7. THE DEVELOPMENT AND TEST OF A LONG-LIFE, HIGH RELIABILITY SOLAR ARRAY DRIVE ACTUATOR

By Don L. Kirkpatrick*
General Electric Company

ABSTRACT

To meet the life and reliability requirements of five to ten year space missions, a new solar array drive mechanism for 3-axis stabilized vehicles has been developed and is undergoing life-test. The drive employs a redundant lubrication system to increase its reliability. An overrunning clutch mechanism is used to permit block-redundant application of two or more drives to a common array drive shaft. Two prototype actuator and clutch assemblies, in continuous vacuum life-test under load at 10^{-8} TORR for more than sixteen months, have each accumulated more than 34,000 output revolutions without anomaly, the equivalent of more than seven years of operation in a 1000 km (600 nm) orbit or nearly ninety-five years at synchronous altitude.

INTRODUCTION

This report discusses the design and test of a new high-reliability solar array orientation drive mechanism, under the auspices of the 1971 and 1972 GE Space Division IR&D Programs. Before proceeding to the discussion of the design features and test results of the new array drive, a brief background description of the vehicle system-level requirements which created the need for this device may be of interest to the reader.

In conjunction with preliminary design studies of a group of large, synchronous altitude communications satellites, a study of the suitability of existing solar array drives to meet vehicle and mission requirements was performed. These requirements included reliable operation thruout the ten-year missions planned; full functional redundancy to prevent mission termination as a result of any single-point failure; and the ability to drive large array inertias at acquisition slew rates as well as orbital rate; and to provide a torque margin of 10:1 relative to the expected beginning-of-life bearing and slip ring friction.

When it became apparent that no known flight-proven drive could be used without extensive modifications to either the drive itself, vehicle configurations being studied, or both, new drive concepts and configurations were examined to determine whether an actuator more compatible with the vehicles' performance and reliability requirements and configurational constraints could be devised. One of the resulting drive design concepts showed sufficient promise of meeting all the major requirements of the class of vehicles under study, (and in addition, a broader applicability to any space vehicle requiring a reliable, long-life rotary actuator), that an IR&D program was formulated to further develop the new concept, build prototype drive mechanisms, and evaluate their performance through bench testing and vacuum life-test. To the extent that the two resulting prototype drive mechanisms have performed successfully thruout sixteen months of continuing bench and vacuum life-test, driving external loads alternately, and in parallel, the goals of the program have been met.

This success was achieved in large part as the result of the efforts of A. Schneider and R. Boileau. Their significant contributions are gratefully acknowledged.

PERFORMANCE REQUIREMENTS

Performance requirements which the Solar Array Drive Assembly (SADA) was designed to meet, and the actual capabilities/performance of the prototype drives built and life-tested, are given in Table 1.

Table 1. Large Synchronous Satellite Solar Array Drive - Summary of Requirements, Constraints and Actual SADA Capabilities

Parameter	Required Capability	Actual Capability
Rotation Rate		
Normal	360 deg/day	360 deg/day
Slew (Minimum)	0.5 deg/min	9 deg/min
Nominal Output Torque	4.4 Nm (3.25 ft-lb)	54.2 Nm (40 ft-lb) minimum
Avail. Torque Margin	9X	11.3X
Load Inertia	13.6 kg-m^2 (10 slug-ft^2)	
Drive Power		
Average Orbital	2 watts	0.3 watt
Slew and Peak	30 watts	9.8 watts
Operating Temperature Range	20°F to 120°F	Meets: upper limit verified by test, lower limit verified by analysis

Table 1 (Continued)

Parameter	Required Capability	Actual Capability
Wear Life	10 years	95 years equivalent demonstrated in life-test of two drives
Redundancy	Full Functional	Meets: demonstrated by test
Reliability (10 years)	0.998	0.9997*
Weight drive	2.7 kg (6.0 lb)	2.7 kg** (6.0 lb)

*Determined analytically for block redundant configuration.
**3.3 kg (7.2 lb) using aluminum gear case tested.

DRIVE CONFIGURATION DESCRIPTION

The SADA configuration which ultimately resulted from the design studies was created with simplicity and low cost as important goals, in addition to the requirements for high torque and performance margins, commensurate with reasonabl input power and weight. The drive is comprised of a high torque, 1.8 degree/step, permanent magnet stepper motor; a 100:1 Harmonic Drive torque multiplier; a 6:05:1 spur gear output stage; and a fully redundant lubrication system. The single-active-element clutch which automatically couples the drive actuator to the solar array shaft during drive operation permits the use of two actuators on a spacecraft to provide full redundancy of the array drive function. A cross-sectional layout of this drive is shown in Figure 1 in the redundant (clutch coupled) configuration. This illustration also shows the type of spacecraft structural interface which this drive requires for proper mechanical alignment.

The motor drives the input of the 100:1 reduction harmonic drive, which in turn drives the pinion of the 6.05 spur gear reduction. The hollow-spur-gear shaft also serves as the input hub for the wrapspring clutch, which drives the array shaft through the spring clutch driven hub when the motor is operating. These major drive train components of the SADA are shown sequentially in their order of operation in Figure 2. From right to left, they are:

1. The stepper motor with shaft position encoder
2. First reduction harmonic drive wave generator, circular spline, and flex-spline

3. Second reduction pinion, and output gear with integral clutch drive hub

4. Wrapspring clutch

5. Clutch driven hub, which attaches to the drive vacuum life-test fixture shaft

The second SADA prototype drive assembly is also shown in this photograph.

DRIVE DESIGN EVOLUTION

The initial SADA design configuration concept is shown in Figure 3. This basic actuator concept is extremely simple in comparison with its predecessors. The major active elements are the dc stepper motor, the harmonic drive, a single pair of output spur gears, and the wrapspring clutch. Support of all rotating elements requires only six ball bearings. By contrast, the solar array drives used on early Nimbus vehicles employed twenty gears, and twenty-two bearings, in addition to the motor and an internal slip clutch, which was necessary to protect the 85,000:1 gear train against damage from torques externally applied to the solar array shaft. (The earlier drives incorporated no provision for redundant application.) A schematic comparison between this design and the Nimbus I-III drive is shown in Figure 4. The prototype drive, ultimately developed from the aforementioned concept, is capable of withstanding high externally applied torques without damage, because of its relatively low (605:1) ratio, and the high strength of its gear train elements.

As originally conceived, the drive employed a frameless "pancake" stepper motor (comprised of a separable rotor and stator); and a Harmonic Drive (HD) 100:1 gear reduction (comprised of a wave-generator bearing, a circular spline, and a flex-spline), with two pairs of ball bearings mounted in a specially designed housing to support these elements. The smaller bearings supported the motor-rotor and the wave-generator (HD input), while the larger bearings supported a cylindrical shell to which the flex-spline (HD output) and the spur gear pinion of the second (6:1) gear reduction were attached. The output gear was mounted between a third pair of bearings. The hollow shaft of this gear extended to form the input hub of a wrapspring clutch, which would transmit the output torque of the drive mechanism to the solar array shaft through a hub pinned to that shaft whenever the drive was operating. In this configuration, the entire array drive was supported on the array shaft by a pair of self-lubricating sleeve bushings, and the drive torque was reacted into the vehicle through a pin or screw which attached the output gearcase to the vehicle structure. Comparison of this layout with the final concept, in Figure 1, will show that many significant design improvements were made over the initial concept in this phase of the program. The most significant changes and improvements incorporated in the prototype relative to the initial concept are:

1. The incorporation of a self-contained motor, which with its double-ended shaft supports the step-sensor (encoder) on one end, and the Harmonic Drive wave generator on the other

2. Straddle mounting of the drive pinion to ensure improved gear alignment and operation in smaller, stiffer bearings while still providing adequate support for the harmonic drive flex-spline.

3. Eliminating the need for the centering bushings between the drive output shaft and the array drive shaft by piloting the drive housing on the array shaft support bearing housing

4. Generally improving the overall housing structural design, ease of manufacture, assembly, alignment, and serviceability.

DESIGN PHILOSOPHY AND COMPONENT SELECTION RATIONALE

A major goal in the design of this device was to achieve long life and reliability through simplicity in both quantity and design of the basic mechanism elements. Further examination of the layout will show that this philosophy has been followed wherever possible in the design of the SADA. The motor rotor shaft is double ended; the harmonic drive wave generator is supported on one end of the motor while the optical encoder disc or pulse generator magnet is supported on the other. Thus, the two motor rotor bearings also support two additional driven elements for simplicity, eliminating the need for other support bearings. The second reduction pinion and the Harmonic Drive flex-spline are supported on a common shaft by a second pair of bearings, which again eliminates the need for additional supports and complexity. The output gear bearings also support the clutch hub, which in turn supports the clutch, further limiting the number of bearings required and helping to achieve accurate clutch alignment.

The stepper motor selected is also an extremely simple device in itself, and its use simplifies the overall SADA design, as well. This high-torque stepper has a machined one-piece rotor and an encapsulated wound field structure. No detents, ratchets, pawls, cams, brushes, or commutator - all of which could cause potentially reduced reliability - are used. Stepping is accomplished through the sequencing of drive current to the four-phase winding by switching transistors and the consequent interaction of magnetic fields. The only contacting mechanical parts in the motor are the two precision ball bearings which support the rotor; the space lubrication technology for these is well-known and widely demonstrated.

Besides its inherent internal simplicity and demonstrated reliability, the motor selected simplifies the overall design of the SADA, functionally replacing a conventional 90 degree dc PM stepper or 2 phase ac servomotor and a two-to-four stage gearhead. This motor produces 18 in-oz torque at nominal rate through each of 200 accurate 1.8 degree steps per revolution, without gearing and with simple digital controls. Small (e.g., size 8 or 11) conventional steppers would require reduction gear ratios of 50:1 to 100:1 to produce the high torque and low effective rotational rate of this motor. AC servomotors must normally run ac several hundred rpm for smooth controllable operation and this again would necessitate the use of significant reduction gear ratios to provide the required low output speed which is achieved without additional gearing by the selected stepper motor. The selected motor thus provides both internal simplicity and a significant reduction in gears, bearings, and rate control electronics over more conventional approaches.

The use of the harmonic drive also results in a significant reduction in complexity over conventional spur gear approaches, which would require approximately three times as many parts to achieve the same 100:1 reduction, multiplying the complexity and severity of lubrication and backlash problems. Although other types of single stage high reduction gearing could achieve this ratio, none are as well-suited from a vacuum lubrication standpoint to perform reliably for long life in space. The teeth of the Harmonic Drive come into engagement without significant sliding and unlike spur gears there is no relative motion between the teeth which are carrying the peak load. The elimination of significant sliding friction loads makes it possible to achieve a greater lubricant life and reliability than could be readily achieved in using conventional gearing at this point in the gear train.

The output pinion rotates at one-one hundredth the rate of the HD input. Since it was possible here to utilize very durable 20 pitch, 20 deg pressure angle gears with 15 tooth Nitralloy 135M pinion, and 115 tooth 7075T6, hard anodized gear, an extremely low maximum pitch line velocity of 0.02 cm/sec (.008 in./sec without incurring an excessive weight penalty, long life is again feasible with conventional boundary lubrication techniques.

To further enhance the reliability of the drive, a dual lubrication system is provided. All gears and bearings of the actuator are lubricated with space-proven liquid lubricants, Krytox AC oils and greases. Wiping lip seals and anti-creep barrier films will be provided at the output shaft of the actuator to retain this lubricant within the actuator housing for flight use. In addition, all surfaces requiring lubrication are coated with compatible space-proven dry lubricants based on plated low-shear strength metallic films or transfer-lubricating polymer film-generating materials. These dry lubricants provide a backup in the event of loss of liquid lubrication. (To verify the efficacy of this dual lubricant approach, the SADA prototype solar array drive actuators were vacuum life-tested; one with Krytox over the plated metallic lubricant films, while the second was lubricated only by the dry film system in the absence of liquid lubricants.)

The wrapspring clutch is the key to providing the desired functional (block) redundancy to increase the reliability of the array drive system. Two or more drive mechanisms may be coupled to the solar array shaft thru these one-piece overrunning clutches. Any or all drives may be operated with additive output torque in the multiple drive case, and any drive can be held in the backup mode without interfering with the operation of any other drive. Each clutch engages automatically when its associated drive operates and disengages automatically when pulsing of the drive's motor ceases. The clutch is lubricated only with a dry lubricant film bonded to the hard anodized hubs which it interconnects.

This lubricant does not interfere with the operation of the clutch during driving; torque of over 135 Nm (100 ft-lb) is required to cause slippage at the clutch, which is 2.5 times greater than the actuator peak/stall torque.

Like the other elements of the SADA, the optical resolver selected is simple and reliable in both its own design and in its application in the drive subsystem. Rotation of the motor is sensed by the resolver, an optical encoder comprised of a light emitting diode, a photosensitive transistor, and a 200 line chopper disc which interrupts the optical path each time the motor steps. This device senses each motor step completed, independent of the motor drive circuit which pulses the motor to "step" in 1.8 degree steps. The motor shaft is geared 605:1 to the output shaft; since each motor step is 1.8 degrees into this 605:1 reduction, then each step of the motor and each output pulse of the encoder = 0.003 deg. This provides both a convenient feedback signal if a position loop is to be closed around the motor and a high-resolution index of array shaft rotation in conjunction with a digital counter.

TYPICAL SPACECRAFT APPLICATION OF SADA SUBSYSTEM

A typical solar array drive subsystem for use in a synchronous altitude communication satellite could operate in the manner described below:

The Solar Array Drive Assembly (SADA) orients the solar array normal to, and steps it to follow, the spacecraft-sun line; and provides array position detection pulses to the Attitude Control System (ACS). Stepping commands are generated by the ACS in response to sun sensor or vehicle clock outputs. Two identical, functionally redundant array drive actuators are provided; a half-system is shown in Figure 1. Although only one drive normally operates while the other is retained as a backup, the functional description of each is identical. The motor drive pulses which originate in the ACS, in clock-triggered bursts of eleven 50 Hz pulses every 8 seconds, cause the drive stepper motor to rotate 19.8 deg every 8 seconds. The output torque of the motor is multiplied by a 100:1 harmonic drive reducer and a 6.05:1 spur gear mesh, so that the array shaft is advanced in an increment of 0.033 degree for each eleven ACS-generated pulses. The drive torque is transmitted from the output of the operating drive to the solar array shaft through a self-energizing unidirectional spring clutch which transmits motion and torque to the array shaft only when the drive is rotating. Rotation of the drive output shaft causes the preloaded clutch spring to tighten with virtually no lost motion about both the driving and driven shafts, locking them together and transmitting the drive motion accurately to the solar arrays.

Motion of the array shaft in the normal direction of array rotation relative to the actuator output hub on each drive disengages the clutch, so that a low but constant frictional drag 0.3 N-m (.25 ft-lb) is present at the non-driving clutch. Either drive may rotate the array shaft while the other remains stationary, and full functional drive redundancy results.

In the highly unlikely event that the required array drive torque exceeds the capacity of a single drive, both drives can be operated simultaneously and the torque of each actuator will be additively applied to the load. Overshoot of the arrays is prevented by the drag torque of the clutches when the drive is not operating and by the friction of the power transfer slip rings and shaft support bearings. It has been determined through analysis that the momentum in the array when moving is insufficient to overcome these restraining torques when the drive is stopped.

Driving the array in the stepping, or incremental, mode provides two distinct, life and reliability-enhancing advantages to the drive. Power is applied to the motor only during the driving periods (magnetic detenting torque of the motor stabilizes the drive between array "steps"). Although the operating motor power is 9.8 watts, the average power is 0.27 watt; this significantly reduces heating of drive lubricants, and thermal stresses on the drive in general, in addition to saving electrical power throughout the mission. Secondly, since actual drive operation is occurring during only 2.7 percent of the mission, a ten-year flight will require the equivalent of only 100 days of continuous drive operation.

The angular position of the array shaft relative to the vehicle is detected through the combined use of two sensors: the shaft quadrant detector, and the motor step pulse generator (encoder). This information is used by ACS to set up AC and SADA control functions.

PROTOTYPE DRIVE EVALUATION TESTING

Two prototype actuators fabricated for evaluation have been subjected to both bench and vacuum testing. A one-week run-in of each drive followed by teardown, cleaning, inspection, relubrication and reassembly preceded the bench tests, which included rate verification, stall and back-driving torque determinatio Overrunning friction of each clutch was also measured.

The endurance/life-test of the two drives and associated hardware is being performed in a bakeable stainless steel vacuum chamber, having a 500 liters/second ion pump and a 5000 liters/second titanium sublimation pump. The arrangement of th test articles and the vacuum life-test equipment including the chamber are shown schematically in Figure 5. Figure 6 shows the drives installed in the vacuum chamber prior to the start of the life-test. The two prototype array drives are connected to a common output shaft through their wrapspring clutches. Either or both drives may operate to rotate this shaft. Two slip ring assemblies are also attached to the common shaft and rotate with it while their brush assemblies are attached to the fixture baseplate. In addition, a third clutch is mounted on a hub which rotates with the shaft. The "leading" end of the coiled clutch spring contacts a stop fixed to the baseplate of the fixture which causes the clutch to sl on the shaft. The tangential components of the frictional drag force unload each coil of the spring by producing an increase in the inside diameter of each preloaded coil of the spring just adequate to relieve the radial preload, permittin the spring to slip freely on the shaft. This arrangement simulates the wear conditions which would be seen by the clutch of a drive being held in standby or a drive which had failed. In representing either case the inclusion of the clutch is intended to determine whether its overrunning throughout the life of the test would adversely affect the operation of the drive(s), or the subsequent ability of the clutch to re-engage.

The output end of the common test shaft is connected to a hermetically sealed rotary motion feed through, which in turn couples the drives to a hysteresis brake, which simulates the expected running friction of the array shaft slip rings and bearings.

To verify the adequacy of the dry lubricants to serve as an effective back-up for the liquid lubricants used, it was decided to omit the liquid lubricants from one of the two drives to be tested in 1972. This would simulate the operation of a drive in space which had lost all effective liquid lubrication; and, since the life of the dry lubricant is primarily wear-cycle limited, a reasonably valid long-term accelerated test could be performed on this unit, in compressed time, since no aging effects have been observed in any of the dry lubricants selected.

Test instrumentation includes an oscilloscope to monitor input and output waveforms, a recording thermocouple potentiometer recording the motor temperatures, as well as those of the baseplate and chamber wall. Vacuum pressure is monitored as a function of ion pump filament current. The motors are driven by stepper motor controller at a frequency controlled by a variable rate oscillator. The control circuitry also includes means of automatically and manually driving either or both drives and sequencing them in an alternate mode. Both motors have been driven simultaneously, however, thruout the entire test (except for brief alternate stops to verify performance of the clutches).

The drive operation was accelerated by a factor of 72 to maximize accumulation of life cycles without significantly over stressing the drives thermally or mechanically and without changing the dynamics of drive operation. In flight, the drive will turn at one rev per day; however, it will only operate for 0.22 second every eight seconds (1/36 duty cycle). The 72:1 acceleration was achieved by first eliminating all dwell time between output drive steps (this provided a 36:1 acceleration) and then doubling the probe rate to the motor. The drives were previously tested at this rate for two weeks in laboratory ambient and operated well.

Although it might appear that the severity of the test was reduced by eliminating the repeated start-ups of the drive under load, this is not in fact the case. The mechanical time constant of the motor rotor is less than four milliseconds, while the pulsing rate of 100 Hz produces motor drive pulses of ten millisecond duration and repetition rate. Therefore, the motor rotor completes each 1.8 degree step in four milliseconds and settles under the electromagnetic damping of the ten millisecond pulse, the effect of the hysteresis brake counter-torque and the friction of the slipring brushes. Therefore, the motor essentially starts and stops with every pulse of the drive circuit. At 30 rpm, which results from the 100 Hz drive frequency, there is no significant momentum development in the system to keep the motor rotor "coasting" between drive pulses.

EVALUATION TEST RESULTS

Bench Tests

The bench tests conducted on the drives were preceded by a ten-day run-in at 100 Hz of each drive. Each was monitored several times daily during this period. Rotational rate and temperature were stable throughout the run-in period for each drive. After run-in each drive was torn down and cleaned. Wear debris, which was slight in both units, was removed. After each drive was cleaned,the liquid lubricants in drive No. 2 were replenished and both drives were reassembled and run for approximately six hours to make certain that they were operating properly. The drives were then installed in the test fixture and bench tested.

In bench testing, each drive delivered a minimum of 58.3 N-m (43 ft-lb) against deadweight torque loading. Clutch overrunning torques were 0.27 to 0.34 N-m (0.2 to 0.25 ft-lb). Combined back driving torque of the two unenergized drives was approximately 37.9 N-m (28 ft-lb). (In prior tests the dry lubricated drive had exhibited 40.7 to 44.7 N-m (30 to 33 ft-lb) back driving torque, while the wet-on-dry lubricated drive required 9.5 Nm to 16.3 N-m (7 to 12 ft-lb) to back drive it. The decrease in the combined torque is attributed to continued bench run-in, cleaning, and relubrication of the drives.)

Vacuum Test

The life-test, originally intended to last five weeks, is continuing beyond its 68th week of operation; since the second week of testing, the pressure has been less than 10^{-7} torr and is currently 3×10^{-8} torr. The drives have operated without significant anomaly throughout the test. More than 34,000 output revolutions have been completed by each unit. At intervals of one to seven days, each drive has been alternately turned off and restarted, demonstrating the continued proper operation of each drive clutch and the reliability of the block redundant system operation. The third clutch continues to offer drag comparable to that seen in the bench test.

The temperature of the hybrid lubricated (No. 2) drive has slowly decreased from 52°C (125°F) to approximately 47°C (116°F). The No. 1 (dry-lubed) unit has remained 1 to 2 degrees warmer than the No. 2 unit. The decrease is partly attributab to a slight decrease in lab ambient and, possibly, to a continuing run-in of the drives. Load torque has remained constant at 4.1 N-m (3 ft-lb). Speed has tracked the input pulse oscillator properly. The test oscillator (a commercial unit) drifted slowly from 72 to 68 Hz in ten months. It was then raised to 78 Hz, where it is still operating.

The stall torque of the drives cannot be measured as long as they remain in the chamber, since the sealed rotary feed through will not safely transmit 40 ft-lb. These parameters will be evaluated when the test is halted.

The conducted sound through the vacuum chamber frame of the drives operating has been evaluated only subjectively by the writer; in the duration of the test to date it does not seem to have changed significantly, if at all.

The slip rings were energized with load current for a short time, but the high amperage produced significant I^2R heating of the chamber wall electrical penetration, which adversely affected temperature measurement of the drives, so this peripheral activity was halted. No significant change of brush-ring series resistance has been observed. When last measured several months ago the resistance variation during one revolution of the ring averaged 0.001 ohm with very infrequent 0.002 ohm peaks.

There has been no measurable change in motor electrical characteristics, except for current change, as a result of winding resistance change with temperature.

CONCLUSIONS

1. The prototype Solar Array Drive Assemblies have greatly exceeded the original performance requirements in terms of both power and life.

2. The efficacy and reliability of the wrapspring clutches to permit block redundant drive application has been fully demonstrated.

3. Both the hybrid redundant lubrication system and the dry lubricant system have been shown to be adequate for long term space operation. While the mixed lube system provides greater efficiency, the dry lube system alone is capable of long life so it can serve as an adequate backup system or a primary system by itself.

4. While the true validity of the test acceleration method used here will not be verified until real-time flight test data can be obtained, increasing the maximum rate by a factor of only two and gaining major time compression by decreasing dwell time appear to be philosophically sound as a method of evaluating long-life performance in relatively little time, since no major uncontrolled stresses or other dissimilarities are introduced. While the method does not provide real-time aging of the liquid lubricant, it is inherently stable at the temperatures of use with a great safety margin, and the chemical makeup of the liquid used is quite stable.

5. The feasibility of developing a highly reliable, low cost actuator for long-life spacecraft use through the careful selection and application of proven, high margin components, advanced materials, and conscious effort to achieve maximum simplicity has been demonstrated.

These conclusions are valid insofar as the extent and severity of the test operations to date are concerned. Further evaluation testing including shock, vibration, and thermal cycling are planned.

It is hoped that the ultimate proof successful long-term on-orbit operation will be achieved within the not-too-distant future. The possibility of achieving this proof is tangible since the drive is a part of the baseline configurations of a number of future spacecraft in the preliminary design stage.

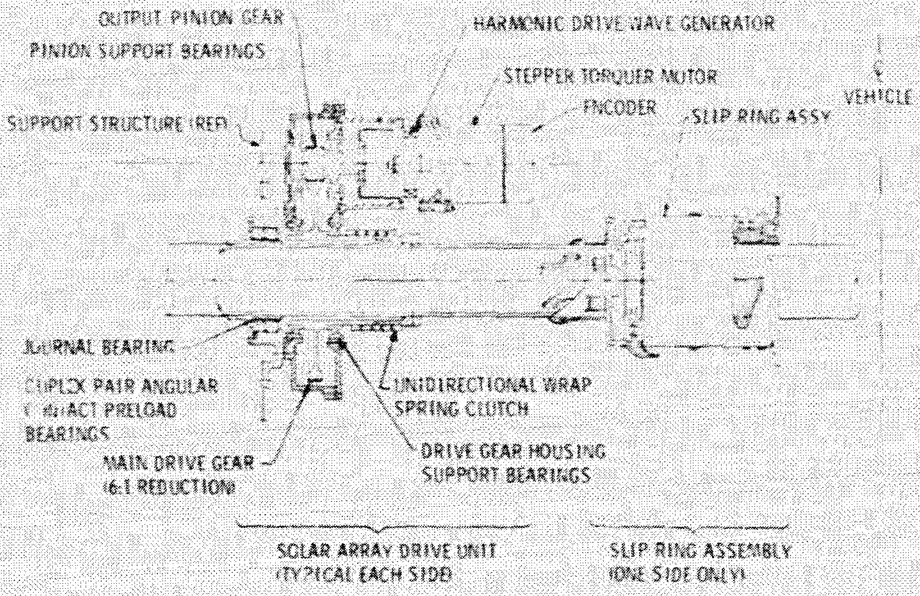

Figure 1.- Layout of advanced solar array drive in typical vehicle installation.

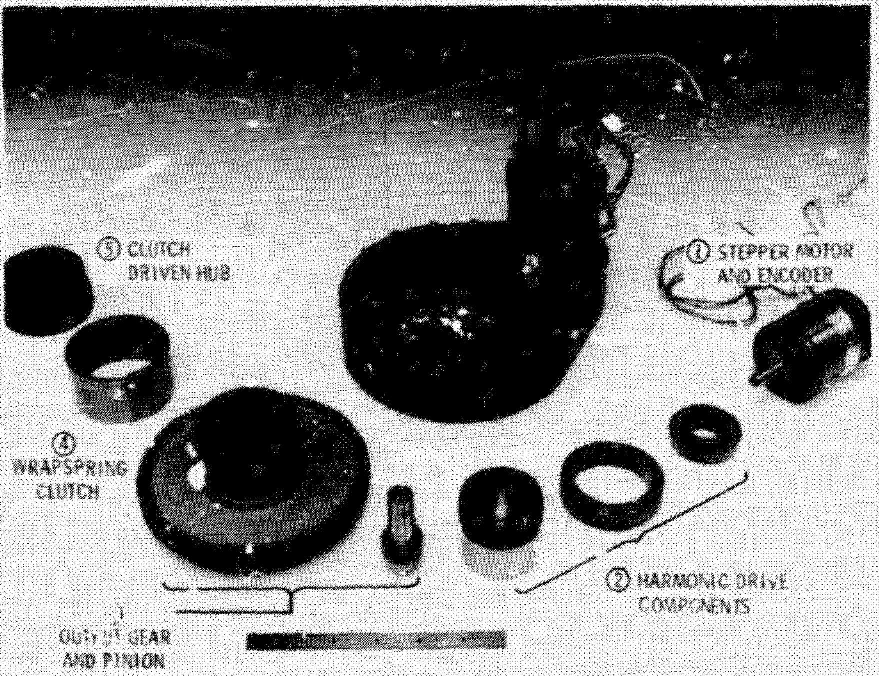

Figure 2.- Major drive train components of advanced solar array drive shown with assembled SADA prototype unit in background.

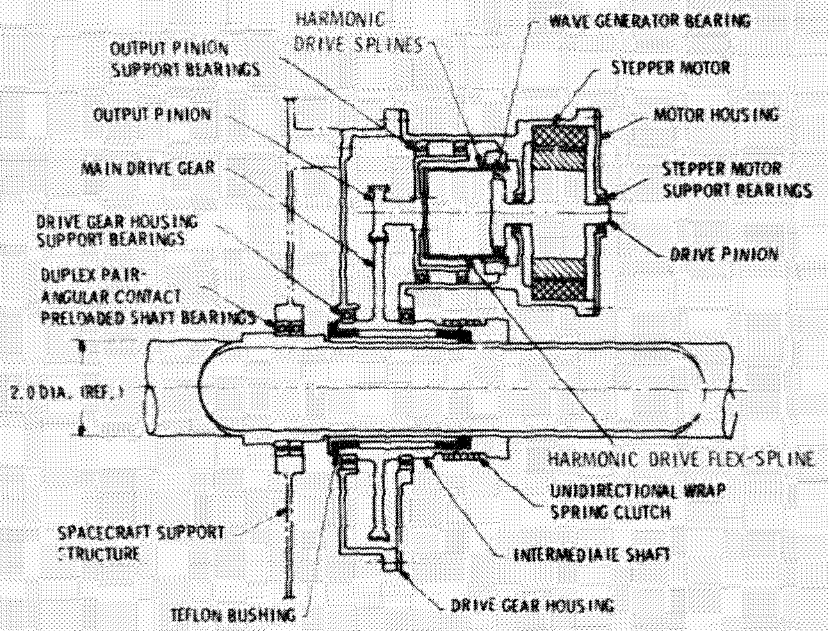

Figure 3.- Preliminary layout solar array drive assembly.

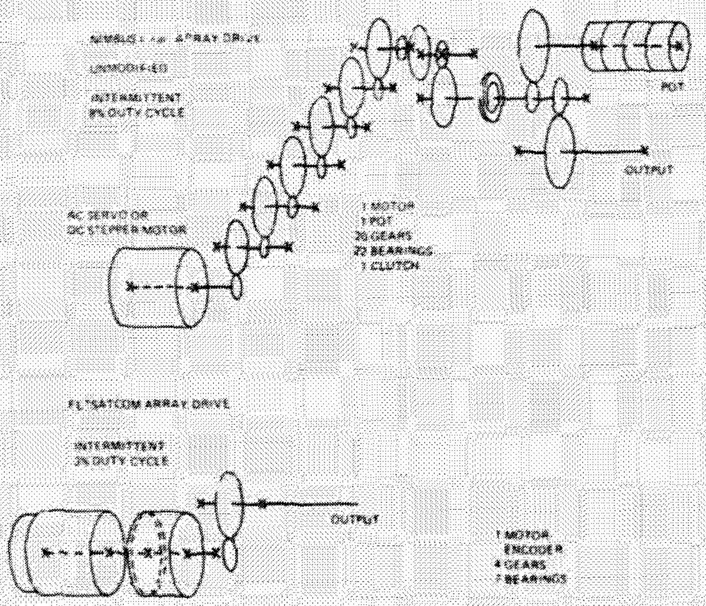

Figure 4.- Comparison of SADA and Nimbus I to III drive complexity.

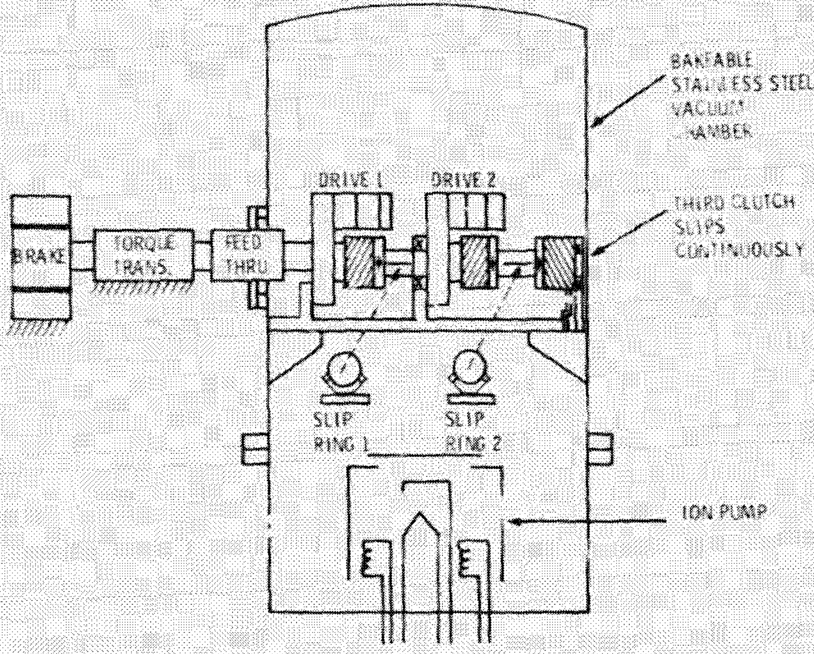

Figure 5.- Schematic layout of SADA vacuum life-test.

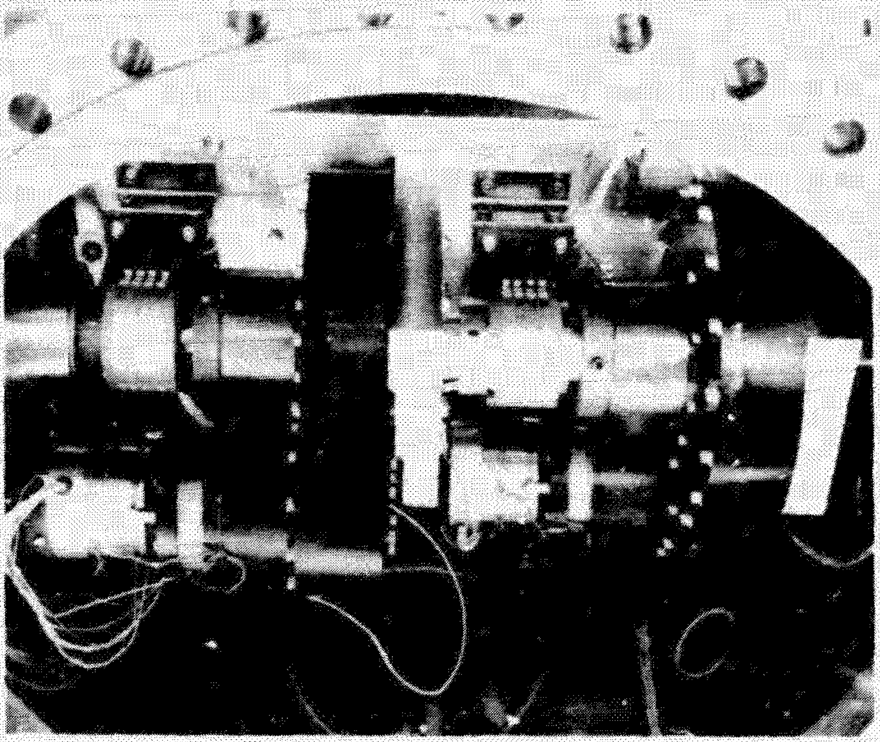

Figure 6.- Prototype SADAs in vacuum chamber prior to life-test.