THE LINEAR BOOM ACTUATOR DESIGNED FOR THE GALILEO SPACECRAFT

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SUMMARY

The Galileo spacecraft (S/C) is designed to be a Jupiter orbiter launched by the Shuttle/Centaur system in 1986. The spacecraft differs from past JPL spacecraft in that it is not three-axis stabilized but is a dual-spin design. A despun section contains some of the science instruments and camera system, while the spun section contains antenna, propulsion, and power generation systems. Power is supplied by two Radioactive Thermo-electric Generators (RTG's), each of which is mounted at the end of a long boom. A third boom mounts a magnetometer. (See Figure 1.) Nutation of the spinning spacecraft is controlled by an articulated attachment of the magnetometer boom to the space-craft. Booms that mount the RTG's are hinged at the spacecraft and restrained from rotating to a 90° position with the spin axis

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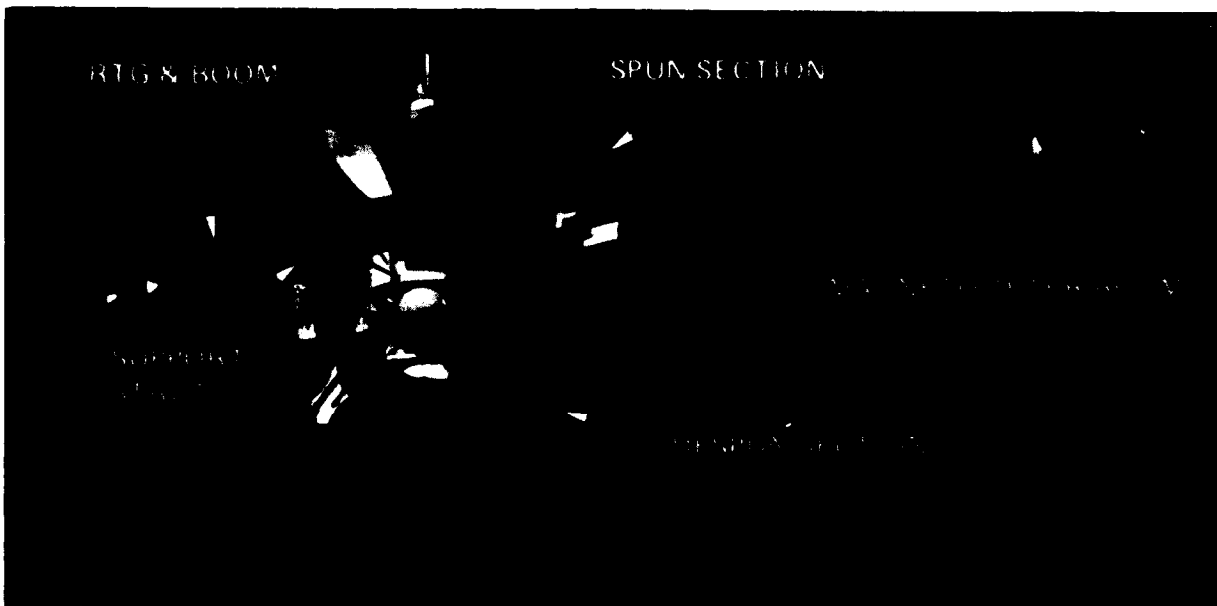

Figure 1.   Galileo Spacecraft Configuration

(Z) by a support strut. The support strut is made up of a folding section (for launch configuration reasons), some straight sections, and the Linear Boom Actuator (LBA). (See Figure 2.) Varying the length of the LBA varies the length of the support strut, thereby controlling the distance of the RTG mass from the spin axis. Changing the position of an RTG mass relative to the spin axis controls the wobble of the spacecraft. One LBA is used on each RTG boom support strut to provide both required degrees of freedom needed for wobble control.
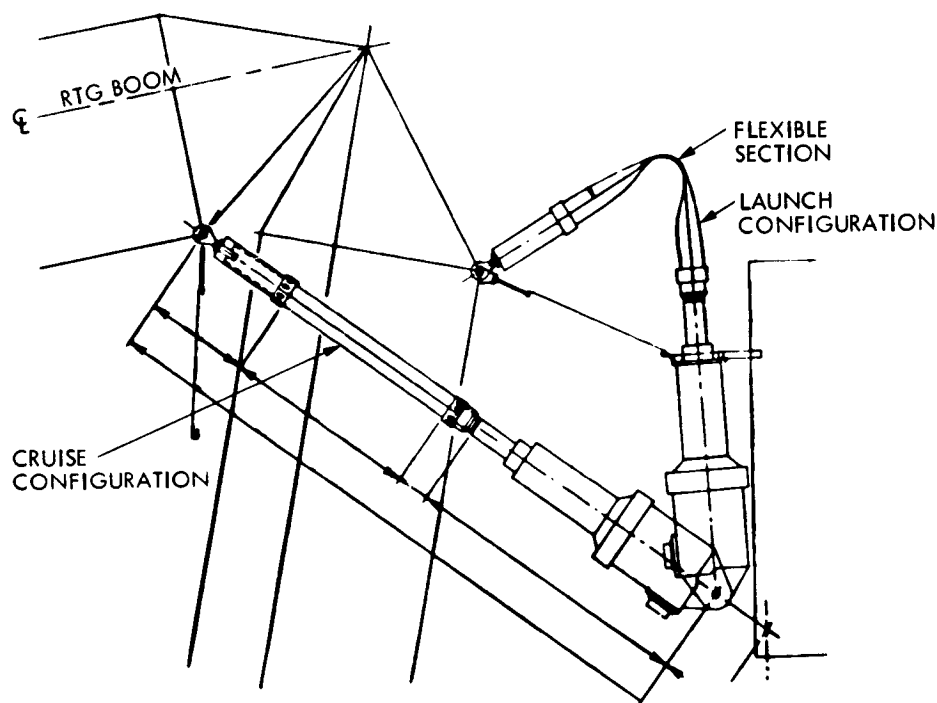

Figure 2.   Support Strut Deployment View

LBA REQUIREMENTS

Because this actuator is to be used on a flight spacecraft, as opposed to a ground-based application, there is a comprehensive set of requirements. First, of course, the actuator must be capable of positioning and holding the load. Initially the load was predicted to be 4448 N (1000 lb) but with subsequent spacecraft configuration changes the load has been greatly reduced to a constant tensile pull of 1477 N (332 lb) due to centrifugal force. Lesser compressive loads of 1317 N (296 centrifugal lb) may be experienced during launch and deployment.

Experience on the Voyager spacecraft emphasized the need for redundancy. Accordingly, this actuator must have the maximum redundancy possible.

Life requirements were defined by the 10.16 to 15.24 cm (4 to 6 in.) total linear travel expected during the five-year flight duration.

Linear range required of the actuator was set at plus and minus 5.08 cm ($\pm$2.0 in.) to accomodate configuration changes, although this linear range is not expected to be used in flight. Since the actuator will be used in a digital system, and because fine position control was needed, stepper motors similar to those used on a Voyager actuator were indicated. Maximum allowable power was set at 5 watts at 30 VDC. Overall length, weight, and backlash were to be held to a minimum with no specifications applied. Overall length was important due to the mounting configuration in concert with the folding struts for each boom. Interchangeability between actuators was required; however, interchangeability was carried further in that all parts and/or matched subassemblies are interchangeable.

Redundant readout of boom angles to 0.1 degrees was also required.

Systems engineers indicated that a gear train ratio of approximately 5000 to 1 in combination with a screw lead of 0.318 cm (0.125 in.) would be compatible with a minimum step size required of 0.10 μm (step size 1.537 x 10^{-7} in.).

Magnetic fields about the actuator were to be held to 5 nT at a 1.0 m distance, because of the magnetometer on board.

Because any parts that might come loose during launch vibration could become lodged in the shuttle bay door hinges, shuttle safety required that all actuator parts have redundant attachments and that the materials be analyzed for launch stress and crack sensitivity. Structural safety factor of the actuator was to be set at four.

The Galileo spacecraft, assuming it makes five orbits in the vicinity of Jupiter, will receive an estimated 10^6 rads of radiation from high energy protons and electrons. All parts and lubrication must be either capable of withstanding this radiation directly or shielded to reduce the radiation level to a level within its capability. Electronic components change their electrical characteristics under radiation, while lubricants harden.

The qualification and flight temperature ranges were established early in the development as:

-40 to +75°C for qualification, and

-20 to +55°C for flight.

Vibration levels were likewise established early in the development period as 8 G's rms qualification level and 5.8 G's rms flight.

The above list of requirements is a brief summary of the major requirements and has omitted much of the detail. With these major requirements in mind, the following design concept was followed to a successful conclusion.

DESIGN CONCEPT

After several preliminary starts the design approach shown on Figure 3 was developed. The low torque redundant gear train design is similar to the Scan Platform Actuator for the Voyager spacecraft in that the motors are similar, steel spur gears are used, and porous sleeve bearings impregnated with lubricant are used with a few exceptions. Ball bearings are used in the motors and potentiometers. Output from one gear train drives the ring gear of a planetary stage while output from the other gear train drives the sun gear. An important feature of this design must be pointed out here: the magnetic detent of the motors when de-energized in concert with the gear train advantage holds the associated gear train from coasting or being back-driven. This feature eliminates the need for either a brake or a clutch. Also with the ball screw locked up, one gear train cannot back-drive the other. Other strong points for this actuator design are the many ways in which it can be operated:

1. Each motor can be operated single- or two-phase.

2. Motors can be used singly or in pairs. Care must be observed to operate motors in opposite directions if used in pairs; otherwise, there will be no output movement.

The Galileo spacecraft is designed to operate the actuator single-phase, one motor/actuator at a time.

Some actuator design constants follow:

Ball screw $T = PL/2\pi e$

TOTAL GEAR RATIO: 5164.7895

DUAL POWER TRAIN: $\left|\dfrac{88}{10}\,\dfrac{96}{20}\,\dfrac{96}{20}\,\dfrac{66}{18}\right| = 743.4240$

COMMON PLANETARY REDUCTION:

$\dfrac{44}{19}(1 + \dfrac{88}{44}) = 6.9473$ SUN DRIVEN

$\dfrac{88}{19}(1 + \dfrac{44}{88}) = 6.9473$ RING DRIVEN

POTENTIOMETER GEAR TRAIN:

$\left|\dfrac{76}{24}\,\dfrac{78}{24}\,\dfrac{78}{24}\right| = 33.4479$

$\dfrac{32 \times 360}{33.4479} = 344.42$ POT ROTATION

PINTLE EXTENDS WHEN:
1. MOTOR B1 ROTATES CCW AND B2 DE-ENERGIZED
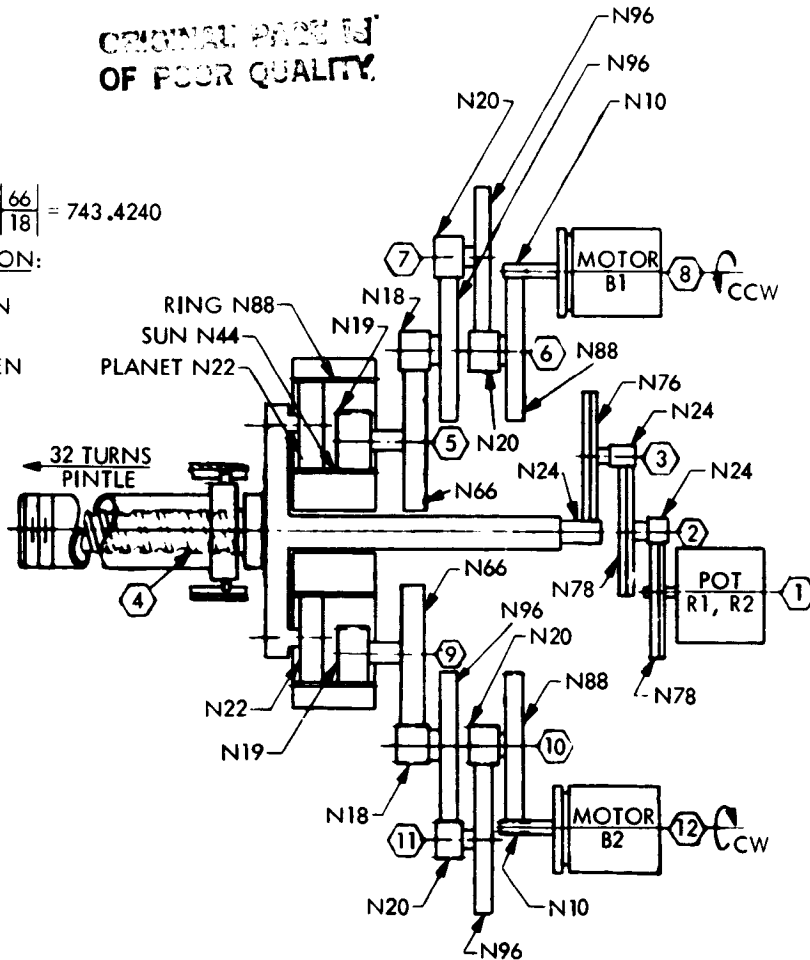2. MOTOR B2 ROTATES CW AND B1 DE-ENERGIZED

Figure 3. Mechanical Schematic

where

T = torque to drive

P = load

e = efficiency (approximately 0.9)

L = pitch/360° = 0.3175 cm (0.125 in.)

Motor max torque at 100 PPS = 0.00127 Nm (0.18 in. ounce)

Motor min detent torque = 0.00113 Nm (0.16 in. ounce)

Gear train efficiency approx 0.8

The 3 planet gears drive the ball screw. Bearings for the planetary stage are all journal type bearings.

The ball screw converts the rotary movement to linear movement at the rate of 0.318 cm (0.125 in.) per one rotation. The ball screw has a total capability of 10.16 cm (4 in.) or 32 turns.

Feedback potentiometers are driven from an extension of the ball screw shaft through a 33.45/1 anti-backlash geared gear train. Total rotation of the potentiometer is 344.4° for the 32 turns of the ball screw. Available electrical rotation of the potentiometer is 347°.

As can be seen from the above discussion and the schematic, the central key element of the actuator is the complex, one-piece ball screw assembly, which includes the planetary spider and the potentiometer drive. (See Figure 4.)
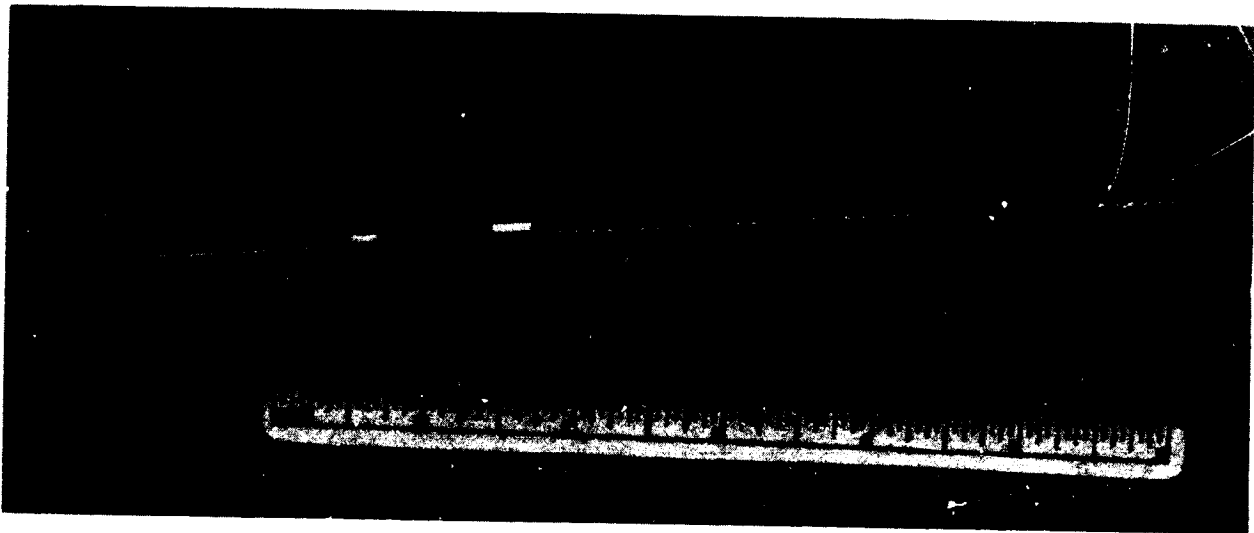

Figure 4. Ball Screw Assembly

The method of driving the ring and sun gears of the planetary gear stage is unique. Both gears (ring and sun) are at least double the width required by the planetary stage in order that the last gear of the power trains could drive the ring and/or sun gears by the same gear track. This also serves to improve the L/D ratio for the plain bearings, and makes fabrication easier. This arrangement also resulted in both gear trains, in combination with the planetary stage, being exactly the same ratio (5164.7895/1).

Travel limits have been incorporated as a part of the ball screw drive by machining stops on both ends of the ball screw nut that engage with similar stops at either end of the ball screw. In so doing, the stops only have to stop the power gear trains and stall the driving motor. The force is much less than stopping the linear motion of the ball screw and is not susceptible to jamming.

The above arrangement of parts results in a very compact design of acceptable length. Keeping the overall length down required the elimination of universal joints and telescoping the ball screw and output tube. However, as was stated before, this arrangement required a great deal of design complexity in one element.

The housing for the actuator maintains a positive pressure of 3.4475 N/cm^2 (5 psig) of GN_2 and incorporates mounting provisions for attachment to the spacecraft. This enclosure, with positive GN_2 pressure, protects the potentiometer from hard vacuum, inhibits lubrication migration and evaporation, and eliminates the entry of Florida salt air.

Materials selection for various elements was based on many factors. The steel gears use 15-5PH CRES, which is a fine-grained, heat-treatable stainless steel, readily available, that has been used with success on Voyager in the same application. The first gear and pinion from the motor, because it rotates as an idler on a steel shaft, is hardened beryllium copper. This makes a dissimilar metal bearing combination which does not readily cold weld or gall. Planet gear shafts and sun gear are made from manganese-silicone bronze per SAE CA674 for reasons similar to the above; good bearing material rotating in association with hardened stainless steel.

The gear train case is made from pure beryllium for two reasons. The primary reason is the matching of thermal expansion characteristics of the steel (11.39×10^{-6} cm/cm/°C, 6.33×10^{-6} in./in./°F) and the beryllium (10.80×10^{-6} cm/cm/°C, 6.00×10^{-6} in./in./°F). The secondary reason is the weight advantage (1.854 g/cm^3 or 0.067 lb/in.^{3}).

Journal bearings for the individual gear shafts other than those mentioned above are made from self-lubricating sintered bearings. These bearings are made from a combination of bronze and iron powders and charged with lubricant. The ring gear rotates in a beryllium pocket and is both dry and wet lubricated. The ball screw nut, of course, rides on stainless steel balls. The tube that extends from the actuator was chosen to be titanium (MIL-T-9047) because of its low heat conductivity, light weight, and high strength.

Lubrication at first was to be silicone oil and grease (F-50 and G-300); however, after analysis of a Voyager actuator anomaly, it was decided to change to a teflon derivative system of oil and grease (perfluorinated polyether 815Z oil and 3L-38-1 grease, which has better staying power and better lubricity). The oil is used to impregnate all the porous bearings and the grease is used on the ball screw, ring gear, planet gear shafts, and all gear meshes. "O" rings are also lubricated with the grease. In addition to the oil and grease system, the ring gear O.D., tube O.D. and the first gear idler shaft (shaft #6 and 10 on Figure 3) are ion plated with molybdenum disulfide to a thickness of 1500 to 2500 A° (angstroms). Idler shaft and planet gear shafts were also provided with a minor flat the length of the bearing surface (approximately 20% of the projected area) for lubricant flow or debris relief. Steel and bronze parts were all specified to have an eight micro-inch (0.203 μm) finish in the bearing and/or relative motion areas. (See Figures 5, 6, and 7.) The Voyager anomaly referred to above was the sticking of the instrument platform on the Voyager spacecraft as it was passing Saturn in 1981. This anomaly has been analyzed as a depletion of lubricant between an idler shaft and gear with subsequent galling and sizing of gear to shaft.
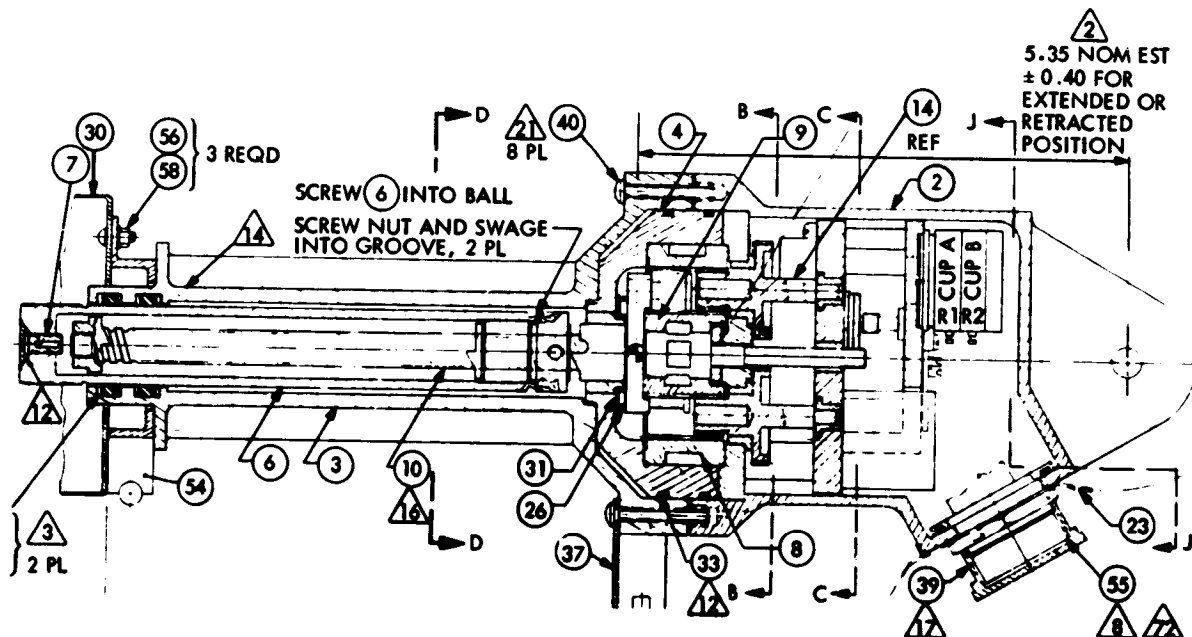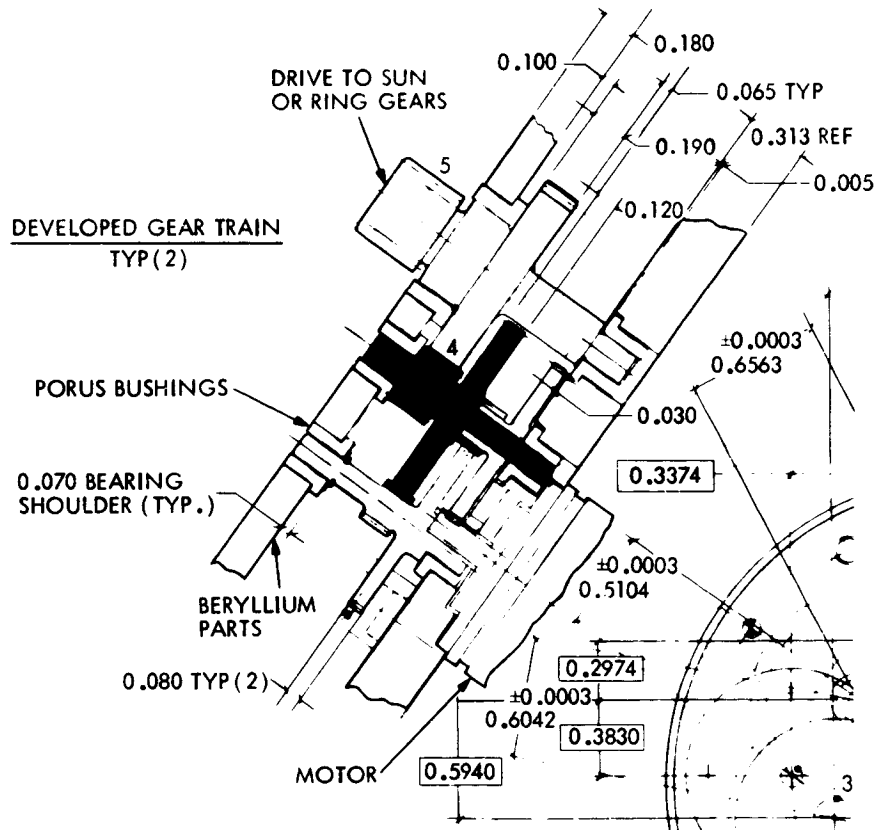

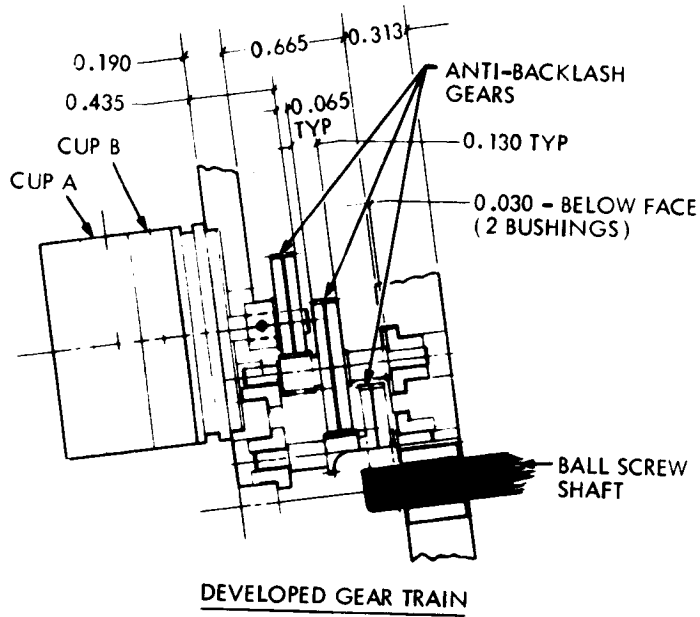Figure 5.   Actuator Cross Section View

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Figure 6.   Power Gear Train

Figure 8 shows the method of pressurizing the actuator with GN$_2$. A special sealed fixture was designed to thread onto the end of the actuator tube with provisions for an "O" ring-sealed screwdriver shaft and pressurizing port. The screwdriver is used to back off the vent screw to allow pressure to enter the actuator housing, after which the vent screw is closed. The vent screw is also sealed by an "O" ring.

FABRICATION

Fabrication of actuator parts and assembly was more or less straightforward with a few notable exceptions. Instead of fabricating an engineering model first for evaluation and then building the flight models, all parts for both engineering and flight models were fabricated at the same time. The engineering model was then assembled and tested, after which the flight models were assembled. Beryllium parts fabrication was a problem due to the

0.190
0.435
CUP B
CUP A

0.665   0.313

ANTI-BACKLASH
GEARS

0.065
TYP

0.130 TYP

0.030 - BELOW FACE
(2 BUSHINGS)

BALL SCREW
SHAFT

DEVELOPED GEAR TRAIN

POTENTIOMETER ROTATES 347°
FOR 32 TURNS OF THE
BALL SCREW SHAFT

Figure 7.   Pressurizing Method

11.25

EPOXY -
1/4 O.D.
TUBE INTO
EX STOCK
ID. x 1/16
"O" RINGS

13.375

2.00 MID
STROKE

0.625

+02
4.000 -00 TRAVEL

HOUSING   0.625

1.100

1.281
DIA

7/8 - 14 UF-2 THD

PRESSURIZING FIXTURE

SCREW DRIVER

TUBE

LBA

BALL SCREW ROTATED 90°
TO SHOW ANTI-ROTATION

SECTION E-E

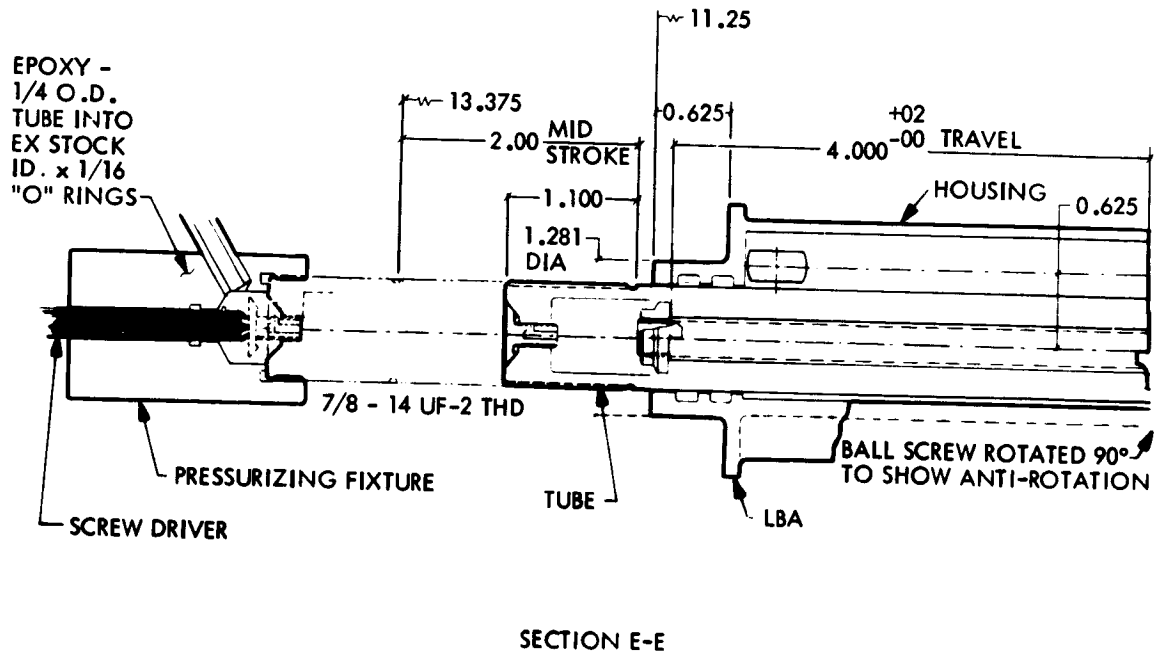**Figure 8.   Potentiometer Gear Train**

toxic nature of the beryllium dust. Beryllium parts had to be
machined to within a few thousands of an inch of final dimensions
and then chemically etched to remove a crazed surface from the
cutting operations. This improved the strength characteristics
of the metal. Sintered bushings machined on the O.D. to press
fit tolerances, cleaned, and lubricant impregnated were then
pressed in place. Matching parts of the gear frame assembly were
then mounted together, and shaft and gear center lines bored
through the bearings to ± 0.0001 in. tolerances on both the
bearing diameters and the center-to-center distances. (See
Figure 9.)

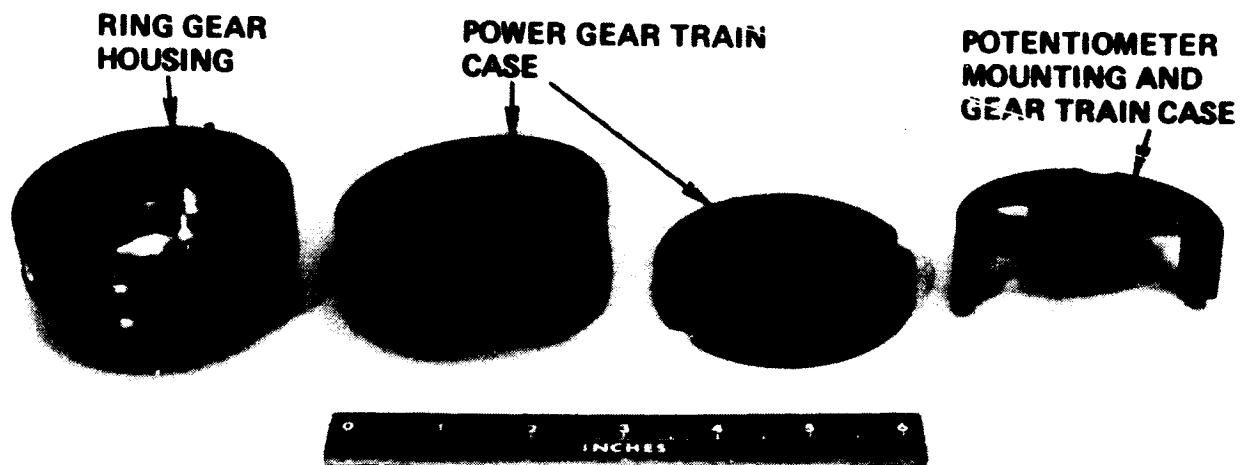**RING GEAR HOUSING**   **POWER GEAR TRAIN CASE**   **POTENTIOMETER MOUNTING AND GEAR TRAIN CASE**

Figure 9.   Beryllium Gear Case Parts

All machining of steel gears, beryllium parts, aluminum
housing, etc. was accomplished at JPL or local machine shops.
The only difference between the engineering model and the flight
models is that the gear frame in the engineering model was made
from aluminum instead of beryllium. The aluminum gear frame was
used as a first article and set-up piece for the fabricators.
This difference in material restricted only usage of the
engineerng model in temperature control and thermal test runs.

TEMPERATURE CONTROL

Originally the design of the actuator called for resistive
heaters of the same wattage consumption as the motors, with the
idea that when the motors are on the heaters would be off. This
would keep power consumption level during operations; however,

power was at a premium and additional weight was tolerable. Therefore the resistive heaters were removed and two Radioactive Heater Units (RHU's) were installed in the two small aluminum enclosures on the outside of the actuator housings. These units will each provide one watt in the form of heat. The RHU's in conjunction with a blanket installed around the LBA will keep the temperature of the actuator between -15 and +50°C. (See Figure 10.) Operation of the LBA motors will add about 3.5 watts to the package and raise the temperature approximately 5°C/hour of operation.
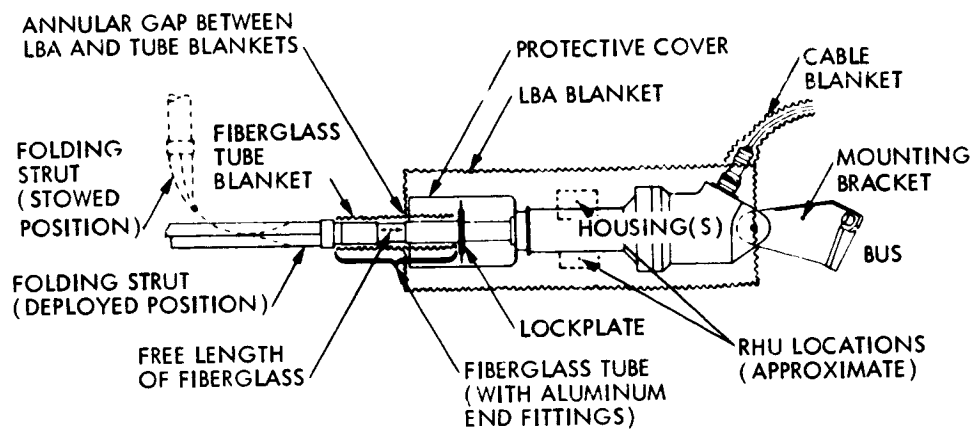

Figure 10. Actuator Insulation Schematic

TESTING AND RESULTS

Testing the LBA to 4448 N (1000 lb) would be a problem if that much force or weight had to be loaded on and off of an actuator test holder or platform; therefore a fixture was designed whereby the actuator could pull against itself thereby springing the fixture. (See Figure 11.) Motor A was stepped at a slow rate (5 PPS) in a retracting direction until the load cell read 1000 lb on the readout instrumentation, then relaxed back to zero; this was done three times, counting the required pulses each time. The average number of pulses were then programmed to 100 PPS to ensure that the torque associated with the higher pulse rate was sufficient to lift the load. There is approximately a 15 - 20% reduction in torque by increasing the pulse rate from 90 ι 100 PPS; this provides a torque pad. Spacecraft usage will be ᴤ 90 PPS. This test lifted the load with no difficulty even at low voltage. Next the 1000-lb load was increased to 1200 lb (5338 N) at the 100 PPS rate, proving that the actuator could position a 1000-lb load.
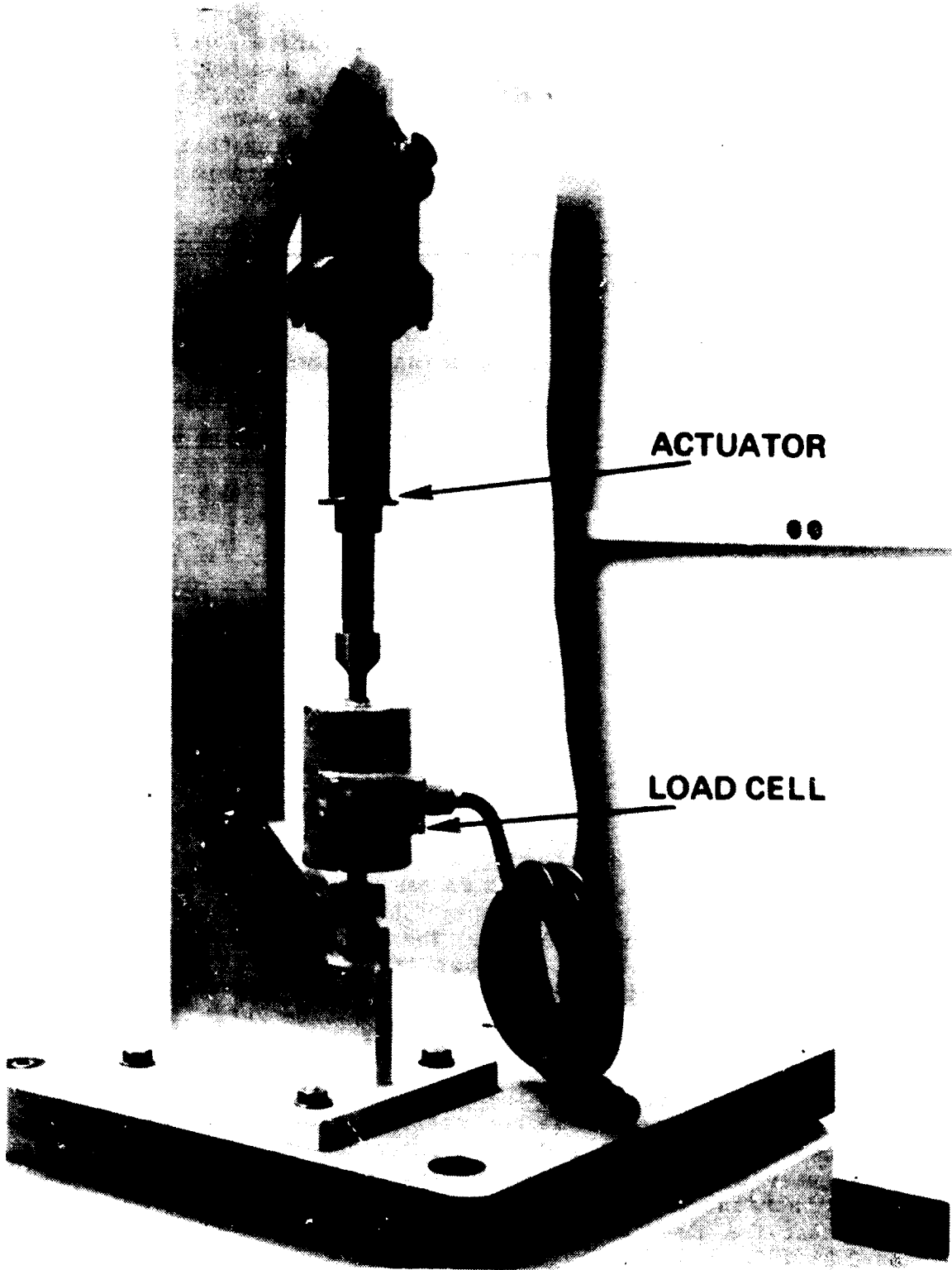
Figure 11.   Stress Test Stand

The next step was to reduce the load from 5338 N (1200 lb) to 4448 N (1000 lb) by extending the actuator and checking for overdriving or coasting when the actuator was de-energized at the 4448 N (1000 lb) load point with no difficulty. The load showed no tendency to back-drive the gear train and motor. The above test was then repeated using the motor B, proving that there is no difference in operation between motor A or motor B and their associated gear trains.

Checking travel from stop to stop required 10.269 cm (4.043 in.) of travel, or a total of 668,209 motor steps, each of which was 1.5368487×10^{-5} cm (6.0505854×10^{-6} in.). This test, as well as a calibration test for eventual usage during flight, was conducted with 444.8 N (100 lb) using the calibration fixture pictured on Figure 12.

Power dissipated is in the range of 3 to 5 watts depending on temperature, voltage and initial resistance.

Overall length is 43 cm (16.93 in.); the weight is 2.35 kg (5.18 lb); diameter at the largest point is 10.03 cm (3.95 in.).

The magnetic field at 1 meter was high due to the use of magnetic steels in both ball screw and ring gear. This tested out at close to 10 nT where a maximum of 5 nT was specified; however, a waiver has been approved allowing up to 15 nT.

Qualification environmental testing of actuator serial #002 consisted of 144 hours at 75°C and 24 hours at -40°C in atmospheric launch conditions. After the above environmental exposures, complete functional testing was repeated.

Life testing consisted of a series of cycles of varying length with the actuator mounted in the Calibration Fixture as in Figure 12 and loaded with 22.675 kg (50 lb). Total travel during this test was 609.6 cm (240 in.). The method of monitoring the actuator during the test is shown in Figure 13. Voltage was varied between about 12 and 22 VDC in steps of one volt, recording the time it took to move the actuator tube weights 0.127 cm (0.050 in.). As the voltage was increased, the motor missed fewer steps, and the points formed a sloping line until the voltage was high enough that the motor no longer missed steps, in which case the line became horizontal. Plotting these points gave two straight lines with sharp intersection. Should the gear train wear or lubricant disappear and torque increase, the time would increase and displace the intersection. Throughout the life test the observed intersection did not increase by as much as 0.25 VDC.

4" DIAL
INDICAT...

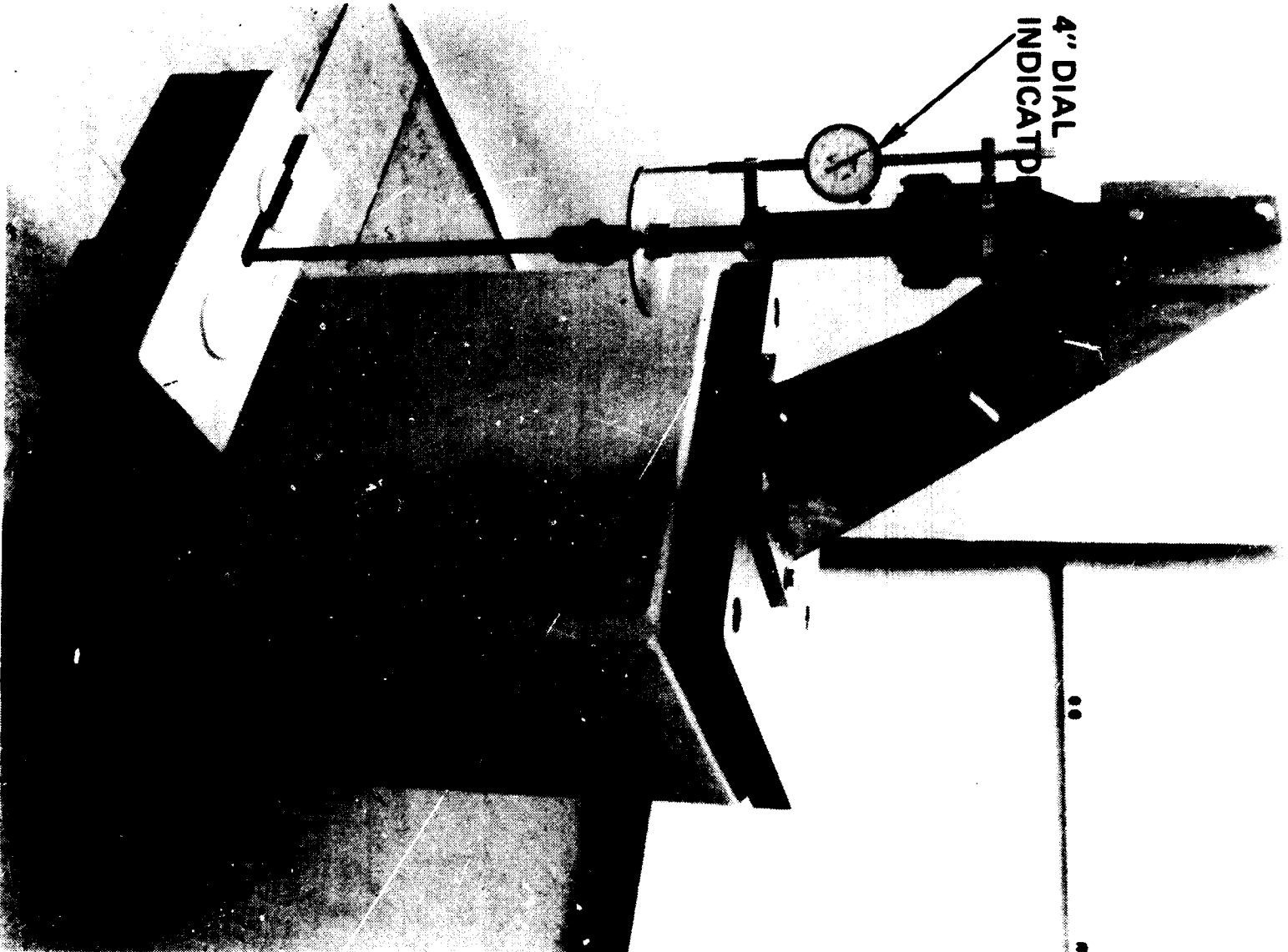Figure 12. Calibration Test Stand

SECONDS/0.050 TRAVEL (PULSES = SECONDS x 100)

TRAVEL TIME VS
DC VOLTAGE

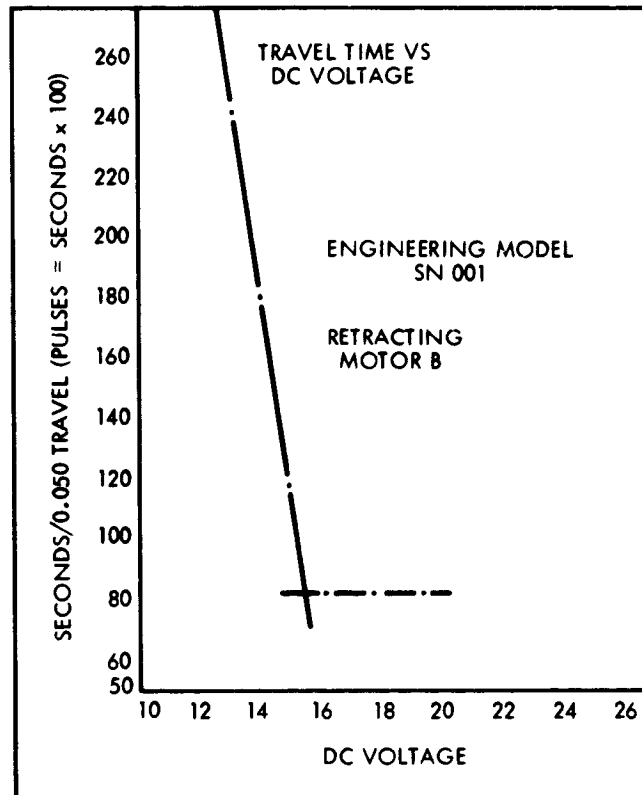ENGINEERING MODEL
SN 001

RETRACTING
MOTOR B

DC VOLTAGE

Figure 13.   Motor B Actuator Serial #001
Engineering Actuator

STATUS

Weight, power, and length restrictions have been met with a redundant gear train containing no brake or clutch. Four models have been built and tested: One engineering model; one qualification/spare model; and two flight models. Although the flight load (tensile) is not expected to be greater than approximately 1557 N (350 lb), the engineering model was tested to 5338 N (1200 lb) and the flight models to 2224 N (500 lb). All models are awaiting system test and spacecraft assembly.

ACKNOWLEDGEMENTS