20

1. Holding Torque: Rating = 20
Torque resisting change of drum position with no power applied to the actuator.
2. Velocity Control Technique: Rating = 25
Method employed to limit the velocity of the actuator to the specification limit.
3. Fail In Place Technique: Rating = 15
Method employed to retain drum position upon loss of electrical power.

FIGURE OF MERIT FOR SAFETY

(AVERAGE OF PARAMETER FINAL VALUES)

Emphasis Factor	Parameter Final Value		Emphasis Factor	Parameter Final Value		Emphasis Factor	Parameter Final Value	
		<u>D. C. MOTOR</u>			<u>P. M. STEPPING MOTOR</u>			<u>BRUSHLESS D. C. MOTOR</u>
0.45	9.0	~3600 in.-lbs. available. Brake engaged.	0.30	6.0	~ 250 in.-lbs. available.	0.25	5.0	~ 200 in.-lbs. available
0.25	6.25	Potentiometer feedback signal differentiated for velocity. Controller error amplifier signal clamped to limit magnitude of motor control signal.	0.50	12.5	Rate of pulse generation limited by controller logic.	0.25	6.25	Potentiometer feedback signal differentiated for velocity. Controller error amplifier signal clamped to limit magnitude of motor control signal.
0.40	6.0	Hold-off solenoid in brake is deenergized permitting brake pad to engage rotor shaft.	0.30	4.5	Magnetic detent torque maintains rotor in preferred position.	0.30	4.5	Magnetic detent torque maintains rotor in preferred position.
	7.1			7.66			5.24	

TABLE 3-3 (Sheet 1 of 4)

ACTUATOR SYSTEM CONSIDERATIONS PARAMETER WEIGHTING VALUE - 15			D. C. MOTOR			P.M. STEPPING MOTOR			BRUSHLESS D. C. MOTOR		
	Emphasis Factor	Parameter Final Value		Emphasis Factor	Parameter Final Value		Emphasis Factor	Parameter Final Value		Emphasis Factor	Parameter Final Value
1. <u>Control Technique</u> Rating - 15 Type, and complexity, of control utilized to drive the motor/transmission pair output shaft to the angular position commanded by the EPIC.	0.30	4.5	Closed loop on output shaft position. Controller converts EPIC digital command to analog signal for use in summing point logic for generation of error control signal. Potentiometer is critical item. Position signal converted to digital for EPIC.	0.45	6.75	Open loop digital control. Controller retains position information. Analog position signal converted to digital for use of EPIC.	0.25	3.75	Closed loop on output shaft position. Controller converts EPIC digital command to analog signal for use in summing point logic for generation of error control signal. Potentiometer is critical item. Position signal converted to digital for EPIC.		
2. <u>Commutation Technique</u> Rating - 25 Method of switching power among the motor armature coils to establish the rotating electromagnetic field.	0.20	5.0	Switching by sliding brush and bar contact. Lubrication of brush surface is critical and difficult. Arcing, vibration, and electrical noise generation problems must be contended with. Switching logic established solely by mechanical layout.	0.50	12.5	Switching of stator poles by controller logic without regard to rotor position. Direction of rotation and rate of rotation established directly by EPIC command signal.	0.30	7.5	Position of rotor monitored by optical means and stator poles switched by controller logic in manner similar to that of the stepping motor.		
3. <u>Drum Position Signal</u> Rating - 30 Transducer technique employed for actuator output shaft position indication. Affect of transducer malfunction upon the system is related to the part taken by the transducer in the overall control system.	0.20	6.0	By film type potentiometer - critical in closed loop control system employed.	0.60	18.0	By film type potentiometer - signal utilized for EPIC monitoring only, and is not critical to the control loop.	0.20	6.0	By film type potentiometer - critical in closed loop control system employed.		

TABLE 3-3 (Sheet 2 of 4)

TABLE 3-3 (Sheet 2 of 4)												
ACTUATOR SYSTEM CONSIDERATIONS PARAMETER:	Emphasis Factor		Parameter Final Value	D. C. MOTOR	Emphasis Factor		Parameter Final Value	P. M. STEPPING MOTOR	Emphasis Factor		Parameter Final Value	BRUSHLESS D. C. MOTOR
6. <u>Cooling Requirements:</u> Rating = 10 Nature of the cooling requirements to hold hot-spot temperatures down and minimize temperature gradients within the actuator affects complexity of the mechanical design and performance under "off-design" conditions such as lack of coolant gas medium or extended high current operation.	0.20	2.0		Heat dissipated in rotor places operating time limit on motor for engine startup functions. No convection cooling available for startup. Heat in rotor due to gamma heating must be dissipated by convection cooling.	0.40	4.0		Heat in rotor due to gamma heating must be dissipated by convection cooling. Negligible heat generated in rotor due to electrical power dissipation.	0.40	4.0		Heat in rotor due to gamma heating must be dissipated by convection cooling. Negligible heat generated in rotor due to electrical power dissipation.
7. <u>Contamination Generation:</u> Rating = 15 Wear products such as gear tooth particles, bearing particles, lubricant, brush dust, outgassing products, etc., affect operation of other system components.	0.15	2.25		Brush wear produces conductive dust. Transmission wear produces contaminant (aggravated by high speed). Brake produces contaminant.	0.50	7.5		Transmission wear produces contaminant. Bearings produce contaminant.	0.35	5.25		Transmission wear produces contaminant. Bearings produce contaminant (aggravated by high speed).
8. <u>Contamination Susceptibility:</u> Rating=20 Component reliability is reducing by deposition of electrically conductive and insulating films on electrically active surfaces and large discrete particle deposition between sliding and rolling mechanical element surfaces. Vulnerability to such contamination affects a system's performance.	0.25	5.0		Potentiometer vulnerable to brush wear particles in coolant flow. Commutator bars/slip rings, motor bearings and transmission bearings vulnerable to gear tooth wear products. Relatively more vulnerable to stalling due to contaminant jamming of rotor.	0.55	11.0		Motor bearings and transmission bearings vulnerable to gear tooth wear products.	0.20	4.0		Motor bearings and transmission bearings vulnerable to gear tooth wear products. Commutating operation and photo-sensitive devices are vulnerable to blanking by contaminants. Vulnerable to jamming of rotor by contaminant.
9. <u>Temperature Susceptibility:</u> Rating = 10 Dimensional change as a function of temperature in dissimilar elements and temperature gradients across similar elements effects changes in load values, wear rates, performance, etc. The degree of change with temperature and the criticality of the considered area directly affect system performance.	0.25	2.5		Rotor and commutation configurations affected by temperature gradients must be compensated for in design/development.	0.45	4.5		Motor air gap dimension affected by temperature gradient.	0.30	3.0		Complex configuration of commutation system as well as motor air gap across dissimilar materials is affected by temperature gradient and must be compensated for in design/development.

TABLE 3-3 (Sheet 3 of 4)

TABLE 3-3 (Sheet 3 of 4)													
ACTUATOR SYSTEM CONSIDERATIONS PARAMETER			Emphasis Factor	Parameter Final Value	D. C. MOTOR	Emphasis Factor	Parameter Final Value	P. M. STEPPING MOTOR	Emphasis Factor	Parameter Final Value	BRUSHLESS D. C. MOTOR		
10.	Low Pressure Susceptability	Rating - 20 The minimum pressure level established for coast periods (10^{-3} torr) severely limits the types and quality of lubricant which can be utilized in the actuator and requires evaluation of component outgassing effect susceptibility.	0.10	2.0	Lubricant critical in high speed operation of motor and transmission. Rotor insulation and encapsulant subject to outgassing effects. Brushes wear rapidly. Potentiometer slip rings wear rapidly.	0.55	11.0	Lubricant relatively less critical in low speed operation of motor and transmission. Potentiometer slip rings wear rapidly.	0.35	7.0	Lubricant critical in very high speed operation of motor and transmission. Potentiometer slip rings wear rapidly. Optics of commutation system subject to degradation by blanking with outgassing products.		
11.	Radiation Susceptability	Rating - 20 The degradation of material characteristics due to radiation effects directly affects performance.	0.30	6.0	Rotor insulation and encapsulant, brushes and potentiometer materials susceptible to radiation to a degree not yet established.	0.55	11.0	Potentiometer materials susceptible to radiation to a degree not yet established.	0.15	3.0	Potentiometer materials susceptible to radiation to a degree not yet established. Photodiodes are marginal in radiation environment and require extensive development effort.		
12.	Radio Frequency Interference Susceptability	Rating - 5 Principal area of concern is the transmission of the position feedback signal to the actuator controller. Noise impressed upon this signal may result in system stability problems.	0.30	1.5	Vulnerable potentiometer signal is critical in control loop.	0.50	2.5	Potentiometer is not a critical component.	0.20	1.0	Vulnerable potentiometer signal is critical in control loop. Photodiode signal to controller is susceptible to noise.		
13.	Quality Assurance Analysis	Rating - 10 Difficulty of component inspection for material quality and conformance of fabrication to specification.	0.25	2.5	Inspection of assembled unit is complex. High degree of material quality and inspection concern.	0.40	4.0	Fewer material quality and inspection concerns.	0.35	3.5	Inspection of assembled unit is complex. High degree of material quality and inspection concern.		

TABLE 3-3 (Sheet 4 of 4)

ACTUATOR SYSTEM CONSIDERATIONS PARAMETER	D. C. MOTOR			P. M. STEPPING MOTOR			BRUSHLESS D. C. MOTOR		
	Emphasis Factor	Parameter Final Value		Emphasis Factor	Parameter Final Value		Emphasis Factor	Parameter Final Value	
14. <u>Controller Complexity</u> : Rating = 10 Analysis of effect of complexity of electronics. Character of components, compatibility with engine controller.	0.30	3.0	Analog requiring conversion of EPIC command signal. Utilizes motor speed control loop, velocity control loop, and position control loop.	0.50	5.0	Digital	0.20	2.0	Analog requiring conversion of EPIC command signal. Utilizes motor speed control loop, velocity control loop, and position control loop. Additional section required for commutation logic.
15. <u>Radio Frequency Interference Generation</u> : Rating = 5	0.20	1.0	Commutation arching is a strong source of RFI. Must shield the potentiometer and housing wiring from the influence.	0.40	2.0	Negligible	0.40	2.0	Negligible
FIGURE OF MERIT FOR ACTUATOR SYSTEM CONSIDERATIONS (AVERAGE OF PARAMETER FINAL VALUE)		3.33			7.67			4.00	

TABLE 3-4

PERFORMANCE CONSIDERATIONS PARAMETER: WEIGHTING VALUE = 15	Emphasis Factor	Parameter Final Value	D. C. MOTOR	Emphasis Factor	Parameter Final Value	P.M. STEPPING MOTOR	Emphasis Factor	Parameter Final Value	BRUSHLESS D. C. MOTOR
1. <u>Maximum Torque at Stall</u> : Rating = 15 Torque available to overcome a high load condition on start of shaft rotation.	0.40	6.0	Theoretical output 3000 in-lbs. Current limited to produce 500 in-lbs because of transmission limitations.	0.25	3.75	420 in-lbs. Inherently operates within transmission limitations.	0.35	5.25	Theoretical output 1000 in-lbs. Current limited to produce 500 in-lbs.
2. <u>Torque at Velocity Limit</u> : Rating = 20 Output torque available to move load at the velocity limit.	0.45	9.0	As required to move load will vary from 16 to 24 in-lbs in normal mode.	0.20	4.00	270 in-lbs fixed. Limited to 100 in-lbs in normal mode by current limiting.	0.35	7.00	As required to move load will vary from 16 to 24.
3. <u>Power Consumption</u> : Rating = 10 Estimated value at velocity limit of 10 degrees per second.	0.35	3.5	37 watts dissipated in motor. 15 watts dissipated in brake. 52 watts total.	0.40	4.00	42 watts.	0.25	2.50	65 watts.
4. <u>Accuracy</u> : Rating = 20 Correspondence between the static output shaft actual position and the command signal.	0.25	5.0	+ 0.5 degree.	0.45	9.00	+ 0.03 degree.	0.30	6.00	+ 0.3 degree.
5. <u>Resolution</u> : Rating = 20 Smallest increment of output change that can be achieved by varying the input.	0.25	5.0	0.5 degree.	0.45	9.00	0.1 degree.	0.30	6.00	0.3 degree
6. <u>Reversing Technique</u> : Rating = 5	0.30	1.5	Separate field winding energized by electronic switching.	0.35	1.75	Sequence of armature commutation altered by controller logic.	0.35	1.75	Sequence of armature commutation altered by controller logic.
FIGURE OF MERIT FOR PERFORMANCE (AVERAGE OF PARAMETER FINAL VALUES)		5.0			5.25			4.75	

TABLE 3-5

DEVELOPMENT CONSIDERATIONS PARAMETER:
WEIGHTING VALUE = 10

	Emphasis Factor	Parameter Final Value	D. C. MOTOR	Emphasis Factor	Parameter Final Value	P. M. STEPPING MOTOR	Emphasis Factor	Parameter Final Value	BRUSHLESS D. C. MOTOR
1. <u>Fabrication Difficulty</u> : Rating = 15 Difficulty of manufacturing components; degree of effort involved in materials development; etc.	0.20	3.0	Tachometer and brake alignment requirements severe. Rotor construction exacting. Extensive brush development effort.	0.65	9.75	Permanent magnet material must be qualified for environment. Rotor must be magnetized after assembly.	0.15	2.25	Permanent magnet material must be qualified for environment. Rotor must be magnetized after assembly. Extensive effort to develop photodiodes qualified for environment. Commutation element alignment critical.
2. <u>Tolerance Requirements</u> : Rating = 10 Criticality of tolerance control.	0.35	3.5	Rotor/stator tolerances critical. Transmission requirements severe.	0.40	4.0	Air gap tolerance critical. Transmission requirements relatively less severe.	0.25	2.5	Air gap tolerance critical. Transmission requirements severe. Optical component manufacturing and assembly tolerances critical.
3. <u>Ease of Assembly</u> : Rating = 5 Degree of complexity and difficulty in integrating components into complete actuator package.	0.30	1.5	Additional effort in assembly of commutation mechanism. Brake and tachometer assembly. Potentiometer alignment exacting. Rotor assembly exacting.	0.45	2.25	Rotor assembly exacting. Rotor must be magnetized after assembly.	0.25	1.25	Rotor assembly exacting. Rotor must be magnetized after assembly. Commutation mechanism assembly critical.
4. <u>Ease of Maintenance</u> : Rating = 5 Degree of inspection and repair for second and extended use.	0.30	1.5	Brushes and commutator bars must be serviced/replaced between missions, etc. Brake pad, insulation and encapsulant inspected visually. Insulation resistance measured.	0.40	2.0	Performance monitored for degradation/failure prediction. Insulation and encapsulant inspected visually. Insulation resistance measured.	0.30	1.5	Performance monitored for degradation/failure prediction. Insulation and encapsulant inspected visually. Insulation resistance measured.
5. <u>Structural Adequacy</u> : Rating = 15	0.30	4.5	High loads and stresses due to high motor speed.	0.50	7.5	Relatively lower loads and stresses.	0.20	2.0	Higher loads and stresses due to very high motor speed.
FIGURE OF MERIT FOR DEVELOPMENT (AVERAGE OF PARAMETER FINAL VALUES)		2.8			5.1			2.1	

TABLE 3-6

ENVELOPE CONSIDERATIONS PARAMETER:
WEIGHTING VALUE = 10

	Emphasis Factor	Parameter Final Value	D. C. MOTOR	Emphasis Factor	Parameter Final Value	P.M. STEPPING MOTOR	Emphasis Factor	Parameter Final Value	BRUSHLESS D. C. MOTOR
1. <u>Size</u> : Rating = 10 Approximate dimensions of best cylindrical envelope enclosing the actuator.	0.25	2.5	11.5 in. x 5.2 in. dia.	0.55	5.5	7.2 in. x 4.7 in. dia.	0.20	2.0	10.5 in. x 5.5 in. dia.
2. <u>Weight</u> : Rating = 20 Approximate actuator weight. Composite analysis of each major component.	0.25	5.0	10.1 lbs.	0.60	12.0	6.3 lbs.	0.15	3.0	13.0 lbs.
3. <u>Wiring Complexity</u> : Rating = 5 Nature of wiring such as shielding requirements, number of conductors, fastening points, connector size, etc.	0.35	1.75	12-wire cable system, 8 of which must be shielded. 2 flexible conductors in brush configuration.	0.45	2.25	12-wire cable system, 6 of which must be shielded.	0.20	1.0	25-wire cable system, 20 of which must be shielded.
4. <u>Number of Components</u> : Rating = 5 Major components considered.	0.20	1.0	11-motor; commutation mechanism; transmission; shaft; potentiometer; main bearings; housing; AMOD trigger; tachometer; brake; connector.	0.45	2.25	8-motor; transmission; shaft; potentiometer; main bearings; housing; AMOD trigger; connector.	0.35	1.75	9-motor; commutation mechanism; transmission; shaft; potentiometer; main bearings; housing; AMOD trigger; connector.
FIGURE OF MERIT FOR ENVELOPE (AVERAGE OF PARAMETER FINAL VALUES)		2.56			5.51			1.93	

TABLE 3-7
COMPARISON MATRIX SUMMARY

Requirement Area	Average Weighting Factor	Figure of Merit		
		DC Motor	PM Stepper	Brushless DC
Reliability	30	3.00	19.50	7.50
Safety	20	7.10	7.66	5.24
Actuator System	15	3.33	7.67	4.00
Performance	15	5.00	5.25	4.75
Development	10	2.80	5.10	2.10
Envelope	10	2.56	5.51	1.93
Overall Figure of Merit	100	23.79	50.69	25.52
		SELECTED CONCEPT		

4.0 ACTUATOR MALFUNCTION OVERRIDE DEVICE (AMOD)

The concept of an actuator malfunction override device grew out of a need to assure that, in the event of an actuator system malfunction, no drum was more than a certain number of degrees away from the "bank". More specifically, no more than a certain number of degrees away from the angle for which the reactor core was orificed. Structural analysis performed on the reactor indicates that an NSS failure will result if one drum is permitted to run full in to the 0° position. The study to evaluate methods of implementing this AMOD device resulted from Technical Direction 69-43, paragraph 2.c, which reads:

"Drum Actuator concepts should be pursued with the objective of ensuring, if at all possible, that credible failures will result in the affected drum or drums being restored to the position for which the core has been orificed (approximately 90 degrees). Stored energy concepts and other approaches should be explored."

For a stored energy concept employing a spring, it is desirable to provide the maximum torque at the end of the AMOD stroke (at the orifice angle) for a given amount of total energy stored in the spring. The development of this maximum is as follows.

- where θ = preload deflection of the spring
 α = working angle (from initial preload to final orifice angle)
 M = initial torque at preload angle
 m = final torque at orifice angle

The energy, W , stored in the spring is

$$W = \frac{M\theta}{2}$$

and by similar triangles

$$m = \frac{(0 - \alpha) M}{\theta} = M - \frac{M\alpha}{\theta} = \frac{2W}{\theta} - \frac{2W\alpha}{\theta^2}$$

maximizing the torque to rotate the drum at the end of spring travel (orifice angle)

$$\frac{dm}{d\theta} = 4\alpha W\theta^{-3} - 2W\theta^{-2} = 0$$

and

$$0 = 2\alpha$$

$$m = \frac{M}{2}$$

therefore, the spring should be designed so that total travel is 1/2 preload travel and final torque is 1/2 preload torque.

4.1 REQUIREMENTS

In the event of an actuator system malfunction, the affected drum or drums should be restored to the position for which the core has been orificed ± 2.5 degrees.

4.1.1 Desirable Design Goals

The following list of design goals has been established as a basis for proceeding with the trade study:

- 1) All of the stored energy should be expended in restoring the affected drum and none in driving the malfunctioned actuator.
- 2) The concept should perform the required function with minimal increase in weight and volume of needed equipment.
- 3) The electrical trigger signal should be hard wired and not require the use of commutating devices.

4) The actuator system maintainability access volume should not increase significantly.

5) The additional equipment should enhance the actuator system reliability and not detract.

4.2 DISCUSSION OF DESIGN APPROACHES

4.2.1 Helical Torsion Spring Concept

A conceptual design of an actuator malfunction override device employing a torsion spring wound longitudinally around the actuator mechanism is shown in Figure 4-1. In this concept, the stored energy is provided by the torsion spring. The figure depicts an actuator consisting of a motor, transmission, potentiometer and output shaft. The output shaft contains a rotating index which moves with the output shaft from about 0° to 180° drum position. The AMOD, in this concept, consists of the torsion spring, the rotating index, the stationary index and the latch and trigger mechanism. The stationary index is located and defines the angle between 0° and 180° for which the core is orificed. In the event of a malfunction of the actuator, the latch and trigger mechanism is energized. This releases the energy stored in the torsion spring causing both ends of the spring to rotate toward the stationary index. One of the bar pickups attached to the ends of the spring contracts the rotating index and moves it until the stationary index is encountered. This only happens if the available torque in the spring exceeds the restraining torque of the malfunction.

By referring to the equations used to calculate a helical torsion spring with rectangular wire*, an approximate equation of the volume of spring material needed to store a desired amount of energy, W , can be obtained.

$$W = \frac{M\theta}{2}$$

$$M = \frac{b t^2}{6 K_c}$$

* - Machinery Handbook, Erik Oberg and F. D. Jones, Eighteenth Edition, 1968, Industrial Press, Inc., New York, New York 10016.

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Figure 4-1. A-MOD Alternate - Torsion Concept

$$\theta = \frac{2 N D}{E t K_c}$$

where

- b = greater of the cross-sectional dimension of rectangular wire, in.
- t = smaller of the cross-sectional dimension of rectangular wire, in.
- σ = tensile or compressive stress, psi
- L = active length of strip, in.
- E = modulus of elasticity, psi
- K_c = Wahl factors for helical springs
- N = number of active coils
- D = mean coil diameter, in.

and

$$W = \frac{\pi D N b t \sigma^2}{6 K_c^2 E} \quad \text{where } \pi D N b t \approx V$$

V = volume of spring material

and

$$W \approx \frac{V \sigma^2}{6 K_c^2 E} \quad \text{from reference 5.1 } 1.04 \leq K_c \leq 1.29$$

therefore

$$K_c^2 \approx 1.0$$

$$W \approx \frac{V \sigma^2}{6 E}$$

For stainless steel

$$\sigma = 11.5 \times 10^{-3} \text{ psi} = 85\% \text{ of yield strength}^*$$

$$E = 28 \times 10^6 \text{ psi}$$

$$\frac{\sigma^2}{E} = 473$$

And finally for the helical torsion spring

$$W \approx 79 V$$

From Section 5.0 for maximum torque at end of stroke

$$W = 2 m \alpha$$

$$\text{therefore } V \approx \frac{2 m \alpha}{79}$$

Assuming 100 in.-lbs to drive the drum and 300 in.-lbs to overcome an actuator full out command and an $\alpha = \pi \text{ rad} \left(-\frac{\pi}{2} \text{ rad for each end of the spring} \right)$

$$V \approx \frac{(2) (400) (\pi)}{79} = 31.8 \text{ in.}^3$$

By adding this volume of spring material longitudinally around the components of the actuator mechanism, the diameter of the actuator housing will increase approximately 1 inch and the weight of the addition housing will be approximately 1 pound. Total increase in weight for both spring and housing is approximately 10 pounds. In summary, the general comments that apply to this concept are as follows:

- 1) Relatively large size and weight.
- 2) Actuator housing enlarged to enclose considerable volume of spring material.

* - Materials Property Data Book, Vol. II, p. 325, AISI 301 SS.

- 3) Actuator very difficult if not impossible to decouple.
- 4) Spring device must overcome any actuator malfunction loading.
- 5) Use of stored energy is inefficient because motion through unoccupied quadrant at either side of orifice angle is wasted.

4.2.2 Spiral Clock Spring Concept

A conceptual design of an actuator malfunction override device employing a spiral clock spring wound radially around the actuator mechanism is shown in Figure 4-2. In this concept, the stored energy is provided by the spiral clock spring. The operation of this device is identical to the concept described in Section 4.2.1. However, the configuration is different and its effect on system size and weight will be examined. By referring to the equations used to calculate a spiral clock spring with rectangular wire, an approximate equation of the volume of spring material needed to store a desired amount of energy, W , can be obtained.

$$W = \frac{M\theta}{2}$$

$$M = \frac{b t^3 \sigma}{6}$$

$$\theta = \frac{2 L \sigma}{E t}$$

and

$$W = \frac{b t L \sigma^2}{6 E} \quad b t L \approx V$$

and

$$W = \frac{V \sigma^2}{6 E} \quad \text{for stainless steel} \quad \frac{\sigma^2}{E} = 473$$

and

$$W \approx 79 V$$

Figure 4-2. A-MOD Alternate - "Clock" Spring Concept

As in Section 4.2.1, the volume of spring material required to drive the drum and overcome a malfunctioned actuator is 31.8 in.³

By adding this volume of spring material radially around the actuator components and assuming a 1 inch wide spring, a flat pancake of spring material results in an added weight because of an increase in housing weight of approximately 2.4 pounds. Total increase in weight for both spring and additional housing is approximately 11.4 pounds.

In summary, the general comments that apply to this concept are as follows:

- 1) Use of stored energy is inefficient because motion through unoccupied quadrant at either side of orifice angle is wasted.
- 2) Actuator very difficult, if not impossible, to decouple.
- 3) Relative size is large and added weight make it largest of concepts.
- 4) Pancake spring arrangement makes actuator housing larger and more difficult to machine.
- 5) Spring device must overcome any actuator malfunction loading.

4.2.3 Drive Shaft Spring Concept

This conceptual design of an actuator malfunction device employs a helical compression spring inside the hollow drive shaft that connects the actuator to the control drum. In this concept, the stored energy is provided by the helical compression spring.

By referring to the equations used to calculate a helical compression spring with rectangular wire, an approximate equation for the volume of spring material needed to store a desired amount of energy, W , can be obtained.

$$W = \frac{P \delta}{2}$$

$$P = \frac{b t^2 \tau}{K_d D}$$

$$\delta = \frac{N D^2 \tau}{K_d K_E G t}$$

P = load, pounds
 δ = linear deflection, inches
 τ = shear stress, pounds per in²
 K_d, K_E = shape factor for helical springs wound with rectangular wire
 G = modulus of rigidity, pounds per in²

$$W = \frac{b \, t \, D \, N \, \tau^2}{2 \, K_d^2 \, K_E \, G} \quad \text{where } \pi b \, t \, D \, N \approx \text{volume of spring material}$$

and

$$W = \frac{V \, \tau^2}{2 \, \pi \, K_d^2 \, K_E \, G}$$

$$2.41 \geq K_d \geq 1.60, \text{ nom.} = 2.1$$

$$.180 \leq K_E \leq .399, \text{ nom.} = .27$$

$$K_d^2 \, K_E \approx 1.2 \text{ nominal}$$

For stainless steel

$$\tau = 57.5 \times 10^3 \text{ psi (42.5\% of tensile yield)}$$

$$G = 10.6 \times 10^6 \text{ psi}$$

and finally for a helical compression spring

$$W \approx 41 \, V$$

from Section 4.0 for maximum torque at end of stroke

$$W = 2 \, m \, \alpha$$

therefore

$$V \approx \frac{2 \, m \, \alpha}{41}$$

Assuming 100 in.-lbs. to drive the drum at the end of the spring stroke (orifice angle), no torque to overcome an actuator malfunction since the actuator will be decoupled, and an $\alpha = \pi/2 + \text{unused travel required to decouple}$ we have

$$V \approx \frac{(2) (100) \left(\frac{\pi}{2} + \frac{\pi}{6} \right)}{41}$$

$$V \approx 10.5 \text{ in}^3 \text{ of spring material}$$

4.2.3.1 Helical Spring in Drive Shaft with a Fusible Trigger Mechanism in Drive Shaft

A conceptual design of an actuator malfunction override drive employing the helical spring discussed in Section 4.2.3 with a fusible trigger mechanism is shown in Figure 4-3. In this concept, the stored energy is supplied by the helical spring in the center of the drive shaft. The AMOD in this concept consists of the helical compression spring, the drive shaft, the ram, the dual helical cam, the cam follower and the fusible wire trigger assembly. The actuator and AMOD are connected at the actuator pedestal interface by the skip tooth crown spline. The AMOD and drum are connected by a like spline at the opposite end. Normal operating torque is from the actuator through the AMOD to the drum. The helical compression spring is held in compression by the fusible trigger wire. In the event of a malfunction of the actuator, an electrical voltage is applied to the fusible trigger causing it to melt. This releases the energy stored in the helical spring. The ram is pushed upward by the force of the spring causing the external spline teeth of the AMOD to disengage from the internal spline of the actuator mechanism. Then the cam follower enters the dual helical cam. As it is forced upward toward the peak of the helical cam, the drive shaft and drum are rotated from their initial position until the cam follower comes to rest at the peak of the helical cam located at the orifice angle.

By using this method, no additional housing volume is required. However, the helical cam adds additional weight of approximately 0.7 lb, the ram about 0.4 lb for a total weight including spring of 4.0 lbs. In summary, the general comments that apply to this concept are as follows:

- 1) Requires commutation of trigger signal to rotating drive shaft.
- 2) Access volume significantly increased because drive shaft must be removed for maintenance or reset.
- 3) Fusible trigger requires very large burn-out current (about 500 amps).
- 4) Decouples malfunctioned actuator, and maximum stored energy is applied to drum in either direction.
- 5) Requires no increase in actuator size. Required additional weight is low.

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Figure 4-3. A-MOD Alternate - Fusible Trigger Concept

4.2.3.2 Helical Compression Spring in Drive Shaft with an Electromagnetic Trigger in Actuator

A conceptual design of an actuator malfunction override device employing the helical compression spring discussed in Section 4.2.3 with an electromagnetic trigger mechanism located in the actuator is shown in Figure 4-4.1. In this concept the stored energy is supplied by the helical compression spring in the center of the drive shaft. The AMOD in this concept consists of the helical compression spring, drive shaft, the ram, the dual helical cam, the cam follower and the electromagnetic trigger and latch assembly. Normal operation and torque transmission is as described in Section 4.2.3.1.

The helical spring is held in compression by the latch mechanism consisting of the latch ring, latch spring and three sets of latch balls. The trigger mechanism in the actuator consists of a cylindrical permanent magnet, a release coil, a trigger spring, magnetic circuit and the trigger hammer. In the event of a malfunction of the actuator, an electrical voltage is applied to the release coil. The trigger hammer is normally held in place against the trigger spring by the flux in the magnetic circuit resulting from the cylindrical permanent magnet. The electrical signal reverses the flux in the magnetic circuit allowing the trigger spring to force the trigger hammer out of the magnet circuit and causes it to strike the latch ring. The force of the trigger spring is greater than the latch spring; therefore, the latch ring is pushed down allowing the latch balls to roll out of the latching groove, releasing the stored energy in the helical compression spring. The ram is pushed upward by the force of the spring causing the external spline teeth of the AMOD to disengage from the internal spline teeth of the actuator mechanism. Then the cam follower enters the dual helical cam. As it is forced upward toward the peak of the helical cam, the drive shaft and drum are rotated from their initial position until cam follower comes to rest at the peak of the helical cam which is located at the orifice angle. Figure 4-4.2 shows the release mechanism just starting to release and Figure 4-4.3 shows the action of the AMOD completed.

By using this method, no additional housing volume is required. However, the helical cam adds an additional weight of approximately 0.7 lb and the ram about 0.4 lb, for a total weight including the helical compression spring of 4.0 lbs. In summary, the general comments that apply to this concept are as follows:

Figure 4-4. AMOD - Magnetic Trigger Concept

- 1) Decouples malfunctioned actuator and entire energy is applied to drum in either direction.
- 2) Trigger signal is hard wired to actuator and no commutation is required.
- 3) Requires no additional high pressure actuator enclosure housing.
- 4) Easily reset after malfunctioned actuator is removed.
- 5) No additional access volume needed for maintenance or reset.
- 6) Required additional weight is low.
- 7) Latch mechanism designed with rolling release and no friction.

4.2.4 Pyrotechnic Concept

A conceptual design of an actuator malfunction override device employing a pyrotechnic gas generator is shown in Figure 4-5. In this concept, the stored energy is supplied by the pyrotechnic gas generator. The AMOD in this concept consists of the drive shaft, the ram including piston seals, the dual helical cam, the cam follower, the restraining spring or wire gas cylinder closure and the pyrotechnic gas generator. Normal operation and torque transmission is as described in Section 4.2.3.1.

The ram is held in its normal operating position by the restraining spring or wire. In the event of a malfunction of the actuator, an electrical voltage is applied to the pyrotechnic gas generator. Gas pressure is generated in the volume between the cylinder closure and the ram. Leakage is held at a low value by the piston seals. The pressure breaks the restraining wire or stretches the spring and begins forcing the ram upward. The external spline teeth of the AMOD disengage from the internal spline teeth of the actuator mechanism. Then the cam follower enters the dual helical cam. As it is forced upward toward the peak of the helical cam, the drive shaft and drum are rotated from their initial positions until the cam follower comes to rest at the peak of the helical cam which is located at the orifice angle. At this point the piston rings will fall into a latch groove to hold the ram at the peak of the helical cam.

Figure 4-5. A-MOD Alternate - Pyrotechnic Concept

By using this method, no additional housing volume is required. However, the helical cam adds additional weight of approximately 0.7 lb and the ram and cylinder closure about 0.5 lb for a total additional weight of approximately 1.2 lbs. In summary, the general comments that apply to this concept are as follows:

- 1) Decouples malfunctioned actuator and entire energy is applied to drum in either direction.
- 2) Requires no additional high pressure actuator enclosure housing.
- 3) High energy density for maximum torque at a minimum weight.
- 4) Anticipate burning rate problems as a function of temperature.
- 5) Commutation of firing signal to rotating drive shaft is required.
- 6) The problems of using a pyrotechnic device in a radiation environment reliably may be formidable.
- 7) Access volume significantly increased because drive shaft must be removed for maintenance or reset.
- 8) Possible reactor contamination by leaked combustion products.

4.2.5 Pneumatic Concept

The concept of an actuator malfunction override device employing a pneumatic pressure is similar to the concept shown in Figure 4-5 except that the gas supply is pneumatic instead of pyrotechnic. In this concept, the stored energy is supplied by the main pump pressure or some stored pneumatic device.

The AMOD in this concept consists of the drive shaft, the ram including piston seals, the dual helical cam, the cam follower, the restraining spring or wire, gas cylinder closure, and the pneumatic pressure device. Normal operation and torque transmission is as described in Section 4.2.3.1. Operation is as described in Section 4.2.4, except that the actuating pressure is pneumatically generated instead of pyrotechnically generated.

By using this method, no additional housing volume is required; however, the helical cam adds an additional weight of about 0.7 lb and the ram and cylinder closure about 0.5 lb for a total additional weight of approximately 1.2 lbs.

In summary, the general comments that apply to this concept are as follows:

- 1) Decouples malfunctioned actuator and entire energy is applied to drum in either direction.
- 2) Requires no additional high pressure actuator enclosure housing.
- 3) Relatively high energy density for high torque at low weight.
- 4) Commutation of pneumatic pressure to rotating drive shaft requires rotating pneumatic seals.
- 5) Access volume significantly increased because drive shaft must be removed for maintenance or reset.

4.3 AMOD COMPARISON MATRIX

The technique used in Table 4-1 compares the AMOD concept configurations on a one parameter at a time basis. No attempt has been made to assign a numerical value to individual concept parameter characteristics in establishing a selected concept. Even a cursory qualitative evaluation of the total matrix is sufficient to clearly establish the helical compression spring housed in the drive shaft with a magnetic trigger as the best concept design approach for development.

TABLE 4-1

AMOD COMPARISON MATRIX

Concept Configuration	Helical Torsion Spring	Spiral "Clock" Spring	Helical Compression Spring Housed in Drive Shaft		Pyrotechnic Gas Generator	Pneumatic Ram Actuator
Parameter			With Fuseable Wire Trigger	With Magnetic Trigger		
Torque Assumed to Overcome Failed Actuator (in-lb)	300	300	NA; Actuator Decoupled	NA; Actuator Decoupled	NA; Actuator Decoupled	NA; Actuator Decoupled
Torque Assumed to Move Drum of Failed Actuator (in-lb)	100	100	100	100	100	100
Total Torque to be Supplied by A-MOD	400	400	100	100	100	100
Effective Working Angle	180	180	120° (Normalized to include linear decoupling motion in addition to 90° working angle) →			
Formula for Spring Volume	$V \approx \frac{2 M \alpha}{79}$	$V \approx \frac{2 M \alpha}{79}$	$V \approx \frac{2 M \alpha}{41}$	$V \approx \frac{2 M \alpha}{41}$	N/A	N/A
Approx. Spring Volume (in ³)	31.8	31.8	10.5	10.5	N/A	N/A
Approx. Increase in System Weight	Housing 1.0 Spring 9.0 Trigger 0.2 Total 10.2 X18 = 184 lb	Housing 2.4 Spring 9.0 Trigger 0.2 Total 11.6 X18 = 209 lb	Spring 2.9 Cam 0.7 Ram 0.4 Trigger 0.2 Total 4.2 X18 = 76 lb	Cam 0.7 Ram 0.4 Trigger 0.2 Spring 2.9 Total 4.2 X18 = 76 lb	Cam 0.7 Ram 0.5 Total 1.2 X18 = 22 lb	Cam 0.7 Ram 0.5 Sol. Trigger 0.5 Total 1.7 X18 = 31 lb
Shaft Commutation	None	None	Electrical	None	Electrical	Pneumatic
Trigger Energy	Moderate	Moderate	Very High	Low	Low	Low
Required Increase in Height of Maintainability Access to Reset A-MOD	None	None	Drive Shaft Length (Approximately 3 ft)	2 in.	Drive Shaft Length (Approximately 3 ft)	Drive Shaft Length (Approximately 3 ft)
Maintenance Reset Task Complexity	Moderate (Actuator Removal)	Moderate (Actuator Removal)	Extreme (Drive Shaft Replacement)	Moderate (Actuator Removal)	Extreme (Drive Shaft Replacement)	Extreme (Drive Shaft Replacement)
Reliability Liability	Trigger mechanism must handle relatively high force loading. Malfunctioned actuator not decoupled.		Increase in series resistance of shaft commutator could inhibit ability to melt trigger wire.	Avoids deficiencies of other devices.	Environmental stability of pyrotechnic material.	Performance dependent on turbopump pressure unless supplemented by bottle storage. Required complexity of control solenoid valve and pneumatic commutation compromises reliability.

5.0 SELECTION OF DESIGN APPROACH

The results of the comparison matrix, along with consideration of the reliability analysis, radiation analysis, thermal analysis, structural analysis, and manufacturing analysis, as well as the quality assurance supporting data, clearly establish the permanent magnet stepping motor concept as the superior design.

The control drum actuator system recommended for NERVA application development consists of the following major components:

- 1) Permanent magnet stepping motor:
 - Twelve pole permanent magnet rotor of Alnico V or Samarium cobalt.
 - Twenty-four pole bifilar wound stator of five-wire logic configuration.
- 2) Epicyclic transmission of 150:1 ratio.
- 3) Digital controller using open-loop control technique.
- 4) Film type potentiometer consisting of three independent decks for indication of drum position to the EPIC.
- 5) AMOD system incorporating a compressed spring in the center of the drive shaft and a trigger mechanism in the actuator housing.

APPENDIX A-1

RELIABILITY SUPPORTING DATA DESIGN COMPARISON FOR CONTROL DRUM DRIVE TRADE STUDY NO. 764

A-1 RELIABILITY SUPPORTING DATA

A-1.0 INTRODUCTION

This appendix contains the reliability analysis used to evaluate the various motor and transmission concepts considered in this trade study. Reliability evaluations of the motors are contained in paragraphs A-1.1.1 through A-1.1.3, and evaluations of the transmissions are contained in paragraphs A-1.2.1 through A-1.2.5.

A failure mode analysis was conducted for each motor concept and each transmission concept considered in Section 2.0. Failure mode analysis is the basis for analyzing a design in order to assure a systematic and detailed review of the possible ways that a component can fail to perform its design functions. The assessment of the probability of failure of the various design concepts provides the basis for reliability assessment. The assumptions used for this initial FMA evaluation are:

1. Identifying the most significant failure modes/mechanisms.
2. Include in the reliability comparison those components which reflect a design difference in each concept being compared; e.g. an actuator housing is required for each motor and there is no essential difference required, hence the housing is not included in the reliability comparison.

The inability to meet specified functional requirements is described as the component mode of failure. Each way in which this can occur is described as the mechanism of failure. Estimated relative failure probabilities for the mechanisms were used to complete the analysis. The failure probability index is as follows:

Highly Probable	1×10^{-4}
Moderately Probable	1×10^{-5}
Not Unlikely	1×10^{-6}
Unlikely	1×10^{-7}
Very Unlikely	1×10^{-8}
Extremely Unlikely	1×10^{-9}

The use of the terms highly probable, moderately probable, etc., should be taken in the sense that the concepts in this trade study are mechanical and can be designed with low failure probabilities.

The failure mode worksheets are included as supporting data for this appendix. Two sets of worksheets are shown; one for the various motor design concepts in Table A-1.0-1 and another for the various transmission design concepts in Table A-1.0-2. Each set contains worksheets for the major components within the motors and within the transmissions.

The major effects that a particular failure mode has on the component assembly or other related components are identified, and a severity rating assigned to them in order to classify the effect of the failure on the nuclear subsystem. Ratings are qualitatively determined based on the following definitions:

<u>Rating Category</u>	<u>Severity Definition</u>
A	Catastrophic - Complete loss of NSS capability.
B	Major - Substantial degradation of NSS capability.
C	Minor - Slight degradation of NSS capability.
D	Negligible - No loss of NSS capability.

Having completed the FMA, it is possible to construct a reliability model from which the mechanism failure probabilities can be brought together into an overall component reliability. For the trade study, a relative probability for each concept is derived, since all the parts within the motors and the transmissions are not included in the analyses. The reliability models for each of the three motor concepts are included in Figures A-1.0-1 through A-1.0-3, and for the transmission concepts in Figure A-1.0-4. These models are in block diagram form and consider the failure

modes significant to each design. Each block representing the failure probability of a mode of failure must be modeled or calculated from the estimated failure probabilities of each mechanism identified in the failure mode analysis. Having obtained the failure probability of each block in the model, the overall relative reliability of each concept is calculated by the mathematical equations shown in Figures A-1.0-1 through A-1.0-4.

In addition to the overall relative failure probability for each concept, a relative severity of effect ranking is used as an aid in assessing the severity effects in each design concept under consideration. The technique employed is done by summing failure estimates weighted by the factors of 60% for Severity A, 30% for Severity B and 10% for Severity C and D. This procedure helps to select a design having a lower likelihood of severe effect in the event of failure. The detailed explanation of the method used to develop the reliability figures of merit for the comparison matrix is obtained in a Trade Study Evaluation Procedure (WANL input to NRP 304).

A-1.1 Discussion of Motor Alternates

A-1.1.1 Series DC Motor

The overall relative failure estimate for this design concept is 2621.7×10^{-6} . The modes of failure having the highest probability of occurrence are: (1) the rotor commutator bars failing due to the bars wearing because of arcing, and (2) commutator brushes failing due to the brushes chipping and wearing.

The relative severity ranking for this design concept is 262×10^{-6} . The modes of failure having the most severe effect for the NSS is failure of the tachometer components which results in failure to maintain velocity control of the motor and causes actuator instability, possibly resulting in short high velocity excursions of the control drum and oscillation about the commanded position.

A-1.1.2 Permanent Magnet Stepping Motor

The overall relative failure estimate for this design concept is 52.4×10^{-6} . The modes of failure having the highest probability of occurrence are: (1) the rotor permanent magnets fail due to loss of fastening, chipping or cracking, or loss of magnetic properties, (2) the rotor bearings fail due to contamination or to galling, (3) the stator windings fail due to electrical opening, and (4) the stator insulation fails due to electrical breakdown.

The relative severity ranking for this design concept is 5×10^{-6} . The mode of failure for this design concept have the same effect for the NSS, hence, they are of the same severity.

A-1.1.3 Brushless DC Motor

The overall relative failure estimate for this design concept is 869.4×10^{-6} . The mode of failure having the highest probability of occurrence is: (1) the rotor commutator aperture fails due to contamination filling the aperture.

The relative severity ranking for this design concept is 220×10^{-6} . The modes of failure having the most severe effect for the NSS is: Failure of the rotor commutator aperture which results in an improper rotor position indication signal to be feedback to the actuator controller and imperiling actuator stability, possibly resulting in short high velocity excursions of the control drum and oscillation about the commanded position.

A-1.2 Discussion of Transmission Alternates

A-1.2.1 Harmonic Drive

The overall relative failure estimate for this design concept is 18.18×10^{-6} when used with the Series DC Motor or Brushless DC Motor, and 2.22×10^{-6} when used with the Permanent Magnet Stepping Motor.

The modes of failure having the highest probability of occurrence for this transmission when used with the two DC motors are: (1) the transmission jamming due

to galling of the wave generator bearing, the planetary mesh and the planetary bearings, and due to contamination of the wave generator, the spline mesh, the planetary mesh and the planetary bearings, and (2) structural failure of the flexspline cup.

The modes of failure having the highest probability of occurrence for the transmission when used with the permanent magnet stepping motor are: (1) galling of the wave generator bearing, and (2) structural failure of the flex-spline cup.

The relative severity ranking for this design concept is 1.82×10^{-6} when used with the two DC motors, and 0.22×10^{-6} when used with the permanent magnet stepping motor.

The modes of failure having the most severe effect for the NSS are the same whether the harmonic transmission is used with the two DC motors or the permanent magnet stepping motor. These modes of failure are: (1) jamming of the transmission, and (2) structural failure of the transmission components. In either application the torque output of the motor is not transmitted to the control drums.

A-1.2.2 Spur Gear

The overall relative failure estimate for this design concept is 27.7×10^{-6} when used with the Series DC Motor or Brushless DC Motor, and 2.52×10^{-6} when used with the Permanent Magnet Stepping Motor.

The modes of failure having the highest probability of occurrence for this transmission when used with the two DC motors are: (1) the transmission jamming due to galling of the gear meshes and the bearings, and (2) structural failure of the gear teeth.

The modes of failure having the highest probability occurrence of this transmission when used with the permanent magnet stepping motor are: (1) the transmission jamming due to galling of the gear meshes and the bearings, and jamming due to contamination of the bearings, and (2) structural failure of the gear teeth.

The relative severity ranking for this design concept is 2.77×10^{-6} when used with the two DC motors, and 0.25×10^{-6} when used with the permanent magnet stepping motor.

The modes of failure having the most severe effect for the NSS are the same whether the spur gear transmission is used with the two DC motors or the permanent magnet stepping motor. These modes of failure are: (1) jamming of the transmission, and (2) structural failure of the transmission components. In either application the torque output of the motor is not transmitted to the control drum.

A-1.2.3 Epicyclic Transmission

The overall relative failure estimate for this design concept is 9.0×10^{-6} when used with the Series DC Motor or Brushless DC Motor, and 0.84×10^{-6} when used with the Permanent Magnet Stepping Motor.

The modes of failure having the highest probability of occurrence for the transmission when used with the two DC motors are: (1) the transmission jamming due to galling of the gear meshes and the bearings, and (2) structural failure of the gear teeth.

The modes of failure having the highest probability of occurrence for this transmission when used with the permanent magnet stepping motor are: (1) the transmission jamming due to galling of the gear meshes and the bearings and jamming due to contamination of the bearings, and (2) structural failure of the gear teeth.

The relative severity ranking for this design concept is 0.90×10^{-6} when used with the two DC motors, and 0.08×10^{-6} when used with the permanent magnet stepping motor.

The modes of failure having the most severe effect for the NSS are the same whether the epicyclic transmission is used with the two DC motors or the permanent magnet stepping motor. These modes of failure are: (1) jamming of the transmission, and (2) structural failure of the transmission components. In either application the torque output of the motor is not transmitted to the control drum.

A-1.2.4 Worm Drive

The overall relative failure estimate for this design concept is 30.4×10^{-6} when used with the Series DC Motor or Brushless DC Motor, and 4.4×10^{-6} when used with the Permanent Magnet Stepping Motor.

The mode of failure having the highest probability of occurrence for the transmission when used with the two DC motors is the transmission jamming due to galling of the worm mesh.

The modes of failure having the highest probability of occurrence for the transmission when used with the permanent magnet stepping motor are: (1) the transmission jamming due to galling of the worm mesh and jamming of the bearings due to contamination, and (2) structural failure of the gear teeth.

The relative severity ranking for this design concept is 3.04×10^{-6} when used with the two DC motors, and 0.44×10^{-6} when used with the permanent magnet stepping motor.

The modes of failure having the most severe effect for the NSS are the same whether the worm gear is used with the two DC motors or the permanent magnet stepping motor. These modes of failure are: (1) jamming of the transmission, and (2) structural failure of the transmission components. In either application the torque output of the motor is not transmitted to the control drum.

A-1.2.5 Wobble Gear Transmission

The overall relative failure estimate for this design concept is 5.4×10^{-6} when used with the Series DC Motor or Brushless DC Motor, and 0.54×10^{-6} when used with the Permanent Magnet Stepping Motor.

The modes of failure having the highest probability of occurrence for the transmission when used with the two DC motors are: (1) the transmission jamming due to galling of the mesh, and (2) structural failure of the gear teeth.

The modes of failure having the highest probability of occurrence for the transmission when used with the permanent magnet stepping motor are: (1) the transmission jamming due to galling of the mesh, and jamming due to contamination in the mesh and in the bearings, and (2) structural failure of the gear teeth.

The relative severity ranking for this design concept is 0.54×10^{-6} when used with the two DC motors, and 0.05×10^{-6} when used with the permanent magnet stepping motor.

The modes of failure having the most severe effect for the NSS are the same whether the Wobble gear is used with the two DC motors or the permanent magnet stepping motor. These modes of failure are: (1) jamming of the transmission, and (2) structural failure of the transmission components. In either application the torque output of the motor is not transmitted to the control drum.

A-1.3 Reliability Selection of Design Concepts

Upon consideration of overall failure estimates and severity of failure effects least detrimental to NSS performance, the selection of design concepts on the basis of reliability preference is as follows:

A. Motor Concepts

1. Permanent Magnet Stepping Motor
2. Brushless DC Motor
3. Series DC Motor

B. Transmission Concepts for DC Motors

1. Wobble
2. Epicyclic
3. Harmonic
4. Conventional
5. Worm

C. Transmission Concepts for Permanent Magnet Stepping Motor

1. Wobble
2. Epicyclic
3. Harmonic
4. Conventional
5. Worm

TABLE A-1.0-1. FAILURE MODE ANALYSES FOR MOTOR CONCEPTS
UNDER CONSIDERATION

DATE 1-20-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator

DATE APPROVED BY COMPONENT Motor DWG NUMBERS

W59150 D = Series DC Motor B = Brushless DC Motor S = Permanent Magnet Stepper Motor

Mode Ident. No.	Component Failure Mode of Failure	Effect of Failure	Severity			Failure Probab Rating		/
			D	B	S	D	B	S
A-1-10	1.0 Rotor							
	A. Shaft Distorts	A. Distorted shaft reduces gap to interfere with stator. Actuator unable to position control drum. AMOD required to position drum to orifice angle.	D	D	D			
	1. High Shock Load					2×10^{-7}	10^{-7}	10^{-7}
	2. Thermal Gradient					2×10^{-6}	10^{-7}	10^{-7}
	B. Laminations Distort	B. Distorted laminations interfere with stator.	D					
	1. High Shock Load					10^{-7}	0	0
	2. Thermal Gradient					10^{-6}	0	0
	C. Windings Fail	C. Rotor current reduced.	D					
	1. Short Circuit					10^{-5}	0	0
	2. Open Circuit					10^{-5}	0	0
	D. Encapsulant Fails	D. Encapsulant chips jam motor.	D					
	1. Shock					10^{-5}	0	0
	2. Thermal					10^{-5}	0	0
	3. Radiation					10^{-5}	0	0

COMPONENT FAILURE MODES ANALYSIS

SHEET

DATE 1-20-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator

DATE APPROVED BY COMPONENT Motor DWG NUMBERS

W59150

D = Series DC Motor B = Brushless DC Motor S = Permanent Magnet Stepper Motor

Mode Ident. No	Component Failure Mode of Failure	Effect of Failure	Severity			Failure Probability Rating		
			D	B	S	D	B	S
1.0 (Cont'd) A-1-11	E. Fasteners Fail	E. Loose rotor elements jam motor.	D	D	D	10^{-5} 10^{-5}	10^{-6} 10^{-6}	10^{-6} 10^{-6}
	1. High Shock Load							
	2. Thermal Expansion							
	F. Commutator Bars Fail	F. Commutator fails causing no torque to be delivered to drum.	D			18×10^{-4} 18×10^{-5} 18×10^{-6} 18×10^{-5}	0 0 0 0	0 0 0 0
	1. Bars Wear Due to Arcing							
	2. Bars Dislodged							
	3. Bar to Winding Contact Opens							
	4. Adjacent Bars Short							
	G. Commutator Aperature Fails	G. Aperature fails to give proper indication to controller.		B			3×10^{-6} 3×10^{-4} 6×10^{-5}	
	1. Aperature Moves from Index Point							
	2. Aperature Blanked By Contaminant							
	3. Aperature Distorts							
	H. Permanent Magnets Fail	H. Actuator fails to deliver torque to control drum.		D	D		12×10^{-6} 12×10^{-6} 12×10^{-6}	12×10^{-6} 12×10^{-6} 12×10^{-6}
	1. Magnet Elements Dislodged							
	2. Magnets Chip or Crack							
	3. Magnets Lose Magnetic Properties							

COMPONENT FAILURE MODES ANALYSIS

SHEET

DATE 1-20-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator

DATE _____ APPROVED BY _____ COMPONENT Motor DWG NUMBERS _____

W59150

D = Series DC Motor B = Brushless DC Motor S = Permanent Magnet Stepper Motor

Mode Ident. No.	Component Failure Mode of Failure	Effect of Failure	Severity			Failure Probability Rating		
			D	B	S	D	B	S
1.0 (Cont'd)	I. Rotor Bearings Fail	I. Rotor unable to turn.	D	D	D			
	1. Bearings Gall 2. Bearings Become Contaminated					2×10^{-5} 4×10^{-5}	2×10^{-6} 2×10^{-6}	2×10^{-6} 2×10^{-6}

A-1-12

COMPONENT FAILURE MODES ANALYSIS

SHEET 1

DATE 1-20-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator

DATE APPROVED BY COMPONENT Motor DWG NUMBERS

W59150

D = Series DC Motor B = Brushless DC Motor S = Permanent Magnet Stepper Motor

Mode Ident. No.	Component Failure Mode of Failure	Effect of Failure	Severity			Failure Probab Rating		
			D	B	S	D	B	S
A-1-13 2.0	Stator							
	A. Stator Laminations Fail	A. Actuator fails to deliver torque to drum.	D	D	D			
	1. Laminations Chip, Crack or Distort					10^{-7}	10^{-7}	10^{-7}
	2. Laminations Short by Contamination					10^{-6}	10^{-6}	10^{-6}
	B. Windings Fail	B. Actuator fails to deliver torque to drum.	D	D	D			
	1. Windings Short					10^{-7}	10^{-7}	10^{-7}
	2. Windings Open					10^{-6}	10^{-6}	10^{-6}
	C. Insulation Fails	C. Actuator fails to deliver torque to drum.	D	D	D			
	1. Insulation Breaks Down					10^{-6}	10^{-6}	5×10^{-6}
	2. Insulation Chips or Flakes					10^{-6}	10^{-6}	10^{-6}
	D. Fasteners Fail	D. Actuator fails to deliver torque to drum.	D	D	D			
	1. Fastener Allows Loose Laminations					10^{-6}	10^{-6}	10^{-6}
	E. Housing Fails	E. Actuator fails to deliver torque to drum.	D	D	D			
	1. Housing Fails Allowing Stator to Jam Rotor					10^{-6}	10^{-6}	10^{-6}

COMPONENT FAILURE MODES ANALYSIS

SHEET

DATE 1-20-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator

DATE APPROVED BY COMPONENT Motor DWG NUMBERS

W59150

D = Series DC Motor B = Brushless DC Motor S = Permanent Magnet Stepper Motor

Mode Ident. No.	Component Failure Mode of Failure	Effect of Failure	Severity			Failure Probab Rating		S
			D	B	S	D	B	
A-1-14	3.0 Commutator							
	A. Brushes Fail	A. Actuator fails to deliver torque to drum.	D					
	1. Brushes Chip and Wear					2×10^{-4}		
	2. Brush Makes Poor Contact with Commutator					2×10^{-5}		
	B. Brush Holders Fail	B. Actuator fails to deliver torque to drum.	D					
	1. Brushes Jam in Holders					2×10^{-5}		
	2. Holders Become Lose					2×10^{-6}		
	C. Brush Spring Fails	C. Actuator fails to deliver torque to drum.	D					
	1. Spring Gradient Too High					2×10^{-7}		
	2. Spring Gradient Too Low					2×10^{-6}		
	D. Flexible Conductor Fails	D. Actuator fails to deliver torque to drum.	D					
	1. Flexible Conductor Breaks					2×10^{-6}		
	2. Flexible Conductor Shorts to Case					2×10^{-6}		

COMPONENT FAILURE MODES ANALYSIS

SHEET _____

DATE 1-20-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator
 DATE _____ APPROVED BY _____ COMPONENT Motor DWG NUMBERS _____

W59150 D = Series DC Motor B = Brushless DC Motor S = Permanent Magnet Stepper Motor

Mode Ident. No.	Component Failure Mode of Failure	Effect of Failure	Severity			Failure Probab'l Rating		
			D	B	S	D	B	S
3.0 (Cont'd)	E. Photo Cells Fail	E. Actuator fails to deliver torque to drum, or actuator stability imperiled.		D or C			4×10^{-6}	
	1. Photo Cells Lose Optical Transmission							
	2. Photo-Electric Properties Change						4×10^{-5}	
	3. Electrical Connection Opens or Shorts							
	F. Light Source Fails	F. Actuator fails to deliver torque to drum.		D			10^{-5}	
	1. Filament Burns Out							
	2. Filament Leads Short or Open						2×10^{-5}	
	3. Envelope Fails, Violating Vacuum Environment of the Filament							
							10^{-6}	

A-1-15

COMPONENT FAILURE MODES ANALYSIS

SHEET _____

DATE 1-20-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator

DATE _____ APPROVED BY _____ COMPONENT Motor DWG NUMBERS _____

W59150 D = Series DC Motor B = Brushless DC Motor S = Permanent Magnet Stepper Motor

Mode Ident. No.	Component Failure Mode of Failure	Effect of Failure	Severity			Failure Probability Rating		
			D	B	S	D	B	S
4.0 A-1-16	Tachometer							
	A. Rotor Fails	A. Motor velocity control loop fails. Actuator stability imperiled.	C or D			10 ⁻⁵ 10 ⁻⁶ 10 ⁻⁶		
	1. Rotor Windings Short or Open							
	2. Rotor Shaft Bends							
	3. Rotor Does Not Move with Motor							
	B. Stator Fails	B. Motor velocity control loop fails. Actuator stability imperiled.	C or D			10 ⁻⁶ 10 ⁻⁶		
	1. Stator Loses Magnetism							
	2. Stator Jams Rotor							
	C. Commutator Fails	C. Motor velocity control loop fails. Actuator stability imperiled.	C or D			2 x 10 ⁻⁵ 2 x 10 ⁻⁵ 2 x 10 ⁻⁶		
	1. Brushes Short Out							
	2. Brushes Do Not Contact Rotor							
	3. Brushes Chip							
TOTAL						2621.7 x 10 ⁻⁶	869.4 x 10 ⁻⁶	52.4 x 10 ⁻⁶

TABLE A-1.0-2. FAILURE MODE ANALYSES FOR TRANSMISSION CONCEPTS UNDER CONSIDERATION

T-26-70

J. Burke/I. Spezialetti

DEPARTMENT

Actuator Design

SUBSYSTEM

Control Drum
Drive Actuator

COMPONENT

Transmission

DWG NUMBERS

DC = DC Motors

Step = Permanent Magnet Stepper Motor

1.0

Conventional Gear Head

A. Transmission Jams to Freeze System

1. Galling of Meshes
2. Contamination of Mesh
3. Galling of Bearings
4. Contamination of Bearings

A. Actuator unable to transmit torque to position control drum. AMOD required to position drum to orifice angle.

D

D

Failure Probability Rating	
DC	Step
1.2×10^{-5}	6×10^{-7}
1.2×10^{-6}	6×10^{-8}
1.2×10^{-5}	6×10^{-7}
1.2×10^{-6}	6×10^{-7}

B. Structural Failure of Transmission Components

1. Gear Teeth Break
2. Bearings Break

B. Actuator unable to transmit torque to position control drum. AMOD required to position drum to orifice angle.

D

D

Failure Probability Rating	
DC	Step
1.2×10^{-6}	6×10^{-7}
1.2×10^{-7}	6×10^{-8}

Failure Probability Rating	
DC	Step
27.7×10^{-6}	2.52×10^{-6}

A-1-17

COMPONENT FAILURE MODES ANALYSIS

SHEET ____ OF ____

DATE 1-26-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator
 DATE _____ APPROVED BY _____ COMPONENT Transmission DWG NUMBERS _____
 DC = DC Motors Step = Permanent Magnet Stepper Motor

	Component Failure Mode of Failure	Effect of Failure	Severity		Failure Probability Rating	
			DC	Step	DC	Step
2.0	Epicyclic Transmission					
	A. Transmission Jams to Freeze System	A. Actuator unable to transmit torque to control drum. AMOD required to position drum to orifice angle.	D	D		
	1. Galling of Meshes				2×10^{-6}	2×10^{-7}
	2. Contamination of Meshes				2×10^{-7}	2×10^{-8}
	3. Galling of Bearings				4×10^{-6}	2×10^{-7}
	4. Contamination of Bearings				4×10^{-7}	2×10^{-7}
	B. Structural Failure of Transmission Components	B. Actuator unable to transmit torque to control drum. AMOD required to position drum to orifice angle.	D	D		
	1. Gear Teeth Break				2×10^{-6}	2×10^{-7}
	2. Bearings Break				4×10^{-7}	2×10^{-8}
					9.0×10^{-6}	$.84 \times 10^{-6}$

A-1-18

DATE 1-26-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator
 DATE _____ APPROVED BY _____ COMPONENT Transmission DWG NUMBERS _____
 DC = DC Motors Step = Permanent Magnet Stepper Motor

3.0	Component Failure Mode of Failure	Effect of Failure	Severity		Failure Probability Rating	
			DC	Step	DC	Step
3.0	Harmonic Drive					
	A. Transmission Jams to Freeze System	A. Actuator unable to transmit torque to control drum. AMOD required to position drum to orifice angle.	D	D		
	1. Wave Generator Electrical Bearing Galls				10^{-6}	10^{-6}
	2. Contamination of Wave Generator				10^{-6}	10^{-7}
	3. Contamination of Spline Mesh				10^{-6}	10^{-7}
	4. Galling of Planetary Mesh				10^{-6}	0
	5. Contamination of Planetary Mesh				10^{-6}	0
	6. Galling of Planetary Bearings				6×10^{-6}	0
	7. Contamination of Planetary Bearings				6×10^{-6}	0
	B. Structural Failure of Transmission Components	B. Actuator unable to transmit torque to control drum. AMOD required to position drum to orifice angle.	D	D		
	1. Wave Generator Bearing Breaks				10^{-8}	10^{-8}
	2. Spline Teeth Shear				10^{-8}	10^{-8}
	3. Planetary Teeth Break				10^{-7}	0
	4. Planetary Bearings Break				6×10^{-8}	0
	5. Flexspline Cup Shears				10^{-6}	10^{-6}
					18.18×10^{-6}	2.22×10^{-6}

COMPONENT FAILURE MODES ANALYSIS

SHEET OF

DATE **1-26-70** PREPARED BY **J. Burke/I. Spezialetti** DEPARTMENT **Actuator Design** SUBSYSTEM **Drive Actuator**

DATE	APPROVED BY	COMPONENT	Transmission	DWG NUMBERS
------	-------------	-----------	--------------	-------------

DC = DC Motors

Step = Permanent Magnet Stepper Motor

No.	Component Failure Mode of Failure	Effect of Failure	Severity		Failure Probability Rating	
			DC	Step	DC	Step
4.0	Worm Gear					
	A. Transmission Jams to Freeze System	A. Actuator unable to transmit torque to control drum. AMOD required to position drum to orifice angle.	D	D		
	1. Galling of Worm Mesh				2×10^{-5}	10^{-6}
	2. Galling of Bearings				4×10^{-6}	2×10^{-7}
	3. Contamination of Bearings				4×10^{-6}	2×10^{-6}
	B. Structural Failure of Transmission Components	B. Actuator unable to transmit torque to control drum. AMOD required to position drum to orifice angle.	D	D		
	1. Gear Teeth Break				2×10^{-6}	10^{-6}
	2. Bearings Break				4×10^{-7}	2×10^{-7}
TOTAL					30.4×10^{-6}	4.4×10^{-6}

A horizontal number line with a central point labeled 30.4×10^6 and a point to the right labeled 4.4×10^6 .

COMPONENT FAILURE MODES ANALYSIS

SHEET ____ OF ____

DATE 1-26-70 PREPARED BY J. Burke/I. Spezialetti DEPARTMENT Actuator Design SUBSYSTEM Control Drum Drive Actuator

DATE _____ APPROVED BY _____ COMPONENT Transmission DWG NUMBERS _____

DC = DC Motors

Step = Permanent Magnet Stepper Motor

	Component Failure Mode of Failure	Effect of Failure	Severity		Failure Probability Rating	
			DC	Step	DC	Step
5.0	Wobble Gear	A. Actuator unable to transmit torque to control drum. AMOD required to position drum to orifice angle.	D	D		
	A. Transmission Jams to Freeze System					
	1. Galling of Mesh				2×10^{-6}	10^{-7}
	2. Galling of Bearings				4×10^{-7}	2×10^{-8}
	3. Contamination of Mesh				2×10^{-7}	10^{-7}
	4. Contamination of Bearings				4×10^{-7}	2×10^{-7}
	B. Structural Failure at Transmission Components	B. Actuator unable to transmit torque to control drum. AMOD required to position drum to orifice angle.	D	D		
	1. Gear Teeth Break				2×10^{-6}	10^{-7}
	2. Bearings Break				4×10^{-7}	2×10^{-8}
					5.4×10^{-6}	$.54 \times 10^{-6}$

A-1-21

FIGURE A-1.0-1

RELIABILITY MODEL AND MATH EQUATION
D.C. MOTOR CONCEPT

$$R = R_1 \times R_2 \times R_3 \times R_4$$

$$Q = Q_1 + Q_2 + Q_3 + Q_4$$

FIGURE A- 1.0-2

RELIABILITY MODEL AND MATH EQUATION
BRUSHLESS D.C. MOTOR CONCEPT

$$R = R_1 \times R_2 \times R_3$$

$$Q = Q_1 + Q_2 + Q_3$$

FIGURE A- 1.0-3

RELIABILITY MODEL AND MATH EQUATION
PERMANENT MAGNET STEPPER MOTOR CONCEPT

$$R = R_1 \times R_2$$

$$Q = Q_1 + Q_2$$

FIGURE A-1.0-4

RELIABILITY MODEL AND MATH EQUATION
TRANSMISSION CONCEPTS

$$R = R_1 \times R_2$$

$$Q = Q_1 + Q_2$$

NOMENCLATURE		ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES			SELECTION
RELIABILITY CONSIDERATIONS		SERIES DC MOTOR 1	PERMANENT MAGNET STEPPING MOTOR 2	BRUSHLESS DC MOTOR 3	
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS					
Goal: Minimize Failure Probability	Overall Failure Estimate	2621.7 x 10 ⁻⁶	52.4 x 10 ⁻⁶	869.4 x 10 ⁻⁶	
	Most Probable Failure Modes	0.018 Rotor commutator bars failing due to wear and arcing (10 ⁻⁴) Commutator brushes failing due to chipping or wearing (10 ⁻⁴)	0.926 Rotor permanent magnets become dislodged, chip or crack, or lose magnetic properties (10 ⁻⁶) Rotor bearings fail (10 ⁻⁶) Stator laminations, windings or insulation fail and cause electrical failure (10 ⁻⁶)	0.056 Rotor commutator operation fails due to distortion or blanking by contamination (10 ⁻⁴)	
	Relative Severity Ranking	262 x 10 ⁻⁶	5 x 10 ⁻⁶	220 x 10 ⁻⁶	
Goal: Minimize Severity of Failure	Most Severe Failure Modes	0.018 Failure of tachometer components	0.960 Failure of stator fastening to the housing	0.022 Failure of the rotor commutator operation	
	Effects of Most Severe Failure Modes	Stability of actuator cannot be maintained, causing the actuator to drive the control drum in short high velocity excursions and oscillation about the commanded position	Actuator fails to deliver torque to the control drum	An improper rotor position indication signal is fed back from the actuator to the controller, imperiling actuator stability, and possibly resulting in short high velocity excursions and oscillation about the commanded position	
	Reliability Figure of Merit	0.018	0.943	0.039	2, 3, 1

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NOMENCLATURE		ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES				SELECTION
RELIABILITY CONSIDERATIONS		HARMONIC DRIVE WITH STEPPER MOTOR 1	CONVENTIONAL DRIVE WITH STEPPER MOTOR 2	EPICYCLIC TRANSMISSION WITH STEPPER MOTOR 3	WORM GEAR WITH STEPPER MOTOR 4	
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS						
Goal Minimize Failure Probability	Overall Failure Estimate	2.22×10^{-6}	2.52×10^{-6}	0.84×10^{-6}	4.4×10^{-6}	0.54×10^{-6}
	Most Probable Failure Modes	0.110 Transmission jamming due to galling of wave generator bearing (10^{-6}) Structural failure of flexspline cup (10^{-6})	0.096 Transmission jamming due to galling and contamination of bearings or gears (10^{-7}) Structural failure of gear teeth (10^{-7})	0.289 Transmission jamming due to galling and contamination of bearings or gears (10^{-7}) Structural failure of gear teeth (10^{-7})	0.055 Transmission jamming due to galling of the worm mesh and contamination of the bearings (10^{-6}) Structural failure of gear teeth (10^{-6})	0.450 Transmission jamming due to galling and contamination of the gear teeth and bearings (10^{-7}) Structural failure of gear teeth (10^{-7})
Goal Minimize Severity of Failure	Relative Severity Ranking	0.22×10^{-6}	0.25×10^{-6}	0.08×10^{-6}	0.44×10^{-10}	0.05×10^{-6}
	Most Severe Failure Modes	0.105 Jamming of the transmission Structural failure of the transmission	0.092 Jamming of the transmission Structural failure of the transmission	0.289 Jamming of the transmission Structural failure of the transmission	0.053 Jamming of the transmission Structural failure of the transmission	0.461 Jamming of the transmission Structural failure of the transmission
	Effects of Most Severe Failure Modes	Torque output of the motor is not transmitted to the control drums	Torque output of the motor is not transmitted to the control drums	Torque output of the motor is not transmitted to the control drums	Torque output of the motor is not transmitted to the control drums	Torque output of the motor is not transmitted to the control drums
	Reliability Figure of Merit	0.108	0.094	0.289	0.054	0.456

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NOMENCLATURE		ASTRONUCLEAR LABORATORY COMPARISON MATRIX OF DESIGN APPROACHES					SELECTION
RELIABILITY CONSIDERATIONS		HARMONIC DRIVE WITH DC MOTORS 1	CONVENTIONAL DRIVE WITH DC MOTORS 2	EPICYCLIC TRANSMISSION WITH DC MOTORS 3	WORM GEAR WITH DC MOTORS 4	WABBLE GEAR WITH DC MOTORS 5	
FUNCTIONAL & TECHNICAL DESIGN REQUIREMENTS							
Goal Minimize Failure Probability	Overall Failure Estimate						
	Most Probable Failure Modes	0,131 Transmission jamming due to galling or contamination of components (10 ⁻⁶) Structural failure of flexspline cup (10 ⁻⁶)	0,086 Transmission jamming due to gal- ling of bearings or gears (10 ⁻⁵)	0,264 Transmission jamming due to galling of bearings or gears (10 ⁻⁶) Structural failure of gear teeth (10 ⁻⁶)	0,078 Transmission jamming due to galling of the worm mesh (10 ⁻⁵)	0,441 Transmission jamming due to galling of the gear mesh (10 ⁻⁶) Structural failure of gear teeth (10 ⁻⁶)	
Goal Minimize Severity of Failure	Relative Severity Ranking						
	Most Severe Failure Modes	0,131 Jamming of the transmission Structural failure of the trans- mission	0,086 Jamming of the transmission Structural failure of the trans- mission	0,264 Jamming of the transmission Structural failure of the trans- mission	0,078 Jamming of the transmission Structural failure of the trans- mission	0,441 Jamming of the transmission Structural failure of the trans- mission	
	Effects of Most Severe Failure Modes	Torque output of the motor is not transmitted to the control drums	Torque output of the motor is not transmitted to the control drums	Torque output of the motor is not transmitted to the control drums	Torque output of the motor is not transmitted to the control drums	Torque output of the motor is not transmitted to the control drums	
Reliability Figure of Merit		0,131	0,086	0,264	0,078	0,441	5, 3, 1, 2, 4

APPENDIX A-2

RADIATION AND SHIELDING SUPPORTING DATA

TRADE STUDY FOR NERVA CONTROL DRUM

ACTUATOR DESIGN CONCEPTS

TRADE STUDY NO. 764

A-2.0 INTRODUCTION

This section provides radiation heating rates and the radiation environment for the various motor, transmission, and actuator malfunction override device (AMOD) concepts. This data is provided for both the unshielded reactor and the reactor shielded by the reference design shield (defined in WANL Drawing 939J685E) composed of BATH which extends to the outer radius of the reflector.

The radiation heating rate data is provided as input to thermal design analysis in order that the Environmental Requirements may be evaluated. The radiation environment data is provided as input to radiation effects analysis in order that the Environmental Requirements may be evaluated.

Since the radiation environment and heating rate data at the control drum actuator is determined in the absence of the actuator assembly itself, the data applies equally to all portions and concepts for the actuator assembly. Therefore, to avoid repetition of the description of the same data for each concept, the data will be described for the first concept only.

A-2.1 DISCUSSION OF MOTOR ALTERNATES

Environmental Requirements

Table A-2-1 provides the following information at the control drum actuator location for both the unshielded reactor and the reactor shielded by the reference design shield defined in WANL Drawing 939J685E :

1. Fast neutron fluence ($E > 1.0$ Mev),
2. Intermediate neutron fluence ($0.4 \text{ ev} < E < 1.0$ Mev),
3. Thermal neutron fluence ($E < 0.4 \text{ ev}$),
4. Gamma dose (ergs/gm-c), and
5. The radiation heating rate (w/gm-Al). (This heating rate may be used for other structural metals because of the relatively constant gamma energy absorption per unit mass.)

These data are provided for the longest single burn and for the total integrated power and are the unperturbed radiation levels in the absence of the actuator assembly. The presence of the actuator assembly will reduce the radiation environment levels so that the use of the unperturbed data is conservative.

The longest single burn at 1505 Mw is based on the requirement for a one hour run during ground testing which will be longer than any single mission burn during flight. The total integrated power is based on ten hours of full power operation with minimal power being generated in the startup and shutdown ramps. At the present time, all of the requirements on the reactor operating profile have not been completely defined; therefore, as new information on the operating profile becomes available, the fluences and doses will be modified to reflect the new information.

A (1σ) uncertainty factor of 3 should be applied to the data in Table A-2-1 to estimate the maximum value of the radiation levels. This uncertainty factor includes calculational uncertainty and is based on previous NRX reactor testing experience.

A-2.2 DISCUSSION OF TRANSMISSION ALTERNATES

Environmental Requirements

Table A-2-1 provides the radiation environment and heating rates at the control drum actuator assembly location. Section A-2.1.1.1 describes this data in detail.

Since the data in Table A-2-1 describe the environment in the absence of perturbation by the actuator assembly itself, they apply equally to all portions and concepts for the actuator assembly. The presence of the actuator assembly will reduce the radiation environment levels so that the use of the unperturbed data is conservative.

A-2.3 AMOD DISCUSSION

A-2.3.1 Clock Spring, Torsion Spring, and Pyrotechnic Devices

Environmental Requirements

Table A-2-1 provides the radiation environment and heating rates at the control drum actuator assembly location. Section A-2.1.1.1 describes this data in detail.

Since the data in Table A-2-1 describe the environment in the absence of perturbation by the actuator assembly itself, they apply equally to all portions and concepts for the actuator assembly. The presence of the actuator assembly will reduce the radiation environment levels so that the use of the unperturbed data is conservative.

A-2.3.2 Spring in Center of Drive Shaft

Environmental Requirements

Table A-2-1 provides the radiation environment and heating rates at the control drum actuator assembly location. Section A-2.1.1.1 describes this data in detail.

Table A-2-2 provides the maximum radiation environment in the AMOD spring and control drum drive shaft which occurs on the control drum drive shaft centerline at the forward end of the reflector. This data is provided only for the shielded reactor. However, the environment data provided will not be significantly affected by the removal of the shield because the location at which the data is provided is 12 inches aft of the shield.

Section A-2.1.1.1 provides a discussion of the type of information provided and a description of the operating profile employed to obtain fluences and doses. A (1σ) uncertainty factor of 1.4 should be applied to the thermal fluence to estimate the maximum value of the thermal fluence while a (1σ) uncertainty factor of 1.2 should be applied to the remaining radiation levels to obtain the maximum.

Figure A-2-1 provides the relative axial distribution of the radiation heating in the control drum drive shaft and AMOD spring. The heating rate at any location along the length of these components is determined in the following manner.

1. Determine the value of the relative axial distribution of heating for the location of interest, and
2. The heating rate (w/gm of stainless steel) is the product of the value of the relative axial distribution and 0.42.

It should be noted that the AMOD concept with the spring in the center of the drive shaft partially fills the hollow drive shaft. This will be beneficial from a shielding standpoint because the spring in the drive shaft would reduce the radiation streaming through the shaft.

TABLE A-2-1
RADIATION ENVIRONMENT AT THE CONTROL DRUM
ACTUATOR FOR LONGEST SINGLE BURN AND TOTAL
INTEGRATED OPERATION AT 1505 MW (U)

Operating Time	Shield Configuration	Neutron Fluence (n/cm ²)(1)			Gamma Dose (1) (ergs/gm-C)	Heating Rate (1) (w/gm-Al)
		E>1.0 Mev	0.4 ev<E<1.0 Mev	E<0.4 ev		
Longest Single Burn	BATH Reference Design (939J685E)	1.4 (14)	2.7 (14)	7.9 (12)	2.9 (8)	8.2 (-3)
	No Shield	3.4 (16)	3.4 (17)	3.8 (16)	1.1 (10)	3.2 (-1)
Total Integrated Operating Time	BATH Reference Design (939J685E)	1.4 (15)	2.7 (15)	7.9 (13)	2.9 (9)	8.2 (-3)
	No Shield	3.4 (17)	3.4 (18)	3.8 (17)	1.1 (11)	3.2 (-1)

(1) Numbers in parenthesis refer to powers of ten

TABLE A-2-2

MAXIMUM RADIATION ENVIRONMENT⁽¹⁾ IN THE CONTROL DRUM
 DRIVE SHAFT AND AMOD SPRING FOR LONGEST SINGLE
 BURN AND TOTAL INTEGRATED OPERATION AT 1505 Mw (U)

Operating Time	Neutron Fluence (n/cm ²) ⁽²⁾			Gamma ⁽²⁾ Dose (Ergs/gm-C)
	E > 1.0 Mev	0.4 ev < E < 1.0 Mev	E < 0.4 ev	
Longest Single Burn	3.8 (17)	3.3 (18)	7.2 (17)	1.8 (11)
Total Integrated Operating Time	3.8 (18)	3.3 (19)	7.2 (18)	1.8 (12)

(1) The maximum environment occurs on the control drum drive shaft centerline at the forward end of the reflector.

(2) Numbers in parentheses refer to powers of ten.

Figure A-2-1. Relative Axial Distribution of Radiation Heating in the Control Drum Drive Shaft and AMOD Spring

APPENDIX A-3

THERMAL ANALYSIS SUPPORTING DATA
FOR NERVA CONTROL DRUM ACTUATOR
DESIGN CONCEPTS
TRADE STUDY NO. 764

APPENDIX A-3

THERMAL ANALYSIS

INTRODUCTION

An analysis was performed to determine the temperature environment and approximate cooling requirements of the various concepts of the control drum actuator. It is necessary that the actuator be cooled to keep the component at feasible operating temperatures, and minimize thermal gradients to reduce thermal stress. In addition, the actuator must be cooled without interfering with the satisfactory performance of any other components. The objective of the Thermal Analysis was to evaluate the capability of the various design concepts to satisfy the cooling requirements discussed above. The thermal/hydraulic environment of this component is consistent with the state point diagram shown in 957A904.

A-3.1 DISCUSSION OF MOTOR ALTERNATES

A-3.1.1 Series DC Motor

The temperature and cooling requirements for the Series D. C. Motor accounts for the internal heat generation due to nuclear radiation and electrical effects. The nuclear heating rates are described in Section A-2. The electrical heating effects are estimated to be 50 watts, of which 15-20 watts is generated in the shaft.

The inlet coolant temperature and pressure is assumed to be 270°R and 970 psig. By means of a one dimensional heat balance assuming free convection cooling, it is estimated that the maximum shaft temperature is 680°R . The internal heating due to electrical effects is less than 20% of the total heat generation. Under startup conditions when no coolant is available, no problem would arise because the amount of radiation heating is very small under this condition.

The following procedure was used to estimate the coolant requirements. A solid cylinder, having the volume of the actuator components was computed by subtracting the void space from the overall actuator volume. By assuming the maximum rise in temperature

of the coolant is 100°R , it is estimated that 30 lb/hour of coolant is required to cool each actuator.

It is concluded that this design concept can satisfy the cooling requirement.

A-3.1.2 Permanent Magnet Stepping Motor

The thermal analysis of the Permanent Magnet Stepping Motor differs from D. C. Motor in that the electrical heating is confined to the field coil. The major problem of cooling will be due to radiation heating effects since the electrical heating contributes 7% of the total internal heat generation. The inlet coolant temperature and pressure is assumed to be 270°R and 970 psig.

Flow circulation for the Stepping Motor indicates that the shaft, bearings, and field coils can be adequately cooled. Conductive cooling exists through the points where the motor housing is attached to the actuator housing. The coolant requirements for the Stepping Motor are similar to the D. C. Motor.

It is concluded that this design concept can satisfy the cooling requirement.

A-3.1.3 Brushless DC Motor

Input N/A (No drawings)

A-3.2 DISCUSSION OF TRANSMISSION ALTERNATES

A-3.2.1 Harmonic Drive

The Harmonic Drive Transmission will be convectively cooled. The flow path (Dwg. 939J978) indicates that the bearings and shaft will receive adequate coolant. Due to the small cross section of the elements of the transmission, the thermal gradients will not be a problem. The inlet coolant temperature and pressure is assumed to be 270°R and 970 psig. By means of a one dimensional heat balance, the maximum temperature of the transmission is estimated to be 490°R . This value is reported in Table 1.

It is concluded that this design concept can satisfy the cooling requirement.

A-3.2.2 Spur Gear

The Spur Gear Transmission (Dwg. 981D711) contains more metal and bearings than the Harmonic Drive. However, there is an adequate flow path for convective cooling in addition to the conduction paths provided by the mounting brackets and the contact between gears and housings. The inlet coolant temperature and pressure is assumed to be 270°R and 970 psig. By means of a one dimensional heat balance, the maximum temperature of the transmission is estimated to be 530° . This value is reported in Table 1.

A-3.2.3 Epicyclic Transmission

The epicyclic transmission (Dwg. 981D713) contains a smaller number of bearings to be cooled than the spur gear transmission. Because the conduction paths will provide a minimal amount of cooling, it is necessary that the transmission be convectively cooled. The thermal characteristics are similar to the other transmissions and can be adequately cooled. The inlet coolant temperature and pressure is assumed to be 270°R and 970 psig. By means of a one dimensional heat balance, it is estimated that the maximum temperature of the transmission is estimated to be 520°R . This figure is reported in Table 1.

It is concluded that this design concept can satisfy the cooling requirements.

A-3.2.4 Worm Drive

Input N/A (No drawing)

A-3.2.5 Planetary Harmonic

The Planetary Harmonic transmission (Dwg. 981D782) has similar characteristics to the other transmissions under consideration in this study. From the aspects of thermal analysis, it can be adequately cooled as the other transmissions. The inlet coolant temperature and pressure is assumed to be 270°R and 970 psig. By means of a one dimensional heat balance, the maximum temperature of the transmission is estimated to be 480°R . This

figure is reported in Table 1.

It is concluded that this design concept can satisfy the cooling requirements.

A-3.3 AMOD DISCUSSION

A-3.3.1 Clock Spring

The clock spring AMOD can be adequately cooled by coolant flowing through the center shaft and free convection of coolant exiting from the actuator. The inlet coolant temperature and pressure is assumed to be 270°R and 970 psig. By assuming a significant dimension of 0.2" and a material of stainless steel, a one dimensional heat balance indicates a maximum temperature of 440°R . This figure is reported in Table 2.

It is concluded that this design concept can satisfy the cooling requirements.

A-3.3.2' Torsion Spring Concept

From thermal analysis aspects the torsion spring concept is similar to the clock spring mechanism. The inlet coolant temperature and pressure is assumed to be 270°R and 970 psig. By assuming a significant dimension of 0.2" and a material of stainless steel, a one dimensional heat balance indicates a maximum temperature of 440°R . This figure is reported in Table 2.

It is concluded that this design concept can satisfy the cooling requirements.

A-3.3.3 Spring in Center of Drive Shaft

A-3.3.3.1 Trigger in Shaft

The adequate cooling of the control drum drive shaft appears to be feasible by channeling coolant through a passage in the center of the shaft. The trigger in the shaft concept can be cooled by this method. The inlet coolant temperature and pressure is assumed to be 270°R and 970 psig. By assuming a hollow cylinder with internal convection cooling the shaft, temperature is calculated to be 680°R . This figure is reported

in Table 2.

It is concluded that this design concept can satisfy the cooling requirements.

A-3.3.3.2 Trigger in Actuator

From the aspects of thermal analysis, the trigger in the actuator concept can be adequately cooled and offers no additional problems than those encountered by the trigger in the shaft concept. The inlet cooling temperature and pressure is assumed to be 270°R and 970 psig. By assuming a hollow cylinder with internal convection cooling, the shaft temperature is calculated to be 720°R . This figure is reported in Table 2.

It is concluded that this design concept can satisfy the cooling requirements.

A-3.4 SUMMARY

A thermal analysis of the various alternatives for the control drum actuator motors, transmissions, and A-MOD devices indicates that any of the alternatives selected can be adequately cooled. The major difference between the permanent magnet stepping motor and the series and brushless DC motors is the shaft electrical heating, which is present in the DC motor and negligible in the permanent magnet stepping motor and brushless DC motor. Although the major source of internal heating is due to radiation during full power operation, heat generated electrically must be removed. During startup, coolant flow is low and care must be taken to prevent rotor burnup in the DC motor alternate. The major difference between transmission alternates is the amount of metal necessary to be cooled. The selection of a transmission will most likely be based on considerations other than thermal analysis, since the thermal environment is qualitatively the same for all alternatives.

TABLE 1

TRANSMISSION	MAXIMUM TEMPERATURE °R
Harmonic Drive	530°R
Epicyclic	520°R
Worm	----
Planetary Harmonic	480°R

$$T_m = T_B + q''' \rho \left[\frac{x}{h_o} + \frac{x^2}{2K} \right]$$

T_m = maximum temperature

T_B = bulk fluid temperature

$q''' \rho$ = internal heat generation

h_o^2 = film coefficient

x = significant dimension

K = thermal conductivity

TABLE 2

AMOD DEVICE	MAXIMUM TEMPERATURE ^{°R}
Clock Spring	450
Torsion Spring	550
Trigger in Shaft	700
Trigger in Actuator	720

APPENDIX A-4

STRUCTURAL ANALYSIS SUPPORTING DATA

FOR NERVA CONTROL DRUM ACTUATOR

DESIGN CONCEPTS

TRADE STUDY NO. 764

A-4 STRUCTURAL ANALYSIS

A-4.0 INTRODUCTION

The structural evaluation of the components involved in the control drum actuator trade study consists of identifying the conditions which tend to reduce loads and stresses. The philosophy is that the best combination of components from a structural sense will consist of those experiencing the lowest loads and stresses during operation. An additional consideration is analytical complexity. This is considered in the sense that a component which requires complex methods of analysis (with associated risk) should provide a significant payoff in functional performance.

After a concept is chosen, a complete structural analysis will be performed and the adequacy of the design will be verified by component testing.

A-4.1 DISCUSSION OF MOTOR ALTERNATES

Selection of the type of motor for the control drum actuator is more of an electrical requirement than a structural one. However, a significant observation can be made regarding the speeds of the two categories of motors. The Series DC motor and the Brushless DC motor operate at 6000 rpm while the Permanent Magnet Stepping motor operates at 250 rpm. The Permanent Magnet Stepping motor is considered better from a structural point of view, because its lower speed will tend to cause lower loads and stresses.

A-4.2 DISCUSSION OF TRANSMISSION ALTERNATES

A-4.2.1 Harmonic Drive

The Harmonic Drive concept is attractive for use because of the small number of parts and because of the balanced wave generating arrangement (diametrically opposed tooth contact). This arrangement tends to produce low bearing loads which reduces contact stresses. A disadvantage of the Harmonic Drive is the complexity of the analysis required to insure a structurally adequate flexible spline. Although this is a proven concept, the details of the required analysis are, in general, unavailable because of its proprietary nature. This transmission arrangement is associated with the Permanent Magnet Stepping motor, therefore, the input speed of the motor is low enough to minimize

loads and stresses.

A-4.2.2 Spur Gear

The Spur Gear arrangement, although analytically straightforward, uses many additional parts in both gears and bearings. The gear tooth separation forces will tend to produce somewhat higher bearing loads and stresses since these forces are not diametrically balanced as in the Harmonic Drive concept. It is noted that the additional 1.5 inches of actuator length, which is mostly occupied by gears, bearings and housing, will result in additional weight and a larger volume requirement for this design. The design is shown with the Permanent Magnet Stepping motor although the basic concept is applicable to either motor category (250 or 6000 rpm). The additional gears and bearings required to achieve the proper reduction with a Series DC motor along with the 6000 rpm speed of the input gear would make it more difficult to provide an adequate structural design.

A-4.2.3 Epicyclic Transmission

The Epicyclic concept is analytically straightforward and requires one additional part over the Harmonic Drive (a ball bearing). Although there is some increase in radial ball bearing load due to gear tooth separation force, larger bearings are provided to insure structural adequacy. This design can also be considered with the 6000 rpm Series DC or Brushless DC motor. The same structural comments as mentioned for the Spur Gear transmission at 6000 rpm apply to the Epicyclic Transmission at this speed.

A-4.2.4 Worm Drive

The Worm Drive transmission has axial thrust forces as well as the usual gear tooth separation forces. These forces can, if of high enough magnitude, cause damaging effects to the ball bearings. Also, the gear tooth surfaces experience a greater amount of sliding contact in this design than in a straight spur gear type design. This condition requires provision of a positive method of lubrication. These considerations are not found in the other transmission concepts. The mentioned considerations become even more of a factor in the design when the 6000 rpm speed category is studied (a modification of the design shown). At this speed the bearings and tooth surfaces experience many more cycles of load

for each rotation of the control drum.

A-4.2.5 Planetary/Harmonic

The Planetary/Harmonic arrangement has the analytical complexity of the Harmonic Drive concept plus additional planetary gearing. Thus, there are additional parts along with greater length and volume in this concept. The 6000 rpm speed of the herring-bone drive gear would make it more difficult to achieve an adequate structural design.

A-4.3 AMOD DISCUSSION

The studied AMOD concepts are structurally equivalent. Although some of the concepts have higher design torque requirements (the Clock Spring and Torsion Spring concepts are designed for 400 in. -lb. of torque whereas the spring in shaft concept is designed for 100 in. -lb.) and some are more complex (because of many parts) none of these considerations are insurmountable from a structural point of view. Non-structural requirements will necessarily be used in the selection of the best arrangement.

A-4.4 SUMMARY

The Permanent Magnet Stepping motor is selected because of the lower loads and stresses associated with lower speeds. These slower speeds also make the structural adequacy of the transmission more easily insured. An Epicyclic Transmission is preferred because of its low risk analytical simplicity. All of the AMOD's are equivalent, structurally. The preferred AMOD design (spring in shaft with trigger in actuator) offers some non-structural benefits which are discussed elsewhere in this report.

APPENDIX A-5

QUALITY ASSURANCE SUPPORTING DATA

FOR NERVA CONTROL DRUM ACTUATOR

DESIGN CONCEPTS

TRADE STUDY NO. 764

APPENDIX A-5

QUALITY ASSURANCE SUPPORTING DATA

INTRODUCTION

This appendix contains the Quality Assurance evaluation of the motor, transmission and A-MOD conceptual designs proposed for the Control Drum Actuator Trade Study. These drawings are of layout detail and since FMECA's and component drawings are not available at this time, no attempt was made to provide a qualitative or quantitative (R_Q) rating.

A-5.1 MOTOR ALTERNATES

It appears that it will be necessary to redesign, develop and qualify nearly all major component motor parts, regardless of the type, because of the stringent environmental conditions and apportioned reliability goal established for the Control Drum Actuator. It appears that the tight manufacturing, inspection and testing controls to be applied will not be significantly biased by motor selection.

A-5.1.1 The permanent magnet stepping motor is preferred over the series DC motor and brushless DC motor because of:

- a) Its simplicity - fewer material quality and inspection concerns.
- b) Its potential greater reliability.
- c) Electronic commutation in lieu of problem-laden mechanical or optical commutation.

A-5.1.2 Quality Assurance Rating

- 1) Permanent Magnetic Stepping Motor
- 2) Brushless DC Motor
- 3) Series DC Motor

A-5.2 TRANSMISSION ALTERNATES

New inspection master gages and comparator charts will have to be designed and procured regardless of the type selected. Verification of quality and performance on bearings is very difficult non-destructively. Special gages, test fixtures, destructive or non-destructive tests will have to be developed. The significant bias on Quality Assurance and Inspection is related to the total number of parts and total number of parts and total number of different type parts incorporated into a given transmission design. Another weighing consideration is that the Harmonic drive will be a "sole source" procurement action, with proprietary restraints which can limit the effectiveness of the total quality control concept and design data and material traceability for PDR.

A-5.2.1 For reasons stated in paragraph 1.2 above, the epicyclic transmission is preferred.

A-5.2.2 Quality Assurance Rating

- 1) Epicyclic Gear Transmission
- 2) Worm Gear Transmission
- 3) Harmonic Drive Transmission
- 4) Spur Gear Transmissicn
- 5) Planetary/Harmonic Drive Transmission

A-5.3 ACTUATOR MALFUNCTION OVERRIDE DEVICE ALTERNATES (A-MOD)

The comments under Section 1.2 on bearings and quantity/type of parts biasing inspection are applicable. The drive shaft spring-fusible trigger and pyro-technic concepts appear to require undesirable disassembly to facilitate reloading or recocking. The clock and torsion spring concepts will be significantly more complex than depicted in the outline to meet the requirements of WANL CP-677585.

A-5.3.1 Since no major Quality Assurance or Inspection problems are apparent, preference was established on the basis of the above design simplicity and inspection's degree of difficulty.

A-5.3.2 Quality Assurance Rating

- 1) Drive Shaft Spring-Electromagnetic Trigger Concept
- 2&3) Torsion and Clock Spring Concept
- 4) Pneumatic Concept
- 5) Drive Shaft Spring-Fusable Trigger Concept
- 6) Pyrotechnic Concept

APPENDIX A-6

MANUFACTURING ANALYSIS SUPPORTING DATA

FOR NERVA CONTROL DRUM ACTUATOR

DESIGN CONCEPTS

TRADE STUDY NO. 764

APPENDIX A-6

MANUFACTURING ANALYSIS

INTRODUCTION

This appendix contains the manufacturing analysis of the control drum actuator system actuator component designs proposed.

A-6.1 PRODUCIBILITY ANALYSIS

Since study layouts including bills of materials are not available, Manufacturing Engineering data is based on discussions with Design Engineering and Materials, and on layout sketches.

The basic materials utilized for the several design concepts are conventional, commercially available materials of known characteristics and machinability. Although most of the components will require close tolerances and precision machining, no manufacturing development of methods or techniques is anticipated in order to achieve the design configurations.

A-6.2 COST ANALYSIS

Although most of the design concepts are supported with layout sketches, insufficient details are delineated to enable Manufacturing Engineering cost estimates to be made. However, the total quantity and complexity of the components of each design concept appear approximately equal, indicating the total costs will be approximately equal, even though there may be significant differences between individual components.

A-6.3 SCHEDULE ANALYSIS

The long-lead component(s) will be either the permanent magnet stepping motor, the epicyclic transmission, and/or the potentiometer. Excluding internal administration of procurement and internal processing after receipt of parts, fabrication time will be probably about 26 weeks. The components of conventional materials and configurations can be manufactured in parallel with the long-lead item(s). Adding about 17 weeks for inspection and assembly brings the total time to 43 weeks.

APPENDIX A-7
REFERENCES - INDEX

A-7 REFERENCES - INDEX

- A-7.1 PWAC-493, "Irradiation and Thermal Testing of LCRE Control Drive Electrical Components".
- A-7.2 NASA TMX-53675, "Evaluation of Direct Current Motors in Vacuum"
- A-7.3 ANL 7262, "Testing of D.C. Motor Brushes in a Dry Argon Atmosphere"
- A-7.4 CG6-168, "Motor Evaluation Test Report for Mod. II Slow Speed Motor and Filter"
- A-7.5 CG6-143, "Motor Evaluation Test Report for Gimballing Servo Actuator Motor and Filter"
- A-7.6 NASA TM 33-382
 - 1. "Development Philosophy for SNAP Mechanisms "
 - 2. "Lubrication of DC Motors, Slip Rings, Bearings, and Gears for Long-Life Space Applications "
 - 3. "A Brushless Despin Drive and Control for a Communication Satellite Antenna"
- A-7.7 NAA-SR-10735, "SNAP 10A Flight System Prototype (FSM-1) Performance"
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- A-7.16 NASA TND-2819, "Development of a Sealed Brushless DC Motor"
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NASA TMX-63530: "Sealed Harmonic Reducer for Vacuum
Application: Tandem Testing - Design,
Assembly, and Operational Techniques",
February 1969

A-7.1

Summary

This report describes a series of tests set up to evaluate gold and Mo S₂ films as the lubricant for Harmonic drive transmission flexspline and circular spline teeth in a vacuum environment. The results obtained from a number of tests run in a specially developed tandem test fixture indicate that considerable additional development of dry lubricant films will be required to make the sealed Harmonic reducer reliable for continuous operation in the space environment. However, results offer considerable evidence that this drive can be used to advantage with gold plate as the lubricant - provided high speed operation is limited to initial or limited duration functions.

Application to NERVA

The Harmonic drive is applicable to the NERVA control drum actuator, particularly in a one-pass configuration with a stepping motor drive. An extensive development effort will have to be undertaken to find a suitable lubricant for the wave generator bearing as well as the flexspline. In NERVA the additional problems of radiation, cryogenic temperature, and stringent contaminant particle elimination requirements must be considered.

Personal contact was made with the author, B. W. Ward, and the work done at Goddard discussed in detail. This discussion is reported in Appendix A-7.23.

NASA TM X-53675: "Evaluation of Direct Current Motors
in Vacuum", November 1967

A-7.2

Summary

Three elements of a direct current motor were tested for operation in a vacuum. One element, the polyimide winding insulation, proved capable of withstanding the vacuum and temperatures to which it was subjected. A second element, the high speed rotor bearings, failed a number of times. The optimum retainer material appeared to be Teflon, which is unacceptable in the radiation environment of the NERVA reactor.

The third element, the brushes and commutator, exhibited arcing and chipping, causing both brush and commutator wear. The material giving optimum performance as brush material was a compact of MoS_2 and Ta. Even this material showed some wear. The behavior of MoS_2 is doubtful under radiation. The motor was operated unidirectionally at constant speed. This overlooked the changes in the transfer function of a position control motor due to changes in internal friction. The effects of cold welding of brushes and bearings in the static condition was also overlooked. Contamination of the bearings by brush chips was a problem leading to bearing wear. The optimum brush material for vacuum operation showed an increased wear when operated in air. This would raise the question of operation in high pressure hydrogen.

Application to NERVA

The brush commutated DC motor can be used in the control drum actuator of the NERVA reactor. Some precautions must be taken when using brushes however. A means must be found to restrict passage of the brush chips into bearings and feedback potentiometers. The motor should not be tested in air and its operation in hydrogen must be proven. Periodic maintenance of the brushes is required to extend the life of the actuator if its brush wear proves to be excessive. The operation of brushes in nuclear radiation and at cryogenic temperatures must also be proven.

ANL-7262: "Tests of Commutating Brushes for Use in DC Motors
Operating in a Dry Argon Atmosphere", Dec. 1966

A-7.3

Summary

The commutator brushes of a direct current motor exhibited rapid wear characteristics when operated in an atmosphere of dry argon. The wear was due to the lack of water vapor which acts as a lubricant for graphite brushes. A similar problem is anticipated with commutator brushes used on the NERVA reactor control drum actuators in a dry hydrogen environment.

The brush material which gave optimum results in the tests delineated in this report was a resin bonded carbon and graphite composite utilizing MoS_2 dry film lubricant. Motors using these brushes were able to operate more than 50 hours in the argon atmosphere. In one instance, however, the MoS_2 caused a buildup of a high resistance film on the commutator. The organic bonding resin of the brushes could undergo degradation under radiation. MoS_2 also has a corrosive effect when subjected to nuclear radiation.

Application to NERVA

A brush commutated motor can be considered as a candidate for the control drum actuator on the NERVA reactor. Due to the radiation environment in which the actuator must operate a substitute for the organic resin bonding agent must be found. The problem of an insulating film buildup of MoS_2 on the commutator must be overcome, perhaps by using the low resistance NbSe_2 as a substitute.

CG6-168: "Motor Evaluation Test Report for Mod II Slow
Speed Motor and Filter", March 1966

A-7.4

Summary

A motor, No. D1816 R&D unit, was tested in a hard vacuum (10^{-6} torr) for a total of 830 seconds running time as an endurance test at continuous rated torque. The motor survived this and an additional 1100 seconds of running time at ambient pressure. The brush and housing temperatures, of great concern in this test, did not exceed permissible values. However, discontinuities in the curve of brush temperature are indicative of the non-linear behavior of brush/slip ring parameters.

Application to NERVA

Development was for short life, extremely short relative to NERVA requirements, and incorporation in an actuator where reliability is attained through extensive redundancy.

CG6-143: "Motor Evaluation Test Report for Gimbaling Servo
Actuator Motor and Filter", Dec. 1965

A-7.5

Summary

Four brush commutated DC motors were tested under a hard vacuum (10^{-6} torr) and 3.5 psia for the purpose of failure mode endurance data.

The first motor failed after 12 minutes of running time due to overheated brushes and a "thrown" commutator bar.

The second motor was turned off and cooled at two-minute intervals. It failed after four minutes of running time due to loss of commutator film with resultant arching of brushes and disintegration of brushes.

The third motor failed after eighty minutes of operation at 3.5 psia due to melting of the solder balance band.

The fourth motor was force cooled with CO_2 to keep the temperature below 450°F at 3.5 psia. It was run for fifty hours; however, the motor performance was erratic and there was evidence of high friction loads on the commutator.

Application to NERVA

These motors were apparently tested in an effort to adapt a standard design to an Apollo application requiring a very short operating life. The brushes appear to have been of the ordinary carbon composition. This testing indicates where the starting point was in attempts to develop a space application DC motor.

A-7.6

1. "Development Philosophy for SNAP"

Summary

Discusses the direct approach concept to hardware development and describes steps taken in development of the SNAP reactor control system mechanisms. Philosophy based on concept that reliability is increased by the elimination of backup systems and by the reduction of the number of parts. SNAP 10 was designed from "scratch" with little regard to design precedent in similar programs, utilizing the end requirements and application of the basic physical laws.

Application to NERVA

The fewer parts-reliability aspect appears to support reliability considerations developed thus far in NERVA Actuator Design. General solution of an electrical stepping motor to meet the similar SNAP requirements lends sport to the independent study made in the NERVA selections.

2. "Lubrication of DC Motors, Slip Rings, Bearings, and Gears for Long-Life Space Applications"

Summary

The VAC KOTE lubrication system of Ball Brothers Research Corporation is described. The system involves the use of fluid organic compounds, solid films, and grease formulations. The theoretical principles involved in lubrication for high vacuum space applications is covered. Several types of mechanisms have been lubricated successfully, including DC torque motor brushes, in various space programs. Thin-film coatings of fluid organic compounds, containing metallo-organic complexes and long-chain hydrocarbon molecules are applied by vacuum processing and adhere to metal surfaces through molecular bonding. Solid film coatings, consisting mainly of molybdenum disulfide, are applied mechanically.

Application to NERVA

The solid film coating of MoS₂ shows promise, but has not been qualified for hard radiation or cryogenic temperatures, or the dry hydrogen atmosphere of the NERVA application. This lubrication technique is being considered for transmission and bearing lubrication and contact with BBRC has been established and preliminary data exchanged.

3. "A Brushless Despin Drive and Control for a Communication Satellite Antenna"

Summary

A resolver-commutated synchronous motor was developed for a satellite despin device. The drive employs a rotary transformer-type resolver which, when properly aligned, acts to commutate the synchronous permanent magnet motor.

Application to NERVA

Requirement of high frequency AC power, necessary to detect phase relationships, modulate and demodulate the control signal make this concept unattractive for NERVA application. It is interesting to note that the principle merit of this concept is stated to be that sliding electrical contact surfaces (brushes) can be avoided, enhancing confidence in a long mission lifetime objective.

NAA-SR-10725: "SNAP 10A Flight System Prototype (FSM-1) Performance",
May, 1965

A-7.7

Summary

Thermal-electrical performance tests were conducted with a full scale, nonnuclear flight system mockup. A major objective of this testing was the performance evaluation of the reactor control mechanism, consisting, in part, of permanent magnet rotor stepping motor actuator, brake and control system. The test was carried successfully to completion. However, a variation in rate of step was observed and determined to be due to pulse generating circuitry malfunction. The mechanical components of the actuator system functioned as per the design characteristics.

Application to NERVA

The stepping motor concept was similar to that proposed for NERVA and functioned well throughout the test; performance was essentially unaffected by the vacuum environment. Although designed to operate along an extensive temperature gradient, as will the NERVA actuator, the SNAP 10A actuator was optimized for operation at approximately 1000°F.

A-7.8

Summary

SNAP 10A system was launched in April, 1965, and operated successfully for 43 days at full power. The reactor was shutdown as the result of electrical failure in the supporting Agena spacecraft. The actuator system operated in all modes without fault. SNAP 10A was affected in a number of ways by the space environment, and in several cases the resulting change in system performance was measurable. Operation of the actuators following ejection of the core reflectors, to shut the reactor down, was carried out to establish the extent of self-welding phenomenon at critical reflector contact points. No significant self-welding took place at these points.

Application to NERVA

Performance of the permanent magnet stepping motor was proven in the hard radiation and vacuum environments.

A-7.9

Summary

Evaluation of the SNAP-8 prototype actuator system under simulated operating conditions was reported. The actuators are based upon the variable reluctance stepping motor. Change to the variable reluctance concept after successful development of the permanent magnet stepping motor of SNAP-10 was undertaken because of the higher temperature requirements of the SNAP-8 application. Problems were discovered in the areas of coil wire failure due to thermal cycling, electrical connector conductor failure due to spring relaxation of the contacts, and brake surface lubricant adherence difficulties. Modification of the design and change in materials are expected to clear up these problems and enhance reliability.

Application to NERVA

The problems arising in this testing were all associated with the high temperature environment. This will not be a consideration in NERVA. However, similar difficulties may arise from the cryogenic requirements.

A-7.10

Summary

Design margin tests and proof tests were conducted on actuators incorporating modifications of the original design of the SNAP 8 development reactor actuators. These actuators are electromagnetic, variable-reluctance, stepping devices with integral spring-loaded brakes. Life testing consisted of thermal cycling, endurance and static operations, and was completed successfully. Design margin testing disclosed several potential weak points involving conductor and insulation failure at high temperature off-design conditions. Design modifications were made in encapsulant, conductor and chip shield materials and cable and phase connections. Problems in each of these areas were related to high temperature operations.

Application to NERVA

Results of high temperature testing is not directly applicable to NERVA. However, procedure should be evaluated for use in developmental testing. Report indicates that emphasis should be placed on solid development of wiring materials and fastening techniques in NERVA. Open loop control proven in conjunction with brake.

NAA-SR-9898: "SNAP 10A Component Development Summary
Vol. I Control Components", August 1964

A-7.11

Summary

A permanent magnet rotor stepping motor was developed for SNAP 10A after a study of five different techniques for driving the control drums. Three of these involved solenoid operated mechanisms; the other two were stepping motors. The "Slo-Syn" principle was adapted in a stepping motor completely redesigned to function under severe environment conditions of radiation, hard vacuum and high temperature. A great deal of effort was expended in finding the best radiation and outgassing resistant materials. Bearing development resulted in use of a combination sleeve-ball, self-aligning bearing.

Application to NERVA

This is very similar in design to the motor proposed in the NERVA PM stepping motor design concept. The SNAP 10A motor drives the drum through a low ratio spur gear train, which is not an integral part of the actuator. A supplemental component, the clutch brake, is very similar to the brake proposed in the NERVA DC motor concept. A good bit of AI development involved survival at high temperatures, which is not applicable to the NERVA case. Testing in vacuum resulted in a number of insulation resistance anomalies. However, direct contact with the people who conducted this testing revealed that latter work established that most of these problems arose because of vacuum testing techniques.

A-7.12

Abstract

Two reactor control systems are described in this paper. One system is a control drum positioning actuator system which positions nine control drums either singularly or in unison in $.01 \pm .0005$ degree increments. The rate of drum positioning is 0.7 degree/second. The system is operated in open loop mode by commanding the actuator to step a predetermined number of steps and counting these command steps. By using up/down counters, the control drums can be positioned bi-directionally. To assure that the drums are moving in response to the command pulses, position potentiometers are used to give a coarse indication of the actuator output shaft position.

The second control system uses an actuator which positions two control drums in a $.1 \pm .005$ degree increments. In operation only one actuator is used at any one time and its velocity is limited to $10^\circ/\text{sec}$. The system operates in the closed power loop mode where control drum position is a function of the power produced by the reactor. The loop incorporates a non-linear control drum system gain which reduces the gain as power demand is increased.

Application to NERVA

Both systems described in this paper use a stepping motor similar to that considered for use in NERVA. The control drum positioning system is applicable to the R-1 control system provided that the drum positioner can be automatically controlled instead of manually controlled. The counting of command pulses may not offer the required reliability and a system to detect actual step accomplishment may be required. The second type of control system which controls on power error is not consistent with the current control drum actuator concept.

A-7.13

Summary

This report describes the design and testing of the SNAP-50 control drum actuation system. The system uses a digital stepping motor, a Harmonic gear reducer, a clutch and spring scram system, and a drum position indicator. The stepping motor was a permanent magnet rotor, two-phase bifilar wound stator motor which produced 1.8 degree per step. The stator coils were of Ceramic-eze magnet wire and potted in Allen PBX. The motors opened with no problems at temperatures below 600F, but at 800F insulation breakdown occurred. The Harmonic gear reducer was tested in both a vacuum and a helium atmosphere. The wave generator was rotated 1.4×10^8 times in a 10^{-8} torr vacuum and 9.6×10^6 times in a helium atmosphere. No problems with the Harmonic gear were experienced.

Application to NERVA

The digital stepping motor appears to be useable in the R-1 actuator provided a more reliable stator winding insulation material can be found. The Harmonic gear reducer is also adaptable to R-1 actuators.

AIAA Paper No. 66-557: "Nuclear Reactor Control with Stepping
Motor Actuators", June 1966

A-7.14

Summary

LASL developed a control drum actuator system utilizing a permanent magnet hybrid rotor stepping motor and Harmonic drive speed reducer. Primary concern was reproducing the drum position to 0.01° . The system was operated in the open loop mode with drum position obtained by counting algebraically the number of electrical pulses which step the motor. The safety philosophy was based upon limiting the pulse rate, which limits the rate of increase of reactivity. A scram system was provided in the form of an electrically-operated clutch, which decouples a control drum from its gear train and allows a spring to scram the drum. This system was developed for the Phoebe-2 ZEPO critical assembly.

Application to NERVA

This actuator design is very similar to the NERVA PM stepping motor concept, differences being the rotor construction and scram requirement. The emphasis in the LASL design was on reliability and safety. They drew upon the work done in developing stepping motor actuators at the Argonne National Laboratory (Advanced Reactor Experiment) and at Atomics International (SNAP 10A). The prime considerations in both of these actuators were reliability, compactness and simplicity.

NASA TN D-2108: "Development of a Brushless DC Motor
for Satellite Application", Feb. 1964

A-7.15

Summary

The Goddard Space Flight Center sponsored a program to develop a brushless motor with true DC motor characteristics. The resultant motor was a fair success; it compared favorably with conventional DC motors. The three-watt prototype motors have a starting torque of 2.7 oz-in and achieve fifty percent efficiency (.67 oz-in) at 3000 rpm, the speed chosen to reduce bearing and gearing problems anticipated in operation in outer space. This motor overcomes the fundamental limitations on the use of DC motors in spacecraft, brush life and arcing, by using photo-optical commutation.

This motor is inverted in comparison to a conventional DC motor in that the rotor is a permanent magnet and the stator is wound. Attached to the rotor is a light shield which serves to direct the light beam of the stationary lamp to a particular photo-diode as it rotates. When illuminated, the photo-diode conducts a current which is amplified and directed to the bases of a pair of switching transistors. These apply the power supply voltage to the proper points on the ring-type stator winding. Thus, this commutation action is identical to that provided by the conventional carbon brush and segmented copper ring, but performed without physical contact of moving parts.

Application to NERVA

Reliability of optical elements has not been established. The radiation environment of the motor in NERVA would preclude use of photo-diodes. The light source would be susceptible to vibration. This concept requires an intimate relationship of light detector and preamplifier electronics, subjecting these electronics to high radiation levels.

The physical motor configuration is identical to that of the proposed stepper motor (PM rotor, wound stator) with the exception of the commutation assembly. The electronic commutating of the stator signal is effectively the same as that of the stepper concept.

NASA TN D-2819: "Development of a Sealed Brushless
DC Motor", May 1965

A-7.16

Summary

This report extends the work reported earlier in NASA Technical Note D-2108. The motors developed in this work have reached efficiencies of 65%. A typical unit develops 0.25 in-oz of torque at 3000 rpm with a power input of one watt. An integral hermetic seal was incorporated to contain component outgassing and improve reliability. The state-of-the-art in electronically commutated DC motors has been advanced to a point where no performance or weight penalty remains relative to brush commutated DC motors.

Application to NERVA

The need to cool all areas of the NERVA actuator, due to gamma heating, precludes incorporating the seal as developed by GSFC. This report indicates that the brushless DC motor concept reliability now surpasses the mechanically commutated motor reliability in satellite environment.

NASA TN D-5265: "A Brushless DC Torquer-Driven
Reaction Wheel for Spacecraft
Attitude Control", July 1969

A-7.17

Summary

This device is a direct application of the technology developed at GSFC over the past decade in the brushless DC motor field. The motor is commutated photo-electronically and drives the load directly without intermediate gear reduction. The device is of a pancake design and contains all electronics internally.

Application to NERVA

The envelope size of a similar configuration optimized for CDA application would be too large to be employed on even an 18-drum basis. This device is heavier and requires more power than a brushless DC instrument motor type approach. In order to hold power requirements at constant speed down, the pancake envelope is necessary.

NASA CR 374: "Final Report for a Brushless DC
Torque Motor", February 1966

A-7.18

Summary

This document reports the design and development of a brushless DC torque motor capable of operation in a vacuum. The final design was a permanent magnet stepping motor utilizing an electromagnetic commutator. The design, when tested, exhibited the characteristics of a DC motor in that its rotational speed was a function of the torque loading. While the DC motor simulation is a more efficient utilization of the stepping motor (power consumption is a function of load requirements), it does however necessitate a more complex control system and its controller power stages, operating in the analog mode, consume power. Also, the increased number of parts and wiring connections required by the electromagnetic commutator reduces its reliability.

Application to NERVA

The motor described in this report can be considered as a candidate for the control drum actuator for the NERVA reactor. This motor will, however, require an increased number of parts over the conventional stepping motor. A greater number of wires between the motor and the controller is also required.

A-7.19

Summary

This report describes a brushless D.C. torque motor. The motor has a permanent magnet rotor and a wound stator. The motor shaft position is detected by a separate permanent magnet rotor and Hall generators which resolve the magnetic rotor position. The rotor position signals control current to the two-phase stator windings which produce torque in the motor. The purpose of the Hall generator feedback is to reduce ripple torque. The motor produces 20 oz. in. of torque maximum at 4 rpm. This torque and speed are equivalent to a power of 0.06 watts, and to achieve this output power, 70 watts are consumed. No information was given on the maximum speed of the motor.

Application to NERVA

The basic design of the motor is the same as a stepping motor with the addition of a rotor position sensor. This added complexity reduces the reliability of the motor. The Hall generators, which must be mounted on the motor shaft, are susceptible to nuclear radiation and thermal effects. The low torque and speed and the high input power of the motor make it less desirable than the present R-1 reference concept.

TR-6219

From : Actuator Design
WIN :
Date : October 17, 1969
Subject : Trip Report

ASTRONUCLEAR LABORATORY

TO: D. D. Armstrong
J. L. Burke
R. A. Clark
J. G. Gallagher
P. R. Greenaway
D. I. Hulbert
R. A. Kelly

W. P. Kovacic
R. W. Marttila
F. D. Retallick
K. L. Rieke
F. R. Spurrier
J. A. Swanson
D. C. Thompson

TRIP TO: Atomics International Division
 North American Rockwell
 Canoga Park, California

 IMC Magnetism Corporation
 Maywood, California

 Los Alamos Scientific Laboratory
 N4 Group
 Los Alamos, New Mexico

DATE OF TRIP: October 8-18, 1969

PURPOSE OF TRIP:

Atomics International - Discuss the development effort and problems encountered by AI in the design of the stepping motor actuators for the SNAP application.

IMC Magnetism Corporation - Evaluate IMC's design and manufacturing capability and discuss the work they have done on other space programs.

LASL - Discuss the stepping motor actuator work carried on at LASL and their experience with the motors in use on the PENE program.

All three of these organizations have had extensive experience in the construction and application of stepping motor drives in difficult environments similar to those to be experienced in NERVA. Identification of the problems encountered and solutions applied in their development efforts will be of significant value in carrying out development of the NERVA actuators.

1. Atomics International

Messrs. Clark and Jelovich of WANL/Large and Mr. V. Winter of WANL/NRDS met with Messrs. O. P. Steel, E. Matlin, L. Donelan and C. Bilibin of AI at the AI plant on October 8, 1969.

A short orientation was given AI presenting the NERVA requirements, environment, etc., and the present actuator study concept. AI described the development of the SNAP-10 and SNAP-8 actuators, the environmental problems encountered and solutions employed. The development efforts in those areas common to both the NERVA and SNAP actuators were covered in greater detail and a number of items directly applicable to the NERVA design effort discussed.

Design of the SNAP-10 actuator was based upon the Slo-Syn stepping motor configuration. This same motor was initially used in the WANL control drum actuator trade study. While satisfied with the ambient performance of the Slo-Syn, AI found it necessary to redesign, develop and qualify nearly all components of the motor to meet the stringent environmental requirements of the SNAP program. At the beginning of the AI program, a study of various alternate candidates led to elimination of the self-commutating DC motor in favor of the PM rotor electric stepper motor because of the stepper motor's simplicity and potentially greater reliability.

At the conclusion of the program, only the original stator laminations were retained. The major design changes applicable to NERVA are as follows:

- a. Rotor Construction - AI went to a solid end cap and hold-down nut configuration in place of the original laminated end cap and rivet construction. This was done for reliability considerations even though it entailed a slight degradation in performance.
- b. Shaft Construction - A titanium shaft utilizing integral bearing journal surfaces are coated with aluminum oxide and function in carbon graphite bearings contained in titanium end bells.
- c. Insulation - The prime concern of AI in all of their insulation development work has been survival at high temperatures as well as under radiation and hard vacuum. While NERVA will not see the high temperatures of the SNAP program, it will face a similar radiation and vacuum environment. As far as these two parameters are concerned, AI has found a number of commercially available materials which are suitable and agrees that WANL's tentative selection of polyimide is valid.

- d. The SNAP reactors utilize a heavy non-symmetrical drum which puts a requirement on the actuator to hold a significant torsional load between steps. Although AI had available a magnetic detent torque in the motor, they felt this insufficient for holding purposes and incorporated a solenoid brake to close unenergized and hold the drum in place. Because the NERVA drum is much more nearly symmetrical and a greater detent torque will be operating through a much higher reduction ratio, a brake will not be necessary to hold position.

The SNAP-8 actuator dropped the permanent magnet rotor concept in favor of the variable reluctance stepping motor concept. Increase of the temperature requirement precluded use of permanent magnet materials in the rotor and was the primary reason for the change to V.R. operation. This configuration also permitted the use of the same material for rotor, stator, shell and end bells, minimizing the effects of thermal expansion.

A new mechanism is presently being developed by AI to replace the explosive squib drum release actuator used in SNAP to lock the drums in the zero position during launch. The new mechanism, a slot, pin and cam arrangement, provides a positive lock of the drum unaffected by rotational loading.

Initial rotation of the control drum actuator removes the pin by means of the cam linkage and enables drum rotation. The lock can be re-energized upon shutdown by full rotation of the control drum actuator to the zero position. If a similar requirement for zero position positive drum locking arises in the NERVA program, application of the AI device or a variation of it should be considered.

A tour of the AI Actuator Lab. was conducted and various actuator components examined in detail. The environmental testing of a SNAP-8 actuator was observed. This testing consists of essentially quiescent operation in a high temperature, hard vacuum environment with very little dynamic operation, and so is not directly applicable to NERVA developmental testing.

2. IMC Magnetics Corporation

Messrs. Clark, Jelovich and Winter met with Mr. C. Conrad, Chief Engineer of IMC, at the IMC plant on October 9, 1969.

Following the presentation and discussion of the NERVA actuator concept, Mr. Conrad described several stepping motors built by IMC for space applications on the Mariner, Surveyor, Lunar Orbiter, OSO and other programs. The design and manufacturing capabilities at IMC were discussed at some length and a tour of the plant conducted.

It appears that IMC would be capable of manufacturing the motor components for the NERVA actuator; however, their lack of clean room facilities and extensive environmental test equipment will limit IMC strictly to the manufacture of motor components to comprehensive specifications.

3. Los Alamos Scientific Laboratory

Messrs. Clark and Jelovich met with Messrs. E. Brown and R. Strait of LASL at Los Alamos on October 10, 1969.

After bringing LASL up-to-date on the work being done on actuators at WANL and the latest NERVA control drum actuator concept, LASL's experience with similar devices was discussed at length. LASL has used the stepping motor and Harmonic drive in several applications. In an application functionally similar to NERVA, LASL uses a Slo-Syn/Harmonic drive configuration actuator to operate the control drums of their PEWEE nuclear studies reactor and PEWEE core furnace reactor. These reactors were toured and the actuator installation and control system examined in detail. Discussion of LASL's approach to control drum actuation established that they are wholly in favor of the electric stepping motor concept.

J. J. Jelovich
Actuator Design

V. E. Winter
NTO

Approved:

R. A. Clark, Jr.
Manager
Actuator Design

/mab

TR-6235

•ASTRONUCLEAR LABORATORY

From : Actuator Design
WIN :
Date : October 31, 1969
Subject : Trip Report

TO: D. D. Armstrong	R. W. Marttila
J. L. Burke	F. D. Retallick
J. G. Gallagher	K. L. Rieke
P. R. Greenaway	F. R. Spurrier
D. I. Hulbert	L. J. Sullivan
J. J. Jelovich	J. A. Swanson
R. A. Kelly	D. C. Thompson
W. P. Kovacik	H. Z. Vance

TRIP TO: Sigma Instruments, Inc.
 Braintree, Mass.

United Shoe Corporation
 Beverly, Mass.

Superior Electric Company
 Bristol, Conn.

DATE OF TRIP: October 15-17, 1969

PURPOSE OF TRIP:

Sigma Instruments - Discussion of design of Sigma permanent magnet electric stepping motors and to inform Sigma of our interest in their motors to get their reactions to some of our preliminary designs.

United Shoe Corp. - Discuss with United Shoe personnel the Harmonic drive transmission and to get some of their design inputs into our preliminary concepts and to get their evaluation of our preliminary concepts.

Superior Electric - To evaluate Superior Electric's Slo-Syn stepping motor and to discuss the adaptation of this design to a control drum actuator with Superior Electric's engineering personnel.

1. Sigma Instruments, Inc.

WANL

D. D. Armstrong	J. Field, Product Design Eng. Specialist
R. A. Clark	R. Gaylord, Section Head
R. A. Kelly	A. Jenney, Chief Electromechanical Engineer
	S. Knapp, Corp. Marketing Manager (part-time)
	F. J. vonMering, Product Manager

A short orientation was given to Sigma personnel presenting the NERVA requirements, environments, history of the program and program schedules, and several of the present actuator study concepts. Specifics discussed were the adaptation of a Wright concept stepping motor, Drawing 100E145, which was presented in the actuator trade study report. Also discussed was a later preliminary drawing of an electric stepping motor actuator employing a Sigma design as shown in Drawing 939J936. A question was asked as to the possibility of obtaining higher torques by making longer stepping motors and Mr. Jenney indicated that it would be possible and should prove to be no problem.

A possible long range consideration should be the use of Samarium cobalt magnets in the permanent magnet rotor. Samarium cobalt has an energy product of two times that of the best Alnico magnets and four times that of the magnets we have previously qualified for reactor use. A design could take advantage of this additional energy product by (1) increasing the rotor-stator gap while maintaining the same torque current relationship, (2) to reduce the current required with the same gap and torque, and (3) to increase the torque while maintaining the same current input and rotor-stator gap. This material was invented by G.E. under a government contract and is now being manufactured commercially by Raytheon Corp. and also is being manufactured by Phillips in Holland. Phillips makes their Samarium cobalt by an extrusion process and Raytheon makes theirs by a sintering process. A Raytheon data sheet on Samarium cobalt, No. PRP-2441-TL entitled "Information Package on Raytheon's Samarium Cobalt Magnetic Material" was given to us by Sigma engineers. Hamilton Watch is also doing preliminary investigations on this material. One disadvantage of the Samarium cobalt is that it does not lend itself to a cast rotor construction, but would probably have to have the magnets attached in some manner to a soft

iron rotor. This may prove the best technique in any event. The design of this stepping motor would probably be conducted using the conventional Alnico magnets while an investigation of the newer Samarium cobalt magnets was underway and at some point downstream in the program take advantage of the newer magnet material after more information was available concerning its properties, environmental capabilities, etc. Sigma did state that standards for the basic process in the manufacture of these magnets are available.

The question of driving a stepping motor using a constant current source was discussed and Sigma felt a reduced operating speed would be the result unless a relatively high voltage was available to initiate the current into the stepper motor windings. Sigma has worked with their motors using inorganics for the stator winding insulation. The sample of a stator using a glass encapsulement indicated that they mastered this technique and if necessary for radiation protection glass-type encapsulement could be substituted for the presently recommended polyimide. Using a glass encapsulement however, stainless steel clad copper wire would have to be used because of the high temperature process required for the glass encapsulation.

Another area that was discussed was assembly of the actuator at WANL and it was determined that assembly fixturing was necessary for insertion of the rotor into the stator to minimize chip generation during the insertion process. Many materials with different magnetic properties should be considered during the design phase. The four materials mentioned were Alnico V, Alnico VIII, Alnico IX, and Samarium cobalt. They recommended giving consideration to beryllium copper bearings in our design.

The visit was ended with a tour of the facilities. Very extensive clean room facilities were available at Sigma. The engineering department consists of approximately 20 engineers and they have a QC department which consists of approximately 25-30 people. The QC department has provided components and assemblies under the requirements of MIL-Q-9858 and NASA NPC 200-2 and 4. Total number of employees at the Braintree plant number approximately 1000. The visit with Sigma left us impressed with their capability and with their desire to be of assistance in the design of a NERVA actuator.

2. United Shoe

WANL

United Shoe

D. D. Armstrong
R. A. Clark
R. A. Kelly

J. Carlsen, Senior Development Engineer
D. Mansfield, Engineering Dept. Manager (part-time)
E. Scott, Assistant Marketing Manager (part-time)

The meeting was begun by a description of the history of the NERVA program including past experience, present concepts and present schedules. Environmental conditions were also discussed. United Shoe was made aware of our concept drawings 100E145 and 939J936, both of which make use of Harmonic drive transmissions. Several suggestions were made by Mr. Carlsen which will be incorporated into our preliminary design.

Mr. Carlsen indicated that there is much information available on the testing and use of Harmonic transmissions in many kinds of applications. One specific one was in a LOX actuator for the Centaur where a gold-plated Harmonic drive was employed. A reliability report on Harmonic transmissions is available and a copy was given to the writer. WANL expressed some concern as to the wear problems of a Harmonic transmission during an approximate 500 hour life test. Mr. Carlsen indicated the use of output revolutions is a meaningful method of determining life of Harmonic drives. He indicated that even for small outputs the input has no localized wearing pattern because with the high reductions each spline tooth makes contact with its mating tooth. For a lubricated application the life of the inner race of the elliptical bearing determines the life expectancy while for the non-lubricated application the spline teeth are the limiting feature. A report of some work done by B. W. Ward, Jr., of the Goddard Space Flight Center, No. X-723-69-31 entitled "Sealed Harmonic Reducer for Vacuum Application: Tandem Testing, Design, Assembly and Operational Techniques", was indicated as a source of information on Harmonic transmissions in a vacuum. These tests evaluated gold-plated Harmonic drives and Mo S₂ lubricating films.

Mr. Carlsen indicated that to his knowledge all Harmonic drives had been made out of their 300 series stainless steel with a few exceptions that had been made from Inconel. We left material data on stainless steel A286 for his evaluation. This material was recommended by our Materials Department as a good candidate for the flexspline when operating in a cryogenic environment. Several other contacts on uses of Harmonic drives in space environments were given to us by Mr. Carlsen. These are:

- a. Sonny Hooper, Ball Brothers, Denver, Colorado.
- b. Art Forster, Aerospace Corporation, El Segundo, California.
- c. Arien (drive for Apollo antennas).
- d. AGC W66 program.
- e. General Dynamics, San Diego, California (Centaur program).

Further discussions of adapting a Harmonic transmission to our control drum actuator indicated that the inner ball bearing race could be made integral with the motor shaft for minimum inertia. Mr. Carlsen also prefers a reduction on the order of 120:1 instead of our proposed 150:1 so that he can use larger teeth in his Harmonic transmission design. We agreed to send a copy of our concept drawing to United Shoe for their comments and recommendations concerning the adaptation of a Harmonic drive transmission. A tour of the plant followed the discussion. Clean room facilities were available although not specifically seen on the tour. The United Shoe QC department has provided components and assemblies under the requirements of MIL-Q-9858 and NASA NPC 200-2 and 4. We were favorably impressed with their capability and desire to offer assistance.

3. Superior Electric

WANL

D. D. Armstrong
R. A. Clark
R. A. Kelly

Superior Electric

E. Madsen, Product Engineering Manager
R. Palmer, Sales Manager

A description of our problem and potential solutions were given to the Superior Electric personnel and a discussion of our 100E145 and 939J936 concept layouts was held. Superior Electric people prefer the Slo-Syn concept which incorporates small step angles. They drive the Slo-Syn actuators using a series of four-step pulses. They indicated that they have applied Slo-Syn steppers to space applications, aircraft applications and underseas applications with customers such as Hughes, AGC, Gulf General, and LASL. Mr. Madsen indicated the failures of Slo-Syn steppers were only a function of ball bearing life. (Editorial comment: This indicated that Superior Electric does not have a real understanding of the inputs that determine an actuator reliability since all components have a potential for failure.) The Slo-Syn motor uses laminated

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Page 6

construction when high accuracy is needed, particularly for reversing where hysteresis is a problem. They do make sintering rotor designs, however. Some parameters on the design of their motor were: Alnico V magnets, radial air gap from .003 to .006 inches, non-grain oriented laminations using silicon steel, not possible to obtain over 10% detent torque with the Superior Electric methods and design.

D. D. Armstrong
Actuator Design

R. A. Kelly, Jr.
Quality Control

Approved:

R. A. Clark, Jr.
Manager
Actuator Design

/mab

A-7.22

TR-6247

ASTRONUCLEAR LABORATORY

From : Actuator Design
WIN :
Date : November 12, 1969
Subject : Trip Report

TO: D. D. Armstrong
J. L. Burke
J. G. Gallagher
P. R. Greenaway
D. I. Hulbert
J. J. Jelovich
R. A. Kelly
W. P. Kovacik

R. W. Marttila
F. D. Retallick
K. L. Rieke
F. R. Spurrier
L. J. Sullivan
J. A. Swanson
D. C. Thompson
H. Z. Vance

TRIP TO: AGC, Sacramento, California

DATE OF TRIP: November 5, 6, and 7

ATTENDEES:	<u>WANL</u>	<u>LASL</u>	<u>SNPO-C</u>	<u>AGC</u>
	R. A. Clark	E. Brown	L. Rizzolla	A. Cornell
	P. R. Greenaway			E. V. Hill
				L. Johnson

PURPOSE OF TRIP:

1. To coordinate and discuss the mechanical interface between the CDA and the pressure vessel closure to determine with AGC the best method of providing this interface.
2. Discuss with AGC preliminary concepts of the interface between the SSCVA and the SSCV.
3. Obtain information and to review hardware used on the Apollo fourth stage gimbal actuator for its adaptability in the NERVA program.

DISCUSSION:

1. A discussion was held around WANL Drawing 939J976 titled "Development Control Drum Actuator and Malfunction Override Device, Layout of". The discussion centered particularly about the mechanical interface between the actuator and the pressure vessel closure but some indoctrination was given to AGC personnel on the contents of the CDA and the actuator

malfunction override device (MOD). AGC was favorably impressed with what they termed an excellent design job on an actuator. They liked the extremely small-size closely integrated package and were also impressed with the MOD which uses the center of the drive shaft as a storage volume for the return springs. AGC is also considering the use of Harmonic drives in some of their actuators so that work in this area will be closely coordinated so that AGC's work complements WANL's work. The interface shown on the drawing is integrally machined as part of the pressure vessel closure with a V-band type clamp making the final mechanical joint between the CDA and the pressure vessel closure. WANL pointed out that the pressure closure side of the joint is a flat surface whose main requirement is a high quality surface finish since it is a sealing surface for the main actuator apex seals. AGC felt that this approach was much simpler than welding an intervening pedestal to the pressure vessel and indicated that it is acceptable from their point of view. The small size of the actuator also makes their job of providing a thrust structure much easier. Previously shown large actuators left little room between actuators for thrust structure members.

In general, they were very favorably impressed, and I think that this coordination meeting was a preliminary step to very good interface design and to close coordination with AGC.

2. Discussion centered around WANL Drawing 914E665 which is a WANL concept drawing showing a control drum type actuator mounted with a V-band clamp to the AGC structural support coolant valve. Since the AGC valve drawing did not show any interface, this drawing was used for discussion purposes. Alignment between the bearings in the valve and the bearings in the actuator may require a short drive shaft with crown splines at either end. The V-band type clamping arrangement was also acceptable to AGC. An unofficial copy of 914E665 was left with AGC for their continued valve work and a copy was also given to Mr. Rizzolla of SNPO-C at his request.
3. A review was held of the Apollo fourth stage gimbal actuator which is used to position the thrust vector of the engine in the pitch and yaw axis after the vehicle has oriented in the proper roll angle. Actuator operation is only during engine firing which totals about 20 minutes firing time. Each pitch and yaw actuator contains two redundant D.C. motors manufactured by EEMCO. These motors run continuously at a relatively constant speed between 13,000 and 9,000 rpm. Each electric motor

drives two magnetic particle clutches. These clutches are then connected to the nut of a ball screw which gives a linear output of about $2\frac{1}{2}$ inches through a bellows seal. Two tachometers separately mounted provide stabilization to the system and two linear differential transformers provide redundant position feedback information. Each motor in the actuator requires about 385 watts during operation.

The guidance system for this actuator is an IBM computer. A "D" to "A" converter supplies an analog output to a Minneapolis-Honeywell amplifier which then controls the speed and direction of the output motion of the gimbal actuator. In general, the D.C. motor is running in a controlled environment since its package is a welded box.

E. V. Hill was the designer of this actuator on the Apollo program and he since has transferred to the Actuator Group in the NERVA program. He stated that his choice of D.C. motors on certain types of on-off valves has been misinterpreted as a blanket recommendation for the use of D.C. motors on all actuator applications. He stated that this is definitely not true and he feels that the selection of a stepper motor for the CDA is the proper way to go.

Following these discussions, a tour of the AGC Cryogenic Test Facility and some of the NERVA test stands was conducted by AGC personnel. The cryogenic facilities are used primarily for relatively low flow tests where a quick turnaround and short schedule are necessary. The SSCV will probably be tested in this facility. However, the high pressure supply dewar will have to be modified or replaced to provide higher quantities of fluid necessary for the tests. A tour was also made of the actuator test lab where Apollo gimbal actuators are currently being tested.

WANL was asked, in particular, to review for all of those persons at the meeting the results of the latest findings in the actuator studies with particular emphasis on recent trips to manufacturers and other sources. In compliance with their request, Mr. Clark presented a synopsis of the recent trips to USM Corp., Sigma Instruments, Superior Electric, IMC Corp., and Atomics International, and related study results.

P. R. Greenaway

Approved:

R. A. Clark, Jr.
Manager
Actuator Design

/mab

TR-6247

From : Actuator Design
WIN :
Date : November 12, 1969
Subject : Trip Report

ASTRONUCLEAR LABORATORY

TO: D. D. Armstrong
J. L. Burke
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D. I. Hulbert
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DATE OF TRIP: November 5, 6, and 7

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P. R. Greenaway

Approved:

R. A. Clark, Jr.
Manager
Actuator Design

/mab

TR-6253

From : Actuator Design
 WIN :
 Date : November 20, 1969
 Subject : Trip Report

ASTRONUCLEAR LABORATORY

TO: D. D. Armstrong	R. W. Marttila
J. L. Burke	F. D. Retallick
J. G. Gallagher	K. L. Rieke
P. R. Greenaway	F. R. Spurrier
D. I. Hulbert	L. J. Sullivan
J. J. Jelovich	J. W. Fisch
R. A. Kelly	D. C. Thompson
W. P. Kovacik	H. Z. Vance

TRIP TO: Goddard Space Flight Center, Greenbelt, Maryland

DATE OF TRIP: November 12 and 13, 1969

PURPOSE OF TRIP:

1. Meeting with Goddard engineering personnel to discuss the work done there in the application of D.C. motors to spacecraft drive mechanisms, and the present NERVA control drum actuator design.
2. Discussion of the experimental test work done at Goddard in lubrication of Harmonic drive transmissions for use in space environment, and the applicability of those test results to the NERVA Harmonic drive transmission configuration.

ATTENDEES:

WANL

J. L. Burke
 J. J. Jelovich

Goddard

H. E. Evans*
 R. Fulcher
 R. A. Studer
 C. E. Vest
 B. W. Ward

*Manager of Mechanical Systems Branch.

1. The NERVA CDA application was presented and the trade study background and present design approaches discussed. Discussion was based upon WANL Drawing No. 939J978.

The overall design approach was well received, particularly the integration of components into a simple compact configuration. In discussing key areas of the design, unanimous agreement was reached upon the transmission being the most critical element in the design and the one which would require the greatest development effort, regardless of the type of transmission chosen.

Mr. Studer described the work done at Goddard over the past decade in developing D.C. motors for use in space applications. The D.C. motor has been the basis for space application because of its high efficiency, relatively small size and simple power requirements. It is especially suited to operation from the type of power available in satellite packages (i.e., batteries, solar panels, and fuel cells). Although the majority of the motors developed have been for torquing applications (despin devices, reaction wheels, etc.), a number of instrument servos have been developed.

In the initial design efforts undertaken by Goddard, all motor configurations were considered. The series D.C. motor, while theoretically the best suited for spacecraft application, has several major shortcomings which severely limit its applicability. Significant among these are the unreliability of mechanical commutation and rotor heat dissipation. Goddard has managed to retain the general characteristics of D.C. motors in developing the "brushless D.C. motor". This motor which is now the prime drive device in scientific satellites is basically an inverted permanent magnet field D.C. motor, commutated optically. In this configuration a P.M. rotor modulates a light source, effectively monitoring shaft position. The resultant light signal, received by photo-electronic sensing elements, is processed by solid state electronics contained within the motor housing and used to commutate the stator electromagnetic field.

Mr. Studer and Mr. Fulcher were asked if they agreed with the flat statement that mechanically commutated motors were not suited to operation in the space environment. They replied in the affirmative indicating the development of such a motor would require a major research and test effort involving a great deal of time and money, particularly in the area of brush lubricant.

In critical analysis of our present design, the duty cycle and reliability requirements of the NERVA CDA, Mr. Studer and Mr. Fulcher stated that they felt it an ideal application for the P.M. rotor stepping motor. The use of just such a motor by Hughes Aircraft Corp. in the solar panel orientation system of the Surveyor lunar probe was discussed. The duty cycle of that motor was very similar to the NERVA duty cycle. As an alternative approach, the utilization of the Goddard brushless D.C. torque motor was discussed. This concept would apply direct drive to the load, eliminating the critical transmission system. However, the motor is of pancake configuration, much heavier and with greater power consumption than our present design, and also presents the reliability problems of optical commutation. The instrument servo-size brushless D.C. motor developed by Goddard is more applicable to NERVA, but as Mr. Studer pointed out, its construction is identical with that of the P.M. stepper motor with the addition of optical commutation in place of remote electronic commutation. The optically commutated motor is best suited to continuous operation and not the intermittent operation of the NERVA application.

The malfunction override device was described and the critical areas of the design discussed. Mr. Studer and Mr. Evans have had experience in the development of similar ball-detenting devices in arming and fusing mechanisms and pointed out areas which will require detailed analysis before the final design is set out.

2. The NERVA CDA application was described and Drawing 939J978 presented with emphasis upon the transmission system. The work done at Goddard in operation of the small hermetically sealed Harmonic drive unit with various lubricants was discussed in detail. In summing up the results of their testing, Mr. Ward made the point that the device can be used successfully in reducer applications where needed lifetimes are of short duration. These include space applications where the operation is limited to initial functions of limited duration or intermittent duty functions. This reducer has been used in the GSFE "in flight friction and wear tester" which has been run a few minutes a day for over a year in space.

In general, both Mr. Ward and Mr. Vest were pessimistic about the results of their testing. None of the results obtained with dry film lubrication can be termed good by conventional standards of long-life gear head operation. Oil-lubricated testing was totally successful with no deterioration of performance in 12,500 hours of operation at

600 rpm. This result demonstrates the adequacy of the basic mechanical design of the unit when sufficient lubrication is provided. This rate of 600 rpm was the standardized speed, representative of typical satellite applications, used in the latter most significant Harmonic drive testing at Goddard. In contrast, the maximum speed which will be encountered in the present NERVA design is 200 rpm, a significantly favorable factor in wear.

The difficulty in applying a Harmonic drive in space environments arises strictly from the attempt to lubricate the spline teeth with dry lubricants which are poorly suited for that purpose. The best approach as determined by GSFC's testing and the one used in the friction and wear tester is a comparatively thick gold plating (200-300 micron-inches). In addition, Mr. Ward feels that certain changes in materials offer promise. A greater hardness on both the flexspline and circular spline teeth would be desirable. For the circular spline, a change to high carbon steel (1-2%) with a titanium carbide treatment would give the surface an extreme hardness. For the flexspline a "Kanigen" (nickel base) plating would raise the hardness to Rockwell C 60-70. In combination with the conventional gold plating, this technique should yield improved results.

All of the people at Goddard concerned with the Harmonic drive testing stressed that this testing was limited to the small, commercially available, sealed unit and only a few lubrication approaches. They pointed out that the WANL design Harmonic drive is significantly different in the areas of tooth flexure stress, size and configuration. The lubrication problem may be more easily handled in our design, particularly in combination with the more favorable performance requirements of the P.M. stepper motor. They felt that WANL should not be discouraged by Goddard's test results, but should pursue development of the WANL Harmonic drive design to the point where its reliability in the NERVA application can be established.

Mr. Vest related that in developing alternate approaches to the Harmonic drive reducer they have been seriously considering implementation of the planocentric gear set, and suggested that we consider this transmission for the NERVA CDA application. This configuration has the advantage of all rigid construction and relatively large gear teeth, permitting use of burnished dry lubricants. In the planocentric gear set a fixed internal tooth gear meshing with an eccentrically mounted external tooth gear, only slightly smaller, provides a high-reduction, high-torque drive

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November 20, 1969
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for in-line shafts. Input is to the eccentric shaft and output is taken from the pinion through a pin coupling which permits radial displacement. Under favorable conditions, efficiency of planocentric gears may be greater than 90 percent.

Although some work is being done in the development of high performance planocentric gearing at Goddard by Prof. C. Hayleck of the University of Maryland, the principal development effort in this area is being carried out by the Laboratory for Atmospheric and Space Physics at the University of Colorado under Prof. R. W. Burgess.

J. L. Burke

J. J. Jelovich

Approved:

R. A. Clark, Jr.
Manager
Actuator Design

/mab

A-7.24

TR-6287 ←

ASTRONUCLEAR LABORATORY

From : Actuator Design
WIN :
Date : January 6, 1970
Subject : Trip Report

TO: D. D. Armstrong
J. L. Burke
J. W. Fisch
J. G. Gallagher
P. R. Greenaway
D. I. Hulbert
J. J. Jelovich
R. A. Kelly

W. P. Kovacik
R. W. Marttila
F. D. Retallick
K. L. Rieke
F. R. Spurrier
L. J. Sullivan
D. C. Thompson
H. Z. Vance

- TRIP TO:
1. NRDS - For the disassembly, inspection and evaluation of a number of XE-Prime pneumatic control drum actuators.
 2. TRW - To discuss with engineering personnel the design aspects, application and operating experience with a high ratio wobble gear transmission.

DATE: December 7-12, 1969

- ATTENDEES:
1. WANL - R. A. Clark, R. A. Kelly
NTO - V. E. Winter
 2. WANL - R. A. Clark, R. A. Kelly
NTO - V. E. Winter
TRW - E. Alexander, Product Design; D. Bull, Electro-mechanical Design; R. Cagle, Product Design Manager; F. Koehler, Laboratory Manager; R. M. Weiner, Application Engineering
1. NRDS - In a semi-clean room established in the high bay assembly area in the E-MAD Building at NRDS, five XE-Prime pneumatic control drum actuators were completely disassembled, examined, photographed and evaluated for any signs of wear or malfunction during their lifetime of testing since leaving WANL.

The five actuators disassembled were Drum Position No. 9, Serial No. 73367; Drum Position No. 1, Serial No. 73377; Drum Position No. 3, Serial No. 73359; Drum Position No. 2, Serial No. 73358; and Drum Position No. 11, Serial No. 73370. Disassembly of the Drum No. 9 actuator proceeded as follows. All external safety wire was carefully cut and removed from the actuator. The potentiometer cover, servovalve cover, P-1 cylinder cover, P-2 cylinder cover, and the rack backup bearing cover were carefully removed. Several photographs were taken at this stage of the disassembly. No observed anomalies were noted. The P-1 and P-2 pistons and cylinder liner were next removed. The servovalve and manifold assembly, lock solenoid, lock pin and lock position indicating microswitches were also removed. The potentiometer was carefully removed after cutting the wires which provided inputs to the potentiometer. No sign of damage was evident on any of the wires to any of the components in this actuator. The shaft assembly, including the potentiometer shaft, soft stop spring, pinion, coolant filter and bearings, were next removed. A careful examination of the gold-plated pinion shaft bearings showed no signs of flaking of the gold-plating and no signs of wear in the bearings. Both upper and lower bearings rotated smoothly and evenly. All separate parts on the actuator were photographed in an exploded view fashion. No anomalies or unexpected signs of wear were noticed during the disassembly of this actuator.

The above procedure was followed with the remaining four actuators with the same typical results; that is, no unexpected signs of wear and no anomalies were noted. All of the lock cams showed evidence of normal scratches which were caused by the lock pin riding on the surface of the lock cam during scrams of the actuators. This is to be expected and the scratching was not excessive. On the actuator in Drum Position No. 3, a heavy build-up of a brown oxide type was noticed on two teeth at the end of the rack. This oxide build-up was in such a position on the rack so as to be out of the normal engagement area between the rack and pinion. This appeared to be a rusting type oxide and indicates that maybe the black oxide protective coating used on these gears is not adequate for use downstream in the NERVA actuators. Tiny pieces of brass were noted in some of the cylinder covers. These would not affect the operation of the actuator and it was determined that they came from the flow resistors which were placed in each actuator in the passage between the servovalve and the cylinders. Similar types of chips were obtained from some actuators in the lab and it must

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be postulated that these have resulted from insufficient cleaning of the flow resistors. Exploded view photographs were taken of all of the disassembled actuators and these photographs will be included in the XE Topical Report on the performance of the XE-Prime actuators to be issued at a later date.

2. TRW - The trip was taken to TRW to discuss with the design personnel the application of a wobble gear transmission in an actuator used on the OGO satellite. This actuator uses a very small DC motor as the prime mover. The motor contains a gear head with a 99:1 speed reduction. The output pinion of this gear motor drives a large ring gear giving an additional reduction of 6:1. The ring gear then drives the wobble gear of the wobble gear transmission. The general output speed of this actuator is about three degrees per minute, which is considerably slower than our standard design speed. The wobble gear transmission is a method of obtaining a high gear reduction through a single-phase gear train. Its basic principle is not unlike the Harmonic drive, but the mechanism of providing the reduction does not use a flexible gear member. In this transmission, the axis of one gear is not parallel with the axis of the other gear, so that the two gears mate at only one place on the gear faces. As an input motion is imparted to the wobble gear, its wobble action, combined with the different number of teeth between the output gear and the wobble gear, causes the output gear to move at a speed reduction by the amount of the gear reduction. In this design, the wobble gear was made from a stainless steel and the output gear was a sintered bronze material impregnated with molybdenum disulfide. It was designed to provide an output torque of 600 in-lbs but upon test failed at above 2000 in-lbs. The small gear motor used standard gear lubricants and their life test was terminated because of a failure in this small gear head. The failure was attributed to a "gumming" up of the grease lubricant and after cleaning and relubricating the unit again functioned properly.

After this discussion, a tour was made of the TRW engineering laboratory to see cutaway models of this actuator, operating models and laboratory test models. An interesting sidelight of this trip was a discussion with the laboratory supervisor (F. Koehler) concerning some life testing on plastic film potentiometers. They have had problems with noisy potentiometers after operation. We have had this problem where feedback potentiometers develop a noisy output after being oscillated for varying periods of time. Although we have never isolated the

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problem, TRW succeeded in capturing the offending material and have determined that it is the binder that is used in the manufacture of the potentiometer track. Identification of the material showed it to be butyl cellusolve acetate and, upon contacting potentiometer manufacturers, it was found that this material is used in the manufacture of all potentiometers. TRW also has experienced problems with their potentiometers developing noise and we were able to help them as a result of some of our lab testing by indicating that the time taken to develop the noise problem is very dependent upon the lack of moisture in the potentiometer environment. Our testing indicates that potentiometers become noisy more quickly in any dry atmosphere as compared to atmospheres containing small amounts of moisture.

Some discussion was held concerning TRW's interest in supplying wobble gear transmissions in the event that this transmission is selected as a result of our trade study. They are more interested in the design aspect than in the hardware aspect but indicated a willingness to evaluate the possibility with their management. They also indicated that the wobble gear is proprietary to TRW, but I think that this is not true since this was developed under government money and has also been used in various other applications. They have agreed to send us available literature and reports as documentation for our use in evaluating the wobble gear transmission.

R. A. Clark, Jr.

Manager

Actuator Design

/mab

A-7.25

WANL-TR-6336
D. Armstrong and
R. A. Clark, Actuator Design

From :
WIN :
Date : February 11, 1970
Subject :

ASTRONUCLEAR LABORATORY

TRIP REPORT

TO: J. L. Burke K. L. Rieke D. C. Thompson
J. G. Gallagher F. R. Spurrier H. Z. Vance
P. R. Greenaway L. J. Sullivan R. A. Kelly
D. I. Hulbert J. W. Fisch
J. J. Jelovich W. P. Kovacik

DATE: January 26, 1970

PLACE: Beckman Instruments Company, Helipot Division, Fullerton, California

PURPOSE: To discuss with Beckman the specific designs to meet our integrated package.

Attendees: Beckman: P. Porath, Regional Sales Supervisor; L. Al-Rawi, Supervisor, Conductive Plastics Section. WANL: D. Armstrong, R. A. Clark.

The meeting was begun by a general description of the NERVA Project, the NERVA control drum actuators, and the need for and the use of a reliable potentiometer for feedback signal. A summary was given of the potentiometer testing being conducted at WANL at the present time. Mr. Paul Porath of Beckman indicated that all conductive track potentiometers are made of a Diallyl Phthalate material which is used as the basis of all manufacturing. Slight differences in composition are the only differences between manufacturers. The substrate is basically the same material with the conductive track formulation sprayed on to provide the desired resistance. The completed potentiometer track is then formed in an oven under pressure to stabilize the resistor. Each track can be individually trimmed on an automatic servo controlled machine if tight tolerances are required. Linearities on the order of 0.025 percent are obtainable with this trimming. In the trimming process, the width of the track is varied on a continuous basis to obtain the specified linearity, and the 0.5 to 0.25 percent linearity which we have used in the past will present no problem, particularly on the larger diameter potentiometer shown in our conceptual designs. On previous designs where a 1-inch potentiometer was used, this linearity specified was somewhat of a problem.

The large shaft bearings that we show in our designs can be used as potentiometer bearings and should give no problems. One problem that Beckman did see was that their largest element to date has too small a hole in the center to accept our shaft; however, new tooling could correct and accommodate this problem.

The quality control from a cleanliness standpoint appears to be very poor during manufacturing. Beckman's experience has shown that assembly in a clean room as opposed to assembly in a standard manufacturing area has a negligible effect on their reject rate, and as a result, they perform no assembly under clean room conditions. They also stated that they have no clean facility in this particular plant, but one is available in another facility in the area, if required. We also noticed that during the process the girls who were making the potentiometers handled them indiscriminately.

At present, an epoxy formulation is used to bond the element to the aluminum housing. We indicated that this was probably not an acceptable method and that some more positive means such as riveting should be employed.

Beckman is now experimenting with ceramic substrate of a steatite composition and spraying Diallyl Phthalate material on to provide the resistive track. We mentioned the possibility of using cemet material, but they expressed concern with the linearity and noise problem that is usually associated with this type of potentiometer. The terminals are connected to the potentiometer track using a slurry of epoxy and silver.

In our integrated design, Beckman preferred that we supply the output shaft and bearings to which they would then assemble and align the potentiometer since we are in a better position to supply this gearing than they are. They also indicated that they can deliver on about a 120 day basis and should have no trouble maintaining this type of schedule.

The immediate program is for WANL to send a drawing to Beckman so that they might insert their ideas for a potentiometer in a first iteration of the detailed design process.

DATE: January 27, 1970

PLACE: Thomas Barish, Consultant, Van Nuys, California

PURPOSE: To obtain Mr. Barish's opinion on our design concepts with advantages and disadvantages of all, and if possible, obtain a recommended selection.

Attendees: Consulting: T. Barish; WANL: R. A. Clark, D. Armstrong

We opened the meeting by describing to Tom Barish the various concepts of transmissions that are under consideration for application to the control drum actuator. The types described were spur gear, Harmonic drive, differential internal planetary, Wabble, and worm.

T. Barish described in general terms that as the ratio of a single step increases the efficiency of transmission decreases. As an example, he cited a single step, spur gear with a 6/1 reduction would have about 1 percent loss. Two steps in series would therefore have a 2 percent loss; whereas if a 36/1 reduction was taken in one step, the losses would be on the order of 6 percent or three times that of a two-pass spur gear.

We also discussed the application of an actuator to the SSCVA. We talked in general about active and passive redundant systems, and T. Barish stated that from his experience, it is necessary to periodically exercise a passively redundant system to obtain the increase in reliability desired, so he feels that an actively redundant system, where both actuators would be in operation continually, would give us an improvement in reliability over the passive system. The following comments were made regarding each specific transmission concept.

Epicyclic

Tom Barish liked this concept because of its simplicity, but he noted that the output load is seen by both meshes in the transmission. Therefore, estimated losses would be on the order of 40 percent for this concept. He recommended a slight modification to this transmission by employing a standard planetary gear with a sun gear driven by the motor and three planet gears on a carrier driven by the sun gear. This would provide the first reduction. The second reduction would be obtained by driving the planets inside two internally cut gears with a difference in the number of teeth on the internally cut gears. This can be done by mating the planet gears at a different pitch diameter on each of the internally cut gears. This is possible if the number of teeth difference in the two gears is small. In this case the difference must be divisible by three in order to properly mate simultaneously with the three planets. By employing this technique, the pitch angle at which the planet gears contact the internally cut gears will be different. He feels that by making this modification to our standard single pitch, eccentrically driven epicycle we can reduce the losses by about half or obtain a resulting efficiency on the order of 80 percent. He also stated that our reduction of 150/1 falls right in the middle of the best operating region for this type of transmission. He feels that the reduction in losses will result in an increase in reliability which will more than offset the reduction in reliability caused by the high number of parts in this design over the epicycle; specifically, more bearings to support the planet gears are necessary. Bearing loads are much reduced and therefore bearings are more reliable because the planet gears operate in a balanced mode. A decision has to be made as whether ball bearings or needle bearings should be used to support the planets, although a large increase in size would probably be required in order to get ball bearings of a sufficiently large size in this design.

Hamonic Drive

Mr. Barish feels that this is an ingenious design, but presents "hair-raising" engineering problems. This design has lower losses than other single-step, large reductions; however, he feels that the design and application of this type transmission is an art rather than a science. If we decide to employ this transmission, he strongly recommends the selection of a standard design which they have tested extensively, because Tom believes that the birth pains with a new design could be extremely severe. The possibility of an incurable problem with a new design would be very probable. He feels that it is impossible for us to calculate the stresses in this design and that we would have to rely on USM in this area. One strength of this design is the use of gear contact at two diametrically opposite positions. A disadvantage is that the ball speed varies with rotation and the balls tend to climb into each other causing higher losses.

Wabble Gear

Although this is a good design, he feels that you can do the same thing with internally cut gears. This design is very sensitive to thrust loads and the control of axially tolerancing is very difficult. He feels that our design as presented will not work reliably because of the single bearing support for the Wabble gear. (We also realize this but have not taken time to change the concept drawing.) The load at the tooth diameter is way off center and a second bearing must be added to support this load. He noted that our two gears rotate on conical surfaces which are flat. He recommended crowning one surface for better operation, and this surface should be designed for a particular Hertzian stress. The major difference and advantage of this design over internal gears is that it allows a smaller difference in number of teeth, therefore providing for a greater reduction with a single mesh. He feels that we should stick with simple known gearing and that our environment problems are enough to tackle without trying other unknown designs. The losses in this design, he feels, will fall between the differential planetary and the epicycle planetary, and he recommends the use of spiral bevel gears with tip relief. As a general philosophy, Tom Barish recommends the use of 32 pitch gears or larger, if possible, because of the ease in inspection associated with larger gearing.

AGC has employed a Wabble gear transmission with a 80/1 reduction in their TPCV pneumatic actuator as built by Bendix.

Spur Gears

Tom noted that our spur gear concept was a three-pass system with two internal meshes. He feels that internal gears in general are difficult to make and that they must be fashioned blind unless they are completely open and can be broached. In this design, the face should not exceed 3/4 of the diameter because of gear twisting and deflection. Special techniques must be employed to insure minimal localized contact. All loads and deflections must be taken into account in the gear designs. He would modify this design to employ only one internal mesh as an output. The first stage would use a very small pinion with a large reduction 8/1 - 10/1, then go to a planetary, probably two stages. An all spur gear transmission is normally only used on extremely

small jobs where the amount of torque output is negligible. Clock transmissions fall into this category. Where any amount of power is to be transmitted, it is preferable to use planetary stages. For our purpose, he suggests two spur gear stages 7/1 and 5/1, then a planetary with a 4/1 ratio. On all transmissions, he would recommend a run-in period with light loads to increase life and reduce wear.

Worm Gear

We spent very little time on this design since he felt that the losses would be on the order of 70-80 percent, and he feels it is completely impractical for our work, particularly when the environmental conditions and the nonlubricated application is considered.

A copy of Tom Barish's report is an attachment to this trip report.

DATE: January 28, 1970

PLACE: Bourns Inc., Trimpot Products Division, Riverside, California

PURPOSE: To access possibilities and desirability of engaging in cooperative efforts by Bourns and WANL to develop potentiometer component of control drum actuator.

Attendees: Bourns: P. Pataky, Director, Product Sales; R. Monty, Manager, Quality Control; W. Jones, Director of Engineering; A. Zimmer, Sales Engineer Specialist. WANL: D. Armstrong

A brief orientation was presented to those personnel representing Bourns, outlining the NERVA and control drum actuator programs. The actuator layout 937J978 incorporating WANL's conceptual potentiometer configuration was examined. Environmental conditions, life requirements and electrical specifications were discussed with particular attention given the problem of localized resistance track wear in a dry gas and vacuum environment.

Four alternative track materials are employed by Bourns in the manufacture of their precision potentiometers; these are wire wound, cemet, conductive plastic and "Bi-film".

Mr. Pataky stated that a wire wound configuration would be made that would satisfy our linearity and resolution requirements.

The conductive plastic is believed to be chemically similar to the material used by Markite, and as such, would be likely to qualify for the radiation environment. Mr. Pataky expressed the view that a more definitive comparison of the chemical properties of these materials could be obtained and provided to WANL.

The more recently developed "Bi-film" material was recommended as having the most desirable properties of both the cement and conductive plastic materials.

It was stated that the 0.25 inch deck height was no problem and that a height of less than 0.20 inch could be made if necessary.

It would be acceptable to Bourns that the shaft, bearings, and end bells be supplied by WANL if we felt that was desirable.

A short discussion with Mr. Jones, Director of Engineering, produced the impression that he is both interested and knowledgeable in the problem area connected with accelerated wear occurring under dry gas operation. He expressed the view that a change in the material of the wiper contact finger could do much toward extending the life under these conditions. It is his belief that our experience, indicating that airborne moisture is important to wear, is due to the combination of such moisture with the small molecules that are fed to the surface of plastic materials to form a lubricating substance, and that this function could be supplanted by incorporating wiper contact finger materials of proper chemistry.

A short tour of the manufacturing facilities left a generally favorable impression; "dirty operations" such as moulding are performed in isolated areas, and other operations are performed in apparently neat, clean and well-equipped areas. Final assembly cleanliness is limited to that obtainable in a class 100 clean booth (Federal Handbook 117). Mr. Monty, Q.C. Manager, expressed the view that if our needs required a clean room, one could be constructed for approximately \$4500. He said that their Q.C. procedures are in conformity to Mil Q 9858-A.

It was tentatively agreed that WANL would supply a concept layout drawing marked to indicate restraining dimensions from which Bourns could establish a detailed configuration layout as a basis for prototype purchases.

DATE: January 28 and 29, 1970

PLACE: Aerojet-General Corporation, Sacramento, California

PURPOSE: To present our design concepts for a CDA and to discuss AGC's thoughts and design concepts on their valve actuators.

Attendees: AGC: L. Johnson, E. Hill, E. Shearer. WANL: R. Clark

AGC has approximately fifteen different valve actuators to design and are considering different types of transmissions for the actuators depending upon the specific valve to which the actuators is attached; that is, specific requirements can change the exact concept to be employed.

E. Shearer needs a valve SSCVA interface drawing as soon as possible. This drawing should show the seal surface finish required for sealing, the dowel pin location, the V-brand clamping arrangement, and the dimensions on the crown spline shaft between the valve and actuator. Tolerances should also be included in this drawing.

AGC also stated that they would like a decision as soon as possible on the full open pressure drop of the SSCV so that they can select the concept. It appears that this pressure drop has an overriding effect on the type of valve selected. The two valves that they are considering are a cone valve which would have a very low (2-3 psi) pressure drop and a cylindrical valve with a high (10 psi) pressure drop. I think they prefer to go with a cylindrical valve if the attendant additional pressure drop can be tolerated by the system.

Editorial Comment: It is of interest to note that we proposed the use of a Rocketdyne cylindrical valve to AGC as much as two years ago, and that they are just now considering this design.

I obtained concept drawings of the cylindrical valve, AGC Drawing No. 1137359, and the cone valve, AGC Drawing No. 1137377. Torque values are shown on these drawings which are relatively high. It was explained that these torque values include the effects of a dynamic seal to keep back-leakage to a minimum during cooldown operation. The values on the order of 300 in.-lbs. are shown on the sketches. AGC stated that these values could be reduced by a factor of approximately three if leakage specifications could be changed to allow elimination of dynamic seals. Since high torques create a penalty on the design of the actuator, this leakage area specification should be carefully considered.

The design people for the lower thrust structure are still concerned about the space available for mounting the thrust structure to the pressure vessel closure. They would like us to maintain as much space between actuators as possible so that thrust structure members can be mounted in or at least passed through the space between the actuators. AGC has been working with the dimensions and configuration shown on the reference design drawing, and I gave them our later thoughts in this area, which include a smaller actuator package, thus allowing greater room between actuators.

A schedule discrepancy exists between the AGC valve schedule and the WANL actuator schedule. AGC is not planning to have a valve available for test with our actuator until the end of 1972. This would represent the first mating of a prototype valve with a prototype actuator. Our thoughts are to have this first testing accomplished about a year earlier. This accelerated schedule is not consistent with the AGC funding. They are not planning to have the prototype design available for the R-1 test.

February 11, 1970

An attempt was made to look at the AGC study layouts showing the control drum actuator above the disc shield. However, the personnel responsible were not available at the time.

AGC is considering differential planetary gearing as recommended to them by Tom Barish. They are considering running the planets without a carrier. I feel this technique will result in very high localized tooth wear. They are also considering the use of a Wabble type transmission where the application warrants it, and they are still contemplating the use of a Harmonic drive in certain applications. They were not aware of the work that had been done on Harmonic drive by the Goddard Space Flight Center, and I gave them the report numbers so that they might investigate this work.

I also indicated to AGC that Ball Brothers appear to have a very satisfactory method of providing a dry lubricant for application to all these transmissions.

SIGNED:

D. D. Armstrong, Actuator Design

APPROVED:

R. A. Clark, Jr., Manager
Actuator Design

/mhb

Attachment

THOMAS BARISH
CONSULTING ENGINEER

5411 TYRONE AVENUE
VAN NUYS, CALIFORNIA 91401
(213) 781-8181

Westinghouse Astronuclear Laboratory
PO Box 10864
Pittsburgh, Penn. 15236

Jan. 30, 1970

Attn: Mr. Roy A. Clark, Jr., Mgr. Actuator Design

Subject: Rotary Electric Actuator

1. The following report summarizes recommendations made during a conference at this office Jan. 27th with you and Mr. Don Armstrong.

2. The design requirements are the utmost in reliability and weight saving, as indicated for space applications. In this case, we add the exotic atmosphere of appreciable radiation, plus a moderate vacuum and the absence of any lasting lubricant that can resist the radiation. This calls for the simplest possible design with the fewest parts.

3. On the other hand, efficiency must be considered quite seriously, not because the power required for governing is considerable, not because of the extra size required in the motor which is not great, but primarily because all losses represent friction occurring in the gears and bearings and represents greater difficulty to obtain reliability and life under the above conditions.

4. On this basis, the worm drive can be immediately eliminated because any worm with a ratio approximately 100 would have far less than 30% efficiency. The very large percentage of rubbing would make reliability without lubrication very difficult if not impossible.

5. This is an example of the general rule applied to all such designs: The more ratio taken in one step, the greater are the losses, practically in proportion. This happens because you combine the very large loads of the output with the high speeds of the input, and the losses are a constant times the product of these two. For example, the design showing three steps of spur and internal gearing would have a total loss of approximately 5% or slightly less. Any arrangement which combined these into a single step with fewer parts, would have the high speed and the high loads, and the losses would be approximately 40%. This, of course, must be modified since certain types of drives have less loss than others. For example, internal gearing is lower loss than spur gearing external.

6. With reference to the design showing three steps of spur gearing, the internal is unfortunate here, because it is quite difficult to make the internal gears, and secondly, the spur gear is always overhung and introduces difficult deflection

problems. A three step spur gear arrangement could be practical, but it is definitely recommended that they all be external gears simply supported. Also, the reduction ratio of the first step can be very much larger, since the loads at this point are so small that both gears need not be excessive in size. Such designs prove most efficient for instruments where there is negligible torque being delivered, but in this type of unit it will be found somewhat better to use later designs discussed, particularly the last.

7. There are two designs shown using the Harmonic drive. One of these uses a DC motor with a much larger reduction ratio, and the planetary gearing ahead of the harmonic drive. This has been eliminated because the stepping motor has been found more favorable. It would need material change since the gearing shown does not have adequate support.

8. The second Harmonic drive with a stepping motor, is very compact and has so few parts that it has considerable merit for this type of work. The major objection to it is this. The Harmonic drive involves some quite difficult and complicated material and design problems. They have been solved by very expensive testing for developing practical materials with these very thin sections, and for developing a ball bearing and a gear that will stand so much deflection, and for developing gear teeth with such large ratio they do not interfere. Before we could use this drive, we would have to face a long time of considerable testing for each of these problems under the unusual atmosphere we have to meet. Not only would there be long testing and developing periods, but there would be the danger that some of the problems would call for radical change, and we would have to start all over after doing much testing. This design is therefore set aside as a very difficult development problem.

9. The nutating bevel gear design needs consideration because it has so few parts. However, such a design was used by Aerojet with considerable difficulty because of the bearing problem in supporting the gears. You were to review this on your following visit in Sacramento. The design proposed has an ingenious support for the gears, but would need modification because the support of the tilted gear requires more rigid bearing arrangements. Also, this type of gear would probably need special development to avoid the equivalent of interference that occurs with an internal gear. If you consider this design, it is strongly recommended you use the TRW Company, since they have already built one, per pictures shown, and have found out what some of the problems would be. They apparently have handled some of this last problem mentioned by making teeth of one of the two gears much shorter than standard. Nevertheless, for our small unit with large ratio, the teeth would be extremely small, approximately 64 pitch or finer.

10. The same would apply to a single internal spur gear arrangement, the last design shown in your sketches. Note that both this design and the nutating gear, since the ratio is taken all in one steps, would have efficiencies in the order of 60%. That is

40% losses. Even this is somewhat low, because an internal gear type of contact is involved. The internal gear arrangement you show could be modified to use a single tooth common gear for the planet, but this would require using about 96 pitch gears. Your arrangement using two separate gears permits using coarser pitch and a more practical design. However, it is recommended that you review it again, because you may even be able to bring the pitch below the 40 pitch shown. It is definitely urged that you do not consider anything finer than 32 pitch gears, and preferably coarser than that. These fine gears are difficult to measure and difficult to make.

11. Furthermore, if you retain the internal gear design, you would need a better bearing support for the planets.

12. It is recommended that you consider a modification of this last design as follows. Use internal gears, one anchored and one driven, with three equally spaced smaller planets. The planets would be single gears, and would be driven by a very small sun gear. This form would divide the ratio into two steps: a planetary giving about 6:1 ratio with practically no additional parts except the sun gear, and an internal gear drive using three points of application. This has the big advantage of no large radial loads carried on the input shaft bearings or the output shaft bearings. The only bearing loads that are appreciable are on the idlers, and if the bearings can be spread, these will not be very large, since they are divided among three units.

13. This design has been used involving a three tooth difference between the two large internal gears. They are machined on a pitch diameter approximately halfway between the usual, and give different pressure angles. This requires careful gear design, but uses standard machinery and is relatively easy to make. For example, you could use a sun gear of 11/12 teeth, 28 pitch (an 11 tooth pinion cut on a 12 tooth pitch diameter). The planets would be 24 teeth, and the internals 61 and 58 teeth cut on approximately 59.5 pitch diameter.

14. This design dividing the reduction gear into two steps, would increase the efficiency to over 80%, probably near 85% with a considerable reduction in losses representing action that needs to be lubricated.

15. For any of the designs, it is desirable to have a runin period with some kind of lubricant used temporarily until the gears achieve a good working finish in the operating position. It has been clearly established that the losses in a very well

finished gear are considerably less, the capacity against scoring is greatly increased. Also, this will help eliminate the possibility of seizure under vacuum because the surface asperities are removed during the run-in.

16. Your proposal to use a surface treatment is definitely indicated. The problem is to find experience that determines which surface treatment among the great many available would be optimum for this application. In any case, it should be so thin that not sufficient debris will be delivered to the bearings to tend to clog them. The baked on Sodium Silicate or one of the impinged finishes, might be indicated.

17. Once the design has been put into approximate final choice of arrangement, it will be necessary to make a very detailed and careful study of each bearing location for type, size, and mounting details.

A handwritten signature in cursive script that reads "Thomas Barish". The signature is written in dark ink and is positioned to the right of the typed name.

TB/jsl

Thomas Barish

Fold
or Cut

TITLE	
	Trade Study for NERVA Control Drum Actuator Design Concepts (U)	
DOCUMENT NO.		DATE
TME-2678		2/2/60
ABSTRACT		
<p>Presentation of a trade study among series DC motor, PM stepping motor, and brushless DC motor design concepts, and various actuator malfunction override devices, for the control drum actuator component of the NERVA nuclear subsystem. Selection of a recommended concept is based upon the construction of a comparison matrix with emphasis upon reliability in the severe environmental conditions.</p>		
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