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CONTROL MOMENT GYRO FOR SKYLAB

By Eugene H. Fikes

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The control moment gyro (CMG) is used in the attitude pointing control system of the Skylab space station. It is primarily an actuator that produces control torques by use of the momentum generated in a large rotating mass. This spinning rotor is supported in a two-gimbal system. The Skylab control system uses three of these two-gimbal CMGs to provide the necessary attitude control torques. The system is redundant because it can function with one CMG out of operation. This report is concerned primarily with the design details of the inner gimbal (IG) assembly of the CMG. This assembly consists of a sealed inner gimbal, rotor, bearings, drive motors, and monitoring instrumentation. Early in the program, a design goal of 10 000 hours for the operating life of the CMG rotor spin bearings was established. The tests summarized in this report verify that the goal has been achieved.

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CONTROL MOMENT GYRO FOR SKYLAB

SUMMARY

The control moment gyro (CMG) is used in the attitude pointing control system of the Skylab space station. It is primarily an actuator that produces control torques by use of the momentum generated in a large rotating mass. This spinning rotor is supported in a two-gimbal system. The Skylab control system uses three of these two-gimbal CMGs to provide the necessary attitude control torques. The system is redundant because it can function with one CMG out of operation. This report is concerned primarily with the design details of the inner gimbal (IG) assembly of the CMG. This assembly consists of a sealed inner gimbal, rotor, bearings, drive motors, and monitoring instrumentation. Early in the program, a design goal of 10 000 hours for the operating life of the CMG rotor spin bearings was established. The tests summarized in this report verify that the goal has been achieved.

INTRODUCTION

The design and development responsibility for the CMG was assigned to the Astrionics Laboratory of the George C. Marshall Space Flight Center (MSFC) in 1965. The original design requirements were based on the first Apollo Telescope Mount program. Since that time, the requirements have changed as the mission evolved to the present Skylab.

The IG assembly of the CMG was designed jointly by the MSFC Astrionics Laboratory and the Navigation and Control (N/C) Division of the Bendix Corporation.

The CMG rotor spin bearings were designed to operate for 10 000 hours. The rotor weighs 63.5 kg (140 lb), runs at 821 rad/s (7850 rpm), and develops an angular momentum of 2713 kg m^2/s (2000 ft-lb-s). It was designed to survive the vehicle launch environment and possibly wide temperature extremes.

GENERAL DESCRIPTION

IG Assembly of the CMG

A cross section of the complete IG of the CMG is shown in Figure 1. The rotor is shown with the drive motors mounted on both sides. Each end of the rotor shaft is supported on a set of ball bearings. These bearings are lubricated with Kendall KG-80[1] oil supplied from the lubricating nut system, which is active only when the wheel is rotating. The complete bearing assembly is mounted in the bearing cartridge, which is a means of interfacing the bearing with the gimbal. The cartridge houses electrical sensors and heaters. A 30- tooth speed gear is mounted on one side of the rotor. The gimbal, shown in a horizontal position, provides a means for sealing the assembly. A completely assembled IG is shown in Figure 2.

Spin Bearing

The complete bearing assembly is shown in Figure 3. The bearing has the following specifications:

Type	Angular Contact 107 (Barden).
Class	ABEC 7.
Material	52100 steel.
Retainer	Vacuum impregnated paper phenolic.
Preload	177 N (40 lb) Belleville washers.
Lubricant	Kendall KG-80 oil.

A lubricant makeup system was necessary to realize the long-life design goal. A unique feature of the bearing is the retainer configuration that was finalized to transfer lubricant to the area of the balls and races. The retainer (Fig. 4) is inner-race riding and accommodates a bearing complement of 15 balls.

The bearing assembly is termed as an integral slider bearing because the outer race is a special design that allows a sliding interface of the bearing to the cartridge or gimbal support.

Lubricating System

The lubricating system nut (Fig. 5) contains 10 g of KG-80 oil. The centrifugal force from the wheel rotation generates a pressure upon this volume of oil that forces the

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1. Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products of manufacturers, either expressed or implied, by the National Aeronautics and Space Administration or any other agency of the United States Government.

oil through a metered port onto the lip of the nut. Centrifugal force carries the oil from the nut lip to the step in the bearing retainer. From this step in the retainer, the oil flows through three holes to the line contact of balls and races.

The interface of the lubricating nut to the ball-bearing assembly is made by screwing the nut onto the end of the wheel shaft. The nut is locked in place with a retaining ring.

The metering element in the nut is a millipore restrictor 4.5×10^{-7} m (0.45 μm) pore size. The restrictors are selected and installed to give a flow of 0.085 ± 0.035 mg/hr at 32°C. The actual flow rate of all nuts is measured before installing them in the IG. A design criterion was that no more than one-half of the total makeup lubricant would be expended at the end of 10 000 hr. This has been met on tests thus far.

Table 1 tabulates the life test fixtures (LTFs) to test lubricating systems and electrical circuits that exist in a complete IG.

TABLE 1. OPERATION OF LTFs

LTF	Location	Flow Rate (mg/hr)	Time (hr)
1	N/C	0.15	17 800
2	MSFC	1.50	18 447
3	N/C	0.015	17 569
4	MSFC	0.04	13 579
5	N/C	0.06	13 930
6	N/C	0.06	13 525
NASA	MSFC	3.5	15 140

Wheel

The gyro wheel is made from 18-percent nickel, maraging 300 steel. The overall configuration is shown in Figure 6. The general characteristics are tabulated in Table 2.

TABLE 2. CHARACTERISTICS OF THE GYRO WHEEL

Type	Single Disc
Diameter	0.559 m (22 in.)
Wheel Weight	63.5 kg (140 lb)
Rim Width	85.25 mm (3.75 in.)
Rim Thickness	30.5 mm (1.20 in.)
Speed	821 rad/s (7850 rpm)
Momentum	2713 kg m^2/s (2000 ft-lb-s) @ 821 rad/s (7850 rpm)
Speed Safety Factor	2.14
Burst Speed	1758 rad/s (16 800 rpm)
Natural Frequency Umbrella Mode	35 Hz
Natural Frequency Fan Mode	65/145 Hz

Drive Motor

The drive motor is a 400-Hz, 3-phase induction motor. The rotor is shown in Figure 7 and the stator in Figure 8. The motor develops 0.078 N-m (11 oz-in.) of locked rotor torque, and there are two motors per IG; therefore, the total torque capability is 0.155 N-m (22 oz-in.).

Cartridge and Sensors

The cartridge (Fig. 9) houses the bearing temperature sensor, the vibration sensor, and the bearing heaters. A cartridge is used to support each of the spin bearings. The bores of these cartridges are precisely aligned and rigidly held by the forged aluminum gimbal. There is a 1.27×10^{-5} m (5×10^{-4} in.) clearance between the outside diameter of the bearings and this bore, which permits a free sliding between the bearing rotor assembly and the gimbal. The bearing heaters mounted in each cartridge are designed to provide 24, 120, or 144 W of heat. The wattage used is determined by the control system.

The thermistor mounted in the cartridge indicates the temperature near the outer race of the bearing. This thermistor[2] has a resistance of 10 kΩ ± 2 percent at 25°C and a range of from -60° to +300°C.

The vibration pickup[3] mounted in the cartridge indicates the individual bearing vibration in the radial direction. The scale factor of the pickup is 100 mV/g.

The vacuum sensor (DV-6M model Hastings vacuum gauge tube) is mounted on the inside of the gimbal and has a range of 0 to 133 N/m² (0 to 1000 μm Hg). The sensor indicates the vacuum level that exists inside the sealed IG; this will be used only during testing of the CMG on earth.

The speed is measured by a magnetic pickup and a 30-tooth gear mounted on the rotating shaft. The pickup senses the passing of the teeth on this gear and produces an output pulse for each tooth. A number of gears were considered, all with different numbers of teeth. The 30-tooth gear gives an output frequency (Hz) that is directly proportional to wheel speed. Three of the 30 teeth are shorter than the other 27, which causes a larger gap between the face of the teeth and the magnetic pickup. This gives a reduced signal on three output waveforms per revolution. With this arrangement, the wheel direction can be confirmed.

Gimbal

The IG of the Skylab CMG houses the spinning gyro. It also has accommodations for a pivot to mount the second gimbal (Fig. 10) for the complete configuration. The following characteristics pertain to the IG.

Type	Elliptical configuration.
Material	6061 forged aluminum.
Weight	4.54 kg (10 lb).
Section	Rectangular ribbed.
Stiffness	Spin axis – 5.4×10^6 N-m (30 600 lb/in.).
	Traverse – 3.5×10^7 N-m (200 000 lb/in.).
Finish	Black anodize.

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2. A modified GB41J3 part manufactured by Fenwal Electronics, Inc.

3. Manufactured by Kistler Instrument Corp. (Model 828M112).

Covers

The covers, made from 6061 sheet aluminum, enclose the gimbal so that a vacuum can be maintained around the spinning wheel. A Parker seal is used between the cover (Fig. 11) and gimbal to maintain the vacuum once it is acquired.

INNER GIMBAL TESTING

Laboratory Environment

The general runup characteristics of the gyro in the IG are shown in Figure 12. The speed curve indicates a constant acceleration up to 827 rad/s (7900 rpm). The rate the speed increases is approximately 1.67 rad/s (16 rpm) per minute; hence, it takes 8 hr to obtain top speed. The power at zero wheel speed was 152 W and decreased to 25 W at top speed. The temperature of each bearing increased to a steady-state value of 34°C. The vibration of bearing 1 settled at 16 mV or 0.16 g rms and bearing 2 settled out at 25 mV or 0.25 g rms. At this speed the total torque about the spin axis is 0.021 N-m (2.9 oz-in.). This is a typical runup curve that is characteristic of all IG CMG tests in the laboratory.

The gyro operates in a sealed IG that is evacuated during testing on earth. In orbit, the IG will be vented to the vacuum of space; this venting will be accomplished by a motor-operated valve mounted on the IG. Rigid outgassing specifications on all materials in the IG permit this vented operation. All materials used in the construction of the IG were subjected to outgassing tests. The tests confirmed that no outgassing of atomic mass units (amu) was greater than 45. To further prove this, an engineering IG was pumped down to less than 0.13 N/m^2 (1 μm Hg) and tested with no additional pumping to maintain this level. This test was to verify the seals of the IG. Any loss of vacuum during this test could be caused by seal leakage or outgassing in the sealed IG.

The test ran for 267 days (6408 hr). The general characteristics of the IG are shown in Figure 13. The curves of this figure show the variation of power and torque with vacuum level. The vacuum reached 66.5 N/m^2 (500 μm Hg) in this time period, indicating a leak from atmospheric pressure or a buildup of partial pressures under the cover. The torque and power increased, but the largest rate of change of both was from low vacuum up to 13.3 N/m^2 (100 μm Hg). The power increased 48 W from 0.13 to 13.3 N/m^2 (1 to 100 μm Hg), but only 11 W from 13.3 to 66.5 N/m^2 (100 to 500 μm Hg). The torque about the spin axis increased 0.049 N-m (7 oz-in.) from 0.13 to 13.3 N/m^2 (1 to 100 μm Hg), but only 0.0106 N-m (1.5 oz-in.) from 13.3 to 63.5 N/m^2 (100 to 500 μm Hg). The vacuum level changed on an average of 0.25 N/m^2 (1.9 μm Hg) per day.

At the end of this test,a cold trap was installed on the IG; the unit was pumped down through the trap to analyze the gas present in the sealed IG. The gas caught in the trap was then analyzed. Mass spectrometer analyses indicated that the sample contained approximately 28-percent carbon dioxide and 4-percent oxygen, and that the remainder of the gas was carbon monoxide and nitrogen. These measured quantities indicated atmospheric gases and not material outgassing. The limited sample prevented the quantification of the carbon monoxide and the nitrogen concentration.

To further prove that the IG would not be a source of contamination, a complete CMG was tested for outgassing in a larger thermal vacuum chamber. The installation of the CMG into the chamber is shown in Figure 14. After the chamber was sealed and evacuated to 2.6×10^{-4} N/m² (2×10^{-3} μm Hg) vacuum level and before venting the IG to this vacuum, a system background mass scan was conducted. This scan showed that only significant peaks were present up to 32 amu. These peaks were attributed to system background gases derived from atmospheric sources.

The mass scan, made immediately after opening the IG valve, showed an increase in intensity of background peaks only, with 17 (OH) and 28 (N_2, CO) amu being two orders of magnitude greater than the background and an 18 (H_2O) amu being three orders of magnitude greater, again indicating a release of entrapped atmospheric gases. After the IG valve had been open for 1 hr, mass scan data showed all amu's to be down two orders of magnitude.

A third test was made with the IG heated and the wheel running. With the heat applied, a mass scan indicated a slight increase in intensity of peaks at 28, 29, 30, 41, and 53 amu. This indicated the release of a loosely bound organic substance, probably a cleaning fluid residue. With the wheel running, no change was observed.

These outgassing tests verified that the IG could be operated vented in space and meet the Skylab outgassing requirements.

Thermal Vacuum Testing

The thermal vacuum tests were performed in a thermal vacuum chamber at a vacuum level of 2.6×10^{-4} N/m² (2×10^{-3} μm Hg). The chamber shroud temperature used during the tests varied from -51° to 75°C. The first test simulated earth-orbit conditions as to time and anticipated temperature variation per orbit. The objective was to determine the time constant and temperature levels experienced on the IG with the preselected period and shroud temperatures. The IG was mounted on Kel-F thermal isolators to minimize heat conduction and to force the heat transfer to be primarily by radiation. During this test, no heat was applied to the bearing heaters. The temperatures of the shroud, 10 points on the IG, and the bearing cartridges were recorded during this test. Figure 15 is a plot of these data. The shroud temperature was manually controlled during the test, but this did not produce as smooth a control as desired. The peak-to-peak temperature variation of the IG bearings was approximately 13°C (curve 3 of Fig. 15). Curve 2 of Figure 15 shows the variation of the gimbal.

The second test in this series was conducted to determine runup and running characteristics when exposed to low temperatures. This runup is shown in Figure 16. The shroud temperature was lowered until the gimbal and bearing stabilized at -51°C. The bearing was soaked approximately 4 hr. The wheel was then energized and dissipated at 155 W; 96 W was also applied to the cartridge heaters. With the 251 W dissipated in the IG, it took 35 min to observe the first rotation of the wheel. This occurred at -41.5°C on the bearing cartridge. The speed curve shows that it took 14.5 hr to obtain 808 rad/s (7720 rpm). The bearing cartridge and gimbal temperatures settled at 14° and 10°C, respectively. The power finally decreased to 75 W with a torque of 0.081 N-m (11.5 oz-in.) about the spin axis.

The third test was conducted to increase power dissipated in the IG and to perform another runup curve. As shown in Figure 17, the IG was stabilized at -50°C for a minimum of 4 hr; 200 W was applied to the cartridge heaters and 155 W dissipated in the wheel. With 355 W applied to the IG, the first motor rotation was observed in 20 min. The wheel experienced a normal runup from these conditions. The bearing cartridge temperature settled at 35°C and the gimbal settled at 31°C. When the wheel was operating at full speed, the power was 16 W. The deacceleration torque indicated 0.011 N-m (1.6 oz-in.) about the spin axis. The test results indicated that the extremely low temperature had not affected the IG.

In this series of tests, the next effort was to simulate the highest anticipated operating temperature. This was done to simulate a CMG in the sunlight when on the lighted side of the earth. The temperature of the shroud was increased until the bearing cartridge reached 70°C. At this point, the chamber shroud was cycled twice (-50° to +70°C) and the bearing cartridge and gimbal had approximately the same response as they did when cycled at the lower temperature.

The IG was returned to the laboratory and a runup was performed. The runup characteristics were identical to those in Figure 12, which shows a runup before the thermal vacuum test.

Life Testing

The life test program was started in 1968. The program involved the engineering IGs E-2 and E-3, as well as six LTFs. MSFC is running engineering IG E-2 and LTFs 2 and 4 continuously. The engineering IG test fixture for E-2 and the LTF testing are shown in Figures 18 and 19, respectively. Life testing of engineering IG E-2 required continuous running 24 hr a day and a means to introduce torque to simulate the functioning of the CMG. While running continuously, the equipment was unattended for 16 hr a day; therefore, a number of protective circuits had to be incorporated in the test equipment. The points selected for protection were over- and under-voltage, overcurrent, overspeed, temperature, and vibration. The tests have been interrupted by transients from electrical storms and power failure, but no IG problems have occurred. IG E-2 has operated for 18 181 hr with no problems; engineering unit E-3 at the Bendix Corporation has operated for 15 300 hr with no difficulty.

The simulated functional torquing of the CMG spin axis is accomplished by a motor-driven worm drive on the vertical axis of Figure 18. The drive motor is a 3-phase, 60-Hz motor. The motor torques the vertical axis of the fixture at a rate of 0.078 rad/s (4.5 deg/s), which produces a maximum bearing radial load from gyroscopic torque of 836 N (188 lb) (acting in vertical plane). The gravitational force in the vertical plane is 311 N (70 lb) on one bearing; hence, the total vertical component of the load varies from negative 524 N (118 lb) to positive 1147 N (258 lb). This fixture was used to simulate loading of the bearings once per orbit for a 56-day mission. Assuming a 90-min orbit, this would load the bearings 896 times. After this life test began, the mission time was extended; therefore, these tests have continued. As of December 1970, the wheel had been load-cycled 7932 times; this is equivalent to a 495-day mission. No problems have been encountered thus far.

Six LTFs that simulate a zero-g operating condition have been used in the life testing of the CMG spin bearings. The complete configuration of the bearing and its mounting in these LTFs is identical to the IG assembly. No mass is on the shaft except a rotor for the ac motor. The total shaft weight is 4.5 kg (10 lb) as compared with the rotor weight of 63 kg (140 lb). The electrical circuits of the LTFs are identical to those of the IG. The six LTFs on test are operating with various simulated environmental conditions. Two of the fixtures are running at elevated temperatures of 71° and 88°C. Two LTFs have bearings that were exposed to simulated launch vibration spectra. The other two are operating in a normal laboratory environment. The flow rate of the lubricating system varies with each fixture.

Table 3 shows the LTFs, their location, and running times in hours accumulated thus far.

The bearings that were vibrated before life testing were assembled into a special vibration test fixture for the vibration tests. The bearing mounting, preload, etc., of this fixture were identical to the IG configuration; a brass weight was used on the shaft of this fixture to simulate the rotor mass. The bearings were not rotating during the vibration test, but were exposed to the vibration spectra shown in Figure 20. These spectra were applied to both radial and axial directions on LTF 2, but only to the radial direction on LTF 3. These spectra exceed the environmental qualification requirements. The units have been operating well during this life testing with no problems with the bearings. A statistical analysis of the bearing running torques shows no significant change in the bearings during the tests.

TABLE 3. OPERATING CHARACTERISTICS OF LTFs

LTF	Hours	Running Location	Remarks
1	17 800	N/C	Normal laboratory environment
2	18 447	MSFC	Flight bearing vibrated
3	17 569	N/C	Flight bearing vibrated
4	13 579	MSFC	Elevated temperature, 71°C
5	13 930	N/C	Normal laboratory environment
6	13 525	N/C	Elevated temperature, 88°C

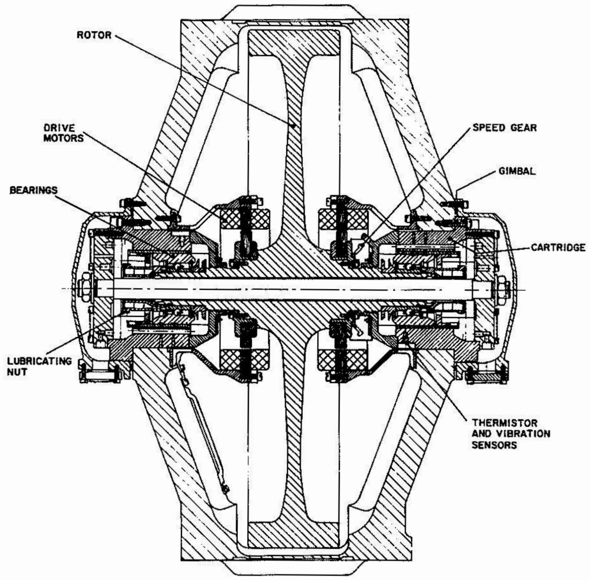

Figure 1. Cross section of the CMG IG.

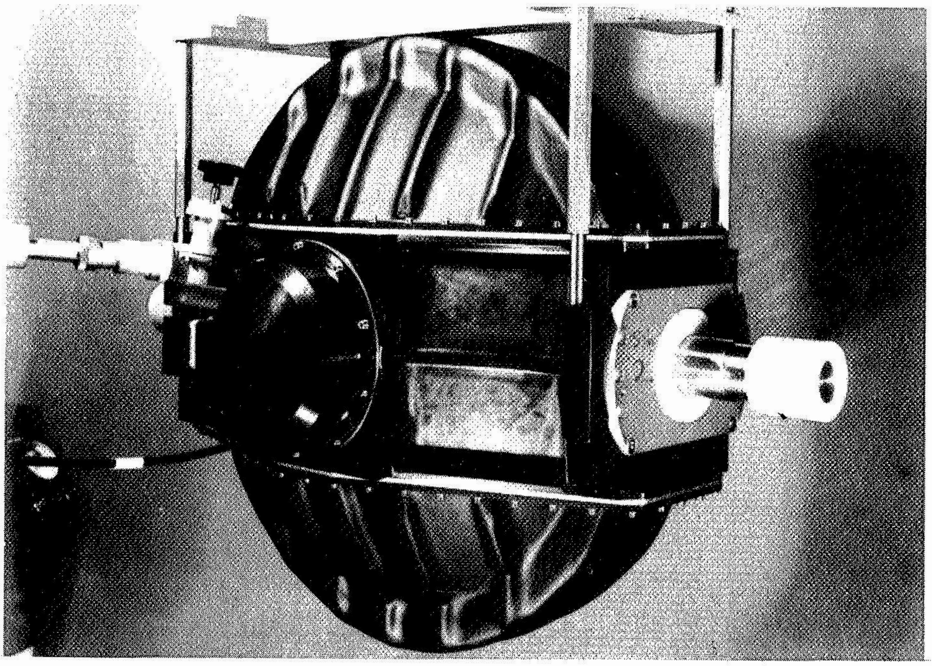

Figure 2. Assembly of the CMG IG.

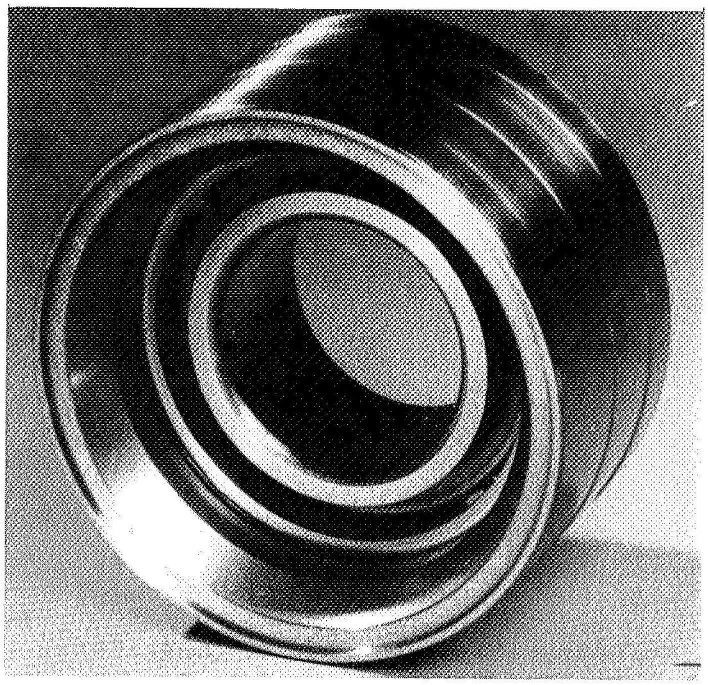

Figure 3. Integral slider bearing assembly.

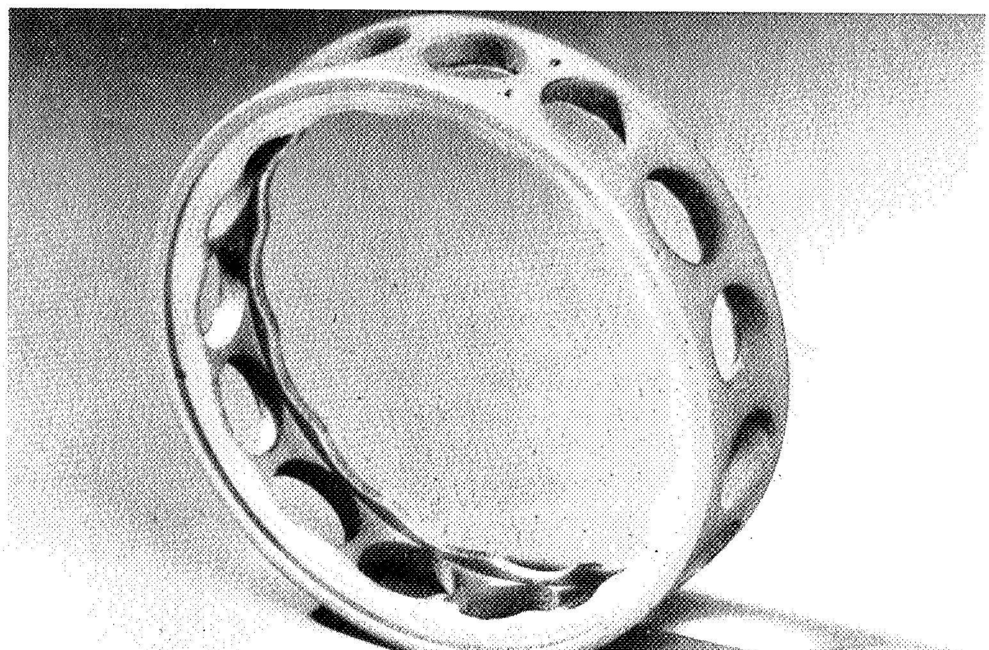

Figure 4. Bearing retainer.

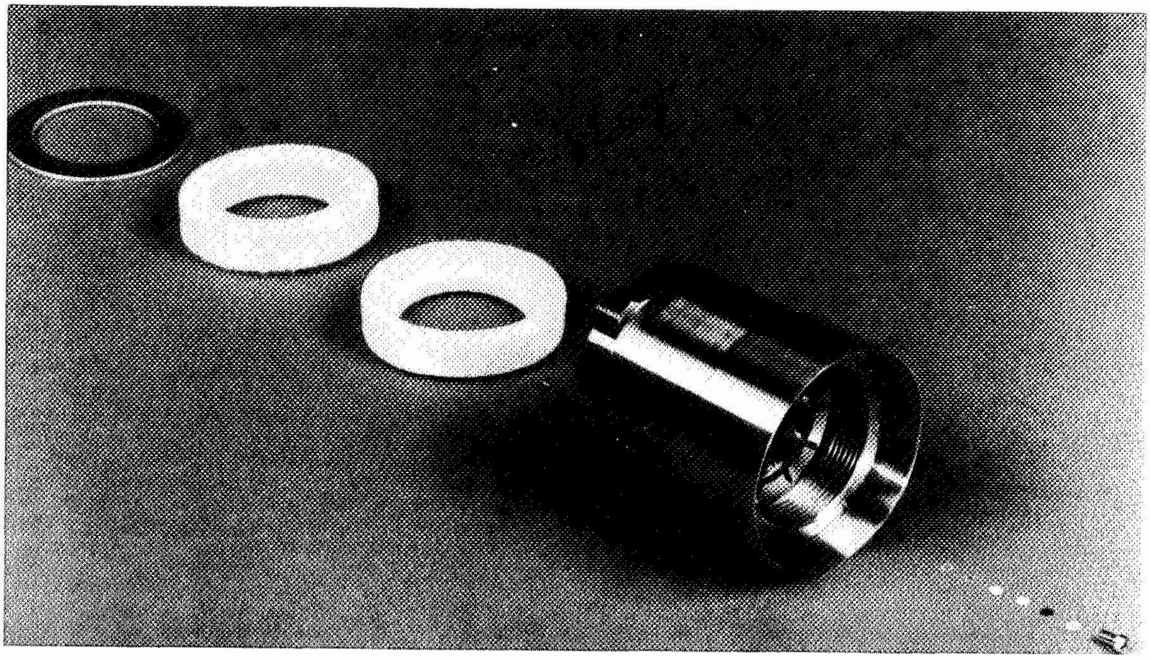

Figure 5. Lubricating nut.

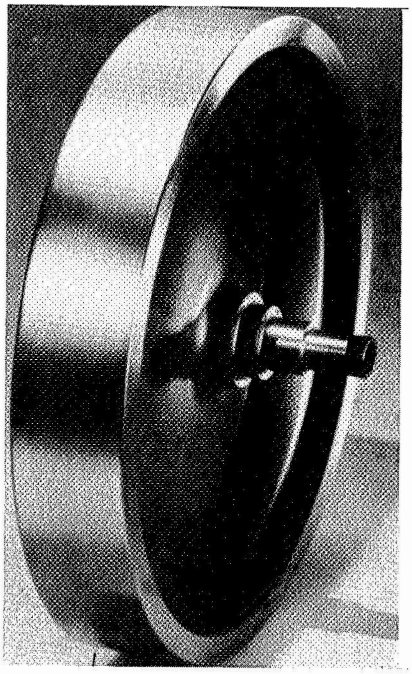

Figure 6. Gyro wheel.

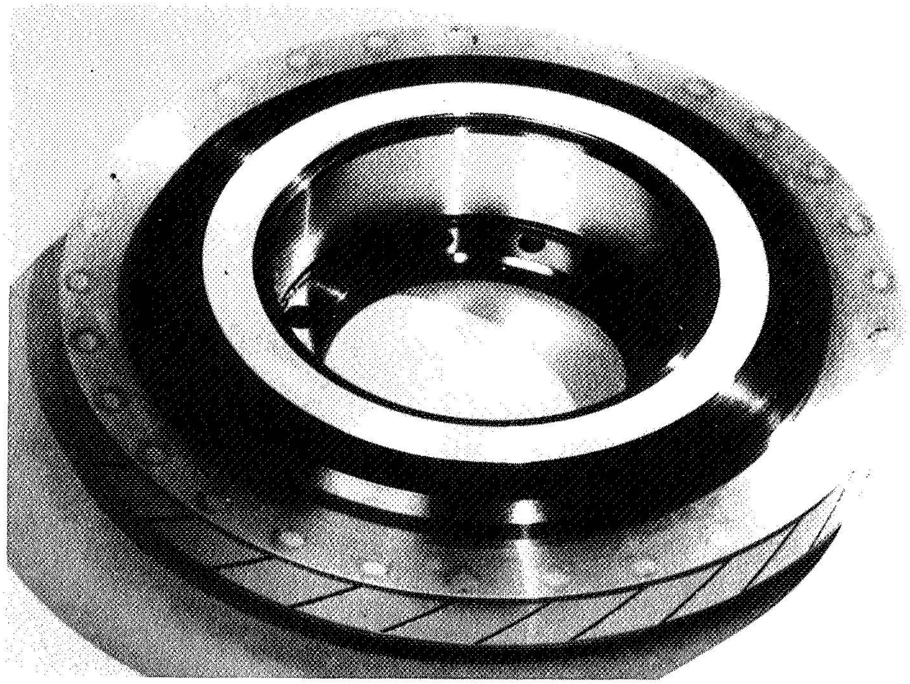

Figure 7. Drive motor rotor.

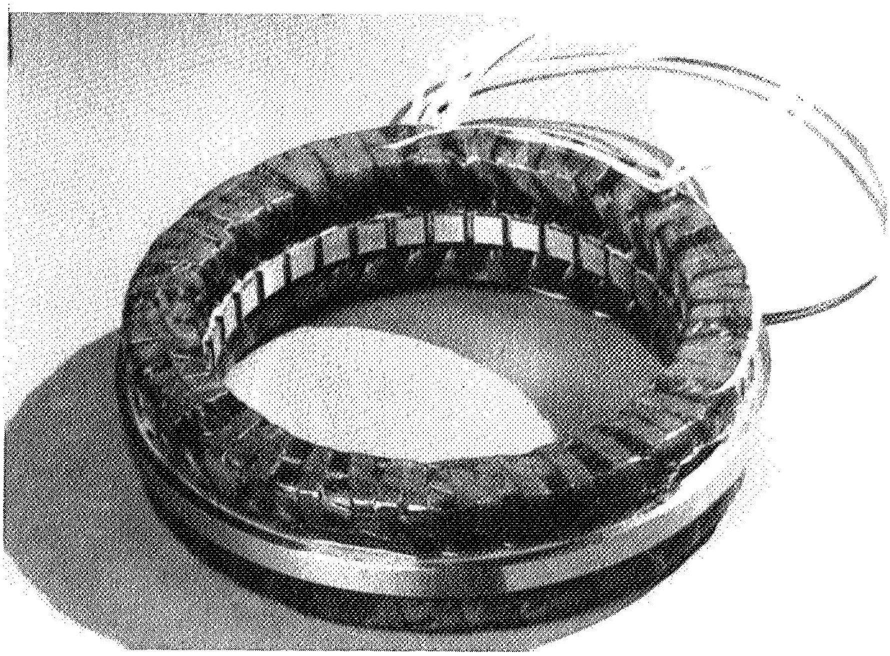

Figure 8. Drive motor stator.

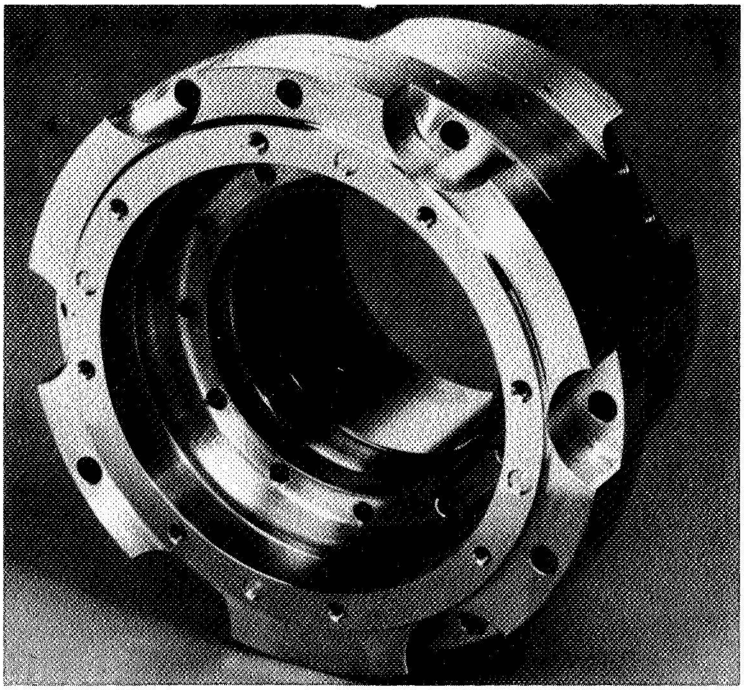

Figure 9. Bearing cartridge.

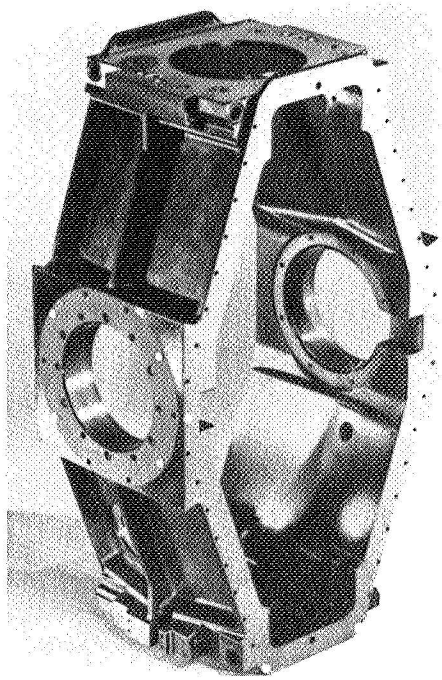

Figure 10. IG.

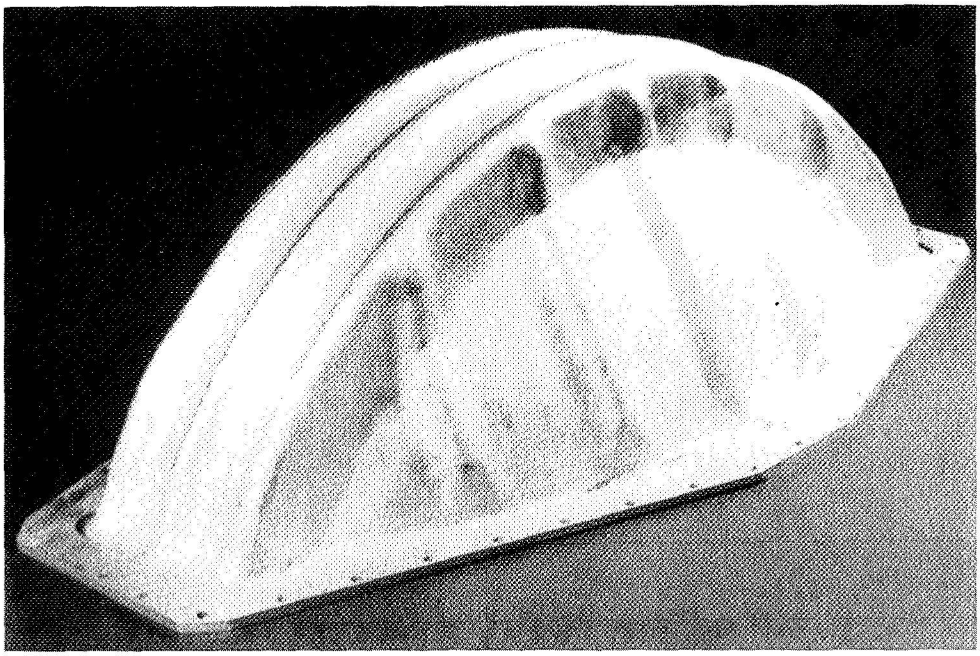

Figure 11. Gimbal cover.

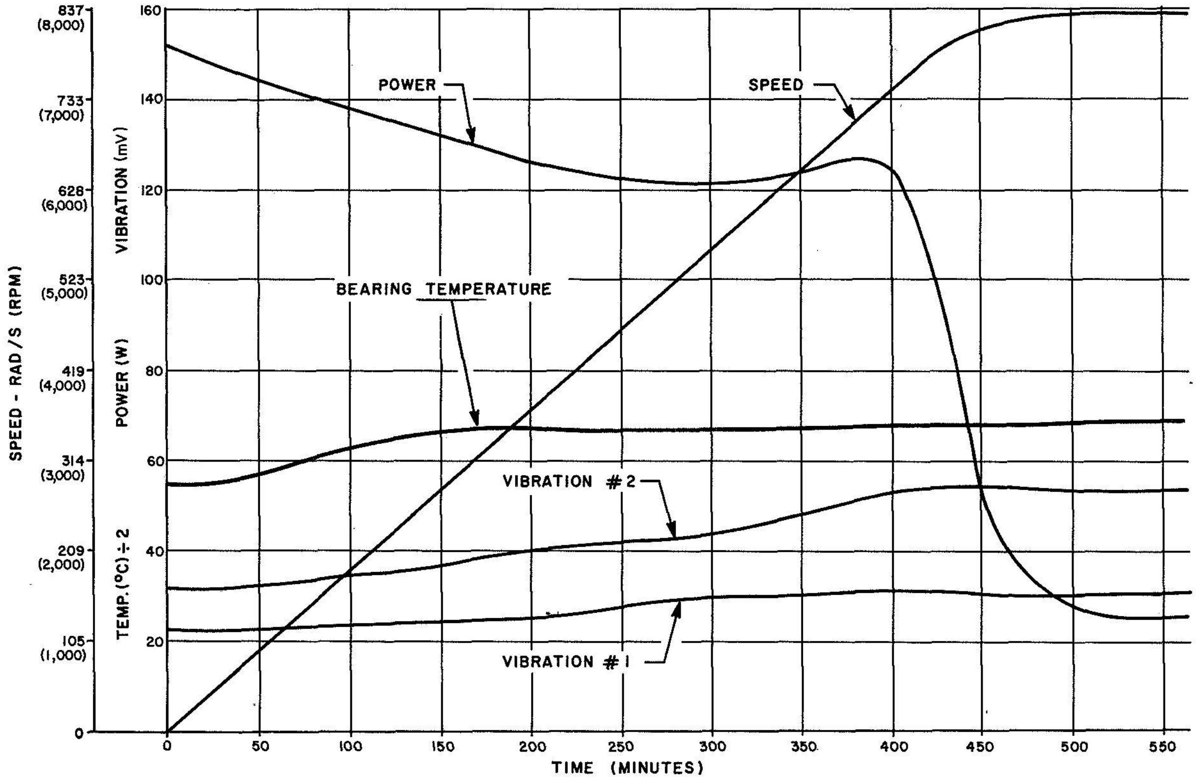

Figure 12. Runup characteristics.

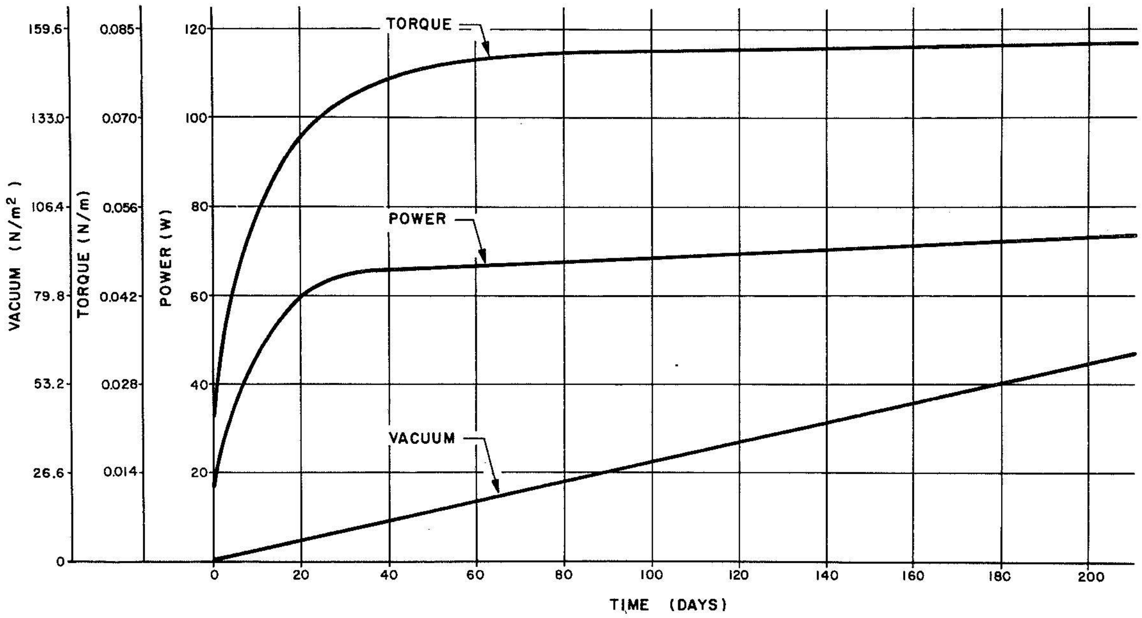

Figure 13. Vacuum leak test.

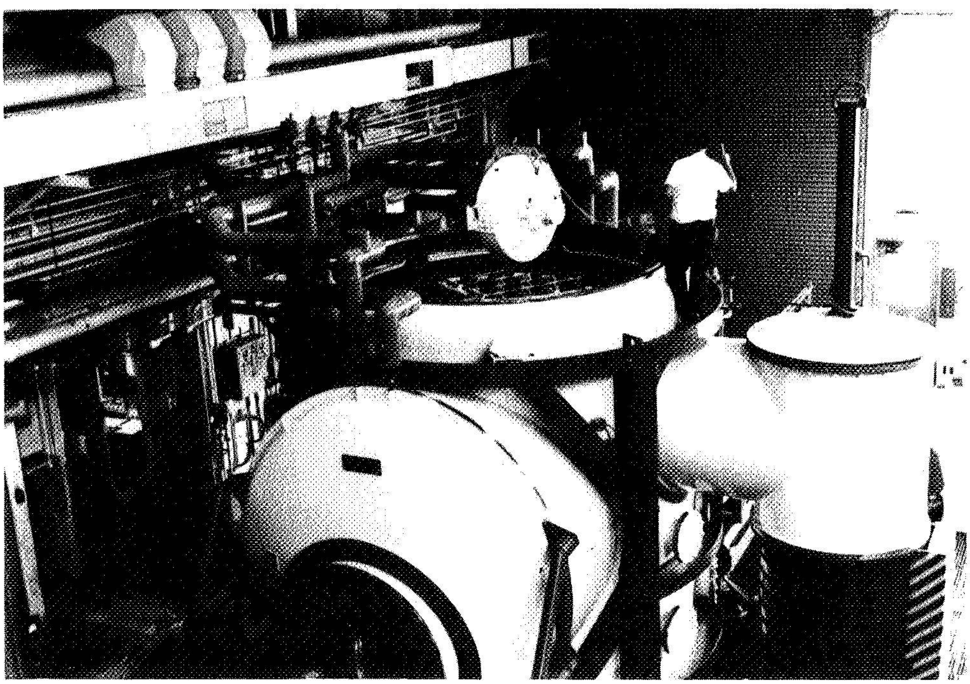

Figure 14. CMG installation into chamber.

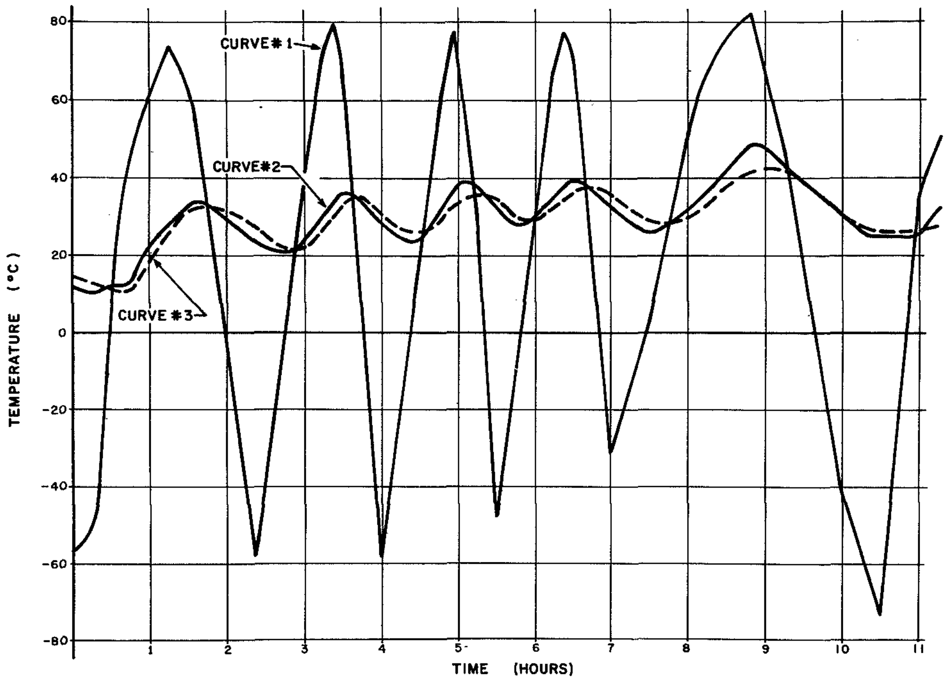

Figure 15. Temperature variation.

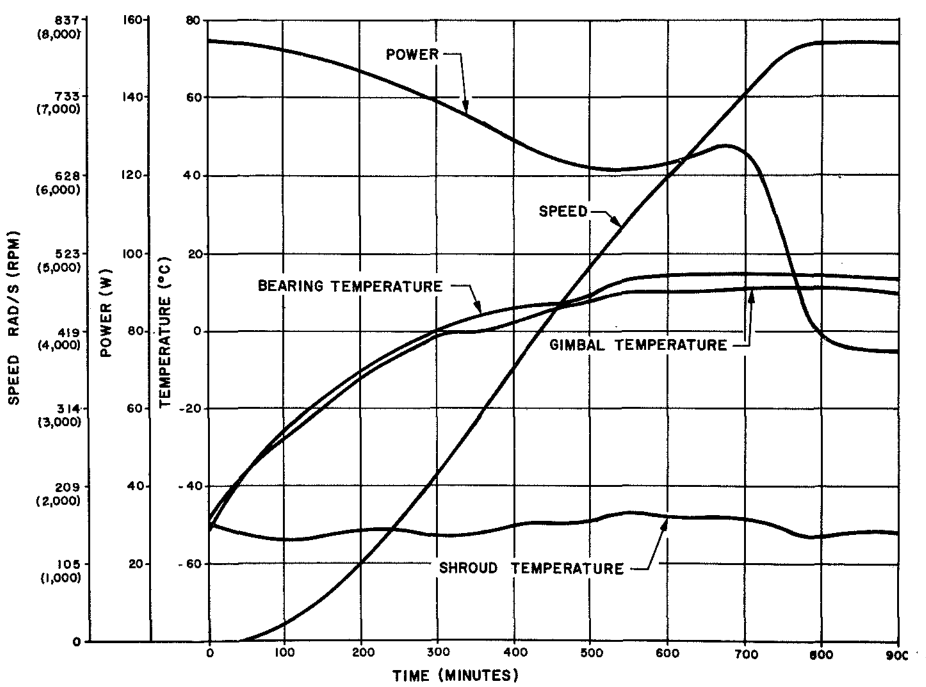

Figure 16. Cold runup characteristics (heater wattage – 96 W).

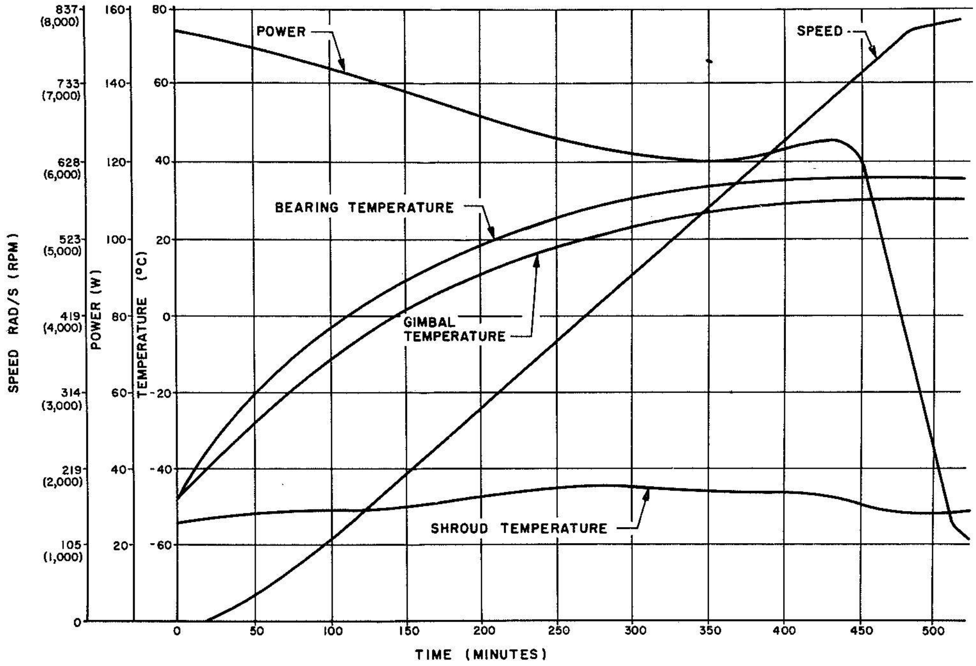

Figure 17. Cold runup characteristics (heater wattage – 200 W).

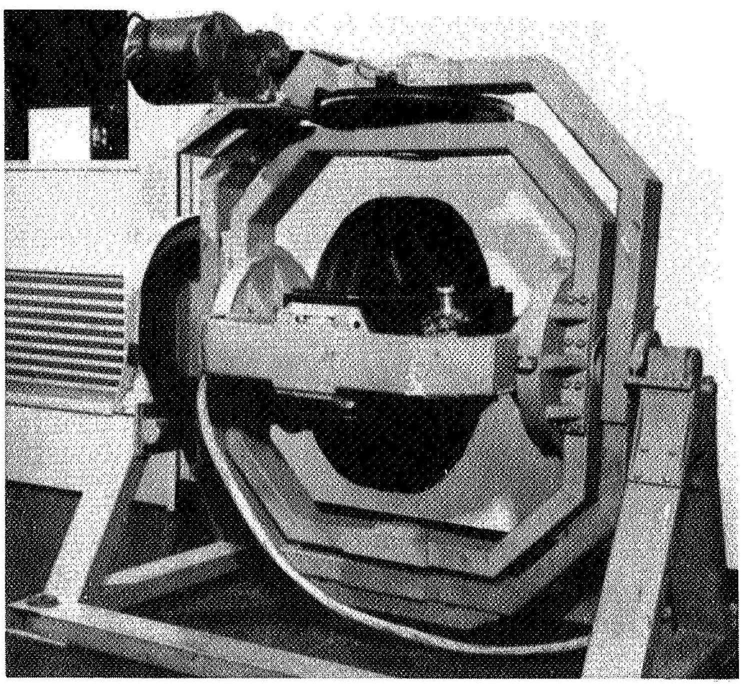

Figure 18. IG life test stand.

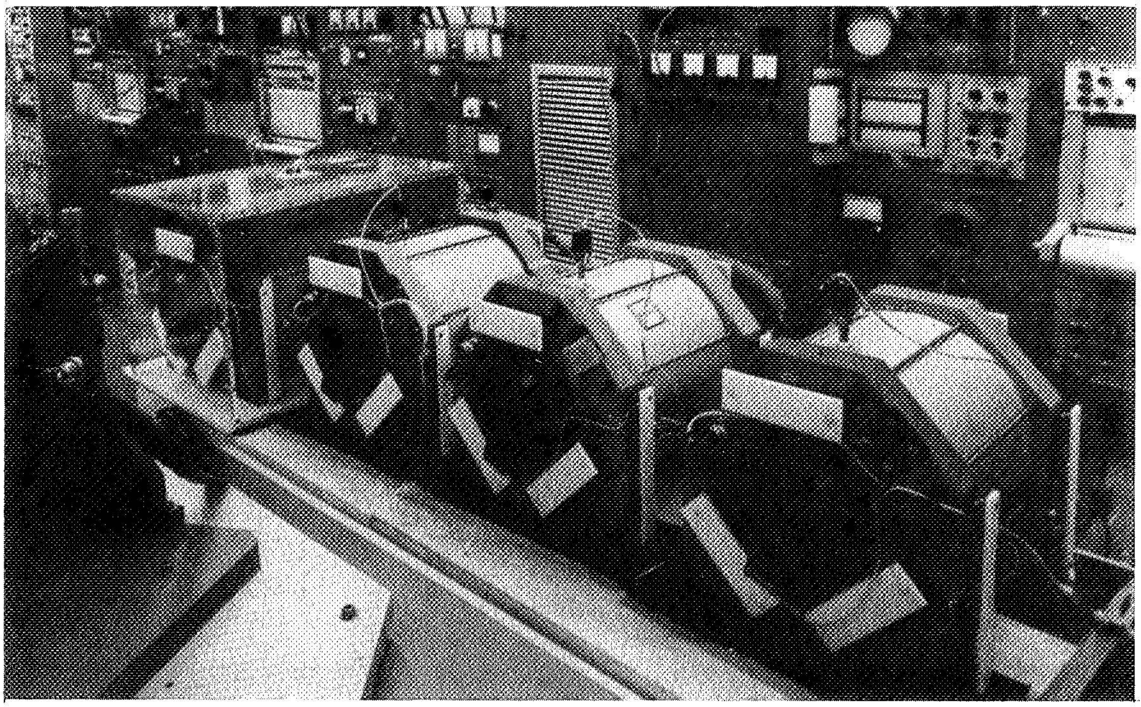

Figure 19. LTFs.

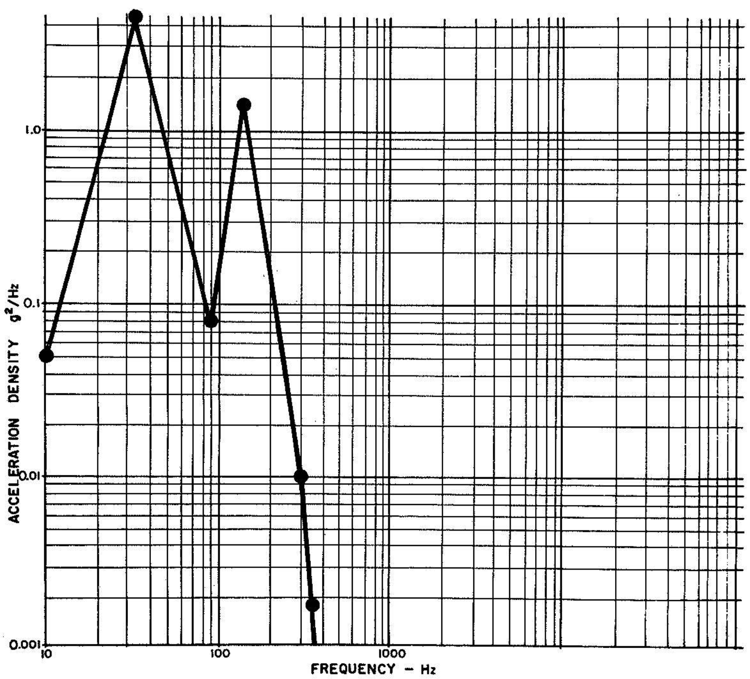

Figure 20. CMG test fixture – radial vibration input.

APPROVAL

CONTROL MOMENT GYRO FOR SKYLAB

By Eugene H. Fikes

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

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