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INSTRUMENT BEARING PERFORMANCE IN SPACE AND LABORATORY VACUUM

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16. Abstract

Instrument-size ball bearings were lubricated with a solid film and were tested in orbit aboard the USAF Orbital Vehicle 1-13 (OV1-13) Satellite and in laboratory (ion-pumped) vacuum. The test devices were specially designed, electronically commutated, sealed dc motors. Test samples were the rotor support bearings. Motor speed was 3000 rpm, with a 2-lb axial bearing preload. Results show that the mean operating time to reach 0.3 - in.-oz torque, considered the upper limit for instrument motors, was 3240 hours in orbit and 2140 hours in laboratory vacuum. It is concluded that ion-pumped vacuum systems provide a reasonable simulation of space vacuum for testing self-lubricating instrument ball bearings. Performance in space can be expected to equal or exceed the performance indicated by laboratory vacuum tests.

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INTRODUCTION

Instrument-size ball bearings are widely used in space flight hardware. Their use includes such basic spacecraft functions as solar-array drives, antenna drives, appendage erection, recording devices, and attitude-control components. Scientific experiments require bearings for scanning and positioning operations.

The primary purpose of this test was to obtain quantitative data on ball-bearing performance in the actual space environment. Another objective was to compare flight results to performance as measured in a laboratory vacuum environment in order to establish the validity of space-simulation testing for this important mechanical element. Extremely high vacuum, absence of molecular reflections, atomic rather than molecular gas species, zero gravity, and penetrating radiation of the space environment are not fully duplicated in the laboratory. This investigation was undertaken to observe the effect of these differences, if any, on bearing performance.

APPROACH

An instrument has been developed that is suitable for testing bearings in both laboratory and space environments. This device applies a desired axial load to the test bearings and accurately and continuously monitors the torque required for rotation. The instrumentation is employed first to amass performance data in representative laboratory vacuum facilities. Sufficient laboratory tests are conducted to establish typical torque-time patterns, failure characteristics, and most significant, the mean time to failure for bearings in the laboratory vacuum environment.

The identical instrumentation is then placed in a high-altitude orbit for a period that exceeds the expected mean time to failure. The device is mounted on the external surface of the spacecraft in a configuration that maximizes exposure to the space environment. Bearing-torque data and the time to failure are monitored by telemetry.

Constraints of space and power limit the size of the sample that can be tested in orbit. The entire sample is, therefore, tested under identical speed and load conditions to eliminate all variables except for those of space versus laboratory environment and the inherent incongruities of the bearings themselves.

INSTRUMENTATION

Instrument Design

Several approaches were studied for the bearing test instrument. The configuration selected as most suitable is shown in Figure 1. The bearings are tested in pairs, with an axial load applied to the outer race of the front bearing.

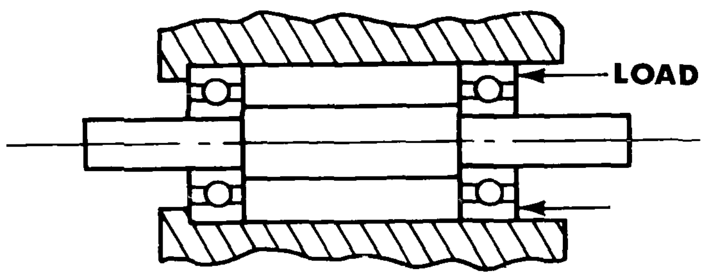


Figure 1—Bearing test configuration showing axial load applied to outer race.

It is desirable to test instrument bearings in pairs, since a single bearing configuration results in instability of the ball track and erratic results. The axial load is simple to apply and gives a repeatable mechanical configuration. This arrangement is widely used in instrument motors and other rotary components with preloaded precision bearings. With this test configuration, the design of the test apparatus consists of a suitable motor to drive the test bearings and to measure the input torque to the bearings. The brushless dc motor recently developed for GSFC is uniquely suited for this purpose.

Test Motor Design

Figure 2 shows the assembly of a bearing test motor. The rotor consists of a permanent magnet of Alnico VI material (Alnico V material was abandoned because of machining difficulties) suspended by the test bearings. Bearing preload is accomplished by means of a calibrated spring at the front of the motor. Vent holes are provided to increase the exposure of the bearings to the environment. The inner diameter of the stator is line bored to assure a bearing outer race clearance of 0.0002 to 0.0006 in. with worst-case tolerances. The bearing inner race fit on the shaft has a 0.0000 to 0.0004-in. clearance. The rotor is balanced to 10 μin.-oz maximum to minimize undesired unbalance loads on the test bearings. Rotor weight is 0.7 oz, and the moment of inertia is 2.3×10^{-5} oz-in.-sec^2.

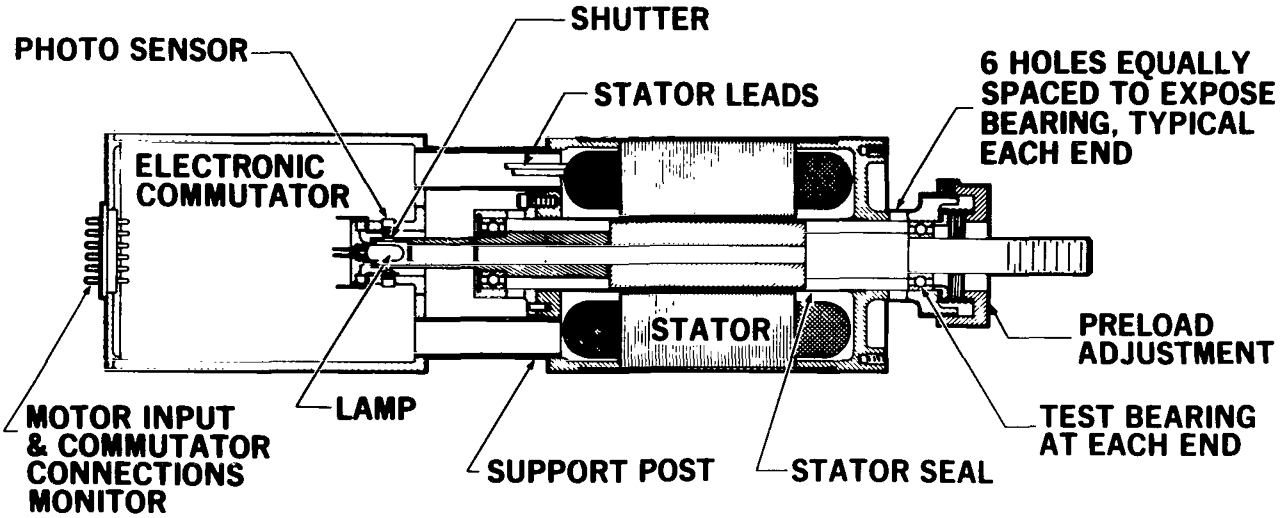


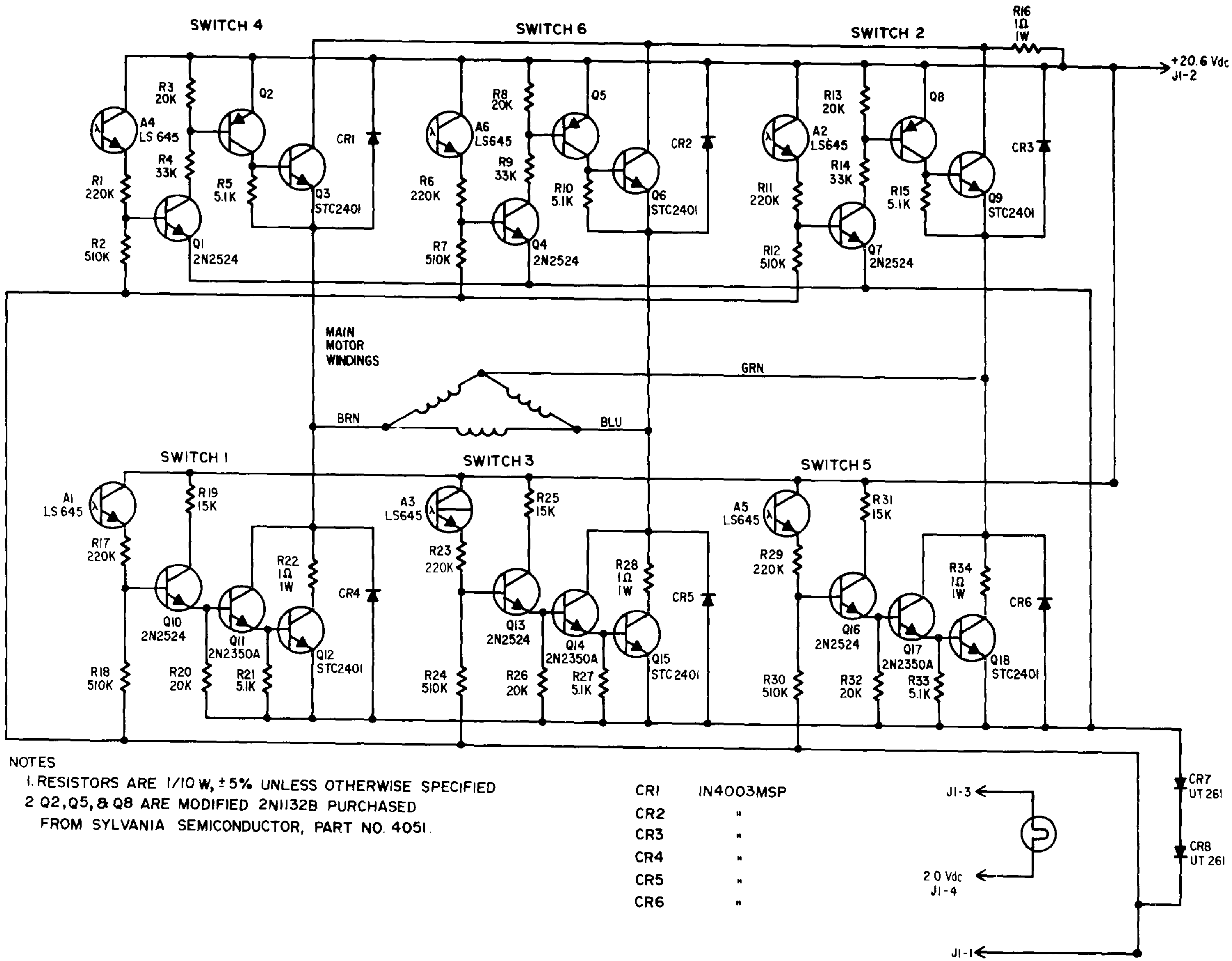
Figure 2–Bearing test motor

The motor windings and electronics are completely hermetically sealed to prevent contamination of the test bearings from outgassed organic products. The key element of the seal is a 0.005-in.-thick nichrome tube that is inserted into the air gap of the motor to seal the stator windings. The remaining parts of the motor housing are of stainless steel and are joined by soft soldering. To provide for exposure of the rear bearings, the motor is separated into two compartments, both of which are hermetically sealed and connected by a tube for passage of the motor winding leads. A glass-Kovar header is used for the input wiring connections to the motor.

A unique sealing problem was encountered in the area of the photosensors. The original motor design used a ceramic header with a metalized surface to which six photosensors and leads were soldered. Experience showed that this design gave unreliable sealing, so a one piece, glass-Kovar bulkhead was substituted.

The motor stator employs a skewed and laminated stack of Carpenter 49 material. Three windings of Formvar-insulated AWG35 copper wire are connected in a delta configuration. Direct-current motor characteristics are obtained by optically sensing the position of the permanent magnet rotor and then energizing solid-state switches in a sequence that maintains the stator electromagnetic field close to 90° to the rotor field. The light source is a tungsten-filament lamp that is operated at a voltage much below rated to significantly increase filament life. Photosensors are light-sensitive transistors. The electrical schematic for the motor is given in Figure 3.

The motor, being of a brushless design, requires no physical contact between rotor and stator other than the test bearings. The relationship of mechanical load (torque) to motor input current is linear, and it can be calibrated to give a very sensitive and accurate measure of bearing torque and speed. Details of motor calibration are given in Appendix A. The motor is highly efficient (60% at rated torque), which is most advantageous because of the limited power available from a typical satellite.



NOTES

1. RESISTORS ARE 1/10 W, ±5% UNLESS OTHERWISE SPECIFIED
2. Q2, Q5, & Q8 ARE MODIFIED 2N1132B PURCHASED FROM SYLVANIA SEMICONDUCTOR, PART NO. 4051.

CR1	IN4003MSP
CR2	"
CR3	"
CR4	"
CR5	"
CR6	"

Figure 3–Electrical schematic for motor.

Control Electronics*

For the flight experiment, control electronics were required for the following operations:

(1) Sensing for each motor when the torque level reaches the preselected "failure" level and removing the motor load from the satellite power supply.

(2) Resetting all motors at each "turn on" to test if the bearings remain in a "failed" condition.

(3) Monitoring the electrical status of the test motors and the temperature of the experiment package and conditioning of all signals for telemetering.

(4) Power conversion and voltage regulation for the experiment.

Packaging and Thermal Design

The four motors for the flight experiment were packaged as shown in Figure 4. The one-piece frame and control electronics housing is made of aluminum and is nickel plated to improve solderability. The electronics compartment, like the motors, is hermetically sealed.

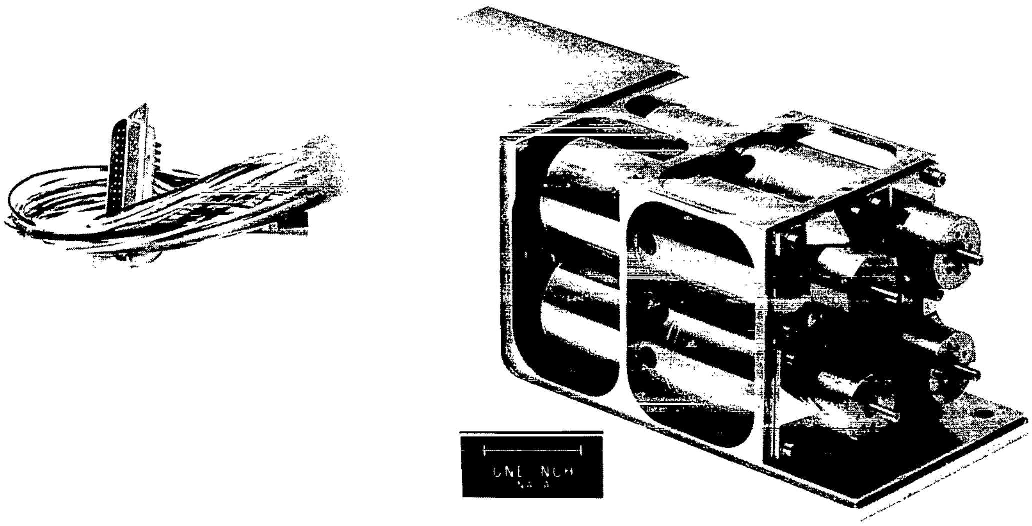


Figure 4—Bearing flight experiment.

*Clem, T. D., "OV1-13 Bearing Experiment Control Electronics," NASA X-712-67-310.

Since the experiment is mounted on the external surface of the satellite, temperature control was an important consideration. Passive control was employed. Since the satellite had a predicted temperature range of 4° to 32°C, which is well within the design range of the instrument, the first step was to couple the experiment thermally to the spacecraft. This was done by applying a highly absorptive material (black paint) to the inner surface of the experiment mounting bulkhead and by making metal-to-metal contact at the experiment mounting pads. Since the spacecraft would see long periods in full sunlight, the high-temperature limit was of prime concern. Accordingly, relatively low α_S/ϵ surface finishes (burnished metal) were employed on the external surfaces. As a result the experiment tended to cool during the relatively short eclipse periods. Tests conducted at the limiting conditions indicated that the worst-case temperature (with the motors turned off) would not go below the experiment's lower design limit of -20°C during a solar eclipse.

Environmental Qualification

The motors and control circuits were designed and tested for proper operation over a temperature range of -25° to +80°C.

The entire experiment package, including motors and control electronics, was qualified to the following vibration levels:

(1) Prototype: Sine - Atlas Agena specification × 2 in amplitude.
Random - Atlas Agena specification (6.1g rms) × 2 in duration.

(2) Flight: Atlas Agena specification for both sine and random.

BEARING TYPE AND TEST CONDITIONS

As mentioned previously, many variables were fixed by arbitrary selection so that any differences between laboratory and space performances would not be masked or obscured by other variables. The following parameters were fixed and used for all laboratory and flight tests.

Bearing Type

Bearings were size SR-2, precision ABEC-7, angular-contact ball bearings. Radial play was 0.0006 to 0.0008 in. Balls and races were made of 440C stainless steel. Retainers were of the solid, self-lubricating, machined type. The bearings were run-in for 3×10^4 revolutions at low speed in air, and their selection was based upon satisfactory torque traces.

Speed

Bearing speed was set at a nominal 3000 revolutions per minute (rpm). Actual speed varied from 3300 rpm at minimum bearing torque to 2100 rpm at the maximum (failure) torque.

Failure Criterion

In any bearing test, it is necessary to define what constitutes failure. If sufficient torque is applied, a bearing may be driven long after it has deteriorated below the level of acceptable, antifriction bearing performance. It was judged that for a small instrument motor, the maximum allowable bearing loss would be of the order of 1 W. At a motor efficiency of 60% and a speed of 2000 rpm, this would be 0.28 in.-oz per bearing pair. For purposes of the flight experiment, this loss would allow for the testing of four pairs of bearings with a maximum power input of 5 W, including electronics. Accordingly, the failure criterion was set at 0.3 in.-oz per bearing pair for all tests. This is approximately six times the normal torque for this type of bearing.

LABORATORY TEST PROGRAM

A program of laboratory vacuum tests was conducted in conjunction with the flight experiment. The primary purpose was to obtain bearing performance data in representative space vacuum simulation chambers for comparison with orbital performance. In addition, prior knowledge of bearing load-life characteristics was required for selection of bearing-failure criteria and for selection of the test load for the flight bearings that would result in failures within the projected satellite life of 6 months. Also, testing of three retainer materials was included to aid in selection of the most promising candidate.

All motors used in the laboratory tests were designed identical to those motors employed in the flight tests. Operation in air was held to a minimum (less than 5 minutes). The bearings ran continuously in one direction except for unavoidable interruptions for power outages, and so forth. All laboratory tests were conducted at ambient temperature.

Laboratory Vacuum Equipment

Laboratory vacuum chambers were required to be representative of good practice for dry-lubricant testing. Accordingly, bakeable stainless steel chambers with metal gasket seals were employed. A totally oil-free pumping system was provided.

A molecular-sieve pumping system was used for evacuation to a pressure of a few microns (1 μm Hg = 10^{-3} torr). Each chamber was provided with an 80-l/sec ion pump and a 350-l/sec titanium sublimation system to achieve ultimate pressures in the 10^{-8} torr range. Ion pumps were chosen because they contain no pump fluids or moving parts and are therefore inherently clean. A controller that provided power to start and operate the ion pump was included in the system. Pressure was measured by reference to the ion-pump current-pressure characteristic curve. The accuracy of this reading is ±10% of full scale.

A rack-mounted system consisting of three complete test bays was built to facilitate testing. Each bay contained one vacuum chamber plus associated pumping systems, power supplies, and controller units.

An eight-channel, ink-writing recorder was used for real-time recording. Each test device required eight channels for data recording—four for normal running and four for indication of bearing failure or overload. All three chambers utilized one recording facility that had a sequencing unit that sequentially sampled the data at 5-minute periods.

Laboratory Test Results

The laboratory program was employed to verify many of the arbitrary selections of bearing type, load, speed, failure criterion, and so forth. One of the basic arbitrary choices was to test only dry-film-lubricated bearings. Oil-lubricated bearings, although of great interest, were not considered because they would have resulted in contamination of an adjacent friction experiment.

Two types of dry-film bearings were considered: (1) single film and (2) lubricating retainer. The single-film types, which include burnished, bonded, and chemically applied coatings of molybdenum disulfide (MoS_2) or other laminar solids, were rejected due to their limited wear life. Accordingly, the lubricating-retainer type of bearing was selected for this program.

Three candidate materials for the retainer were briefly evaluated:

(1) Duroid 5813—A composite of Teflon laminated with glass fibers (40%) and containing 2% MoS_2.

(2) Rulon A—Similar to the Duroid except the glass fibers are shorter and randomly oriented. Contains 5% MoS_2.

(3) Salox M—A composite of Teflon reinforced with 40% bronze powder.

Figure 5 shows the results of early vacuum tests of the three materials at relatively high values of axial load. These tests are too few to enable a conclusive comparison of the three materials (for example, additional tests on Duroid at 2-lb loads also resulted in early failure). However, based upon the available data, it was decided that Duroid was a good choice because it appeared to outperform Salox at lower loads (more representative of instrument application) and because Rulon appeared more susceptible to early failures. Accordingly, Duroid 5813 was selected for the flight program, and additional laboratory data were obtained for this material.

Laboratory Test Results for Duroid-Retainer Bearings

Figure 6 presents the laboratory test results for the Duroid-retainer bearings. These data show that if the bearings were loaded at a 2-lb axial force, failure could be expected within the life of the satellite (6 months). These data also show that the failure criterion (0.3 in.-oz for a bearing pair) was high enough to avoid failure indication because of transient torque fluctuations at the 2-lb load value. Occasional rough spots were experienced with peak torques which approached and very infrequently exceeded the failure level, but the 100-ms time constant of the sensing circuit prevented actuation until the failure level was maintained for a period of time.

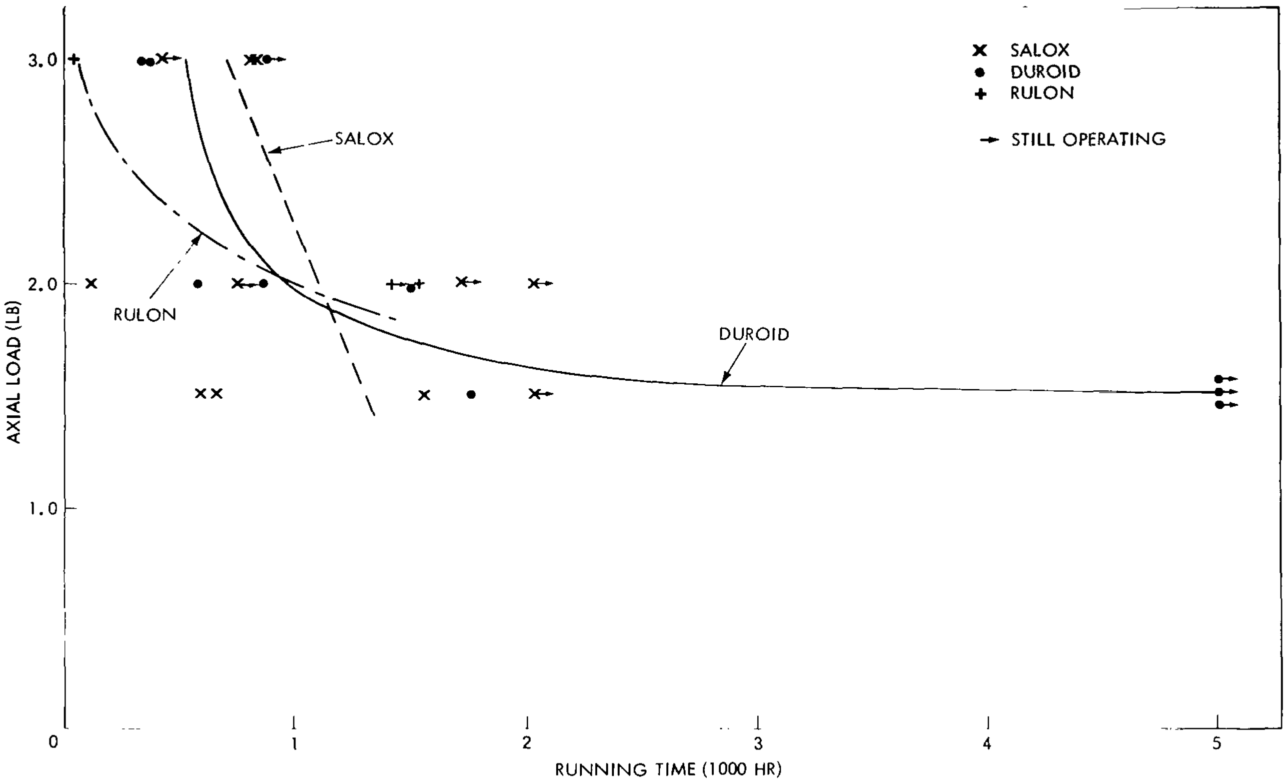


Figure 5–Load versus time to failure for early laboratory vacuum tests of Duroid, Rulon, and Salox materials–3000 rpm speed.

Examination of the bearings after "failure" also supported the choice of the failure criterion. Invariably, the bearings showed severe wear in the retainer ball pockets and excessively heavy debris buildup in the raceways. Occasionally, the retainer ball pockets were worn completely through, and the retainer was split in half (see Figure 7). Thus, it can be stated with confidence that when the failure criterion is exceeded, then the bearings have reached the end of their useful life.

In spite of considerable effort to assure uniformity in the manufacture and run-in of the bearings and in the test conditions, there is wide variation in performance from bearing to bearing. Also, the apparent longer life at a 1.5-lb load as compared to a 1.0-lb load was not expected. It was suspected that an optimum value of preload (greater than zero) would exist, but it was not expected at so high a load level.

Another characteristic of the Duroid-retainer bearings was observed. If, after some period of satisfactory operation, the bearings are stopped and restarted, a temporary period of high and erratic torque is experienced. This effect is particularly pronounced if the bearings are in air when the restart is attempted. In fact, a torque well in excess of the 0.3-in.-oz failure level was sometimes required to start rotation under these

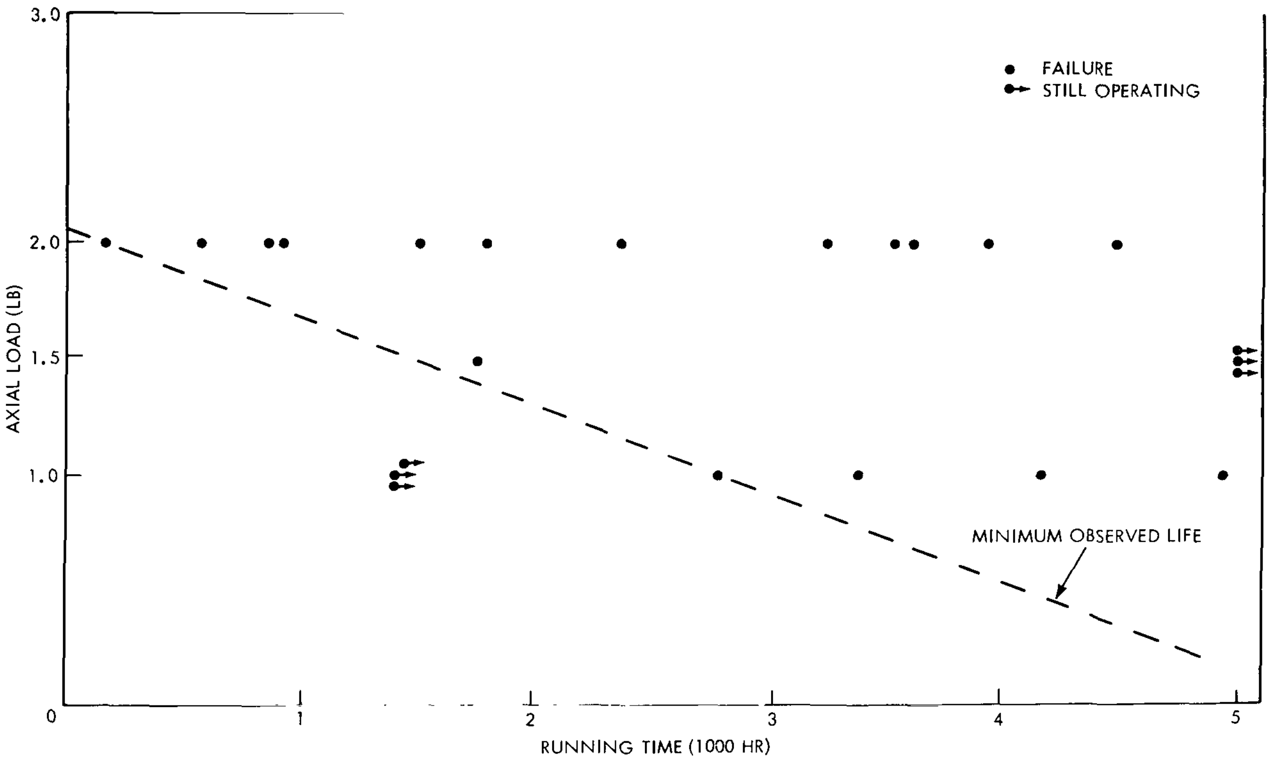


Figure 6—Load versus time to failure for laboratory vacuum tests of Duroid-retainer bearings—3000 rpm speed.

conditions. If the restart was attempted in vacuum, high torques were also observed, but they were always less than the failure level. No adverse effect on bearing lifetime could be attributed to interrupted operation of the bearings in vacuum. For example, the two shortest lifetimes observed were run without interruption.

SPACE FLIGHT PROGRAM

The orbital phase of the program was conducted aboard the OV1-13 Satellite. This vehicle was launched from the Western Test Range on April 6, 1968.

Spacecraft Description

The basic OV1 satellite is a medium-sized (300-lb) spacecraft designed for launch by the Atlas booster. Essentially, the satellite is a cylinder 27 in. in diameter and 54 in. long. Solar-cell domes occupy each end of the vehicle. A secondary propulsion system including a solid-propellant motor and an orbital-insertion guidance system is provided to complete the orbital vehicle.

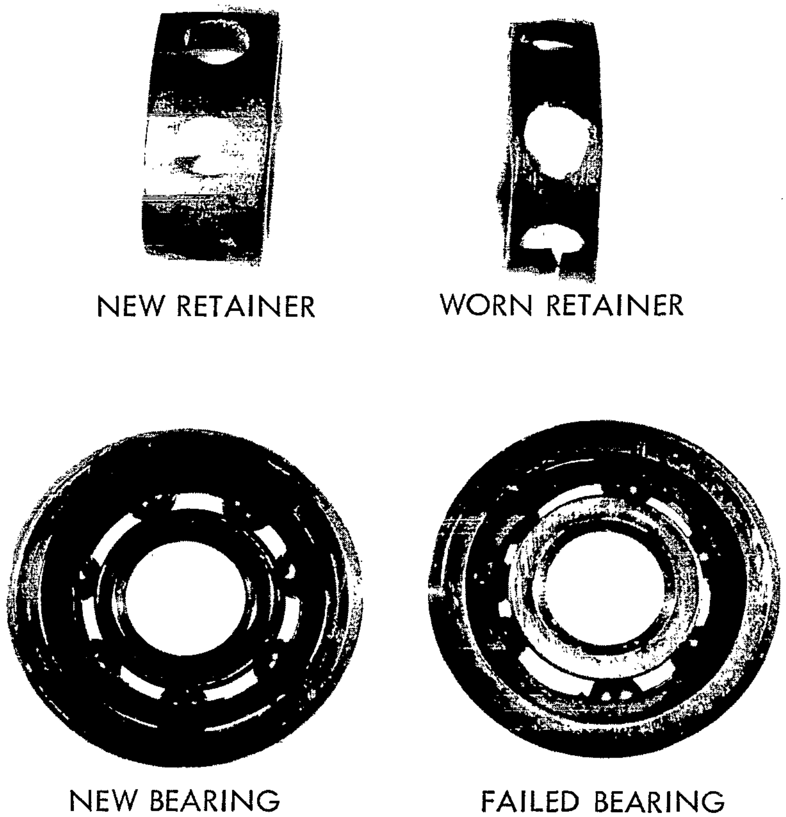


Figure 7—Duroid-retainer bearing—new and failed—at 5X magnification.

The satellite telemetry is a Pulse Code Modulated PCM-FM system. System capability permits the combination of analog and digital data with a series pulse train that gives a data rate of 2048 bit/sec. This system permits a readout of 253 prime channels of information and 64 channels of subcommutated information. Both real time and stored data can be obtained. Stored data are accumulated on a reel-to-reel, digital-data, magnetic tape recorder. This recorder has a 4-hour recording capacity. In the playback mode, the recorded data are reproduced in reverse order at 16 times the recording rate (the 2048-bit/sec recording is played back at 32 768 bit/sec). This permits the entire contents of the recorder to be transmitted in 15 minutes. Bearing torque data are sampled at a rate of once per second, and the accuracy of the telemetered level is within $\pm 1\%$.

Orbital Parameters

The satellite was placed in a near polar orbit (100° inclination) with an apogee of 5030 and a perigee of 303 n. mi. Orbital period is 3.3 hours. The satellite is spin stabilized with its spin axis initially normal to the ecliptic plane, as shown in Figure 8. In this orbit, the satellite sees a pressure environment ranging from 5×10^{-9} torr at perigee to less than 10^{-12} torr at apogee.

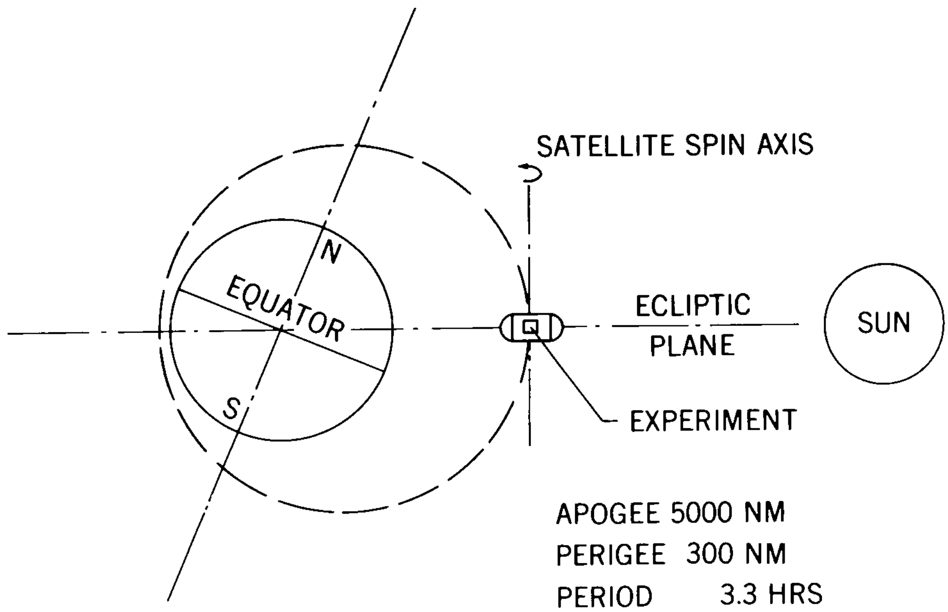


Figure 8—OV1-13 orbital parameters.

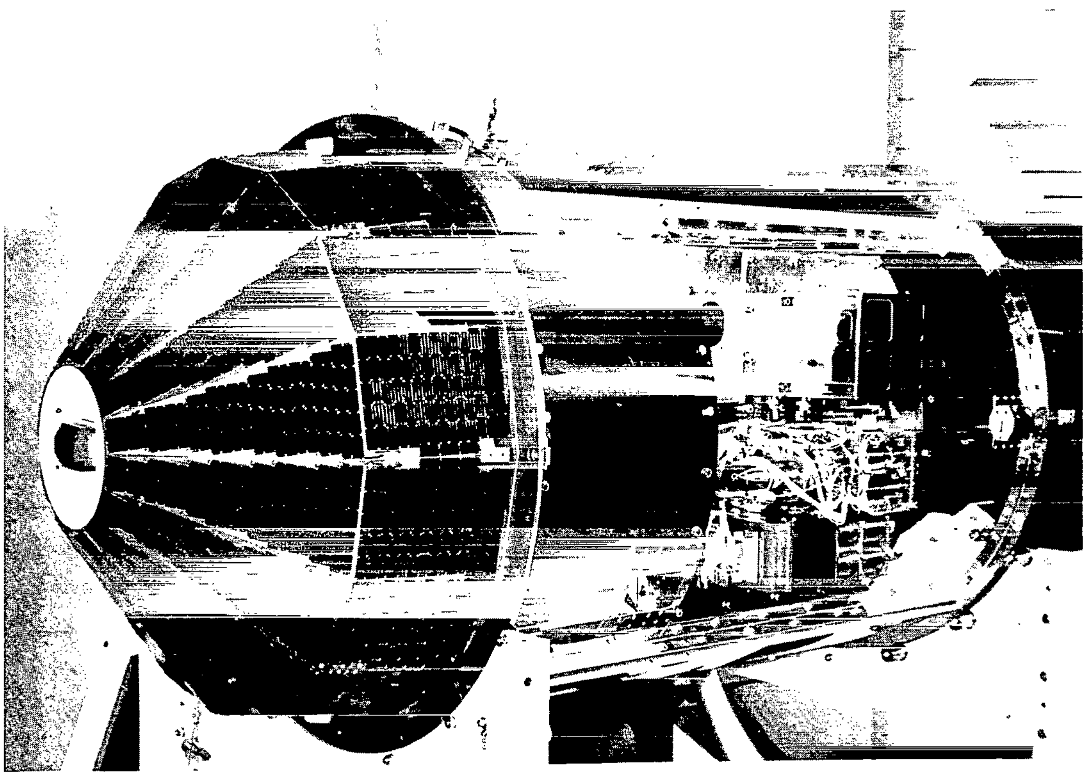


Figure 9—Experiment mounted on OV1-13 satellite.

Space Exposure

The bearing test experiment was mounted on the external surface of the satellite, as shown in Figure 9. The external surfaces are clean, polished aluminum. The experiment surfaces were also clean stainless steel and aluminum. The adjacent friction experiment was also designed for minimum outgassing and, except for Teflon wire insulation, used no organic materials.

Size, Weight, Power

The flight experiment had the following physical parameters:

Size	Weight	Power
3 in. × 3 in. × 8.5 in.	4.0 lb	2.2 W

Pre-Launch Operations

After calibration, the motors were thoroughly cleaned and the test bearings were assembled at the motor contractor's plant. The motors were stored in sealed packages until assembly in the test unit. The complete test unit was subjected to a flight-level vibration test. After integration on the satellite, a low-level vibration test and a magnetic-interference test were conducted. The bearings were operated after each test, and torque levels were normal. Operation in air was held to a minimum (6 minutes total). Handling procedures for the experiment were designed to minimize contamination. A dust cover was employed for protection and was removed only for brief tests in a laboratory environment. For shipment to the launch site, the experiment was sealed in a container purged with dry nitrogen. At the launch site, handling was done in an area equipped with dust and humidity control. The experiment and spacecraft were assembled in the shroud for movement to the launch pad and attachment to the booster. The shroud was continuously purged with dry clean air during the countdown. The experiment dust cover was not removed until 6 hours before launch.

Flight Test Results

The bearing experiment was turned on during the seventh orbit of the satellite—at approximately 21 hours. Two of the four pairs of bearings showed initial torque variations with peak readings of twice the normal level. Such variations are common during the early life of Duroid retainer bearings. After 30 minutes, all bearings were operating smoothly and at nominal torque levels. It was clear that the bearings survived the launch shock and vibration without damage.

Temperature of the experiment, measured at two places in the frame and electronics housing, varied from 24°C to 29°C during the early orbits, which underwent shadow periods of 25 minutes. The temperature rose gradually to a constant 40°C as the orbit came into full sunlight at approximately 2000 hours.

In orbit, the bearings were operated continuously except for four intervals (average duration: six 19-hour orbits each) and once-per-week turnoff periods of approximately 1-minute duration each, such durations being required by satellite-operation considerations. The complete torque history for the flight-test bearings is given in Appendix B. Time to failure for the bearing pairs was as follows:

Pair	Time to failure (hr)
A	2698
B	6096
C	2070
D	2095
	3240 mean

COMPARISON OF FLIGHT AND LABORATORY RESULTS

One measure of comparison of the flight and laboratory results is the mean time to failure at the same load (2 lb) and speed (3000 rpm):

	Sample size	Mean time to failure (hr)
Flight	4	3240
Laboratory	12	2245

The data indicate that bearing mean life in the space environment will equal or exceed that shown by laboratory tests at a confidence level of 83% (see Appendix C). Since the data fail to pass the test at the 90% confidence level, substantially longer life is not indicated, and the difference in means is primarily due to one unusually long (6096 hr) data point.

A second comparison may be made, this being the torque-life characteristic of the bearings. The average torque over the bearing lifetime is very similar for the laboratory and flight samples. Torque varies between 0.05 and 0.10 in.-oz for both groups. In all cases, the flight bearings failed suddenly, with last torque readings before the failure being at normal level. Similar failures are observed in about one-half of the laboratory cases. (See Figure 10). In the remaining laboratory cases, there is some warning of impending failure, with the torque beginning to rise some 100 hours in advance of the failure as shown in Figure 11. Thus, the torque characteristics for the two groups of bearings are quite similar, the only observable difference being that of the flight failures consistently occurring suddenly.

The foregoing results are consistent with known facts concerning the Duroid lubricated bearing system. These facts are as follows:

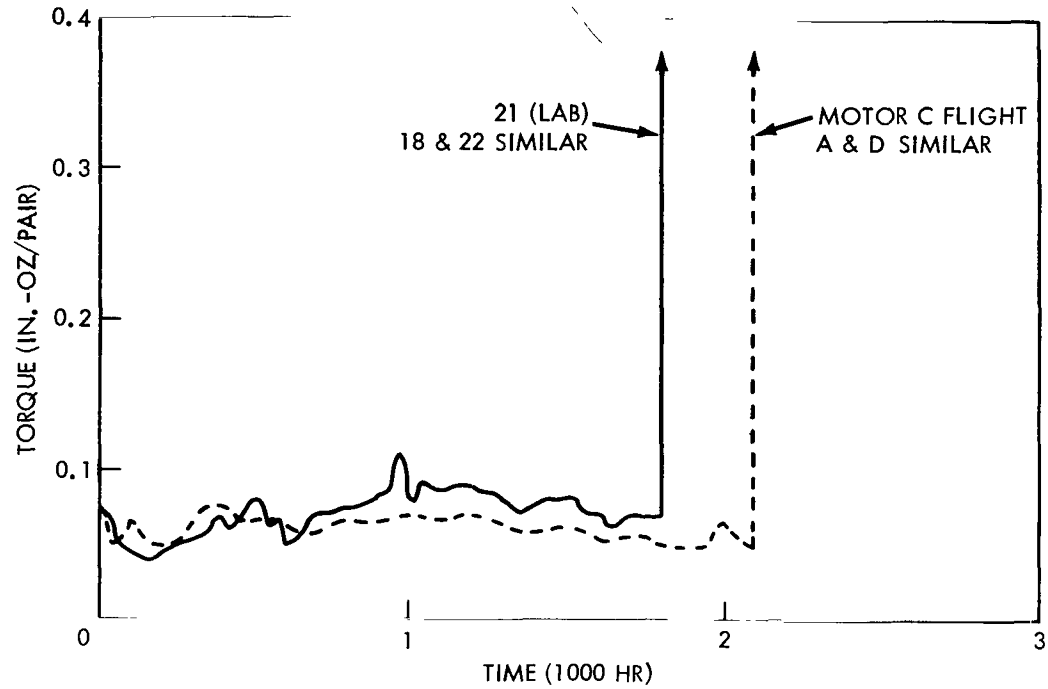


Figure 10—Comparison of flight versus laboratory failure mode.

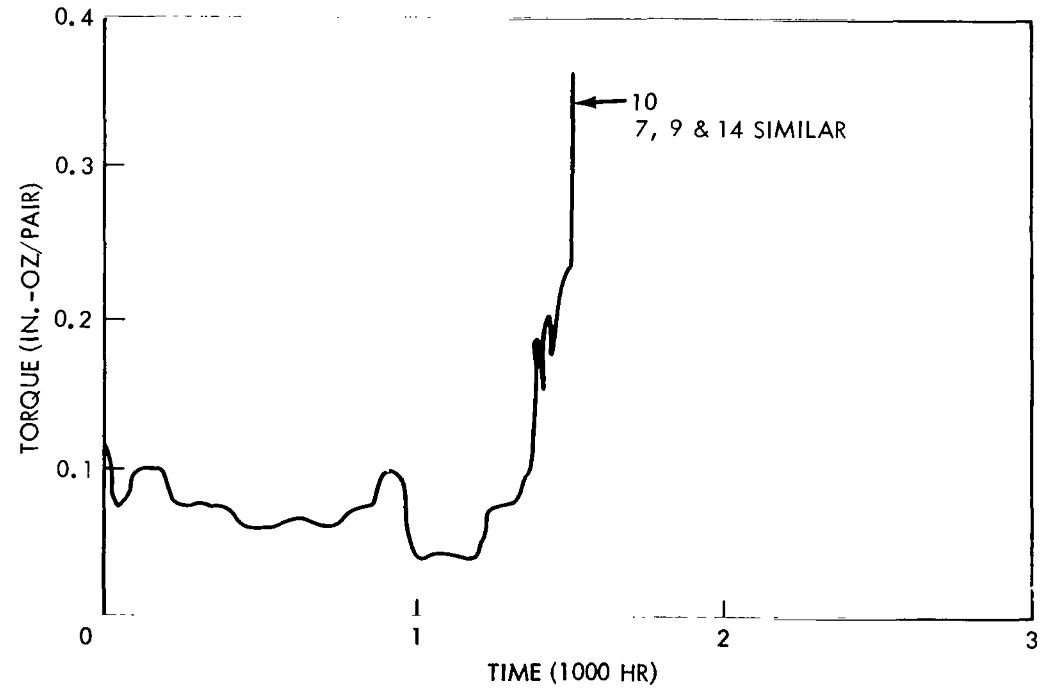


Figure 11—Laboratory failure mode.

(1) Duroid retainers are subject to rapid wear when operated in the presence of oxygen and water vapor (Ref. 1).

(2) MoS_2 has a higher coefficient of friction in air than in vacuum (Refs. 1 and 2).

Therefore, it is expected that more complete removal of oxygen and water vapor will better the performance of this type bearing. As the flight bearings were operated at a pressure at least 1 decade lower than the laboratory samples, some slight improvement would be predicted.

CONCLUSION

It is concluded that ion-pumped vacuum systems provide a reasonable simulation of space vacuum for testing self-lubricated instrument ball bearings. Performance in space can be expected to equal or exceed that indicated by laboratory vacuum tests. This conclusion is based upon 6 months of space exposure, and it does not consider long-term unshielded radiation effects on the lubricating materials.

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Goddard Space Flight Center
National Aeronautics and Space Administration
Greenbelt, Maryland, April 29, 1970
125-19-17-01-51

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APPENDIX A

MOTOR CALIBRATION

For a dc motor, the total mechanical torque T developed is a linear function of armature current I:

$$T = kI.$$

The torque T includes the following:

$$T = T_e + T_B + T_M + T_W,$$

where

T_e = any external load torque,

T_B = bearing coulomb friction torque,

T_M = magnetic torque including hysteresis and eddy-current effects,

T_W = windage torque (unmeasurably small for this motor, in air as well as vacuum).

The calibration procedure is explained with reference to Figure A1. The T_e versus I characteristic is determined by means of a dynamometer (curve A). For purposes of calibration, the motor is assembled with oil-lubricated bearings which have a constant (and smooth) torque T_{BO} over the speed range of interest.

The motor torque constant can be determined from

$$k = \frac{k_e (I_{R/2} - I_R) + T_{M,R/2} - T_{MR}}{I_{R/2} - I_R}$$

$$= k_e + \frac{T_{M,R/2} - T_{MR}}{I_{R/2} - I_R}.$$

T_{MR} is the magnetic torque at rated speed which is measured for each motor. The method consists of measuring the difference in the torque required to rotate a magnetized rotor compared to a demagnetized rotor.

$T_{M,R/2}$ is the magnetic torque at 1/2 rated speed:

$$T_{M,R/2} = \frac{3}{4} T_{MR}.$$

I_R and $I_{R/2}$ are the armature currents at rated and 1/2 rated speed, respectively (note that the correction in slope due the speed dependence of the magnetic torque is about 1.5 percent):

$$k = k_e - \frac{T_{MR}}{4(I_{R/2} - I_R)} .$$

It can be shown that

$$I_M = I_R - \frac{kI_R}{k_e} + \frac{T_{MR}}{k_e} ,$$

where I_M is the current required to overcome the magnetic loss in the absence of any other torque and I_R is the armature current at rated (3000 rpm) speed.

Since, in the bearing test situation, the only measurable torque other than the magnetic torque is the bearing torque T_B, then

$$T_B = k_e (I - I_M) ,$$

or

$$T_B = k_e I - C ,$$

where

$$C = I_R (k_e - k) + T_{MR} .$$

Motor speed can also be determined from the telemetered value of motor current. Figure A2 shows a typical speed armature current calibration for a flight motor. The curve can be extrapolated with high confidence to cover bearing torque less than that of the oil-lubricated bearings used in the calibration.

Carefully controlled tests showed that motor calibration is not significantly affected by disassembly, provided that proper remagnetization and stabilization procedures are employed. This requires magnetization in a 25,000-A-turn fixture to fully saturate the magnet and subsequent stabilization by stalling the motor at an overvoltage (27 Vdc) level.

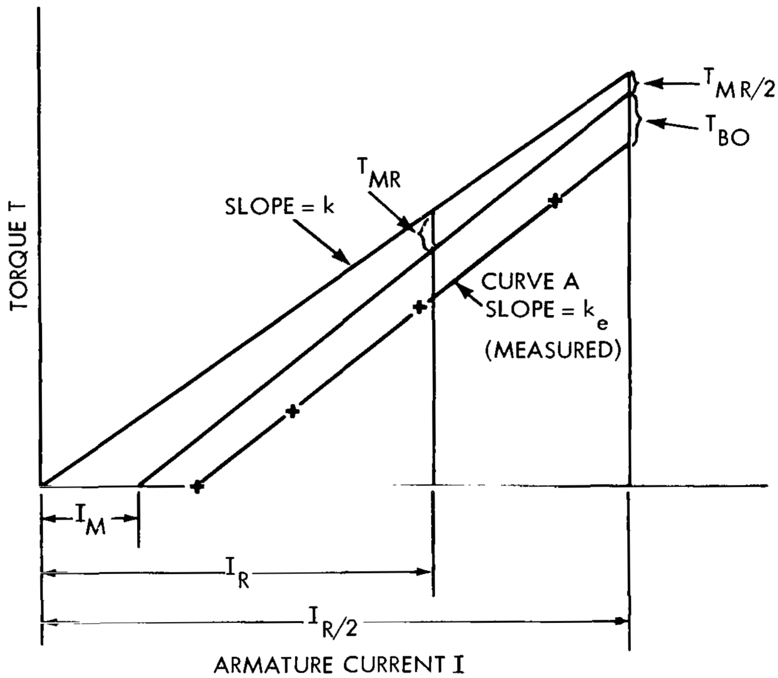

Figure A1–Torque-armature current relationships.

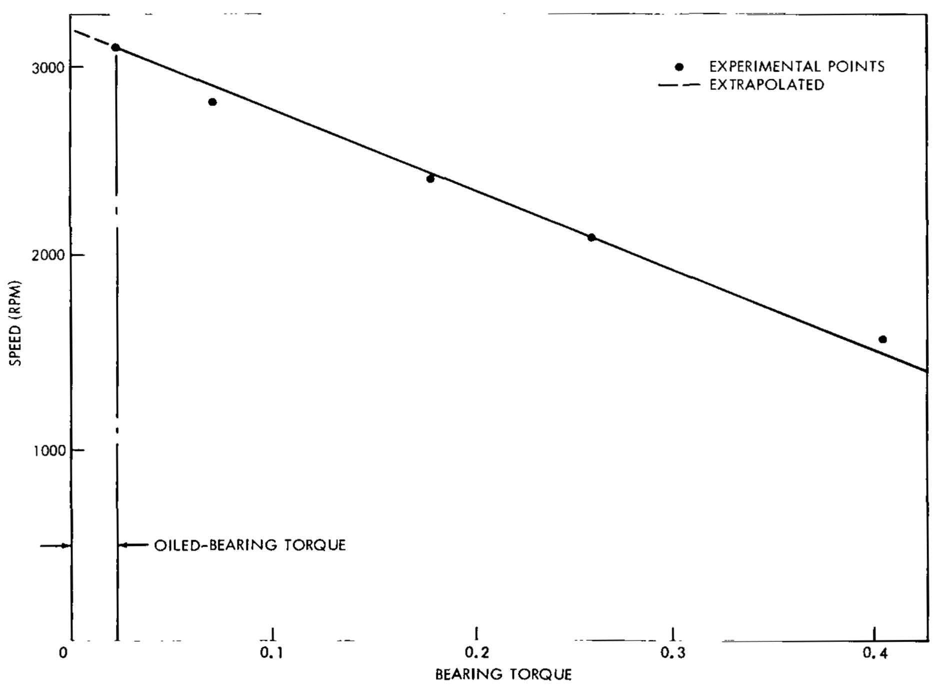

Figure A2–Typical speed-torque characteristic.

APPENDIX B

TORQUE HISTORY FOR FLIGHT TEST BEARINGS

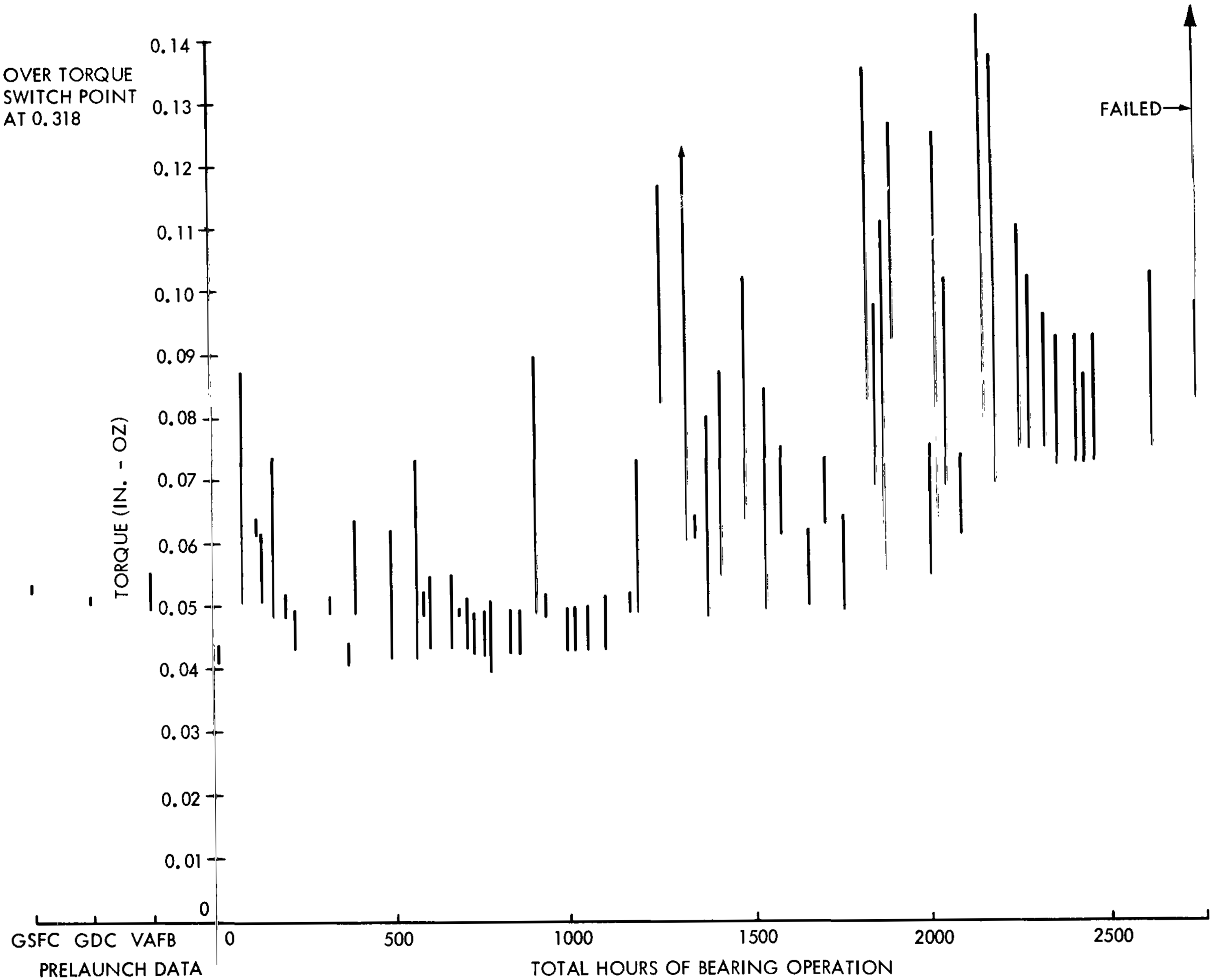

Figure B1—Bearing data of motor A (number 11) on OV1-13.

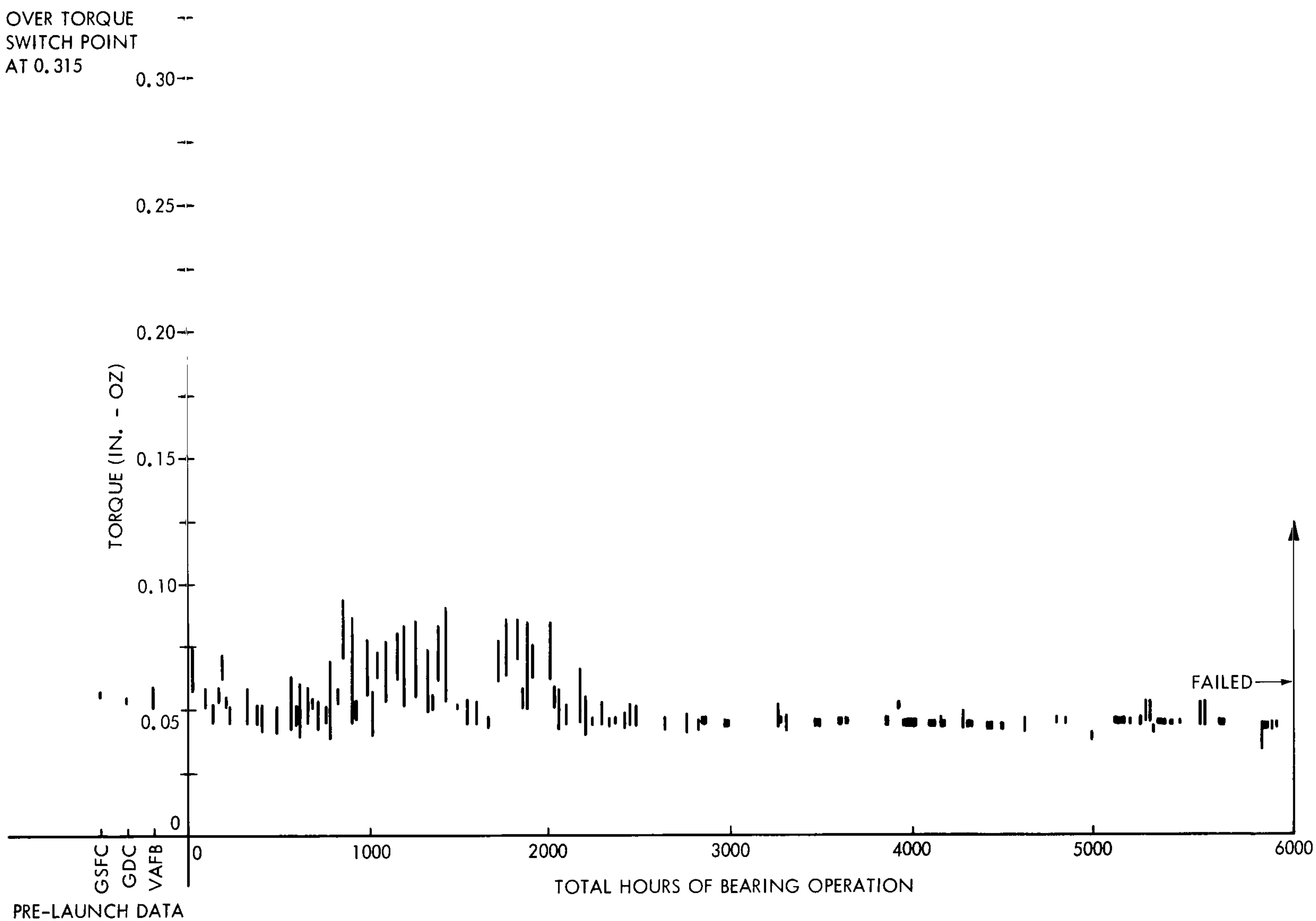

Figure B2–Bearing data of motor B (number 16) on OV1-13.

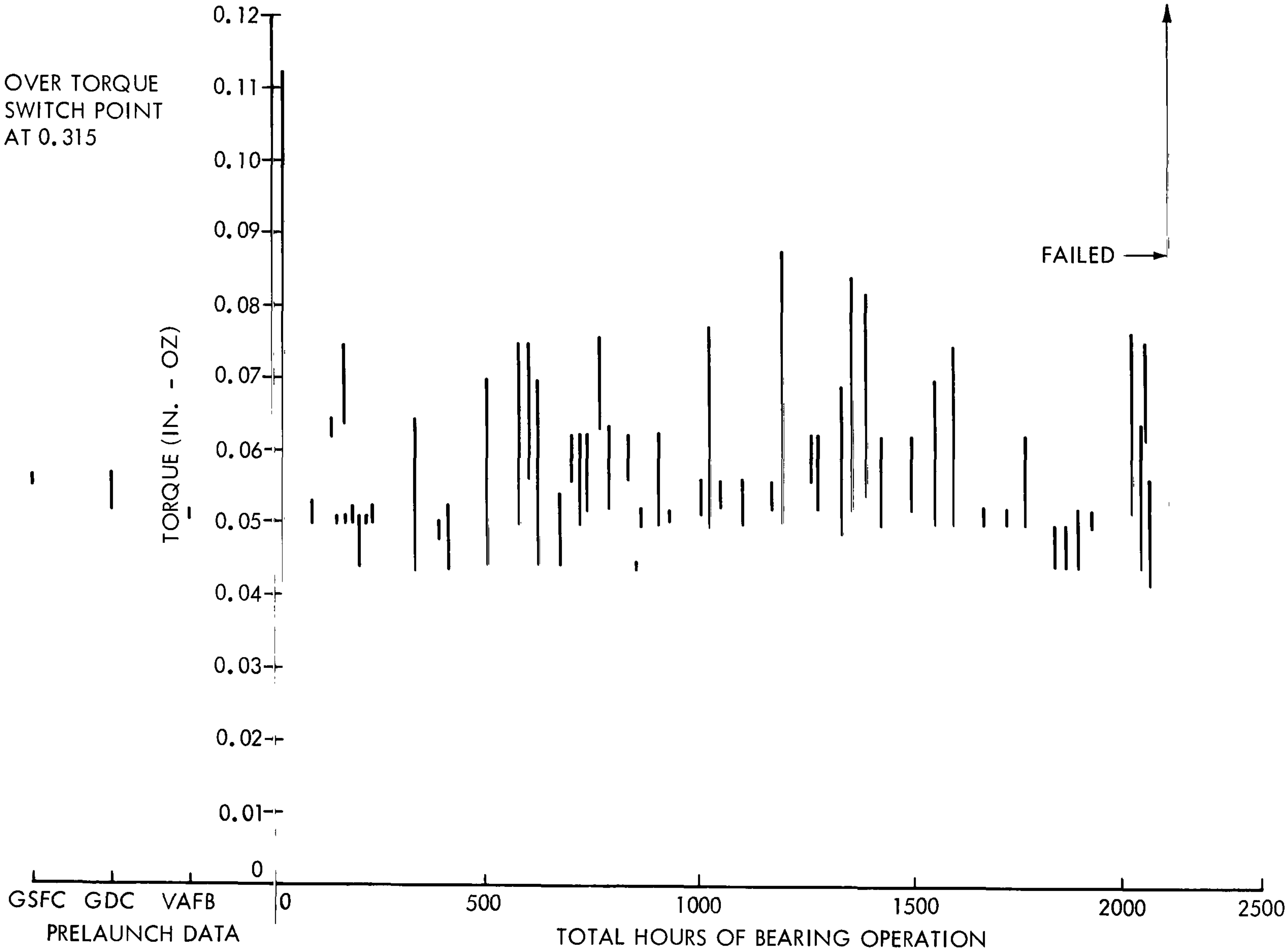

Figure B3—Bearing data of motor C (number 26) on OV1-13.

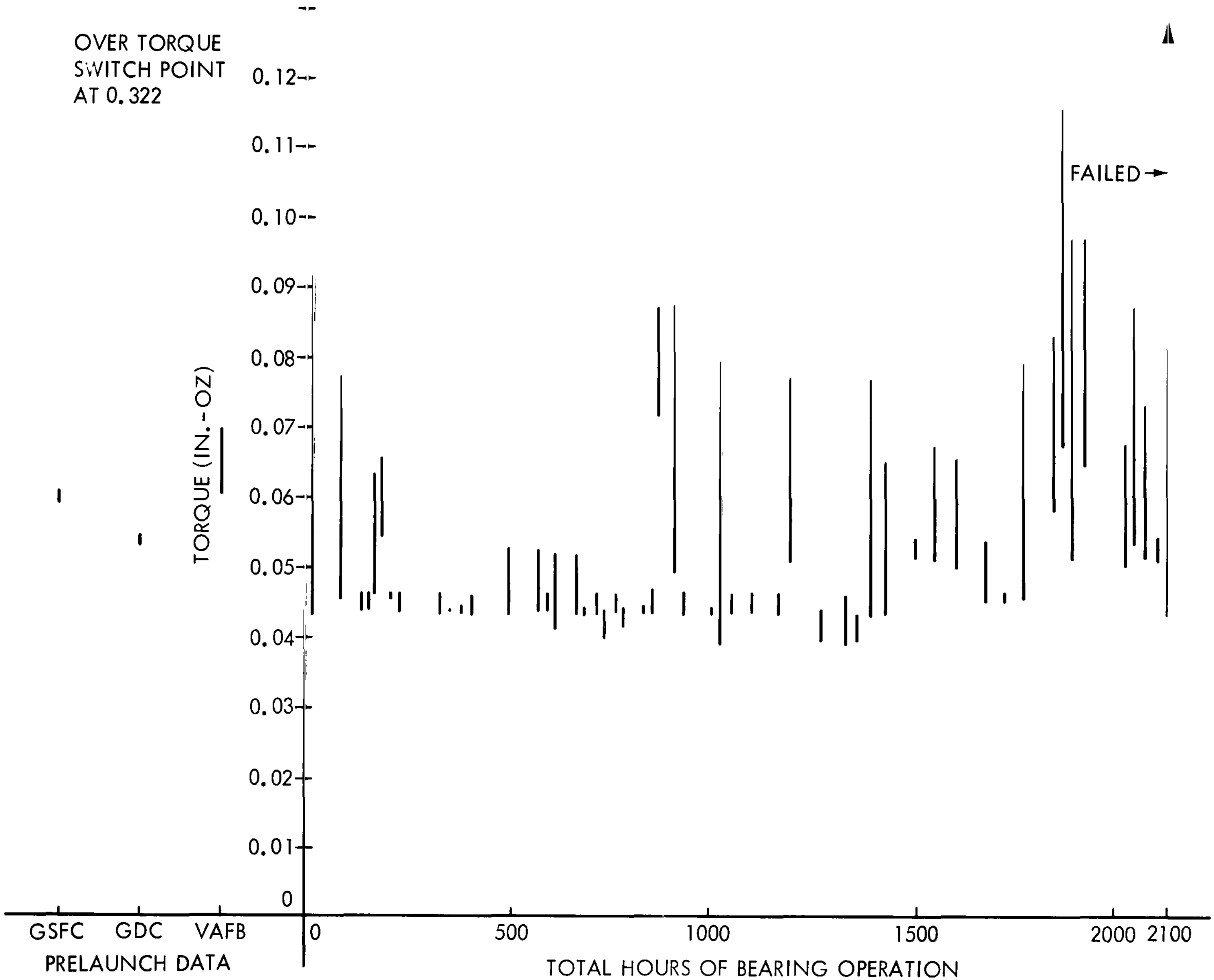

Figure B4—Bearing data of motor D (number 30) on OV1-13.

APPENDIX C

STATISTICAL ANALYSIS OF DATA

Statistical parameters for the two groups of data are—

	Number of Samples	Mean	Standard Deviation
Flight Tests	$N_1 = 4$	$\bar{X}_1 = 3234$ hr	$S_1 = 1930$ hr
Laboratory Tests	$N_2 = 12$	$\bar{X}_2 = 2245$ hr	$S_2 = 1472$ hr

Student's t distribution will be employed to test the significance of the difference of the means.

$$\sigma = \sqrt{\frac{N_1 S_1^2 + N_2 S_2^2}{N_1 + N_2 - 2}} = 1709 \text{ hr},$$

and

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sigma\sqrt{\frac{1}{N_1} + \frac{1}{N_2}}} = 1.002;$$

degrees of freedom = 14.

The hypothesis that bearings operated in flight will have a mean life equal to or greater than those tested in laboratory is verified at the 83% confidence level.

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