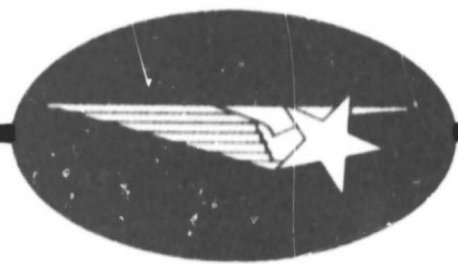


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Final Report

**VIBRATION/VACUUM SCREENING
OF SPACE LUBRICANTS**

by

Francis J. Clauss and Sanford P. Drake, Jr.

LMSC-684903

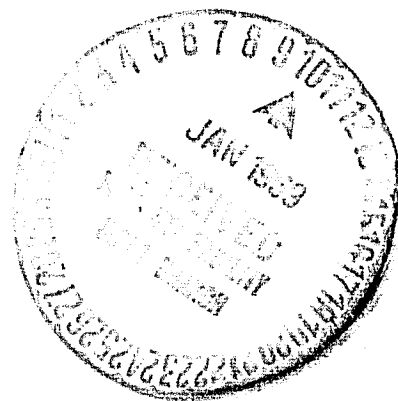
31 December 1967

Contract NAS 9-5114

National Aeronautics and Space Administration

Manned Spacecraft Center

Houston, Texas



**Lockheed Missiles & Space Company
A Group Division of Lockheed Aircraft Corporation
Sunnyvale, California**

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FOREWORD

This report, Vibration/Vacuum Screening of Space Lubricants, is prepared in response to Contract NAS 9-5114 for the National Aeronautics and Space Administration, Manned Spacecraft Center, Houston, Texas. This is the final report and fulfills the requirements of the contract.

The authors wish to express their appreciation to Messrs. W. Rohr, W. Tierney, R. Smithback, and R. Beckworth of the Reliability Engineering Organization of LMSC, and Mr. Eugene C. Smith of Research Devices, Inc. for their efforts in conducting tests and resolving serious equipment difficulties.

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ABSTRACT

Selected solid-film lubricants and self-lubricating retainer materials have been evaluated for use on small ball bearings operating in a simulated space environment. Test conditions include a combination of vacuum (10^{-7} torr), low and moderately elevated temperatures (-200°F to $+200^{\circ}\text{F}$) and severe vibration (28g rms, 85g peak). The effects of operating in such environments on the subsequent lifetime in vacuum has been experimentally measured. Results are compared with those for a selected oil and grease.

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Section 1 INTRODUCTION

This investigation was conducted to determine the effects of a combined environment of ultrahigh vacuum and severe vibration on the performance of selected lubricants. The evaluation was also to extend over a range of temperatures, from -200° to $+200^{\circ}$ F, so that the suitability of the selected lubricants could be determined for operating in a space environment.

Considerable research has been conducted during the past ten years to evaluate lubricants for use in space, and the literature reports many studies of the effects of vacuum, temperature, speed, load, and radiation. Vibration is used as a measure of bearing quality. Manufacturing studies have been conducted to improve bearing quality in order to suppress vibration and noise, especially where bearings are used on submarine equipment. During the preliminary phase of this investigation, an extensive survey of the literature was also conducted. Although no systematic studies were found of the effects of vibration on lubricant performance, it is generally known that vibration is detrimental to solid lubricants.*

Where parts are accessible, good lubrication practice and periodic relubrication can be followed, and the lifetime of bearings is limited by the mechanical loads and their variation during service. This is the normal situation on earth, where the cause of failure is metal fatigue, and ball bearing manufacturers can provide adequate statistical data for estimating bearing life. The situation for aerospace mechanisms that must operate for prolonged periods in orbit is quite different. Here the loads are small, except for the launch phase, and bearing lifetimes depend upon lubrication practice. Moreover, parts on orbiting mechanisms are inaccessible for relubrications in the normal sense, and the lifetimes of the lubricants themselves become the controlling factor in the lifetimes of the bearings.

*K. E. Demorest and E. C. McKannan, "Vibration of Journal Bearings in Vacuum," Lubrication Engineering, Feb 1963, pp. 59-66.

Lubricants include not only oils and greases, but a variety of solid lubricants as well. Although relatively unknown or ignored in the past, solid lubricants have recently attained major importance. Their increased use is due to:

- **The advanced requirements of modern-day technologies, which impose operating conditions that are beyond the practical limits of oils and greases**
- **Improved economics, which make solid lubricants less expensive than conventional lubricants for many applications**
- **Improvements in the materials and processes used in solid lubrication**

Solid lubricants include a variety of bonded film and self-lubricating composites of such materials as graphite, molybdenum disulfide, tungsten diselenide, boron nitride, and Teflon. These materials are often combined with adhesives, binders, or sintered metals. Compared to conventional oils and greases, these materials are relatively nonvolatile and are usually more resistant to thermal and radiation damage. Among their specific advantages for use in spacecraft systems are:

- **Better stability under vacuum conditions**
- **Less contamination of the atmospheres in manned cabins, thereby reducing the load on environmental control systems**
- **Less contamination of nearby optical surfaces, a consideration that has been responsible for their selection over oils and greases for certain space experimental equipment**
- **Longer lifetimes at high temperatures and intense radiation doses, such as those experienced by spacecraft flying in the Van Allen radiation belt or as experienced by unshielded equipment operating near nuclear reactor power sources**

On the other hand, the absence of the hydrodynamic damping protection provided by oils and greases is a major consideration in designing with solid lubricants. Without this protection they are more susceptible to vibration damage, which is irreversible and largely catastrophic.

Because of the inherent advantages and potential usefulness of solid lubricants in a greater number of applications on both manned and unmanned spacecraft, these lubricants have received special emphasis in this investigation. Their performance has been compared to that of fluorosilicone oil and silicone grease.

Section 2 EQUIPMENT AND PROCEDURE

This investigation included subjecting ball bearings with the selected lubricants to a combined environment of ultrahigh vacuum, severe vibration, and controlled temperature; and then operating them to failure* (or 1000 hours, whichever occurred first) in ultrahigh vacuum. Suitable control tests were performed in order to isolate the effects of the variables.

2.1 BEARINGS AND LUBRICANT SYSTEMS

The following lubricant systems were evaluated:

- Solid-film lubricants
- Special bearing retainer materials
- Oil
- Grease

All lubricant systems were evaluated with standard R3 size ball bearings having balls and races of 440C stainless steel. In all cases, standard bearing designs were used; but such features as the type of race, retainer and shielding were varied as appropriate to the lubricant system, as indicated.

2.1.1 Solid-Film Lubricants

The 23 solid-film lubricants selected for evaluation are listed in Table 2-1. All 23 of these lubricants were tested in Phase A tests (described in subsections 2.2.1 and 2.3).

*Failure is defined as the deterioration of the lubricant system to the extent that the bearing torque increased to above 1 inch-ounce, which is approximately 40 times the normal running torque of the test bearings and was sufficient to stall the test motors.

Table 2-1
SOLID-FILM LUBRICANTS

Lubricant	Test Phases Conducted					
	A		B	C	D	E
	Vib. in Air	Vib. in Vacuum				
Alpha-Molykote E3C	x	x				
Alpha-Molykote X-106	x					
Titanium Carbide	x					
General Magnaplate Drilube	x	x	x			x
Electrofilm 2606	x	x				
Electrofilm 2007	x					
Electrofilm 2008P	x		x			x
Electrofilm 2306	x					
Electrofilm 2396	x					
Electrofilm 4306	x		x	x	x	x
Electrofilm 5396	x					
Everlube Inlox 44	x	x	x	x	x	x
Everlube 620	x	x				
Everlube 811	x	x	x	x	x	x
Everlube 811B	x	x				
Everlube 811B2	x	x				
Everlube 1329	x	x				
Lubeco 905	x	x				
Lubeco 905S	x	x	x	x	x	x
Lubeco N-350-A	x					
Hohman Surf-Kote A-1625	x	x				
Hohman Surf-Kote M-1284	x	x				
General Magnaplate Hi-T-Lube	x	x	x	x	x	x

Because of relatively severe damage to many of these lubricants during the Phase A tests, further testing in Phases B, C, D, and E was limited to selected lubricants, as indicated in Table 2-1. Each solid-film lubricant was individually applied by the film vendor to the races of the test ball bearings. These ball bearings were standard, deep-groove (Conrad type) ball bearings of the R3 size with ribbon-type retainers of 302 stainless steel, as shown in Fig. 2-1.

The solid-film lubricants were first coated on the bearing races by the lubricant vendors, then the coated races were returned to the bearing manufacturer for assembly. The solid lubricants caused these bearings to run rough when first received from the bearing manufacturer. The bearings were run-in by rotating them slowly back and forth several times by hand and blowing out any loose debris with a jet of compressed nitrogen. The bearings were then operated at 4 rpm for 10 minutes in one direction, blown out, operated at 4 rpm for 10 minutes in the opposite direction, and blown-out again. This procedure was repeated at 8000 rpm. After run-in, these bearings were smooth running with low torque.

2.1.2 Special Bearing Retainer Materials

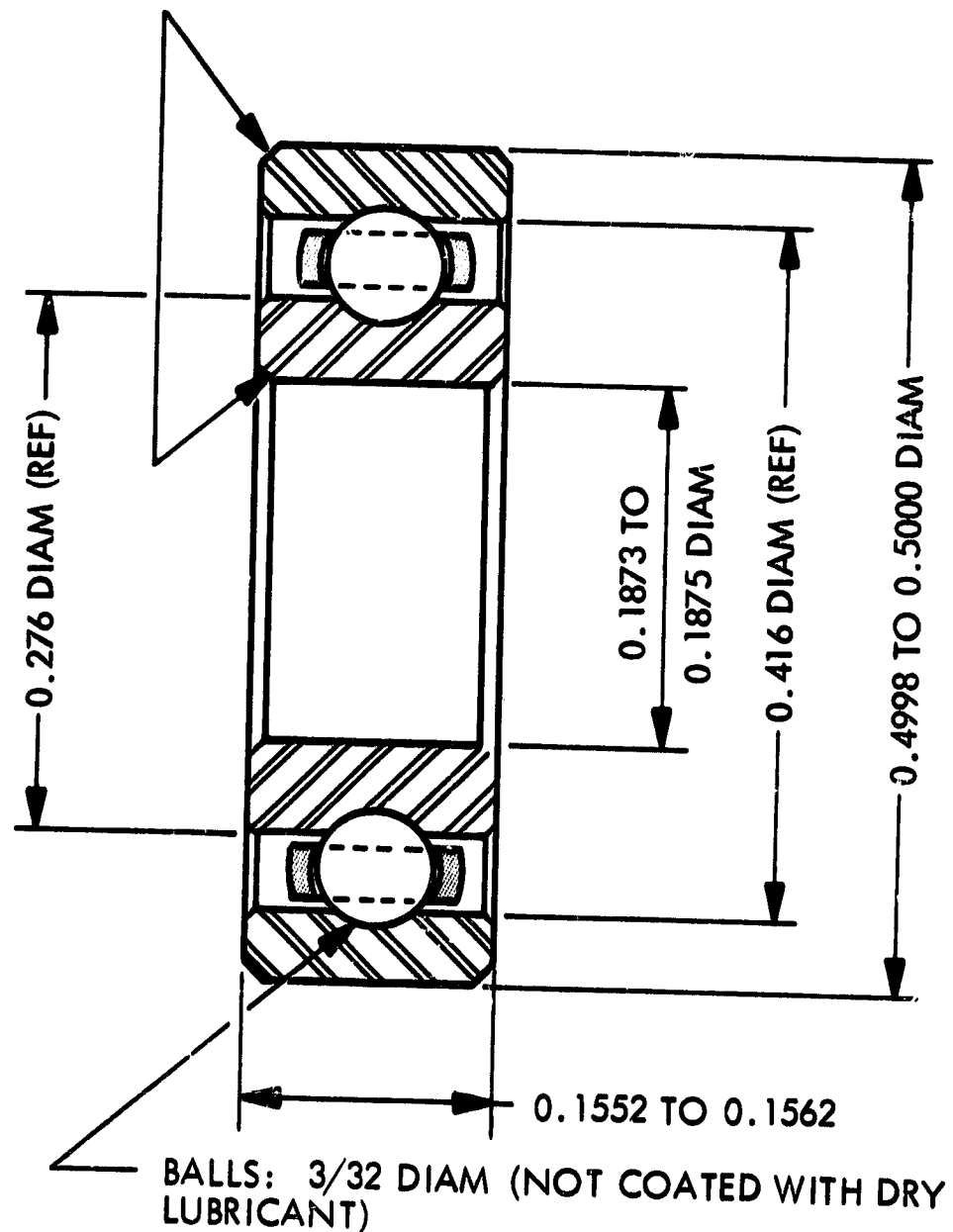
Table 2-2 lists the 25 materials that were selected for testing as self-lubricating retainers. The retainers were of the one-piece, machined-type; they were assembled into R-3 size, angular-contact ball bearings, as indicated in Fig. 2-2.

Six of the selected materials could not be machined satisfactorily into retainers. All of the remaining 19 materials were tested in Phase A tests (described in subsections 2.2.1 and 2.3). Because of relatively severe bearing damage with many of these materials during the Phase A tests, further testing in Phases B, C, D, and E was limited to selected materials, as indicated in Table 2-2.

2.1.3 Oil

Dow Corning FS-1265 fluorosilicone oil (250 centistoke grade) was used for comparison with the other types of lubricant systems. This oil was selected on the basis of its

BEARING WILL CLEAR 0.012 RADIUS



ALL DIMENSIONS IN INCHES

NOTES:

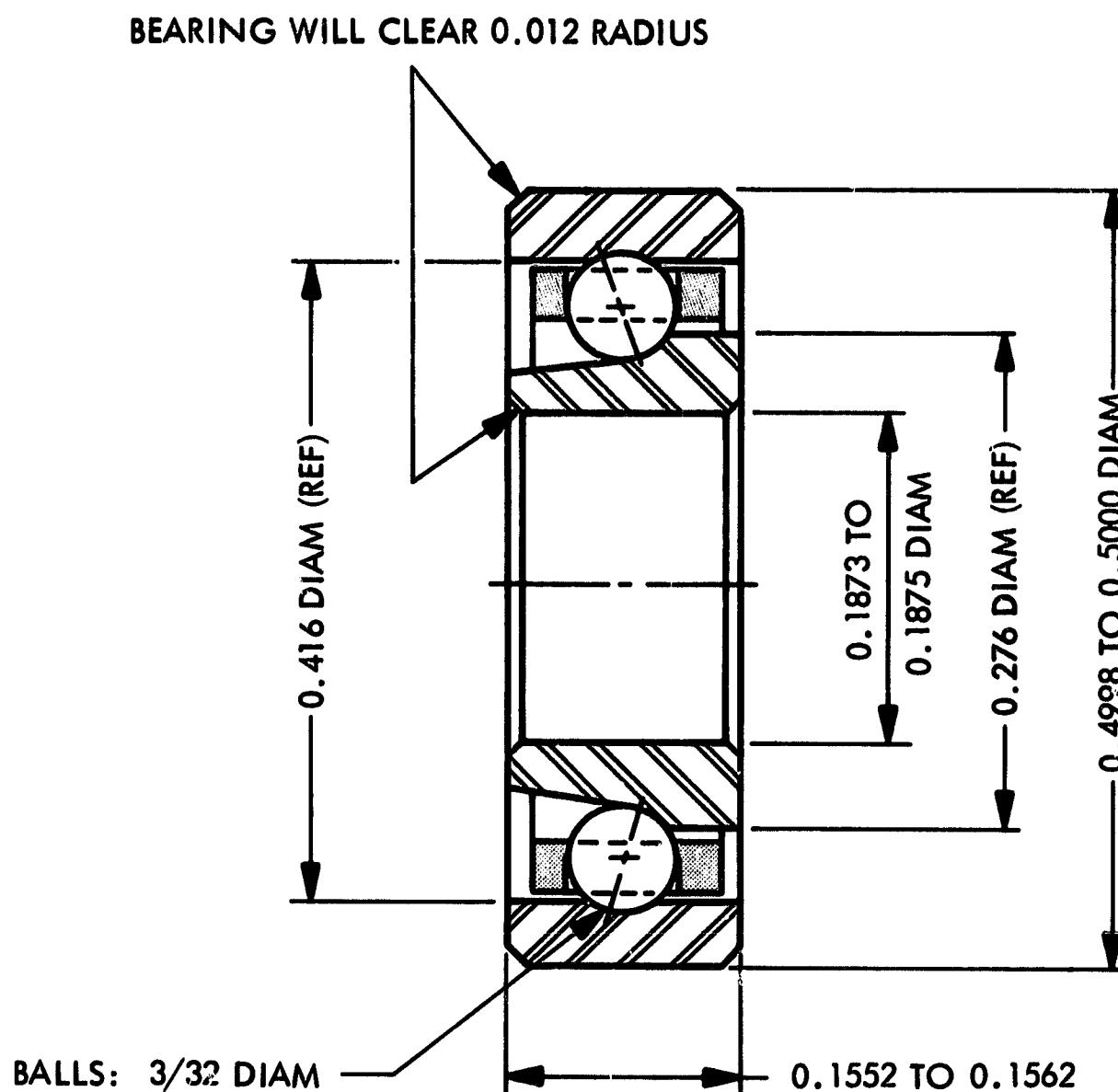
1. MATERIAL: 440-C STAINLESS STEEL RINGS AND BALLS (CERTIFIED AIR-MELT 440-C)
2. TOLERANCE: PER A.B.E.C.-7P
3. RADIAL PLAY: 0.0008 TO 0.0011 (BEFORE COATING WITH DRY LUBRICANT)
4. CAGE MATERIAL: 302 STAINLESS STEEL (NOT COATED WITH DRY LUBRICANT)
5. INNER AND OUTER RACEWAYS WERE COATED WITH SOLID-FILM DRY LUBRICANT

Fig. 2-1 Test Bearing Assembly for Solid-Film Lubricant Systems

Table 2-2
SPECIAL BEARING RETAINER MATERIALS

Retainer Material	Test Phases Conducted					
	A		B	C	D	E
	Vib. in Air	Vib. in Vacuum				
Barden Bar Temp	x	x	x	x	x	x
Boron Nitride	x	x				
Duroid 5813	x					
Vespel SP-3	x		x	x	x	x
Turcite A	x					
Ilkalo AFIL - M10	x		x			x
Ilkalo AFIL - M20	x					
Ilkalo AFIL - W20(a)						
Ilkalo AFIL - W25(a)						
Ilkalo AFIL - C10	x					
Tetraloy 1101(a)						
Nylafil G1/30/MS/5	x		x	x	x	x
Polymet AG	x					
Salox M	x					
Westinghouse Composite: 70 Ag, 20 Teflon, 10 WSe ₂ .	x					
Westinghouse Composite: 60Cu, 30 Teflon, 10 WSe ₂ (a)						
Westinghouse Composite: 45Cu, 15 Ag, 30 Teflon, 10WSe ₂ (a)						
Westinghouse Composite: 45Cu, 15 Bronze, 30 Teflon, 10 WSe ₂ (a)						
Sinitex	x					
Rulon C	x		x	x	x	x
Kel - F	x					
Kynar	x					
Fluoray	x					
15% Glass-Filled Teflon	x					
MB Bronze-Filled Teflon	x		x	x	x	x
FS-1265 Oil	x		x	x	x	x
EG-509 Grease	x		x	x	x	x

Note a: These materials could not be machined into retainers.



NOTES:

1. MATERIAL: 440-C STAINLESS STEEL RINGS AND BALLS (CERTIFIED AIR-MELT 440-C)
2. TOLERANCE: PER A.B.E.C.-7P
3. RADIAL PLAY: 0.0013 TO 0.0016, CONTACT ANGLE 18 TO 22 DEG
4. CAGE MATERIAL: SPECIAL, SELF-LUBRICATING

ALL DIMENSIONS IN INCHES

Fig. 2-2 Test Bearing Assembly for Special Retainer Material Lubricant Systems

superior performance in ultrahigh vacuum, as determined in tests at Lockheed. * The oil was used on standard, deep-groove (Conrad type) ball bearings of the R3 size with conventional, machined retainers of Synthane (a porous, paperbase phenolic laminate). Balls and races were of 440C stainless steel, and the bearings were double-shielded. Approximately 55 milligrams of oil was vacuum impregnated into each of the ball bearings to provide lubrication during testing. (Note: Except for the retainer and shields, these bearings were similar to those shown in Fig. 2-1 for evaluating solid-film lubricants.)

2.1.4 Grease

Marlin-Rockwell EG-509 silicone grease was also used for comparison with the other types of lubricant systems. This grease was selected on the basis of its superior performance in ultrahigh vacuum, as determined in tests at Lockheed. * The grease was used on standard, deep-groove (Conrad type) ball bearings of the R3 size with conventional ribbon retainers of 302 stainless steel. Balls and races were of 440C stainless steel, and the bearings were double-shielded. Approximately 100 milligrams of the grease was distributed inside the bearing to provide lubrication during testing. (Note: Except for the shields, these bearings were similar to those shown in Fig. 2-1 for evaluating solid-film lubricants.)

2.2 TEST CONDITIONS

Ball bearings with the selected lubricant systems were subjected to five different sets of test conditions. One group of ball bearings was vibrated and inspected to observe the effects of vibration alone (Phase A). Three groups of bearings were vibrated and then lifetime tested in vacuum (Phases B, C, and D). The difference between these three groups was in the ambient temperature during vibration (room temperature, -200° F, and +200° F, respectively). The fifth group of bearings was lifetime tested in vacuum without prior vibration (Phase E) in order to provide baseline data for

*H. I. Silversher and S. P. Drake, Jr., "Lubrication Evaluation", Report MRI 503.01, Lockheed Missiles & Space Co., Sunnyvale, California, September 1967.

comparison with Phases B, C, and D to disclose effects of vibration on lifetime capability. Further details are given in the following subsections.

2.2.1 Phase A Tests

Ball bearings were vibrated while rotating at 8000 rpm in air at room temperature for 5 minutes at an acceleration spectral density of $0.8 \text{ g}^2/\text{cps}$ from 90 to 400 cps, falling off at 3 db/octave from 400 to 2000 cps and falling off at 6 db/octave from 90 to 10 cps. One pair of bearings with each lubricant system was tested in this environment, as indicated in Tables 2-1 and 2-2. With a number of the lubricants (14 solid-film lubricants and 2 special retainer materials), duplicate tests were run with the vibration conducted in a vacuum of 1×10^{-7} torr rather than in air, as indicated in Tables 2-1 and 2-2. This was done to check the similarity of the effects of vibration under these two conditions. Following vibration, the bearings were disassembled and examined to determine any damage caused by vibration. (Bearings subjected to vibration in Phase A were not subjected to lifetime testing after vibration, as was done in Phases B, C, and D.).

2.2.2 Phase B Tests

Ball bearings were vibrated while rotating at 8000 rpm in vacuum (pressure of 5×10^{-7} torr, or lower) at room temperature for 5 minutes at an acceleration spectral density of $0.8 \text{ g}^2/\text{cps}$ from 90 to 400 cps, falling off at 3 db/octave from 400 to 2000 cps and falling off at 6 db/octave from 90 to 10 cps. Following vibration, the bearings were operated at 8000 rpm at a pressure of 5×10^{-7} torr, or lower, in ion-pumped vacuum systems for a period of 1000 hours or until prior failure. Prior failure was defined as the deterioration of the lubricant system to the extent that the bearing torque increased to above 1 inch-ounce, which is approximately 40 times the normal running torque of these bearings and is sufficient to stall the test motors. During lifetime testing in vacuum, the motors were allowed to heat up in a normal manner, due primarily to power losses in the motor windings and to bearing friction, so that bearing temperatures ranged from 130 to 190° F during the lifetime testing. Four bearings with each

of seven selected coatings, six selected retainer materials, one oil, and one grease were tested in this manner (i. e. , a total of 15 different lubricant systems were tested in Phase B).

2.2.3 Phase C Tests

These tests were identical to the Phase B tests, except that prior to the lifetime testing in vacuum, the bearings were vibrated in vacuum at -200°F instead of at room temperature. Bearings lubricated with the oil and grease could not be rotated at -200°F , so these bearings were vibrated in a non-rotating condition. Because of their poor performance in the Phase B tests, testing of two solid-film lubricants and one special retainer material was discontinued. (See Tables 2-1 and 2-2).

2.2.4 Phase D Tests

These tests were identical to the Phase B and C tests, except that prior to the lifetime testing in vacuum, the bearings were vibrated in vacuum at $+200^{\circ}\text{F}$ instead of at room temperature or -200°F . Because of their poor performance in the Phase B tests, testing of two solid-film lubricants and one special retainer material was discontinued. (See Tables 2-1 and 2-2.)

2.2.5 Phase E Tests

Ball bearings were operated without prior vibration at 8000 rpm at a pressure of 5×10^{-7} torr, or lower, in ion-pumped vacuum systems for a period of 1000 hours or until prior failure. Prior failure was defined as the deterioration of the lubricant system to the extent that the bearing torque increased to above 1 inch-ounce, which is approximately 40 times the normal running torque of these bearings and is sufficient to stall the test motors. Four bearings with each of seven selected coatings, six selected retainer materials, one oil, and one grease were tested in this manner (i. e. , a total of 15 different lubricant systems were tested in Phase E). These tests were

conducted to determine the lifetime capabilities of the lubricant systems in vacuum without prior vibration for comparison with the lifetime results from Phase B, C, and D, where the lifetime testing was preceded by vibration in vacuum at three different temperatures.

2.3 TEST EQUIPMENT

2.3.1 Bearing Test Fixture

Test bearings were mounted in a fractional horsepower motor (Fig. 2-3). This is an induction-type 3-phase motor, rated at 1/20 horsepower. Test bearings were conventionally mounted to support the rotor. Both bearings on any one motor received the same lubricant system; that is, the bearings were tested in pairs. Four bearings (i.e., two pairs) with each of the selected lubricants were tested in Phase B, C, D, and E, as indicated in subsection 2.2; at least two bearings (i.e., one pair) with each of the selected lubricants were tested in Phase A.

The stator of the motor was "canned" in a stainless steel jacket to prevent outgassing. To protect the motor against electrical breakdown of stator windings at high temperatures, Teflon insulation was used on the stator windings. Bearing temperatures under lifetime testing were measured by thermocouples attached to the bearing housings. The weight of the rotors (approximately 9.7 oz) imposed a radial load of approximately 4.85 oz on each of the two motor bearings when the motors were operated in the horizontal position during lifetime testing. The axial preload on all bearings tested was 2 lb.

2.3.2 Motor Control Panel and Power Supply

The motor control panel (Fig. 2-4) and power supply provided motor control and supplied power throughout the tests. The circuit for each motor was wired through a relay which automatically switched off the power to the motor and its associated timer when the motor stalled. The panel also contained a milliammeter and a temperature

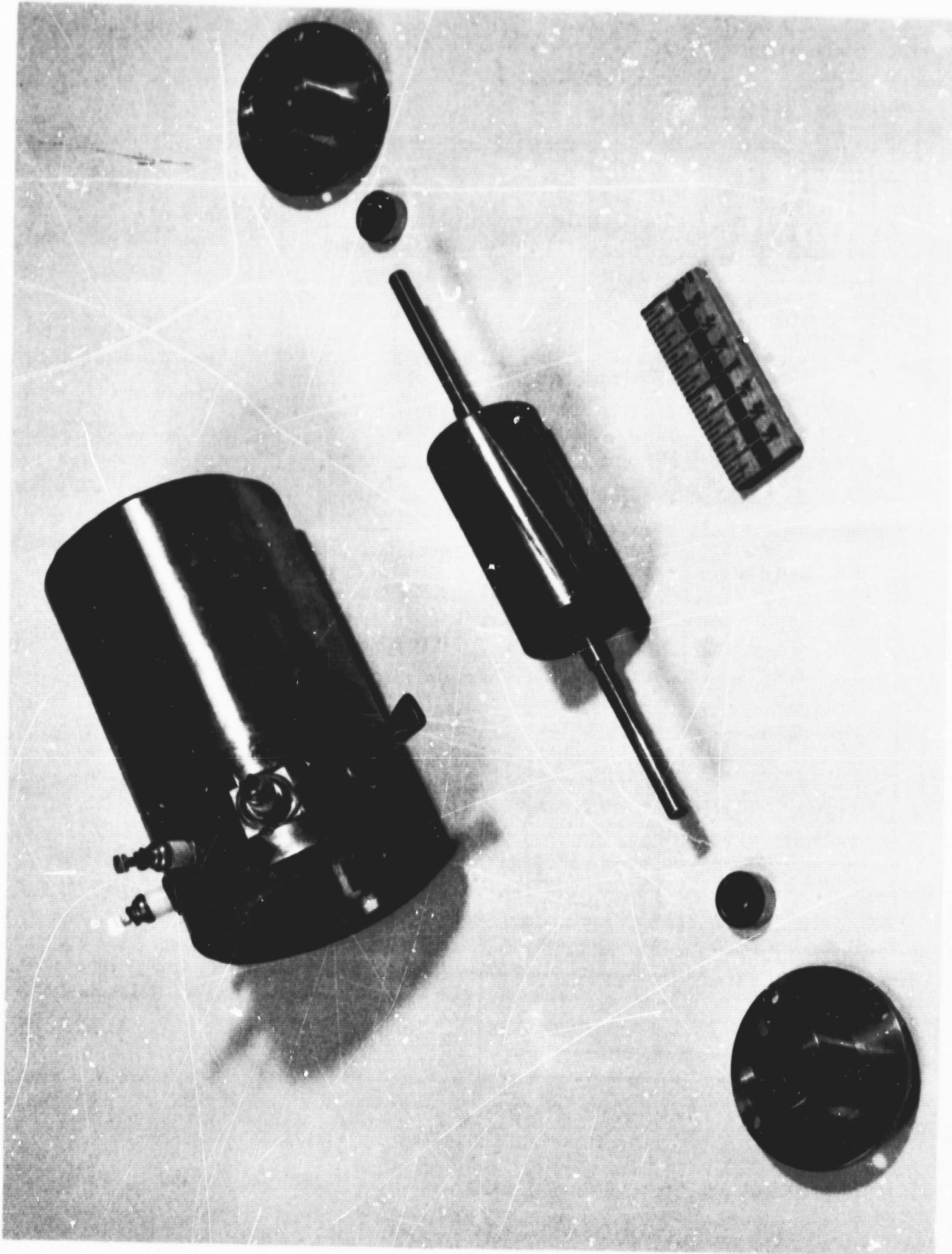


Fig. 2-3 Test Motor With "Canned" Stator

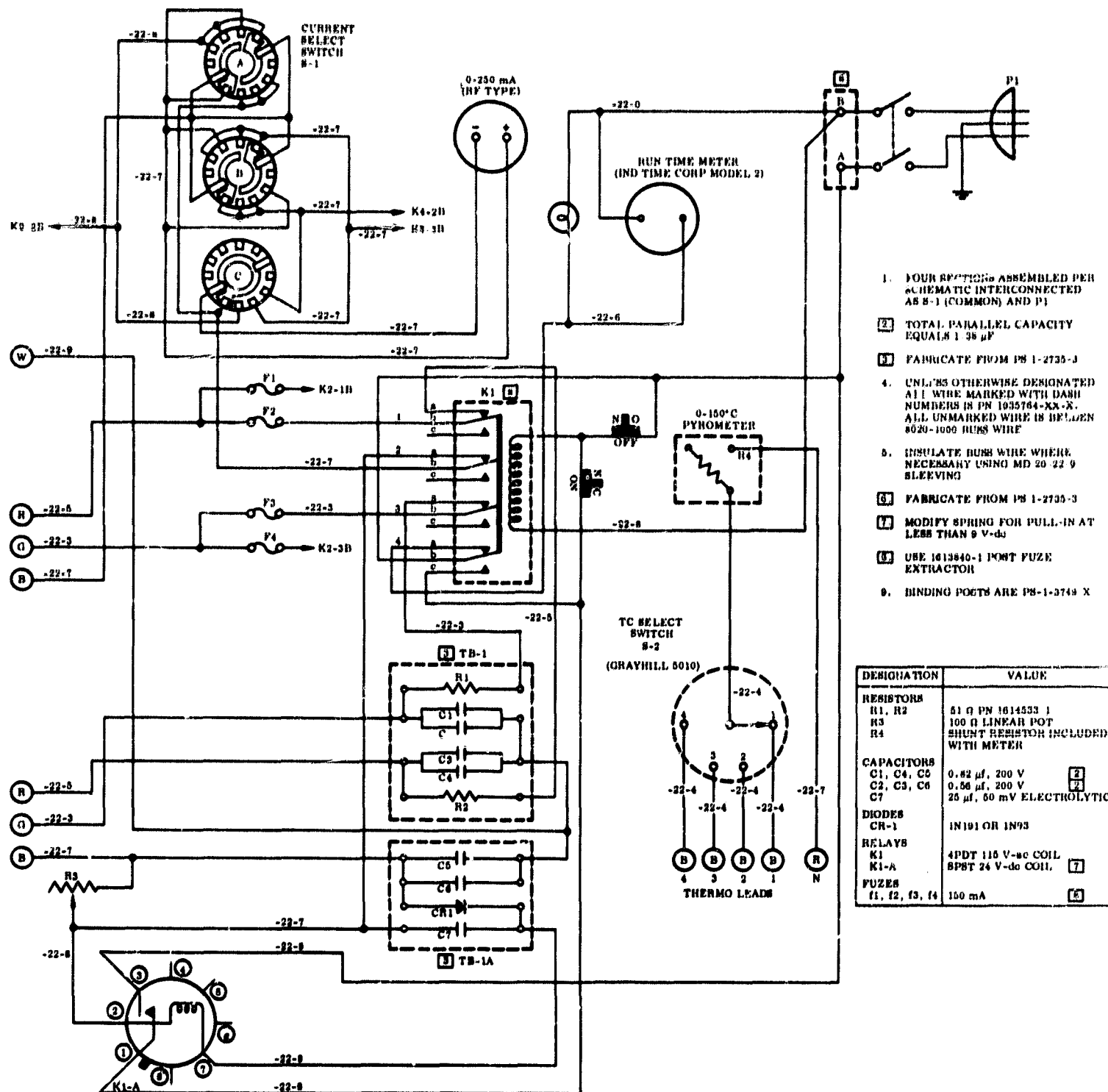


Fig. 2-4 Motor Control Panel Circuit Diagram

indicator to monitor the performance of each motor. The power supply was a Behlman Invertron with an output of 120 volts, 400 cps, 3-phase. The output was lowered below 100 volts to keep the motor and bearing temperature lower than 200° F. Motor speed was maintained at approximately 8000 rpm by the 400 cps frequency of the power supply.

2.3.3 Motor Mounting Block for Phases A and B Vibration Tests

Figure 2-5 illustrates the motor mounting block assembly used in vibration testing under Phases A and B (room temperature). This consisted of an aluminum cylindrical block with holes located at the bottom end of each motor to assure proper outgassing of the fixture, motor and test bearings. The block was bolted to a base plate which was attached directly to the electrodynamic shaker. The block was designed to hold four test motors, each with two bearings, with the motor axes parallel to the vibration axis. A thermocouple and accelerometer were attached to each motor.

After assembly of each test set-up, a functional check of the system was made in air. This involved operating the motors at 8000 rpm in air for 5 minutes. During this functional check, the coast-down time (i. e., the time required for the motors to slow down from 8000 rpm to a full stop when the power was cut off) was measured in order to establish the running qualities of the bearings before vibration. This measurement was repeated in air after the test fixtures had been vibrated.

Figure 2-6 shows a typical power spectral density plot of the vibration exposure. The nominal distribution was $0.8 \text{ g}^2/\text{cps}$ from 90 to 400 cps, falling off at 3 db/octave from 400 to 2000 cps and falling off at 6 db/octave from 90 to 10 cps. This amounts to an integrated total acceleration of 28.3 g rms. While it was impossible to reproduce the nominal distribution exactly each time, the total acceleration was maintained at 28.3 g rms from one test to another, and the total range was maintained from 10 to 2000 cps.

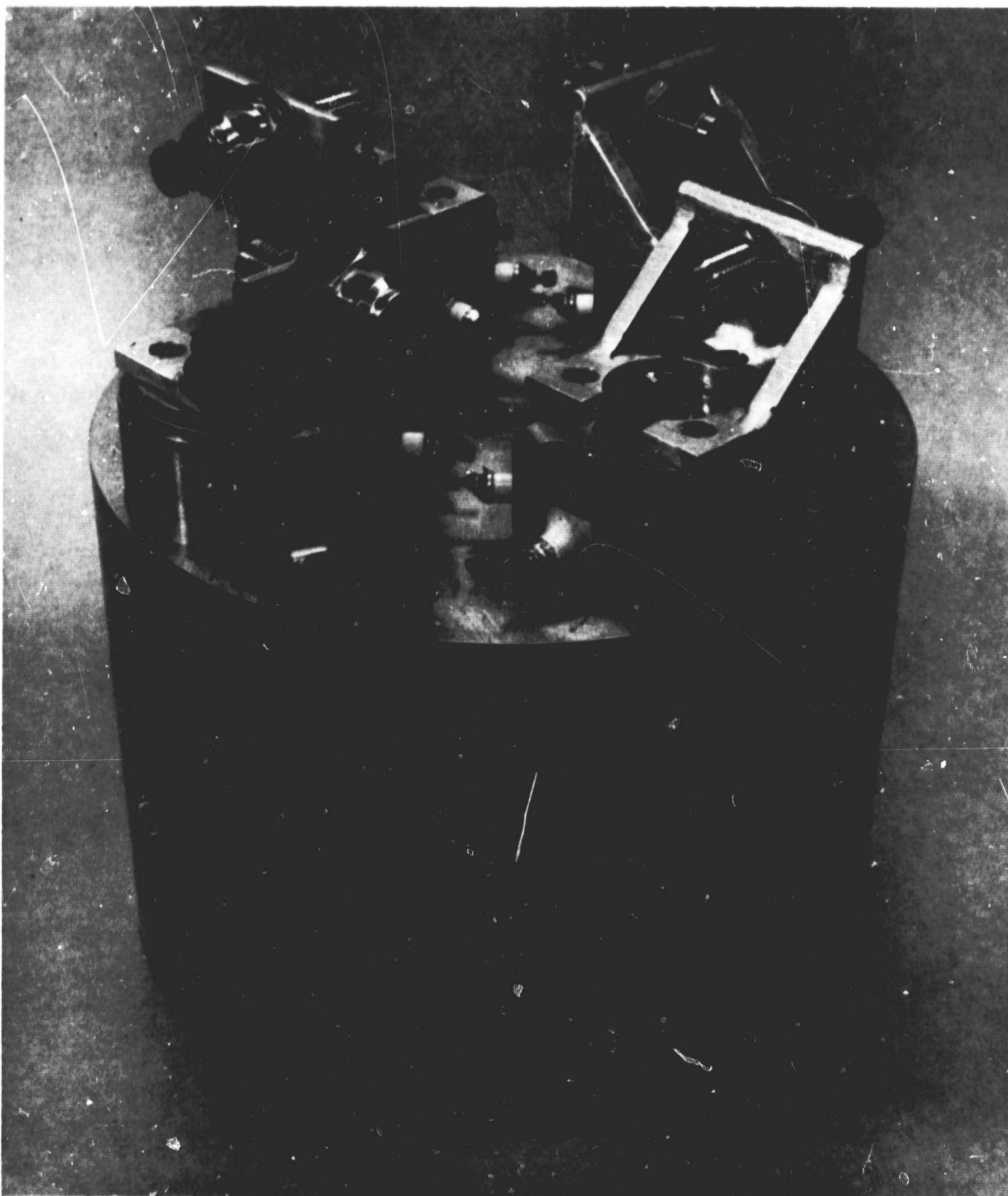


Fig. 2-5 Motor Mounting Block for Room Temperature Vibration Tests

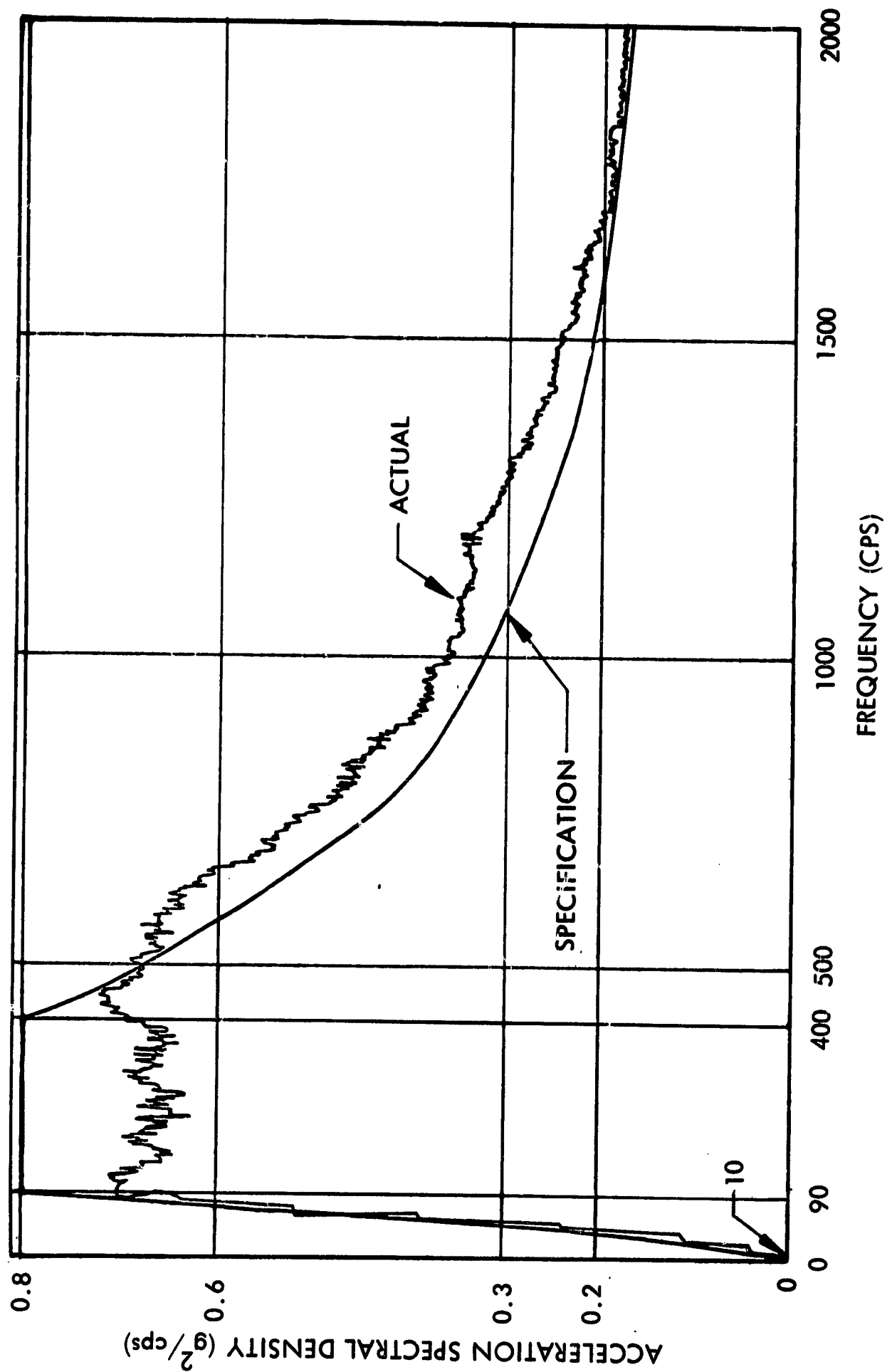


Fig. 2-6 Power Spectral Density Plot (Typical)

2.3.4 Vibration/Vacuum System for Phases A and B Vibration Tests

The vibration/vacuum system (Fig. 2-7) contained the motor block assembly during shake tests. The chamber was bolted directly to the shaker and connected to the vacuum system through a stainless steel flanged bellows assembly. The bellows assembly was added to limit vibration to the chamber. A liquid nitrogen trap was added to the high vacuum side of the system for cryogenic pumping to maintain lower pressures within the chamber. Pumping during vibration testing was accomplished with a 360 liter/second ion pump. Initial pumpdown of the entire system was accomplished with a liquid nitrogen trapped diffusion pump and mechanical back-up pump combination, which was valved off after the ion pump started.

2.3.5 Multiple Environment Motor Block Assembly

The multiple environment motor block assembly (Fig. 2-8) was machined from one piece of aluminum and attached directly to the electrodynamic shaker. This one-piece construction allowed the block and motors to achieve an even temperature level upon heating to +200° F with hot air, and cooling to -200° F with liquid nitrogen. The remaining configuration of this block was similar to the initial block assembly (Fig. 2-5).

2.3.6 Special Cryogenic Vacuum Seal (Tec-Seal)

Because of the low temperatures and vibration, some difficulty was encountered in selecting an adequate vacuum seal. The Tec-Seal (Fig. 2-9) was the only adequate seal of those evaluated that was able to maintain a vacuum tight seal with the motors at -200° F under severe vibration. Prior to testing the Tec-Seal, seal evaluations were undertaken with results as indicated below:

- Aluminum foil gasket — Vacuum-tight seal not obtainable because of the inability to apply sufficient pressure.
- Solder wire gasket — Seal obtained at room temperature. Leak occurred when the temperature of the motors reached -150° F which was 50° F higher than the desired test temperature. Two such O-rings were tried, using several different torque values on the flange bolts. Vibration was applied during temperature descent at each 50° increment. Seal flattened out during vibration.

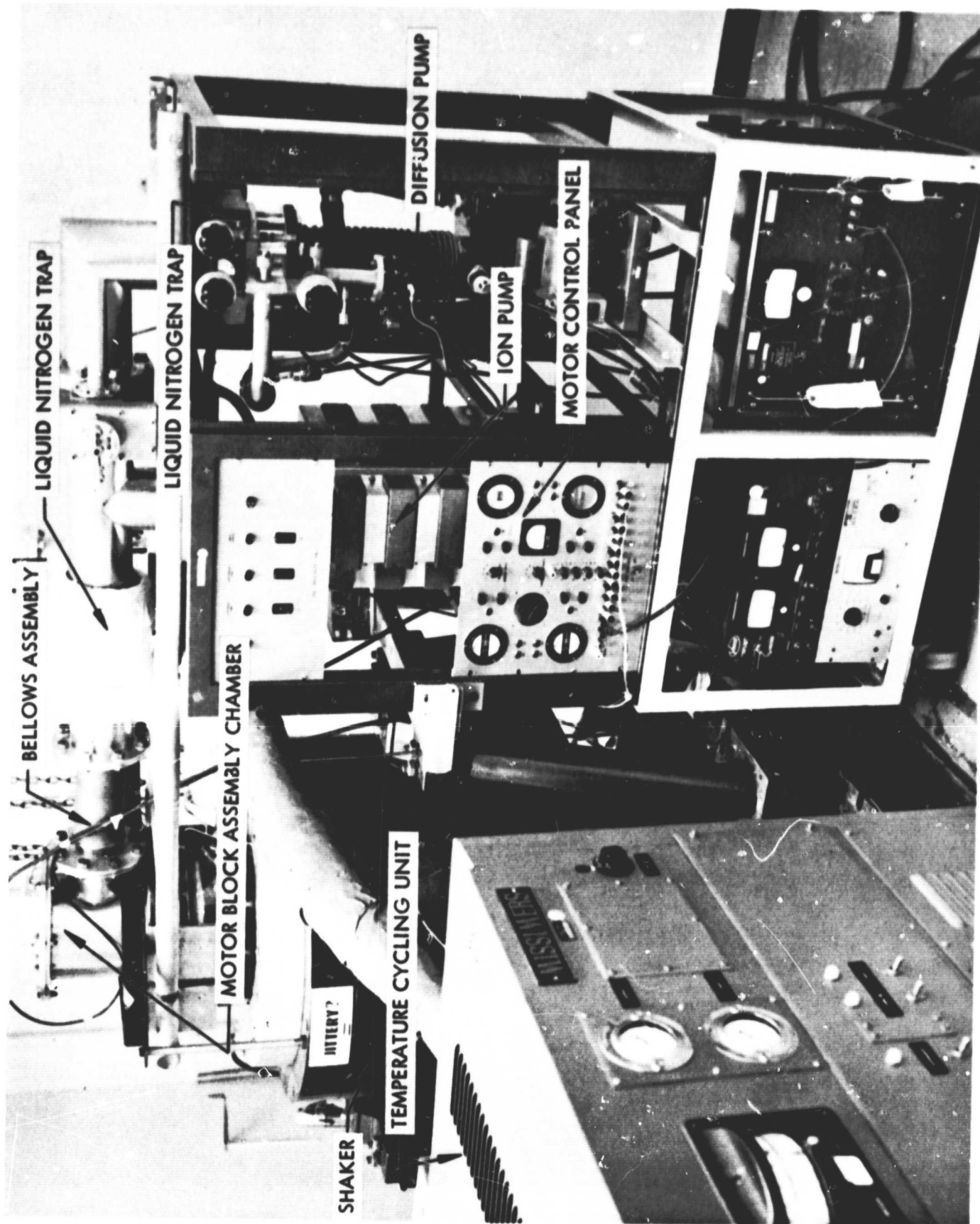


Fig. 2-7 Vibration/Vacuum System for Vibration Tests

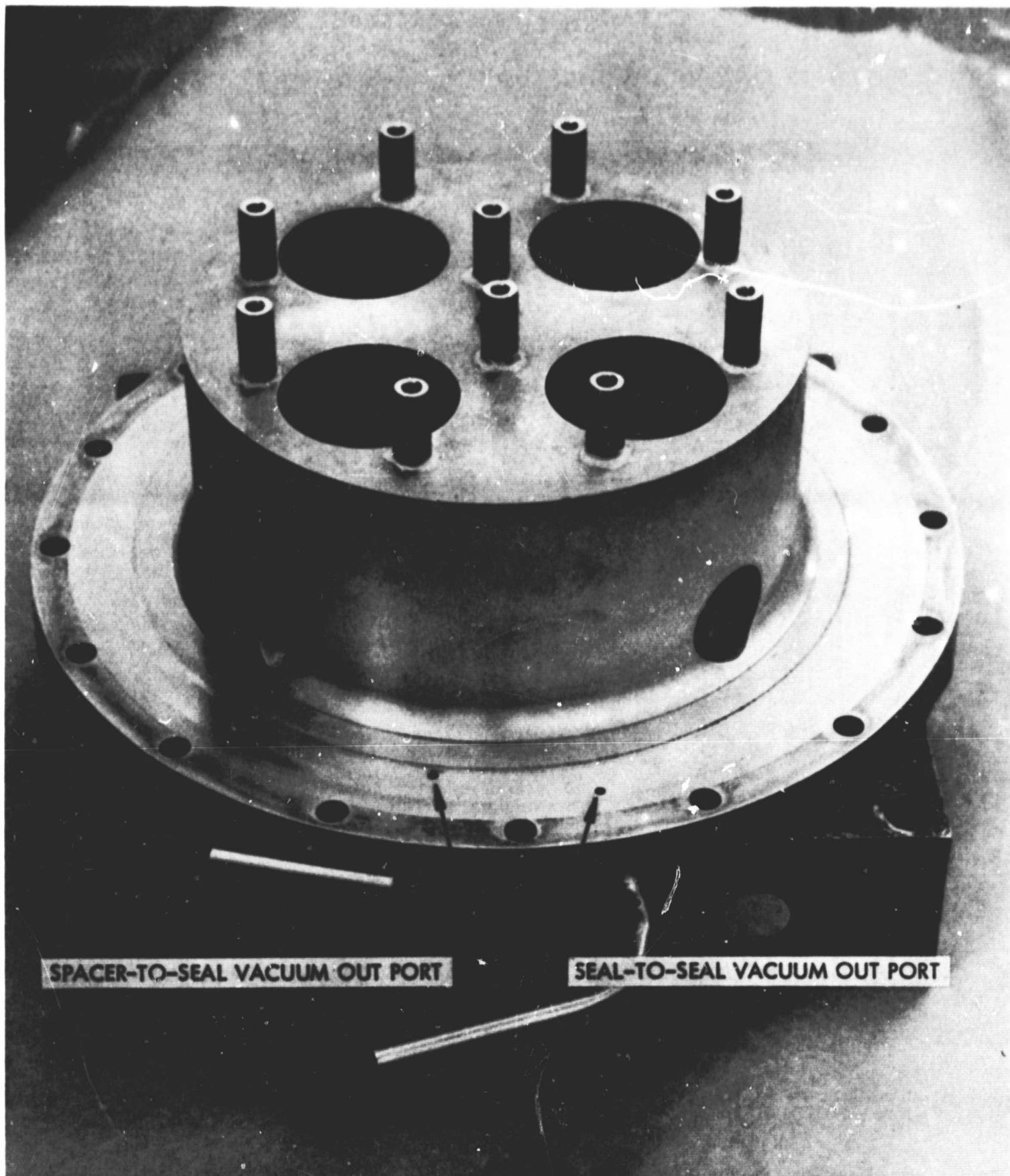


Fig. 2-8 Multiple Environment Motor Block Assembly

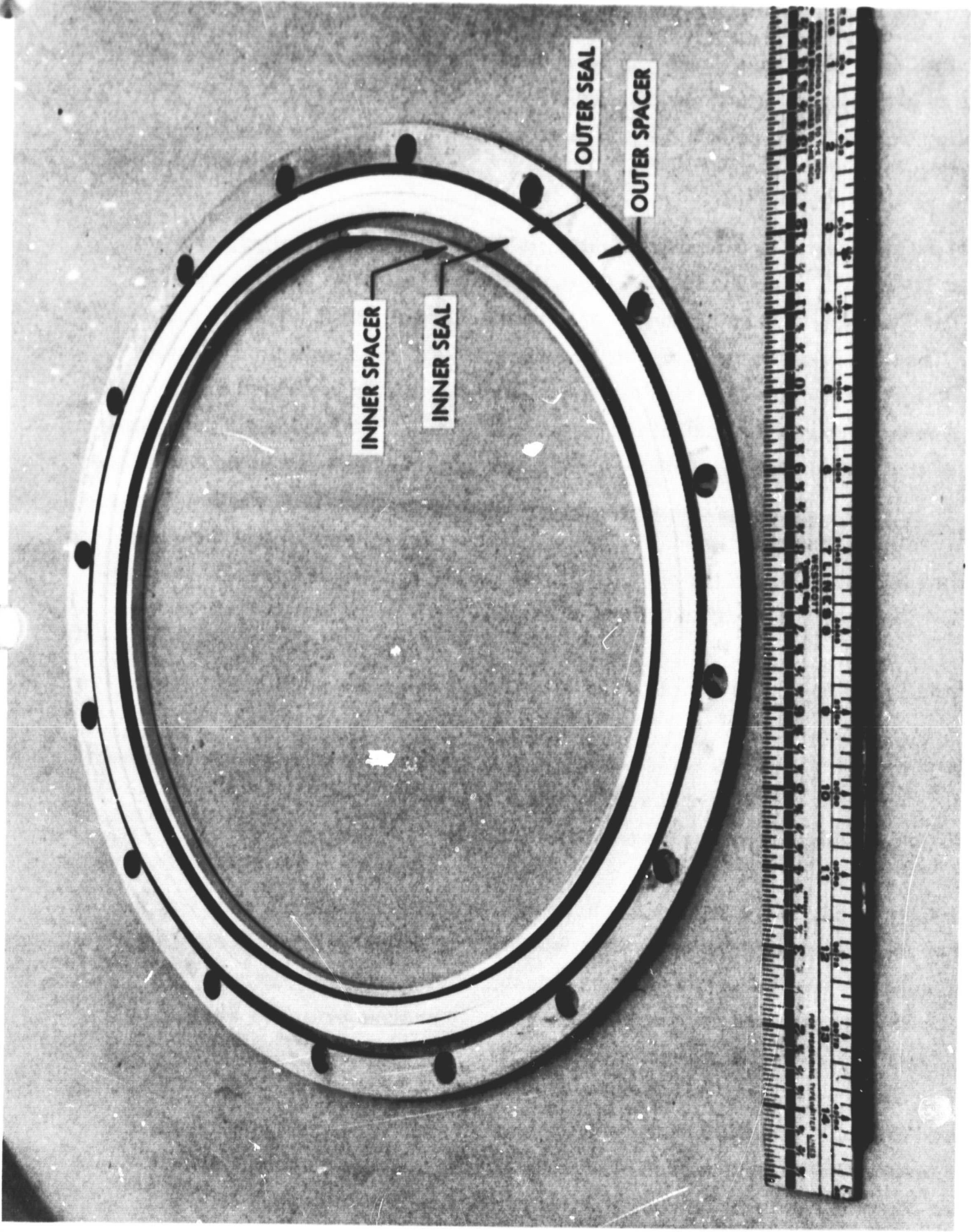


Fig. 2-9 Special Cryogenic Seal (Tec-Seal)

- Flat silicone elastomer gasket, 3/8 in. thick - System failed to pump down due to high outgassing rate and/or leaks.
- Teflon O-ring - Seal operated satisfactorily at room temperature; leak occurred at -125° F.

The multiple environment motor block assembly, with the Tec-Seal installed, is illustrated in Fig. 2-10. Note the location of vacuum pump-out ports as illustrated in Fig. 2-8. The Tec-Seal uses an inner spacer, an outer spacer, an inner seal, and an outer seal. The area between the two seals was evacuated with a mechanical vacuum pump. The area between the inner seal and inner spacer was also evacuated to prevent slow gassing to the high vacuum side of the system. The inner seal and outer seal were formed into a "U" shaped circular Teflon channel with a stainless steel coil inside the channel. The stainless steel coil was added to give resiliency to the seal while temperature cycling. The outer spacer and inner spacer prevent crushing of the seals while installing the seal between the mating flanges. This seal was 100 percent successful during all temperature cycling and vibration tests.

2.3.7 Multiple Environment Vacuum System

The multiple environment vacuum system (Fig. 2-11) contained the motor block assembly for all Phase C and Phase D tests. The motor block assembly, housed within the multiple environment vacuum system, was bolted directly to the shaker.

Initial pump-down of the entire system was accomplished with a liquid nitrogen trapped diffusion pump and mechanical back-up pump combination, which was valved off after the ion pump started. The vacuum system was designed for combined vacuum-vibration-high/low temperature environmental testing. The base pressure was 5×10^{-9} torr with a potential of ultrahigh vacuum capability.

Pumping speed available was 6000 liters/sec for handling peak outgassing during high temperature tests. Contamination-free evacuation during testing was accomplished with a sputter-ion pump and titanium sublimation pump on a liquid nitrogen cooled surface.

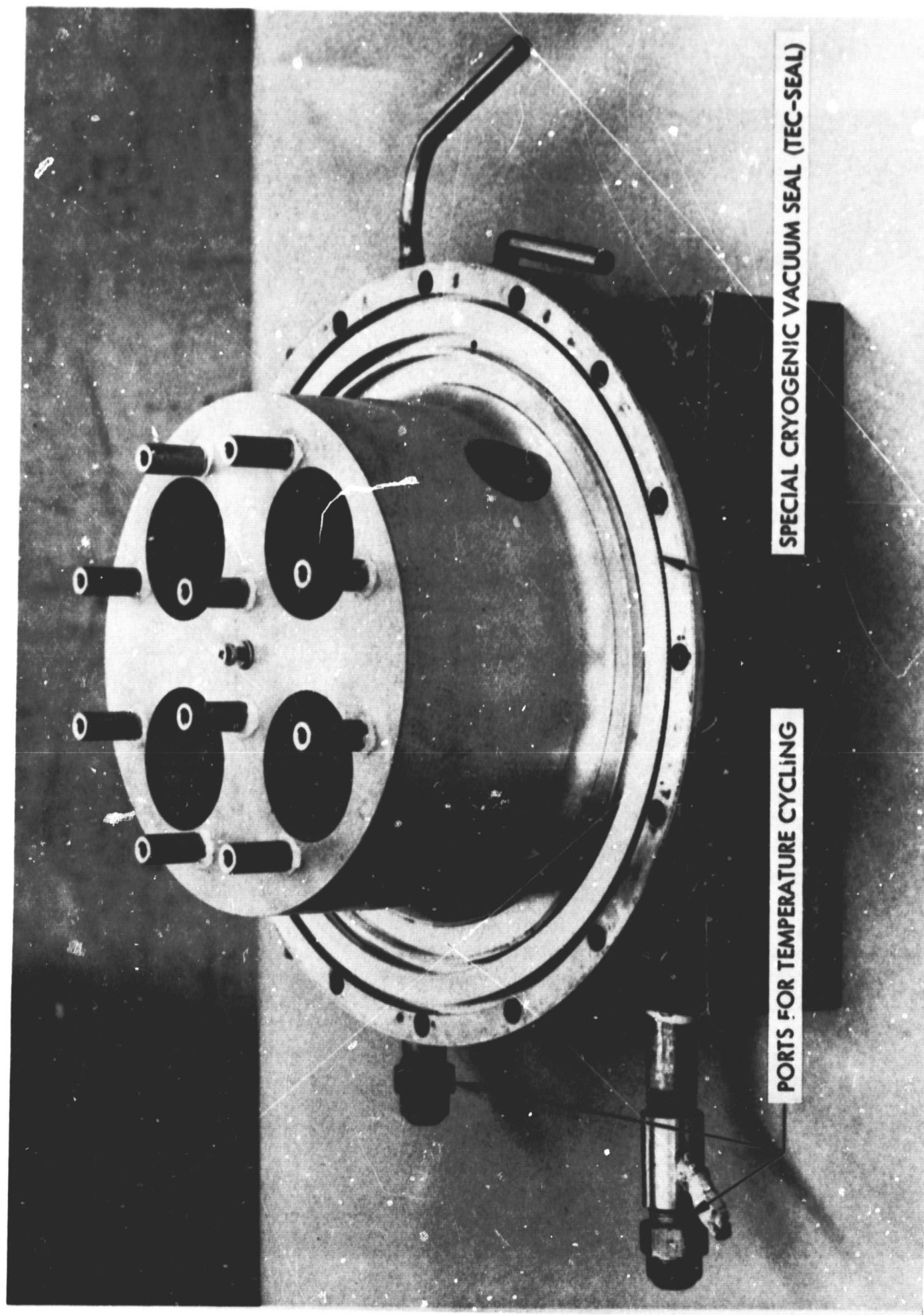


Fig. 2-10 Multiple Environment Motor Block Assembly, Tec-Seal Installed

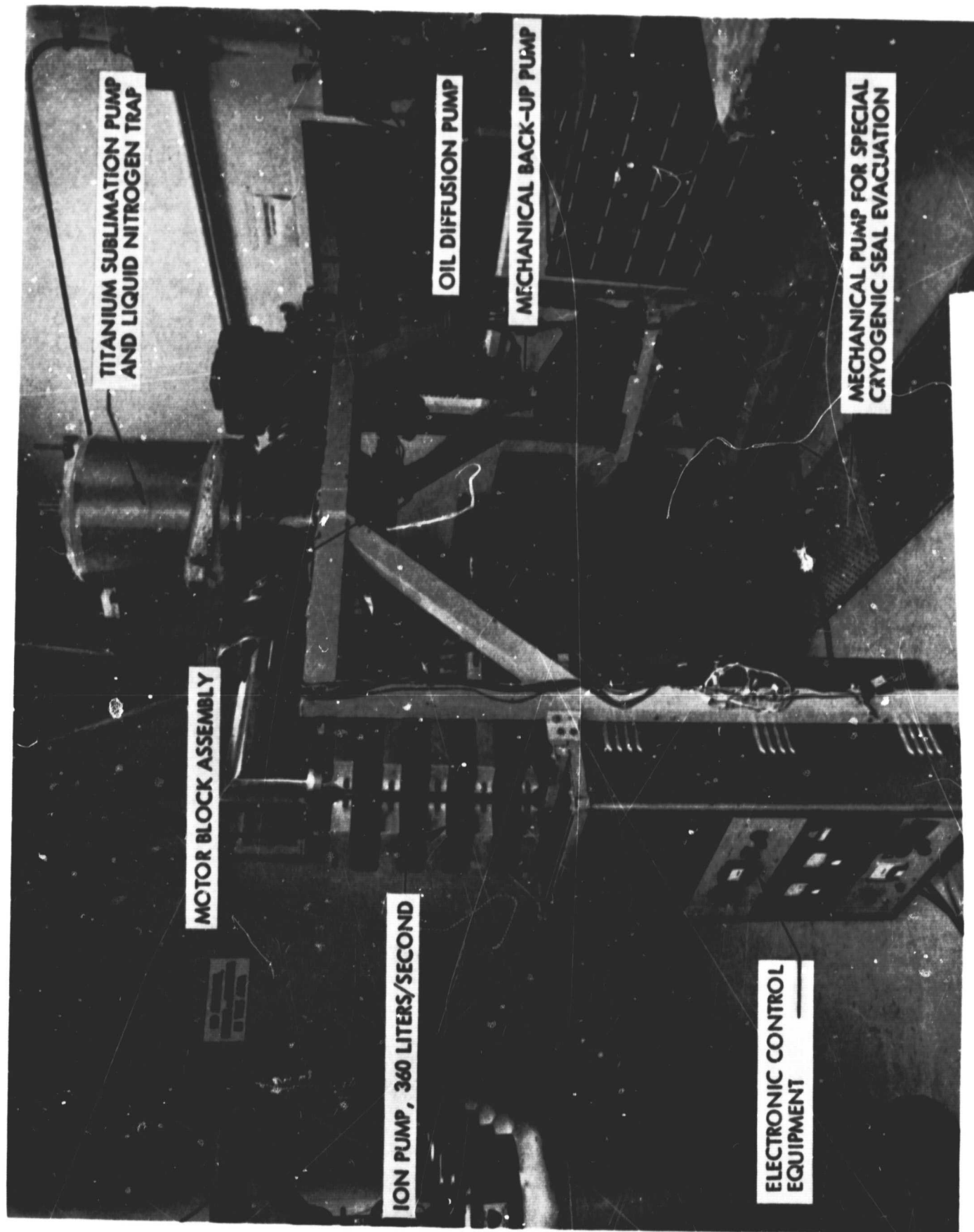


Fig. 2-11 Multiple Environment Vacuum System

Actual combined environment tests were conducted as follows:

- Vacuum at 2×10^{-7} torr or lower
- Temperature at -200° F with liquid nitrogen as coolant or at $+200^{\circ}$ F with air as a heat exchange medium in a closed loop system flowing through the test fixture
- Vibration at 28 g rms random using a 7500 pound-force shaker.

Flexible stainless steel bellows were coupled to each side of the high vacuum chamber to isolate the vacuum equipment from vibration forces. The system equipment was mounted on a wheeled frame (Fig. 2-12) which permitted installation and removal from the shaker without breaking vacuum.

2.3.8 Lifetime Test Vacuum Systems

Figure 2-13 is a view of the lifetime test area. Two sizes of ion pumps were utilized. Five vacuum systems incorporated an ion pump with a speed of 90 liters/sec. The chambers contained two motors each. The motors were clamped to a rod which was attached to the top flange plate. Two one-inch diameter pyrex view ports were provided for visual observation of the bearings and shaft rotation during test. Electrical vacuum-tight leads and a pump-out valve were installed in the top flange plate. Three vacuum systems incorporated an ion pump with a speed of 360 liters/second. Two chambers contained four motors each and one chamber contained three motors. The motors were clamped to rods which were welded to the base plate as illustrated in Fig. 2-14. Electrical leads and pump-out valve were installed in the base plate. Two three-inch diameter pyrex view ports were provided at 90 degree angles in the bell jar to observe the performance of the motors during test. All motors were mounted with their axes horizontal during lifetime testing, so that bearing loads were 4.85 oz in the radial direction and 2 lb in the axial direction.

All eight systems were fabricated of stainless steel with a copper step-gasket seal in the small systems and a Viton "O"-ring seal in the larger systems. This set-up permitted a total of 21 motors or 42 bearings to be lifetime tested at one time. As

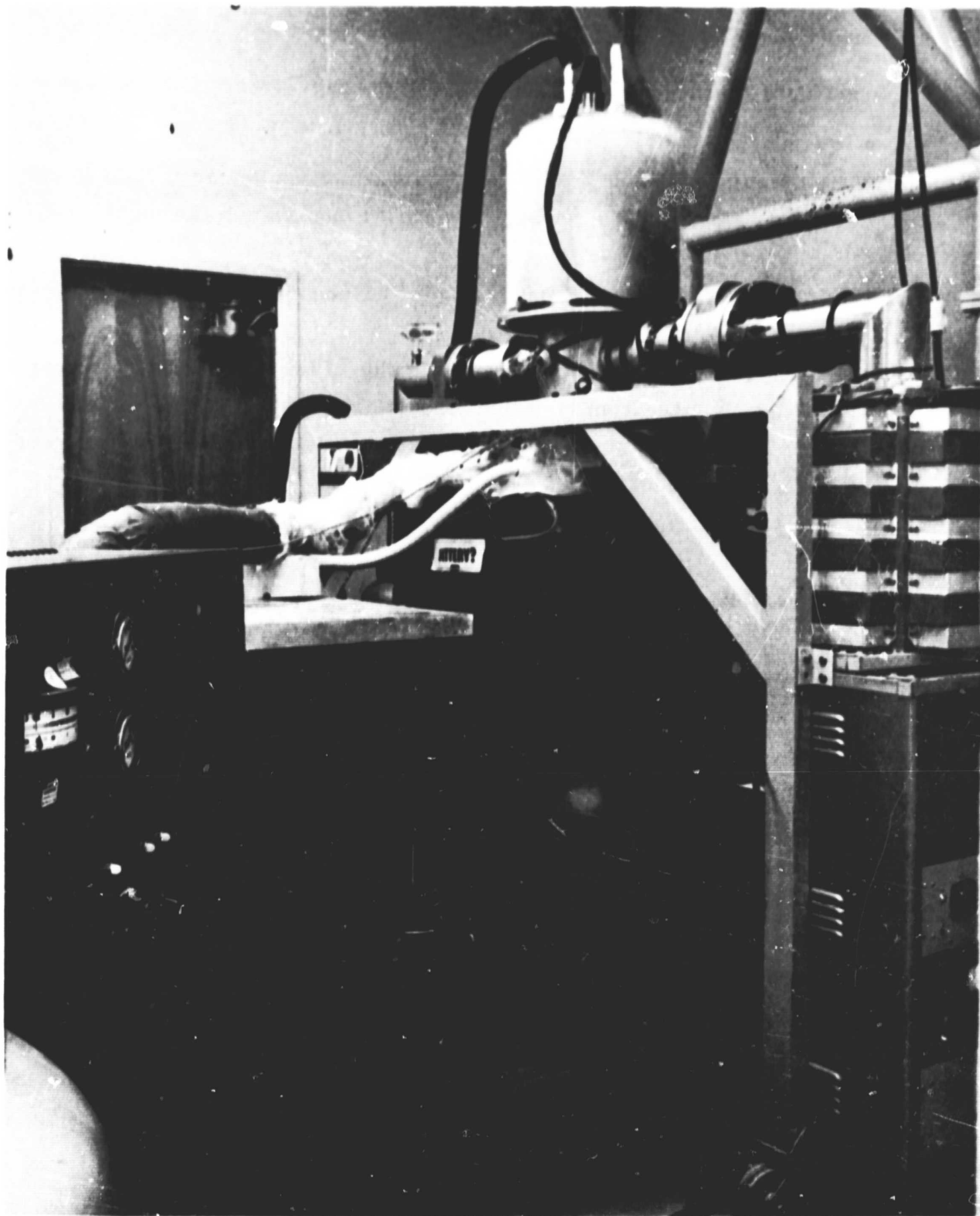


Fig. 2-12 Multiple Environment Vacuum System Mounted on Shaker



Fig. 2-13 Lifetime Testing Area With Ion-Pumped Vacuum Systems and Electronic Control Equipment

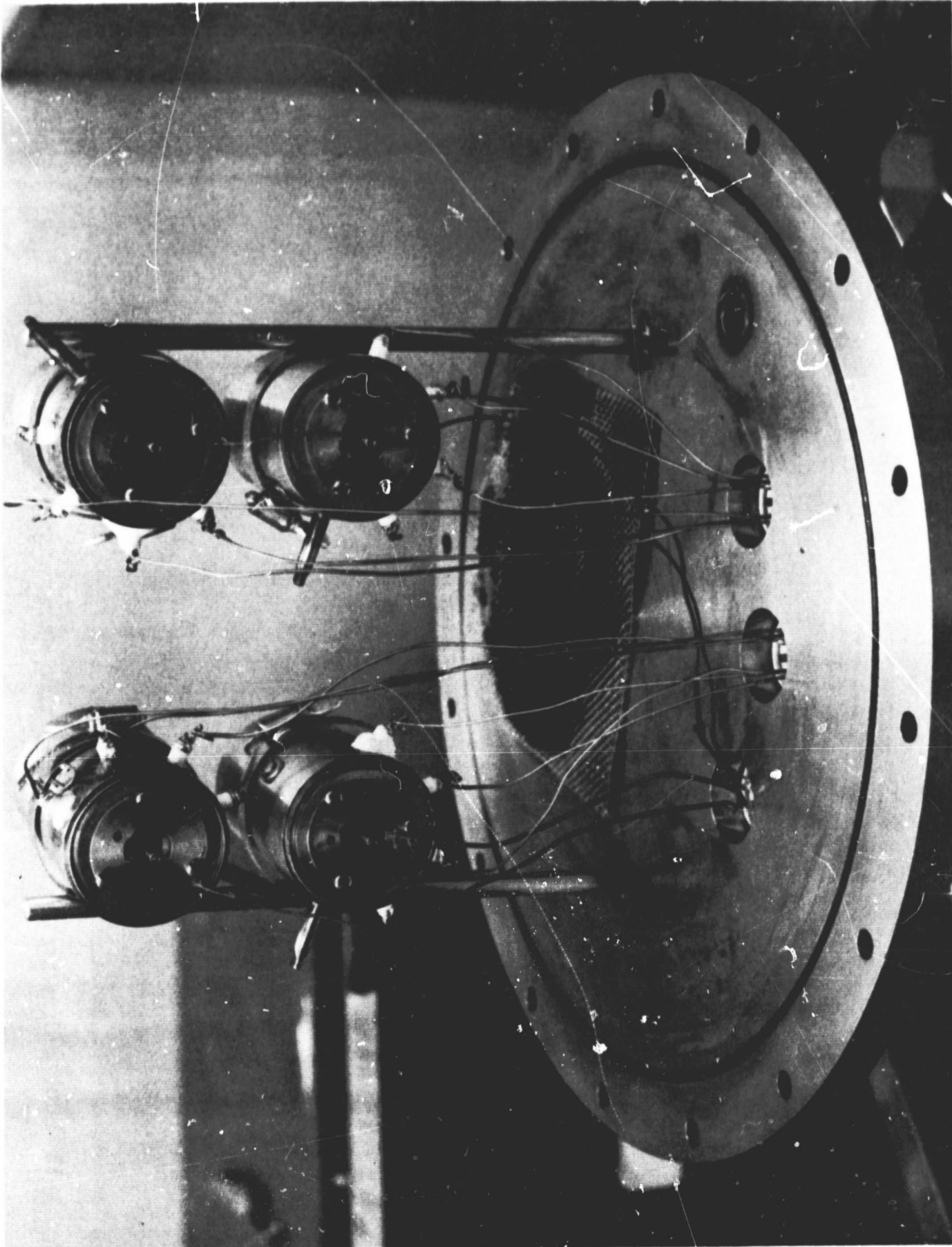


Fig. 2-14 Test Motors Mounted for 360 Liters/Sec Vacuum System for Lifetime Testing

failures occurred, the motor was removed from the system and replaced with the next test. Periodic checks were made of the coast-down times in vacuum.

Because of power losses and bearing friction, the test motors heated in a normal manner during lifetime testing in vacuum. Bearing temperatures (as measured by thermocouples on the bearing housings) usually ran about 130 to 190° F during life-time testing in vacuum.

Appendix A describes equipment modifications necessitated by the severe vibration and temperatures encountered during the tests.

Section 3 RESULTS AND DISCUSSION

3.1 RESULTS

3.1.1 Phase A Tests

Ball bearings lubricated with FS-1265 oil and EG-509 grease survived the 5-minute vibration in air with no visible degradation. Coast-down times increased slightly as a result of vibration.

Results of Phase A tests on solid-film lubricants and special retainer materials are presented in Tables 3-1, 3-2 and 3-3. (Fourteen of the solid-film lubricants and two of the special retainer materials were evaluated after vibration in vacuum as well as in air; these results are also included in the tables.)

Most of the bearings lubricated with solid-film lubricants turned more freely after vibration than before, as indicated by the increases in motor speed and coast time. In a few cases, these quantities decreased.

In many cases, the solid lubricant film was largely removed from the raceway as a result of the Phase A vibration, and it was doubtful that adequate lubricant remained for subsequent operation. Because of the extensive testing time required for lifetime testing, it was not possible to perform lifetime tests on all lubricants. Six solid-film lubricants were therefore selected which, on the basis of Phase A tests, appeared to have the best chance of surviving the lifetime tests in Phases B, C, D, and E; these lubricants were: (1) Hi-T-Lube, (2) Everlube Inlox 44, (3) Everlube 811, (4) Drilube, (5) Electrofilm 2008P, and (6) Electrofilm 4306. A seventh solid-film lubricant, Lubeco 905S, was also retained for testing in Phases B, C, D, and E because of its interest for special applications.

Table 3-1

MOTOR SPEEDS AND COAST TIMES BEFORE AND AFTER VIBRATION-PHASE A TESTS

Lubricant System	Motor Speed (rpm)		Coast Time (min:sec)	
	Before	After	Before	After
<u>Solid-Film Lubricants - Vibrated in Air</u>				
Molykote E3C	7926	7968	00:18	01:47
Molykote X-106	7890	7950	07:06	04:38
Molykote X-106	7956	7974	00:44	02:52
Electrofilm 2606	7974	7968	01:28	02:49
Electrofilm 2007	7980	-	05:07	05:35
Electrofilm 2007	7788	7980	02:03	05:04
Electrofilm 2008P	7890	7980	06:24	04:02
Electrofilm 2306	7944	7986	00:30	05:43
Electrofilm 2396	7974	7986	01:48	03:27
Electrofilm 4306	7950	7980	00:39	02:03
Electrofilm 5396	7980	7974	05:34	04:17
Everlube Inlox 44	7968	-	03:38	03:40
Everlube 620	7950	7950	00:43	02:25
Everlube 811	7896	7848	00:34	06:25
Everlube 811B	7944	7980	00:34	03:02
Everlube 811B2	7944	7980	01:12	03:29
Everlube 1329	7962	7980	01:42	05:20
General Magnaplate Drilube	7962	7974	01:16	02:56
General Magnaplate Hi-T-Lube	7938	7980	00:07	05:12
Surf-Kote A-1625	7974	7962	02:31	02:36
Surf-Kote M-1284	7944	7956	00:29	00:55
Lubeco 905	7980	7980	02:04	03:24
Lubeco 905S	7974	7980	02:07	07:16
Lubeco N-350-A	7974	-	01:56	03:04
Titanium Carbide	8170	8230	01:18	00:55
<u>Special Retainer Materials - Vibrated in Air</u>				
Duroid 5813	7926	7974	00:34	02:54
Ilkalo AFIL-M10	7932	-	00:25	01:14
Ilkalo AFIL-M10	8200	8030	02:50	00:38
Ilkalo AFIL-M20	7884	7968	00:11	02:22
Ilkalo AFIL-C10	7680	7780	00:58	01:24
Vespel SP-3	Motor stalled after 3 min running			
Nylafil G1/30/MS/5	Motor stalled after 3 min running			
West. 70Ag-20TFE-10 WSe ₂	7974	7986	01:42	02:30
Turcite A	7824	7836	00:07	00:13
Polymet AG	7944	7980	00:17	06:25

Table 3-1 (Cont.)

Lubricant System	Motor Speed (rpm)		Coast Time (min:sec)	
	Before	After	Before	After
<u>Special Retainer Materials - Vibrated in Air</u>				
Salox M	7686	7860	00:04	00:06
Sinitex	7830	7890	00:32	02:41
Rulon C	7956	7962	00:50	00:56
Kel-F	7866	7962	00:10	01:55
Kynar	7940	7970	00:10	00:12
Fluoray	7950	7980	00:46	02:36
15% Glass-Filled Teflon	7630	8000	00:25	00:36
MB Bronze-Filled Teflon	7810	7940	00:06	00:05
Boron Nitride	7950	Stalled	00:06	00:00
Bar Temp	7914	7980	00:14	06:44
<u>Solid-Film Lubricants - Vibrated in Vacuum</u>				
Electrofilm 2606	-	-	09:00	04:00
Everlube 620			04:15	02:15
Everlube 811	7992	7992	04:00	05:40
Everlube 811B	7998	7998	07:30	07:30
Everlube 811B2	7410	7017	00:30	02:45
Everlube 1329	7995	8001	05:35	05:50
Lubeco 905	7992	7992	04:30	05:30
Lubeco 905S	7986	7986	03:40	04:30
General Magnaplate, Hi-T-Lube	7998	8007	06:10	13:45
General Magnaplate Drilube	7995	8001	05:08	07:14
<u>Special Retainer Materials - Vibrated in Vacuum</u>				
Boron Nitride	Motor stalled after 30 sec			
Bar Temp	7998	7998	04:45	07:00
Bar Temp	7998	7998	04:30	02:30
<u>Oil and Grease - Vibrated in Air</u>				
FS-1265 Oil	7920	7940	00:07	00.09
EG-509 Grease	7930	8000	00:07	00.17

Table 3-2
CONDITION OF BEARINGS WITH SOLID-FILM LUBRICANTS AFTER VIBRATION - PHASE A TESTS

Vibrated in Air (5 min)	Vibrated in Vacuum (5 min)
1. <u>Molykote E3C</u> - No release of wear particles during disassembly. Lubricant film worn off raceways; raceways generally have shiny, metallic appearance with some scoring on shoulders. Balls have small wear pits and several are scratched. 2. <u>Molykote X-106</u> - Fine particles released during disassembly. Raceways lightly discolored, with metallic sheen; wear pits along base of raceway of inner race of top bearing. Balls discolored and pitted. Small amount of fine dust released during disassembly. Inner races have silvery metallic sheen, with wear evident along base of raceway and on shoulders; outer races lightly discolored, with metallic sheen and some wear. Balls darkly discolored, with many small wear patches. 3. <u>Titanium Carbide</u> - Lubricant film on loaded edge of raceways flaky and worn off. Balls dull with orange peel surface. Retainers satisfactory. 4. <u>General Magnaplate Drilube</u> - No release of wear particles during disassembly. Lubricant film worn off raceways. Balls bright and shiny with only slight pitting. Ball pockets satisfactory.	<u>Molykote E3C</u> - Small amount of wear particles released during disassembly. Lubricant film largely removed from raceways; no wear on raceways, races of lower bearing brinelled. Balls pitted. <u>General Magnaplate Drilube</u> - No debris on disassembly. Lubricant film appears largely removed from raceways. Balls still bright, with very few wear pits.

Table 3-2 (Cont.)

Vibrated in Air (5 min)	Vibrated in Vacuum (5 min)
5. <u>Electrofilm 2606</u> - Wear particles released during disassembly. Races have silver-matte finish, with wear bands evident on both races of lower bearing. Balls also have silver-matte finish, with numerous small wear patches; one ball in top bearing has deep gouge. 6. <u>Electrofilm 2007</u> - Races have smooth, dull finish; no wear on races; lubricant film cracked at junction of lands and raceways. Balls still shiny. Very small amount of fine particles released during disassembly. Lubricant film appears largely removed, with highly burnished thin film remaining on raceways. Balls slightly tarnished, with small wear pits. 7. <u>Electrofilm 2008P</u> - Very small amount of fine particles released during disassembly. Lubricant film largely removed from raceways. Balls in good condition - shiny, no wear. 8. <u>Electrofilm 2306</u> - Considerable fine particles released during disassembly. Lubricant film largely removed from raceways; some metal plucking along bottom of outer raceway of rear bearing. Balls tarnished and show metal plucking.	<u>Electrofilm 2606</u> - Small amount of debris released during disassembly. Lubricant film appears largely removed from raceways, but many small patches still present; no wear or brinelling on races. Balls lightly discolored; balls from top bearing have no wear, those from bottom bearing are pitted.

Table 3-2 (Cont.)

Vibrated in Air (5 min)	Vibrated in Vacuum (5 min)
9. <u>Electrofilm 2396</u> - Small amount of fine particles released during disassembly. Lubricant film largely removed from raceways. Balls discolored a yellowish-tan with some wear patches.	
10. <u>Electrofilm 4306</u> - Limited amount of fine particles released during disassembly. Raceways, balls, and cages in good condition. Balls still bright.	
11. <u>Electrofilm 5396</u> - Very slight amount of fine wear particles released during disassembly. Lubricant film appears largely removed from raceways. Balls satisfactory, with only small amount of fine roughening.	
12. <u>Everlube Inlox 44</u> - Fine particles released during disassembly. Lubricant film appears largely removed from raceways. Balls satisfactory.	<u>Everlube Inlox 44</u> - Very little debris released during disassembly. Lubricant film appears largely removed from raceways, but many small patches are still present; no wear or brinelling on races. Balls still shiny, but blackened and appear to have a transfer film of the lubricant; no pitting on balls.
13. <u>Everlube 620</u> - Metal particles present. Lubricant film largely removed from raceways. Balls have lustre finish, not shiny.	<u>Everlube 620</u> - Practically no fine debris released during disassembly. Lubricant film appears largely removed from raceways; no raceway wear or brinelling. Balls still shiny, but darkened and appear to have small patches of transferred lubricant film; no pitting on balls.

Table 3-2 (Cont.)

Vibrated in Air (5 min)	Vibrated in Vacuum (5 min)
14. <u>Everlube 811</u> - Fine debris released during disassembly. Races have grey burnished appearance, with no wear; lubricant film is largely worn off raceways in ball contact area. Balls discolored with some wear patches, though generally not too bad.	<u>Everlube 811</u> - Very little dust released during disassembly. Lubricant film appears removed in ball contact areas of raceways. Balls pitted.
15. <u>Everlube 811B</u> - Very little fine debris released during disassembly. Lubricant film largely removed from raceways. Balls lightly tarnished on upper bearing, still bright and polished on lower bearing; not much ball wear. (Rerun) - Lubricant film largely removed from raceways. Balls of top bearing are lightly tarnished. Balls of lower bearing are shiny. Retainers satisfactory.	<u>Everlube 811B</u> - Small amount of dust released during disassembly. Lubricant film appears removed in ball contact areas of raceways. Balls discolored and pitted.
16. <u>Everlube 811B2</u> - Very little debris released during disassembly. Lubricant film largely removed from raceways. Balls bright but pitted.	<u>Everlube 811B2</u> - Very little dust released during disassembly. Lubricant film appears largely removed on raceways. Balls dark, but not pitted very much.
17. <u>Everlube 1329</u> - Very little debris released during disassembly. Lubricant film largely removed from raceways. Balls bright, light straw color, with very little pitting.	<u>Everlube 1329</u> - No debris on disassembly. Lubricant film removed from raceways; inner race brinelled; outer race has wear and indentations along bottom of groove. Balls dark, but not pitted very much.

Table 3-2 (Cont.)

Vibrated in Air (5 min)	Vibrated in Vacuum (5 min)
18. <u>Lubeco 905</u> - Practically no fine debris released during disassembly. Lubricant film largely removed from raceways. Balls have grey discoloration, but still shiny to matte finish; no general pitting on balls, but a few wear patches.	<u>Lubeco 905</u> - Lubricant film appears removed in ball contact areas on raceways. Balls lightly tarnished, but look good.
19. <u>Lubeco 905S</u> - Same comments as for Lubeco 905, except for a few wear patches on several balls.	<u>Lubeco 905S</u> - Lubricant film appears removed in ball contact areas on raceways; wear and scoring on inner race. Balls dull but not pitted; several balls have scratches.
20. <u>Lubeco N-350-A</u> - Lubricant film largely removed from raceways; races shiny and metallic appearing. Balls slightly worn.	
21. <u>Surf-Kote A-1625</u> - Very small amount of fine particles released during disassembly. Lubricant film largely removed from raceways. Balls pitted but still shiny, with no discoloration.	<u>Surf-Kote A-1625</u> - Very little debris released during disassembly. Lubricant film worn off raceways; races worn and scored, especially along shoulders. Balls pitted, although still bright and shiny.
22. <u>Surf-Kote M-1284</u> - Very small amount of fine particles released during disassembly. Lubricant film largely removed from raceways. Balls have numerous small wear pits; balls from upper bearing still shiny, only slightly discolored; balls from lower bearing are discolored and have matte finish.	<u>Surf-Kote M-1284</u> - Bearings clean, with no debris released during disassembly. Lubricant film worn off raceways; some wear and scoring on raceways. Balls discolored and badly pitted.
23. <u>General Magnaplate Hi-T-Lube</u> - Lubricant film retained on raceways better than any other solid-film lubricant, although there are narrow bands where it appears to have worn away. Balls are discolored but remain shiny with no wear pits.	<u>General Magnaplate Hi-T-Lube</u> - No debris released during disassembly. Lubricant film appears largely removed. Balls still bright, with very few wear pits.

Table 3-3

CONDITION OF BEARINGS WITH SPECIAL RETAINER MATERIALS
AFTER VIBRATION - PHASE A TESTS

1. Bar Temp - Bearings in good condition. (Vibrated in vacuum: Light brinelling against shoulder of the relieved land on the inner race; wear or debris against shoulder; outer race appears either worn in patches or to have debris along the bottom of the groove. Balls and retainers satisfactory.)
2. Boron Nitride - Two pairs of bearings were jammed by wear debris generated during run-in. White, powdery coating on balls and races and inside motor housing after vibration. Balls and races worn. Retainers survived vibration without shattering, but ball pockets were badly worn and there was considerable pickup of metallic debris on the retainers. (Vibrated in vacuum: Three out of four retainers shattered.)
3. Duroid 5813 - Bearings in good condition. Raceways smooth and polished. Balls smooth and shiny; balls still silvery metallic on upper bearing, lightly discolored a yellowish-tan on lower bearing. Ball pockets wearing and releasing small bits of debris.
4. Vespel SP-3 - Bearings generally look good. Races of top bearing excellent; lower bearing has very slight brinelling on inner race and slight wear band on outer race. Balls shiny with slight wear and pitting. No significant ball pocket wear.
5. Turcite A - Top bearing fairly clean; races in good condition; some ball pocket wear; balls have thin bronze-colored coating, still highly polished, with very little wear or pitting. Lower bearing dirty; ball pockets worn; balls have silvery-grey discoloration and are covered with wear debris.
6. Ilkalo AFIL-M10 - Both races on top bearing deeply brinelled; ball pockets satisfactory; balls shiny but numerous small "flats"; metal stringers present; top bearing discolored, with appearance of having reached a high temperature. Races on lower bearing also brinelled; wear bands on ball pockets; metal debris present. Source of much of the metal debris appears to have been filings from the metal shims.

(Rerun) - Races have wear bands. Lower bearings raceway is brinelled at the edge. Balls are shiny but have an orange peel surface. Ball pockets of lower retainer are worn in a radial direction. Metal wear debris present.

Table 3-3 (Cont.)

7. Inkaloy AFIL-M20 - Races have wear bands. Ball pockets are worn. Balls are freckled with wear pits; balls from top bearing are discolored, those from lower bearing are still bright and shiny.
8. Inkaloy AFIL-W20 - Unable to be machined satisfactorily into retainers.
9. Inkaloy AFIL-W25 - Unable to be machined satisfactorily into retainers.
10. Inkaloy AFIL-C10 - Races brinelled and worn; outer and inner diameters of both bearings appear burnt. Both retainers badly worn, with ball pockets elongated. Balls from bottom bearing have numerous small wear pits. Motor casing filled with metal particles.

(Rerun) - Races brinelled and scored, especially outer race of top bearing and inner race of bottom bearing. Ball pockets slightly worn. Balls have small amount of metal plucking. Small amount of loose metal debris in motor.
11. Tetraloy 1101 - Unable to be machined satisfactorily into retainers.
12. Nylafil G1/30/MS/5 - Top bearing in good condition. Slight brinelling on inner race of bottom bearing; wear band on outer race of bottom bearing; balls slightly discolored and pitted in bottom bearing. No significant ball pocket wear.
13. Polymet AG - Races brinelled and badly scored. Retainers scored on both inner and outer diameters; some wear on ball pockets. Balls generally not too bad; still shiny, but several have large scuffed areas.
14. Salox M - Inner race of lower bearing is brinelled. Races worn, especially on lower bearing. Retainers have picked up metallic wear debris, particularly on lower bearing. Balls pitted.
15. Westinghouse 70 Ag-20 PTFE-10WSe₂ - Retainers broken into small pieces. Both inner and outer races brinelled. Balls discolored and scratched, with surface identifications.
16. Westinghouse 60 Cu-30 PTFE-10WSe₂ - Unable to be machined satisfactorily into retainers.
17. Westinghouse 45 Cu-15 Ag-30 PTFE-10WSe₂ - Unable to be machined satisfactorily into retainers.
18. Westinghouse 45 Cu-15 Bronze-30 PTFE-10WSe₂ - Unable to be machined satisfactorily into retainers.

Table 3-3 (Cont.)

19. Sinitex - Top bearing generally satisfactory; some wear in ball pockets; balls metallic and shiny. Bottom bearing has brinelling and scoring against shoulders of inner race; retainer is worn, with elongated ball pockets; thick copper-bronze transfer film on balls.
20. Rulon C - Races generally in good condition, with some wear on races of top bearing. No significant ball pocket wear. Balls from top bearing pitted, with many wear patches; balls from bottom bearing have light orange tinge with very little pitting. Metal debris present, especially in top bearing.
21. Kel-F - Races in good condition; slight wear patches on inner race of the bearing and patches of light-orange colored debris in raceway grooves. Balls in good condition. Very little ball pocket wear; balls snug in many pockets.
22. Kynar - Races in fairly good condition; several skid marks on outer race of top bearing, wear band on shoulder side of inner race of lower bearing. Few wear patches on several balls of lower bearing. Retainers slightly worn with fine fibers of wear debris.
23. Fluoray - Races in excellent condition, with no brinelling or wear. Some wear on ball pockets of retainers. Balls in excellent condition - still shiny with no wear.
24. 15% Glass-Filled Teflon - Balls and races in excellent condition. Retainers have fine fibers protruding from surfaces but have no signs of wear.
25. MB Bronze-Filled Teflon - Balls, races and retainers in excellent condition. Outer diameter of retainer on lower bearing rubbed against shoulder of outer race, generating wear debris in this bearing.

Most of the special retainer materials selected for evaluation could be machined by the bearing manufacturer into satisfactory retainers, albeit with difficulty in several cases. Six of the materials, however, could not be machined satisfactorily despite numerous attempts. Specific comments by the bearing manufacturer on their machinability are as follows:

1. Tetraloy 1101: "This material disintegrated during machining and continued efforts and trials in trying to fabricate the cages met with no success."
2. Ilkaloy AFIL - W20: "This material is so brittle that we were unable to get past the turning or drilling stages."
3. Ilkaloy AFIL - W25: Same comments as for Ilkaloy AFIL - W20.
4. Westinghouse 60 Cu-30 TFE-10 WSe₂: "This material is very hard to deburr in that it is exceedingly stringy. The material is exceedingly brittle and some of the cages which we finally did machine cracked when we attempted to deburr them."
5. Westinghouse 45 Cu-15 Ag-30 TFE-10 WSe₂: Same comments as for Westinghouse 60 Cu-30 TFE-10 WSe₂.
6. Westinghouse 45 Cu-15 bronze-30 TFE-10WSe₂: Same comments as for Westinghouse 60 Cu30 TFE10 WSe₂.

Most of the bearings with special retainer materials turned more freely after vibration than before, as indicated by the increases in motor speed and coast time. In a few cases, these quantities decreased.

Some of the special retainer materials provided good self-lubricating characteristics, whereas with others the races and balls showed varying degrees of wear and scoring. Several retainer materials wore badly, and one broke into small pieces during vibration. Six retainer materials were selected which, on the basis of Phase A tests, appeared to have the best chance of surviving the lifetime tests in Phases B, C, D, and E and provided a range of material types; these materials were: (1) Bar Temp, (2) Rulon C, (3) Vespel SP-3, (4) Nylafil G1/30/MS/5, (5) MB bronze-filled Teflon, and (6) Ilkaloy AFIL-M10.

Although none of the metal-base composites performed well in Phase A testing, Ilkaloy AFIL-M10 was included in order that at least one metal-base composite could be evaluated under Phases B, C, D, and E conditions. All of the other five materials are plastic-base composites.

3.1.2 Phase B Tests

Results of Phase B tests are presented in Tables 3-4, 3-5, and 3-6. Of the solid-film lubricants, only Hi-T-Lube gave lifetimes of 1000 hours in both pairs of bearings after vibration. Other solid-film lubricants gave short and erratic lifetimes.

Four of the special retainer materials (Nylafil G1/30/MS/5, Rulon C, MB Bronze-Filled Teflon, and Bar Temp) gave lifetimes of 1000 hours after vibration, as did the oil and grease. One pair of bearings lubricated with the grease failed in less time because of unrelated fixture difficulties.

The following two solid-film lubricants and one special retainer material were eliminated from Phases C and D testing because of the poor performance obtained under Phases B and E testing:

- Solid-film lubricants: Electrofilm 2008P and Drilube
- Special retainer material: Ilkaloy AFIL-M10

3.1.3 Phase C Tests

Results of Phase C tests are presented in Tables 3-7, 3-8, and 3-9. These results are closely parallel to results of Phase B tests.

3.1.4 Phase D Tests

Results of Phase D tests are presented in Tables 3-10, 3-11, and 3-12.

Table 3-4

**MOTOR SPEEDS AND COAST TIMES BEFORE AND AFTER VIBRATION AT ROOM
TEMPERATURE IN VACUUM - PHASE B TESTS**

Bearing Pair	Lubricant System	Motor Speed (rpm)		Coast Time (min:sec)	
		Before	After	Before	After
Solid-Film Lubricants					
5A-3	Electrofilm 2008P	8000	8000	02:58	02:28
5A-4	Electrofilm 2008P	8000	8000	04:18	02:41
8A-3	Electrofilm 4306	8000	8000	03:50	03:00
8A-4	Electrofilm 4306	8000	8000	03:41	03:10
10A-3	Everlube Inlox 44	8050	7900	05:39	03:16
10A-4	Everlube Inlox 44	8050	7920	03:02	02:20
12A-3	Everlube 811	8000	7980	05:19	00:57
12A-4	Everlube 811	8000	7980	04:40	01:12
16A-3	General Magnaplate Drilube	8000	7950	03:19	00:06
16A-4	General Magnaplate Drilube	8000	7950	03:21	00:19
17A-3	General Magnaplate Hi-T-Lube	8000	7910	03:19	04:37
17A-4	General Magnaplate Hi-T-Lube	7980	7900	03:32	03:51
21A-3	Lubeco 905S	8000	8000	02:23	02:14
21A-4	Lubeco 905S	8000	8000	03:57	03:06
Special Retainer Materials					
3B-3	Ilkaloy AFIL-M10	8006	7740	01:16	02:08
3B-4	Ilkaloy AFIL-M10	8000	7690	00:16	00:38
8B-3	Vespel SP-3	7720	7910	00:27	01:56
8B-4	Vespel SP-3	7740	7920	00:38	02:13
9B-3	Nylafil G1/30/MS/5	8007	7740	04:24	01:43
9B-4	Nylafil G1/30/MS/5	8006	7740	07:19	03:46
18B-3	Rulon C	7750	8000	00:24	02:04
18B-4	Rulon C	7750	8010	04:27	04:52
23B-3	MB Bronze-Filled Teflon	8000	8000	03:20	05:23
23B-4	MB Bronze-Filled Teflon	8000	8000	06:20	06:19
26B-3	Bar Temp	8000	7980	01:31	04:36
26B-4	Bar Temp	8000	7960	06:04	03:33
Oil and Grease					
O-3	D.C. FS-1265 (250 c. s.) Oil	7650	7720	00:07	00:15
O-4	D.C. FS-1265 (250 c. s.) Oil	7840	7910	00:25	00:35
G-3	EG-509 Grease	7600	7760	00:07	00:16
G-4	EG-509 Grease	7850	7850	00:26	00:30

Table 3-5

RUNNING LOG FOR LIFETIME TESTS - PHASE B TESTS

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp. (° F)	Speed (rpm)	Remarks
		<u>Solid-Film Lubricant</u>			
5A-3	Electrofilm 2008P	0	78	8000	
		2	120	-	
5A-4	Electrofilm 2008P	-	-	-	Failed Test aborted-fixture difficulties
8A-3	Electrofilm 4306	0	78	8000	
		74	150	8000	
		171	182	8000	
		177	200	8000	
		243	-	-	Failed
8A-4	Electrofilm 4306	0	78	8000	
		2	100	-	Failed
10A-3	Everlube Inlox 44	0	80	8000	
		27	135	8000	Coast time 10 min 36 sec
		122	140	8000	
		337	139	8000	
		362	142	7900	
		467	165	-	Failed
10A-4	Everlube Inlox 44	0	80	8000	
		2	100	8000	Coast time 6 min 20 sec
		6	158	-	Failed
12A-3	Everlube 811	0	107	8000	Motor running rough
		42	178	8000	Motor running smooth
		163	141	8000	
		241	145	7950	
		330	150	-	Failed
12A-4	Everlube 811	0	115	7980	Motor would only start by hand
		46	177	7980	
		60	-	-	Failed
16A-3	General Magnaplate	0	78	7740	
	Drilube	8	170	-	Failed
16A-4	General Magnaplate	0	78	7850	
	Drilube	1	140	7700-	
				7850	Speed erratic
		46	170	7890	
		103	-	-	Failed
17A-3	General Magnaplate	0	80	8000	
	Hi-T-Lube	26	166	8000	Coast time 9 min 46 sec

Table 3-5 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp. (° F)	Speed (rpm)	Remarks
17A-4	General Magnaplate Hi-T-Lube	362	165	7960	Completed test; coast time 11 min 40 sec
		515	160	7960	
		852	153	8000	
		945	160	8000	
		1000	159	8000	
		0	80	8000	Coast time 14 min 0 sec
		26	167	8000	
		362	165	7920	
		515	159	7940	
		852	154	8000	
		1000	159	8000	Completed test; coast time 15 min 5 sec
		21A-3	Lubeco 905S	0	80
157	185			8000	
162	—			—	
21A-4	Lubeco 905S	0	80	8000	Failed
		161	177	8000	
		196	172	8000	
		384	—	—	
3B-3	Ilkaloy AFIL-M10	0	78	8000	Failed
		74	181	8000	
		240	206	8000	
		291	255	—	
3B-4	Ilkaloy AFIL-M10	0	95	7600	Failed
		42	184	7600	
		154	—	—	
8B-3	Vespel SP-3	0	104	8000	Failed
		95	166	8000	
		342	164	7980	
		433	158	7980	
		502	—	—	
Special Retainer Materials					
8B-4	Vespel SP-3	0	104	7980	Failed
		95	171	7980	
		342	168	7950	
		502	143	8000	
		562	—	—	
9B-3	Nylafil G1/30/MS/5	0	78	7980	Speed decreased Speed increased
		43	158	8000	
		305	180	8000	
		383	186	7450	
		544	155	7950	

Table 3-5 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp. (° F)	Speed (rpm)	Remarks
9B-4	Nylafil G1/30/MS/5	639	175	7950	Completed test
		808	179	7950	
		904	181	7950	
		1005	180	7950	
		0	78	7980	
		43	158	8000	
		185	180	8000	
		383	186	7950	
		477	155	7960	
		573	176	7960	
		742	180	7960	
		838	183	7950	
18B-3	Rulon C	1005	185	7950	Completed test
		0	105	8000	
		95	171	8000	
		264	175	8000	
		342	168	7950	
		502	143	7950	
		597	152	7950	
		863	155	8000	
		1004	154	8000	
		0	104	7980	
		95	174	7980	
		342	170	7900	
18B-4	Rulon C	433	165	7900	Completed test
		502	145	7900	
		597	154	7900	
		696	154	7950	
		863	155	8000	
		1004	155	8000	
		0	78	8000	
		95	175	7950	
		268	175	8000	
		612	170	8000	
		1004	170	8000	
		0	78	8000	
23B-3	MB Bronze-Filled Teflon	95	117	7950	Completed test
		268	175	8000	
		612	170	8000	
		1004	170	8000	
		0	78	8000	
		95	117	7950	
		268	175	8000	
		612	170	8000	
		1004	170	8000	
		0	78	8000	
		95	117	7950	
		268	175	8000	
23B-4	MB Bronze-Filled Teflon	612	170	8000	Completed test
		1004	170	8000	
		0	78	8000	
		95	117	7950	
		268	175	8000	
		612	170	8000	
		1004	170	8000	
		0	78	8000	
		95	117	7950	
		268	175	8000	
		612	170	8000	
		1004	170	8000	

Table 3-5 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp. (° F)	Speed (rpm)	Remarks
26B-3	Bar Temp	0	75	7980	Completed test
		47	146	7980	
		241	145	7950	
		667	130	7950	
		1002	131	7950	
26B-4	Bar Temp	0	75	7980	Completed test
		47	165	7980	
		167	171	7980	
		241	166	7950	
		667	145	7950	
		1002	145	7950	Completed test
Oil and Grease					
O-3	D.C. FS-1265 (250 c. s.) Oil	0	78	7600	Completed test
		7	165	7600	
		145	145	8000	
		649	148	8000	
		1000	149	8000	
O-4	D.C. FS-1265 (250 c. s.) Oil	0	78	7900	Completed test
		7	165	7900	
		145	148	7950	
		410	146	8000	
		483	151	8000	
		1000	150	8000	Completed test
G-3	EG-509 Grease	0	78	7540	Completed test
		7	190	7540	
		145	170	7840	
		410	169	8000	
		482	184	8000	
		583	187	8000	Completed test
		816	182	8000	
		1000	181	8000	
G-4	EG-509 Grease	0	78	7940	
		2	130	7940	
		7	120	7900	Motor stalled. Bearings still satisfactory.
		10	140	7900	
		13	140	—	

Table 3-6
RESULTS OF LIFETIME TESTS - PHASE B

Bearing Pair	Material	Lifetime (hr)	Results
			<u>Solid-Film Lubricant</u>
5A-3	Electrofilm 2008P	2	Bearing failure; both bearings jammed. Lubricant film largely removed from raceways. Balls heavily pitted and brinelled. Retainers slightly worn.
5A-4	Electrofilm 2008P	-	Test aborted because of fixture difficulties.
8A-3	Electrofilm 4306	243	Bearing failure; ends of motor filled with wear debris. Front bearing has a broken retainer and is badly worn throughout. Rear bearing jammed with broken retainer. Most of lubricant film is still present on balls and raceways.
8A-4	Electrofilm 4306	2	Bearing failure; front bearing jammed. Lubricant film pushed aside by balls running in same band of raceways. Balls still shiny with only minor pitting. Retainers satisfactory.
10A-3	Everlube Inlox 44	467	Bearing failure, excess play in bearing allowed rotor to rub against stator. Metal particles throughout motor and bearing housings. Bearing raceways were badly brinelled and smashed. Balls brinelled and pitted. Retainers worn and bent.
10A-4	Everlube Inlox 44	6	Bearing failure. Both bearings jammed. Metal wear particles on shaft and bearing housings. Raceways badly worn. Balls pitted. Retainers still in good condition.
12A-3	Everlube 811	330	Bearing failure. Metal wear particles inside motor and bearing housings. Lubricant film completely removed from raceways which were worn and pitted. Balls of top bearing have sand-blasted surface appearance. Balls of lower bearing are pitted with bits of retainer material cold welded to surface. Retainers badly worn and broken.

Table 3-6 (Cont.)

Bearing Pair	Material	Lifetime (hr)	Results
12A-4	Everlube 811	60	Bearing failure. Small amount of wear particles inside motor and bearing housings. Lubricant film largely removed from raceways with little wear. Balls shiny with minor pitting. Retainers satisfactory.
16A-3	General Magnaplate Drilube	8	Bearing failure; lubricant film largely removed from raceways. Balls still shiny but pitted. Retainers have slight wear.
16A-4	General Magnaplate Drilube	103	Bearing failure; same as 16A-3 except inner race of rear bearing is brinelled.
17A-3	General Magnaplate Hi-T-Lube	1000	Completed life test satisfactorily. Lubricant film was retained on raceways well enough to leave a shiny band at ball contact with no wear. Balls are discolored but remain shiny. Retainers satisfactory.
17A-4	General Magnaplate Hi-T-Lube	1000	Same as bearings 17A-3.
21A-3	Lubeco 905S	162	Bearing failure; front bearing jammed. Lubricant film largely removed from raceways. Balls pitted. Retainers have minor wear.
21A-4	Lubeco 905S	384	Bearing failure; retainer of front bearing is broken and bent. Balls and raceways are pitted and worn.
<u>Special Retainer Materials</u>			
3B-3	Ilkaloy AFIL-M10	291	Bearing failure. Metal wear particles inside motor and bearing housings. Races have wear bands. Balls still shiny but pitted. Retainers broken and completely worn out.
3B-4	Ilkaloy AFIL-M10	154	Same as 3B-3.
8B-3	Vespel SP-3	502	Bearing failure; retainer of rear bearing is broken and completely worn out. Front retainer is heavily worn.

Table 3-6 (Cont.)

Bearing Pair	Material	Lifetime (hr)	Results
8B-4	Vespel SP-3	562	Same as 8B-3.
9B-3	Nylafil G1/30/MS/5	1005	Completed life test satisfactorily. Bearing housings have some wear debris from retainers. Raceways show slight wear. Balls are discolored with retainer particles. Retainers have only minor wear.
9B-4	Nylafil G1/30/MS/5	1005	Same as 9B-3 except retainers are in better condition with very little if any wear.
18B-3	Rulon C	1004	Completed life test satisfactorily. Raceways and balls are discolored with wear bands and deposits of lubricant particles from retainer. Retainers show very little wear.
18B-4	Rulon C	1004	Same as 18B-3 except the raceways and balls of front bearing are shiny with no discoloring.
23B-3	MB Bronze-Filled Teflon	1000	Completed life test satisfactorily; wear debris from retainer present in ends of motor. Both bearings have a large amount of bronze particles cold welded to the raceways. Surface of balls have a minor sand blasted appearance. Retainers show very minor wear.
23B-4	MB Bronze-Filled Teflon	1000	Completed life test satisfactorily; condition of bearings similar to 23B-3.
26B-3	Bar Temp	1002	Completed life test satisfactorily. Raceways, balls, and retainers are in excellent condition. Particles from the retainers were deposited around the surfaces inside the bearings for good lubricating qualities.
26B-4	Bar Temp	1002	Same as 26B-3.
<u>Oil and Grease</u>			
O-3	FS-1265 Oil	1000	Completed life test satisfactorily. Both bearings are still in the original condition with no wear. Oil still present within bearings and retainer.
O-4	FS-1265 Oil	1000	Same as O-3.

Table 3-6 (Cont.)

Bearing Pair	Material	Lifetime (hr)	Results
G-3	EG-509 Grease	1000	Completed life test satisfactorily. Both bearings are still in the original condition with no wear. Grease still present within bearings.
G-4	EG-509 Grease	13	Motor stalled. Failure was caused by shims becoming loose during vibration, which allowed excessive end play of the rotor. The bearing end stops on the rotor were smashed, causing a bind on one bearing and misalignment. Both bearings are still in the original condition with no wear. Grease still present within bearings.

Table 3-7

**MOTOR SPEEDS AND COAST TIMES BEFORE AND AFTER VIBRATION
AT-200° F IN VACUUM - PHASE C TESTS**

Bearing Pair	Lubricant System	Motor Speed (rpm)		Coast Time (min:sec)	
		Before	After	Before	After
	<u>Solid-Film Lubricant</u>				
8A-5	Electrofilm 4306	8000	8000	02:22	03:20
8A-6	Electrofilm 4306	7950	8000	02:54	02:20
10A-5	Everlube Inlox 44	8000	8000	00:20	00:01
10A-6	Everlube Inlox 44	8000	8000	04:40	02:10
12A-5	Everlube 811	8000	Stalled	01:55	00:00
12A-6	Everlube 811	8000	8000	01:17	00:55
17A-5	General Magnaplate Hi-T-Lube	8000	8000	02:10	03:51
17A-6	General Magnaplate Hi-T-Lube	8000	8000	04:59	03:24
21A-5	Lubeco 905S	8000	8000	03:42	04:28
21A-6	Lubeco 905S	8000	8000	02:40	05:44
	<u>Special Retainer Material</u>				
8B-5	Vespel SP-3	8000	8000	04:12	02:03
8B-6	Vespel SP-3	8000	8000	03:24	02:53
9B-5	Nylafil G1/30/MS/5	8000	8000	00:33	01:30
9B-6	Nylafil G1/30/MS/5	8000	8000	00:26	01:03
18B-5	Rulon C	8000	8000	03:25	02:45
18B-6	Rulon C	8000	8000	00:35	00:36
23B-5	MB Bronze-Filled Teflon	7980	8000	01:09	01:58
23B-6	MB Bronze-Filled Teflon	8000	8000	01:26	03:55
26B-5	Bar Temp	7980	8000	06:25	07:04
26B-6	Bar Temp	8000	8000	07:15	06:15
	<u>Oil and Grease</u>				
O-7	D. C. FS-1265 (250 c. s.) Oil	7650	7650	00:12	00:08
O-8	D. C. FS-1265 (250 c. s.) Oil	7740	7750	00:55	00:15
G-7	EG-509 Grease	7640	7650	00:08	00:04
G-8	EG-509 Grease	7900	7900	00:38	00:20

Table 3-8

RUNNING LOG FOR LIFETIME TESTS -- PHASE C

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp. (° F)	Speed (rpm)	Remarks
8A-5	Electrofilm 4306	<u>Solid-Film Lubricant</u>			
		0	80	8000	
		20	180	8000	Stalled and restarted
		39	262	8000	Off-high temp.
		39	100	8000	Restart
		46	270	8000	Off-high temp.
		46	80	8000	Restart
		53	263	8000	Off-high temp.
		53	100	8000	Restart
		55	220	8000	Off-high temp.
		55	95	8000	Restart
		60	248	8000	Off-high temp.
		60	80	8000	Restart
		153	275	8000	
		180	270	—	Failed
8A-6	Electrofilm 4306	0	80	8000	
		7	—	—	Stalled
		7	87	8000	Restart
		11	—	—	Stalled
		11	95	8000	Restart
		15	98	8000	Stalled and restarted
		18	100	8000	Stalled and restarted
		24	100	8000	Stalled and restarted
		28	100	8000	Stalled and restarted
		33	120	8000	Stalled and restarted
		41	96	—	Failed
10A-5	Everlube Inlox 44	0	80	7300	Coast time 0 min 8 sec
		1	—	—	Failed
10A-6	Everlube Inlox 44	0	80	7700	Coast time 3 min 55 sec
		10	250	7700	High temp.
		10	80	7700	Restart
		280	140	7700	
		347	120	7570	
		441	138	7570	
		535	190	—	Failed
12A-5	Everlube 811	0	80	7600	Coast time 2 min 22 sec
		14	198	7600	
		38	164	7600	
		301	155	7600	
		367	155	7520	
		462	158	7520	
		618	—	—	Failed

Table 3-8 (Cont.)

Bearing Pair	Lubricant	Elapsed Time (hr)	Temp. (° F)	Speed (rpm)	Remarks
12A-6	Everlube 811	0	80	7600	Coast time 2 min 40 sec
		14	200	7600	Lowered voltage
		31	164	7600	
		301	—	—	Failed
17A-5	General Magnaplate Hi-T-Lube	0	80	7500	Coast time 5 min 45 sec
		8	145	7500	
		274	125	7500	
		349	121	7570	
		603	123	7570	
		1013	122	8000	Completed test
					Coast time 3 min 26 sec
17A-6	General Magnaplate Hi-T-Lube	0	80	7400	Coast time 2 min 20 sec
		171	78	7400	Stalled and restarted
		193	120	7350	
		290	183	7350	
		510	231	—	Failed
21A-5	Lubeco 905S	0	80	7600	Coast time 4 min 12 sec
		171	151	7600	
		236	149	7570	
		599	156	—	Failed
21A-6	Lubeco 905S	0	80	7500	Coast time 2 min 4 sec
		274	134	7500	
		349	121	7690	
		435	131	7690	
		603	123	7690	
		1013	130	8000	Completed test
					Coast time 4 min 2 sec
<u>Special Retainer Material</u>					
8B-5	Vespel SP-3	0	80	7650	Coast time 2 min 25 sec
		12	145	7650	
		17	155	7650	
		42	190	7650	
		138	180	8000	
		313	186	8000	
		474	216	—	Failed
8B-6	Vespel SP-3	0	80	7700	Coast time 3 min 22 sec
		12	155	7700	
		17	170	7700	
		42	190	7700	
		138	198	7700	
		245	205	7700	
		457	150	—	Failed

Table 3-8 (Cont.)

Bearing Pair	Lubricant	Elapsed Time (hr)	Temp. (° F)	Speed (rpm)	Remarks
9B-5	Nylafil G1/30/MS/5	0	75	7800	Coast time 1 min 18 sec
		26	175	7800	
		46	268	7800	Stalled and restarted
		127	169	7800	
		555	166	7800	
		1010	166	7800	Completed test
9B-6	Nylafil G1/30/MS/5	0	70	7825	Coast time 1 min 5 sec
		5	123	7825	Off and restart
		103	250	—	Stalled. Bearings still in good condition
					Coast time 3 min 15 sec
18B-5	Rulon C	0	75	7820	
		5	173	7820	
		46	200	7820	
		175	174	7820	
		604	170	7820	
		1010	170	7820	Completed test
18B-6	Rulon C	0	75	7750	Coast time 1 min 32 sec
		26	175	7750	
		46	198	7750	
		175	173	7750	
		267	169	7750	
		604	169	7750	
		1010	169	7750	Completed test
23B-5	MB Bronze-Filled Teflon	0	80	8000	
		19	130	8000	
		39	88	8000	Stalled and restarted
		398	134	8000	
		560	142	8000	
		734	140	8000	
		1067	139	8000	Completed test
23B-6	MB Bronze-Filled Teflon	0	80	8000	
		19	128	8000	
		489	135	7800	
		587	139	8000	
		852	138	8000	
		1093	138	8000	Completed test
26B-5	Bar Temp	0	80	8000	Coast time 7 min 2 sec
		46	143	8000	
		337	144	8000	
		1009	145	8000	Completed

Table 3-8 (Cont.)

Bearing Pair	Lubricant	Elapsed Time (hr)	Temp. (° F)	Speed (rpm)	Remarks
26B-6	Bar Temp	0	80	8000	Completed test
		47	148	8000	
		337	149	8000	
		1009	152	8000	
Oil and Grease					
O-7	D.C. FS-1265 (250 c. s.) Oil	0	72	7680	Coast time 0 min 9 sec
		19	150	7680	
		412	148	7600	
		573	169	7600	Completed test Coast time 0 min 9 sec Coast time 0 min 17 sec
		839	164	7600	
		1080	168	7800	
O-8	D.C. FS-1265 (250 c. s.) Oil	0	72	7750	Completed test Coast time 0 min 35 sec Coast time 0 min 6 sec
		19	165	7750	
		412	176	7750	
		477	178	7700	
		572	180	7700	
		838	178	7700	
G-7	EG-509 Grease	1080	178	7800	Stalled and restarted Stalled and restarted Stalled and restarted Failed
		0	72	7750	
		3	139	7750	
		6	170	7750	
		8	112	7750	
		9	120	7750	
G-8	EG-509 Grease	9	125	—	Coast time 0 min 24 sec Completed test Coast time 1 min 10 sec
		0	72	7850	
		19	140	7850	
		412	163	7850	
		572	163	7850	
		838	163	7850	
	1080	162	7900		

Table 3-9

RESULTS OF LIFETIME TESTS - PHASE C

Bearing Pair	Material	Life-time (hr)	Results
<u>Solid-Film Lubricant</u>			
8A-5	Electrofilm 4306	180	Bearing failure; rear bearing gritty with lubricant build-up on loaded side of raceways. Balls have minor pitting. Retainers show no wear. Front bearing still okay except some lubricant build-up on loaded side of raceways.
8A-6	Electrofilm 4306	41	Bearing failure; both bearings similar to rear bearing of 8A-5.
10A-5	Everlube Inlox 44	1	Bearing failure; high bearing torque caused motor to stall. Bearings still in fair condition.
10A-6	Everlube Inlox 44	535	Bearing failure; retainers broken and badly worn. Balls and raceways pitted. Metal wear debris throughout bearings.
12A-5	Everlube 811	618	Bearing failure; both bearings fell apart. Balls pitted. Retainers worn. Lubricant film largely removed from raceways.
12A-6	Everlube 811	301	Bearing failure; balls and raceways pitted. Retainers badly worn.
17A-5	General Magnaplate Hi-T-Lube	1013	Completed life test satisfactorily. Lubricant film was retained on raceways well enough to leave a shiny band at ball contact with no wear. Balls are still shiny. Retainers satisfactory.
17A-6	General Magnaplate Hi-T-Lube	510	Bearing failure; retainer of front bearing broken and bent. Raceways badly worn. Rear bearing still satisfactory.
21A-5	Lubeco 905S	599	Bearing failure; front bearing retainer separated and bent. Balls pitted and brinelled. Lubricant film largely removed from raceways. Rear bearing retainer badly worn.

Table 3-9 (Cont.)

Bearing Pair	Material	Life-time (hr)	Results
21A-6	Lubeco 905S	1013	Completed life test satisfactorily. Lubricant film left a shiny orange peel surface on balls and raceways. Retainer shows minor wear.
<u>Special Retainer Materials</u>			
8B-5	Vespel SP-3	474	Bearing failure; retainers of both bearings are broken and badly worn.
8B-6	Vespel SP-3	457	Bearing failure; retainers of both bearings are broken and completely worn out.
9B-5	Nylafil G1/30/MS/5	1010	Completed life test satisfactorily. Retainers show just enough wear to furnish a dark lubricant coating on balls and raceways.
9B-6	Nylafil G1/30/MS/5	103	Motor stalled due to bearing misalignment caused by vibration test. Both bearings still in good condition.
18B-5	Rulon C	1010	Completed life test satisfactorily. Retainers show just enough wear to furnish a dark lubricant band around balls and raceways at point of contact.
18B-6	Rulon C	1010	Completed life test satisfactorily. Balls and raceways have even lubricant coating as picked up from retainers.
23B-5	MB Bronze-Filled Teflon	1067	Completed life test satisfactorily. Both bearings have bronze particles from retainer burnished on balls and raceways. Retainers show very minor wear.
23B-6	MB Bronze-Filled Teflon	1093	Completed life test satisfactorily. Bearings similar to 23B-5 except balls of rear bearing have a highly polished mirror-like bronze surface.

Table 3-9 (Cont.)

Bearing Pair	Material	Life-time (hr)	Results
26B-5	Bar Temp	1009	Completed life test satisfactorily. Both bearings are still in excellent condition. Raceways still shiny. Balls still shiny with a dark film of lubricating material from retainers. Retainers show only enough wear to furnish proper lubrication to the balls.
26B-6	Bar Temp	1009	Completed life test satisfactorily. Bearings condition similar to 26B-5 except balls and raceways show minor wear.
<u>Oil and Grease</u>			
O-7	D. C. FS-1265 (250 c. s.) Oil	1080	Completed life test satisfactorily. Both bearings are still in the original condition with no wear. Oil still present within bearings.
O-8	D. C. FS-1265 (250 c. s.) Oil	1080	Completed life test satisfactorily. Bearing condition same as O-7.
G-7	EG-509 Grease	9	Bearing failure; grease in rear bearing is dried out. Bearing shows minor wear. Front bearing still in original condition.
G-9	EG-509 Grease	1080	Completed life test satisfactorily. Both bearings are still in the original condition with no wear. Grease still present within bearings.

Table 3-10

**MOTOR SPEEDS AND COAST TIMES BEFORE AND AFTER VIBRATION
AT +200° F IN VACUUM - PHASE D TESTS**

Bearing Pair	Lubricant System	Motor Speed (rpm)		Coast Time (min:sec)	
		Before	After	Before	After
<u>Solid-Film Lubricant</u>					
8A-7	Electrofilm 4306	8000	8000	01:07	04:56
8A-8	Electrofilm 4306	8000	8000	02:01	04:09
10A-7	Everlube Inlox 44	8000	8000	04:17	03:20
10A-8	Everlube Inlox 44	8000	8000	03:38	04:02
12A-7	Everlube 811	8000	8000	03:28	02:46
12A-8	Everlube 811	8000	8000	02:43	02:22
17A-7	General Magnaplate Hi-T-Lube	8000	8000	03:03	04:26
17A-8	General Magnaplate Hi-T-Lube	8000	8000	04:55	03:14
21A-7	Lubeco 905S	8000	8000	05:32	02:56
21A-8	Lubeco 905S	8000	8000	02:13	05:21
<u>Special Retainer Materials</u>					
8B-7	Vespel SP-3	8000	Failed	02:12	—
8B-8	Vespel SP-3	8000	8000	05:43	02:12
9B-7	Nylafil G1/30/MS/5	8000	8000	01:46	02:42
9B-8	Nylafil G1/30/MS/5	8000	8000	05:20	04:02
18B-7	Rulon C	8000	8000	01:09	03:08
18B-8	Rulon C	8000	8000	05:33	02:48
23B-7	MB Bronze-Filled Teflon	8000	8000	00:25	08:40
23B-8	MB Bronze-Filled Teflon	8000	8000	08:42	06:51
26B-7	Bar Temp	8000	8000	04:22	02:03
26B-8	Bar Temp	8000	8000	01:23	03:05
<u>Oil and Grease</u>					
O-5	D. C. FS-1265 (250 c. s.) Oil	7740	7850	00:28	00:18
O-6	D. C. FS-1265 (250 c. s.) Oil	7800	7940	01:02	00:25
G-5	EG-509 Grease	7800	8000	00:34	00:20
G-6	EG-509 Grease	7800	7950	00:50	00:27

Table 3-11

RUNNING LOG FOR LIFETIME TESTS - PHASE D

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp (° F)	Speed (rpm)	Remarks
Solid-Film Lubricant					
8A-7	Electrofilm 4306	0 134	80 270	3000 —	Failed
8A-8	Electrofilm 4306	0 24	83 —	7940 —	
10A-7	Everlube Inlox 44	0 5	80 175	8000 —	Failed
10A-8	Everlube Inlox 44	0 24 30	83 131 135	7680 8000 —	Failed
12A-7	Everlube 811	0 50 387	78 147 150	8000 8000 8000	
12A-8	Everlube 811	481 0 50 175	235 78 148 150	— 8000 8000 —	Failed
17A-7	General Magnaplate Hi-T-Lube	0 98 552 725 1001	82 130 136 135 125	7960 8000 8000 8000 8000	
17A-8	General Magnaplate Hi-T-Lube	0 98 552 725 1001	82 126 132 132 125	7940 8000 8000 8000 8000	Completed test
21A-7	Lubeco 905S	0 21 141	80 147 210	8000 8000 —	Failed
21A-8	Lubeco 905S	0 20 193 477	80 150 123 —	8000 8000 8000 —	
Special Retainer Materials					
8B-7	Vespel SP-3				Test aborted because of fixture difficulties.
8B-8	Vespel SP-3	0 211	80 —	8000 —	

Table 3-11 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp (° F)	Speed (rpm)	Remarks
9B-7	Nylafil G1/30/MS/5	0	80	8000	Coast time 2 min 14 sec
		398	168	8000	
		443	155	8000	
		682	146	8000	
		873	148	8000	
9B-8	Nylafil G1/30/MS/5	1041	145	8000	Completed test Coast time 3 min 28 sec
		0	80	8000	
		393	172	8000	
		438	160	8000	
		677	150	8000	
18B-7	Rulon C	868	153	8000	Completed test
		1036	150	8000	
		0	80	8000	
		19	152	8000	
		73	155	8000	
18B-8	Rulon C	528	152	8000	Completed test
		1003	152	8000	
		0	80	8000	
		19	155	8000	
		73	157	8000	
23B-7	MB Bronze-Filled Teflon	528	155	8000	Completed test
		1003	155	8000	
		0	80	8000	
		19	162	8000	
		73	163	8000	
23B-8	MB Bronze-Filled Teflon	528	162	8000	Completed test
		1003	162	8000	
		0	80	8000	
		19	158	8000	
		73	160	8000	
26B-7	Bar Temp	528	158	8000	Completed test
		1003	158	8000	
		0	80	8000	
		187	150	8000	
		641	148	8000	
26B-8	Bar Temp	1001	130	8000	Completed test
		0	80	8000	
		187	150	8000	
		662	147	8000	
		1000	143	8000	Completed test

Table 3-11 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp (° F)	Speed (rpm)	Remarks
		<u>Oil and Grease</u>			
O-5	D.C. FS-1265 (250 c. s.) Oil	0	80	8000	Completed test
		389	155	8000	
		798	143	8000	
		1000	140	8000	
O-6	D.C. FS-1265 (250 c. s.) Oil	0	80	8000	Completed test
		389	155	8000	
		809	143	8000	
		1002	143	8000	
G-5	EG-509 Grease	0	80	8000	Completed test
		434	148	8000	
		909	143	8000	
		1011	143	8000	
G-6	EG-509 Grease	0	80	8000	Completed test
		434	156	8000	
		909	150	8000	
		1011	150	8000	

Table 3-12

RESULTS OF LIFETIME TESTS - PHASE D

Bearing Pair	Material	Lifetime (hr)	Results
		<u>Solid-Film Lubricant</u>	
8A-7	Electrofilm 4306	134	Bearing failure; uneven build-up of lubricant film on raceways caused balls to jam in front bearing. Rear bearing still in fairly good condition.
8A-8	Electrofilm 4306	24	Bearing failure; front bearing jammed. Lubricant film largely removed from raceways. Balls heavily pitted. Retainers still satisfactory.
10A-7	Everlube Inlox 44	5	Bearing failure; front bearing jammed. Lubricant film largely removed from raceways. Balls still shiny. Retainers satisfactory.
10A-8	Everlube Inlox 44	30	Bearing failure; both bearings jammed. Balls have a sand blasted surface appearance. Lubricant film largely removed from raceways. Retainers have minor wear.
12A-7	Everlube 811	481	Bearing failure; retainer of front bearing is broken. Balls shiny but pitted. Lubricant film largely removed from raceways. Rear bearing still in fair condition with only minor wear of retainers.
12A-8	Everlube 811	175	Bearing failure; metallic debris from worn retainers present within motor. Lubricant film largely removed from raceways. Balls still shiny.
17A-7	General Magnaplate Hi-T-Lube	1001	Completed life test satisfactorily. Lubricant film was retained on raceways. Lubricant pressed irregularly on surface of balls in front bearing. Balls of rear bearing are still shiny. Retainers satisfactory.

Table 3-12 (Cont.)

Bearing Pair	Material	Lifetime (hr)	Results
17A-8	General Magnaplate Hi-T-Lube	1001	Completed life test satisfactorily. Both bearings still in excellent condition. Lubricant film was retained on raceways. Balls have a dark shiny mirror finish. Retainers satisfactory.
21A-7	Lubeco 905S	141	Bearing failure; front bearing jammed. Lubricant film removed from raceways at ball contact. Balls pitted. Retainers satisfactory.
21A-8	Lubeco 905S	477	Bearing failure; front bearing same as 21A-7. Rear bearing jammed with broken retainer.
<u>Special Retainer Materials</u>			
8B-7	Vespel SP-3	—	Test aborted because of fixture difficulties.
8B-8	Vespel SP-3	211	Bearing failure; retainer of front bearing is broken and completely worn out. Rear bearing retainer is heavily worn. Balls discolored and pitted. Raceways are heavily worn.
9B-7	Nylafil G1/30/MS/5	1041	Completed life test satisfactorily. Retainers show very little wear. Balls lightly pitted with a dark surface caused by burnishing of retainer lubricant particles. Raceways are pitted and worn.
9B-8	Nylafil G1/30/MS/5	1036	Completed life test satisfactorily. Same as 9B-7.
18B-7	Rulon C	1003	Completed life test satisfactorily. Retainers have just enough wear to furnish good lubrication to balls. Balls still shiny and in original condition. Raceways have minor wear.
18B-8	Rulon C	1003	Completed life test satisfactorily. Same as 18B-7 except balls of rear bearing have a dark surface finish and are worn.

Table 3-12 (Cont.)

Bearing Pair	Material	Lifetime (hr)	Results
23B-7	MB Bronze-Filled Teflon	1003	Completed life test satisfactorily. Retainer ball pockets are still round and indicate minor wear. Bronze particles burnished on surface of balls and raceways which indicate minor wear.
23B-8	MB Bronze-Filled Teflon	1003	Completed life test satisfactorily. Same as 23B-7.
26B-7	Bar Temp	1001	Completed life test satisfactorily. Balls of front bearing still shiny. Retainer and raceways indicate only minor wear. Balls of rear bearing are black with particles from retainer. Raceways are worn.
26B-8	Bar Temp	1000	Completed life test satisfactorily. Front bearing still in original condition. Rear bearing shows some wear on balls and raceways. Retainer still in good condition.
<u>Oil and Grease</u>			
O-5	FS-1265 Oil	1000	Completed life test satisfactorily. Both bearings are still in the original condition with no wear. Oil still present within bearings and retainer.
O-6	FS-1265 Oil	1000	Completed life test satisfactorily. Both bearings almost dry. Balls and raceways show minor pitting and wear. Retainers satisfactory.
G-5	EG-509 Grease	1011	Completed life test satisfactorily. The majority of the original grease is still present in both bearings. Balls and raceways have minor wear. Retainers satisfactory.
G-6	EG-509 Grease	1011	Completed life test satisfactorily. Same as G-5.

3.1.5 Phase E Tests

Results of Phase E tests are presented in Tables 3-13 and 3-14.

3.2 DISCUSSION

Table 3-15 summarizes the lifetimes of the ball bearings with selected lubricant systems in vacuum.

Considering the very severe vibration conditions to which they were subjected, the bearings and their lubricants survived very well. For example, one of the solid-film lubricants (Hi-T-Lube) was still in good enough condition after vibration to lubricate the ball bearings for more than 500 hr of operation at 8000 rpm in ultrahigh vacuum; in fact, five of the eight test bearings with this lubricant survived the full 1000 hr of lifetime testing in vacuum without failure, despite prior vibration.

3.2.1 Solid-Film Lubricants

The following general comments can be made for the behavior of solid-film lubricants as a result of vibration in Phase A tests:

- In most cases, fine particles were released during disassembly of the bearings; this debris represents the solid-film lubricant that was worn off the bearing raceways during vibration.
- Removal of lubricant was usually not complete; in some cases a few patches of lubricant remained on the raceways, and in most cases the raceways appeared to have a thin, burnished film of lubricant remaining.
- In several cases the coatings were removed to expose metal, and the raceways were worn.
- Ball condition varied from those that were still shiny with no evidence of wear after vibration to those that were generally pitted and had wear patches.
- Some balls were discolored to varying degrees, and others had transfer films of solid lubricant.

(General comments continued on page 3-51.)

Table 3-13
RUNNING LOG FOR LIFETIME TESTS - PHASE E

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp (° F)	Speed (rpm)	Remarks
		<u>Solid-Film Lubricant</u>			
5A-1	Electrofilm 2008P	0	78	7950	Failed
		1	110	-	
5A-2	Electrofilm 2008P	0	78	7950	
		70	135	7950	Failed
		167	150	7650	
		239	190	-	
8A-1	Electrofilm 4306	0	78	7950	
		12	171	7950	Failed
		96	175	7950	
		194	188	7950	
		361	191	7950	
		551	189	7950	
		737	190	8000	
		901	185	7950	
		984	145	-	
8A-2	Electrofilm 4306	0	78	7950	
		22	169	7950	
		96	171	7950	Stalled and restarted
		139	145	7700	
		190	188	7950	Failed
		357	190	7950	
		428	191	7950	
		546	189	7950	
		732	186	8000	
		894	175	-	
10A-1	Everlube Inlox 44	0	85	7970	Failed
		18	121	7970	
		106	140	7970	
		155	149	7650	
		178	175	-	Failed
10A-2	Everlube Inlox 44	0	84	7900	
		0.5	-	-	Failed
12A-1	Everlube 811	0	130	7800	
		23	157	7800	
		95	166	7800	
		118	185	7800	
		149	168	7800	
		262	178	7800	
		335	158	7950	
		429	150	7950	
		675	148	7850	

Table 3-13 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp (° F)	Speed (rpm)	Remarks
12A-2	Everlube 811	859	160	7790	Failed
		988	200	—	
		0	131	7950	
		23	145	7950	
		95	162	7950	
		118	240	7950	
16A-1	General Magnaplate Drilube	191	245	—	Stalled and restarted
		0	78	8000	Failed
		2	120	—	Failed
16A-2	General Magnaplate Drilube	0	78	8000	Failed
		10	105	—	
17A-1	General Magnaplate Hi-T-Lube	0	135	8050	Coast time
		5	175	8050	13 min 24 sec
		8	195	8050	
		10	207	8050	
		19	173	8050	
		90	128	8050	
		258	124	8050	
		354	140	8050	
		425	145	8050	
		474	160	8050	
		497	173	8050	Coast time
					1 min 45 sec
		501	135	7810	Off and restarted
		532	172	7810	
		581	212	7810	Off and restarted
17A-2	General Magnaplate Hi-T-Lube	603	145	7810	
		751	147	7700	
		843	215	—	Failed
		0	150	8050	Coast time
		5	195	8050	12 min 13 sec
		8	215	8050	
		10	230	8050	
		19	186	8050	Lowered voltage
		90	135	8050	
		258	127	8050	
		354	145	8050	
		450	163	8050	
		474	158	8050	
		497	185	8050	Coast time
					0 min 37 sec

Table 3-13 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp. (° F)	Speed (rpm)	Remarks
21A-1	Lubeco 905S	497	131	7650	Off and restarted Failed Coast time 2 min 35 sec
		501	138	7650	
		533	174	7650	
		581	225	—	
		0	70	7800	
21A-2	Lubeco 905S	4	130	7800	Failed Coast time 3 min 4 sec Stalled and restarted Failed
		108	149	7800	
		126	240	—	
		0	70	7850	
		3	170	7850	
		4	—	—	
Special Retainer Materials					
3B-1	Ilkaloy AFIL-M10	0	78	7980	Power failure- restarted
		17	78	7980	
		88	165	7980	
		111	190	7980	
		161	139	7980	
3B-2	Ilkaloy AFIL-M10	185	—	—	Failed Power failure- restarted
		0	78	7950	
		16	78	7950	
8B-1	Vespel SP-3	87	158	7950	Failed
		111	290	—	
		0	78	7930	
		75	196	7930	
		144	155	7980	
8B-2	Vespel SP-3	166	177	7950	Failed
		240	182	7950	
		407	260	—	
		0	78	8000	
		75	189	8000	
9B-1	Nylafil G1/30/MS/5	144	148	8000	Off and restarted Failed
		167	174	7950	
		339	167	7950	
		409	174	7950	
		434	180	—	
		0	78	8000	
		75	197	8000	
		144	154	8000	
		166	180	7900	

Table 3-13 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp (° F)	Speed (rpm)	Remarks
9B-2	Nylafil G1/30/M/5	240	190	7900	Stalled and restarted Failed
		252	125	7900	
		275	250	—	
		0	78	8000	
		75	275	—	Stalled Restarted
		76	117	8000	
		123	147	8000	
		146	173	7950	
		317	164	7950	Transferred to another system
		388	153	7950	
		413	158	7950	
		413	78	7950	
		562	140	7960	Power off- restarted
		642	78	7960	
18B-1	Rulon C	714	158	8000	Completed test
		979	164	7960	
		1000	162	7960	
		0	78	8000	
		74	183	8000	Completed test
		240	183	8000	
		338	157	8000	
		505	161	8000	
		694	160	8000	
		743	164	8000	
18B-2	Rulon C	917	164	8000	Completed test
		1001	128	8000	
		0	78	8000	
		74	175	8000	
		240	182	8000	Completed test
		338	156	8000	
		505	161	8000	
		743	162	8000	
		917	165	8000	
		1001	130	8000	
23B-1	MB Bronze-Filled Teflon	0	78	8000	Completed test
		48	145	7950	
		270	140	8000	
		351	78	8000	
		422	165	8000	Off and restarted
		592	160	8000	

Table 3-13 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp (° F)	Speed (rpm)	Remarks
23B-2	MB Bronze-Filled Teflon	687	175	8000	Completed test
		760	165	8000	
		926	167	8000	
		1005	166	8000	
		0	78	8000	
		48	150	7950	
		97	148	7950	
		270	145	8000	
		351	78	8000	
		422	173	8000	
		592	160	8000	
		687	180	8000	
		759	168	8000	
		925	169	8000	
26B-1	Bar Temp	1005	168	8000	Completed test
		0	78	7980	Power failure-restarted
		20	78	7980	
		92	145	7980	Off and restarted
		188	90	7980	
		230	170	7980	
		351	158	7980	
		428	150	7950	
		518	151	7950	
		686	152	7950	
		782	155	7950	
		854	135	7950	
		951	138	7950	
		1002	138	7950	Completed test
		0	78	8000	Off and restarted
		150	135	7950	
		230	78	7950	
		301	154	8000	
		471	151	8000	
		566	158	8000	
		639	137	8000	
		806	138	8000	
		897	75	8000	
		1008	138	8000	Completed test
O-1	D. C. FS-1265 (250 c. s.) Oil	<u>Oil and Grease</u>			
		0	100	7850	Lowered voltage
		6	120	7850	
		12	126	7850	
		39	200	7850	

Table 3-13 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp (° F)	Speed (rpm)	Remarks
O-2	D. C. FS-1265 (250 c. s.) Oil	131	174	7900	Off and restarted
		180	175	7950	
		215	78	7950	
		317	166	8000	
		481	168	7950	
		650	170	7950	
		745	170	7800	
		917	170	7950	
		1010	157	8000	
		0	99	7700	Completed test
		6	118	7700	
		13	125	7700	
		40	200	7700	Lowered voltage
		131	173	7850	
		180	175	7940	Off and restarted
		216	78	7940	
		318	173	7980	
		481	174	7950	
		562	177	7950	
G-1	EG-509 Grease	746	175	7750	
		818	178	7750	
		919	177	7950	
		986	179	7980	
		1010	160	8000	Completed test
		0	103	7500	
		6	118	7500	
		76	182	7500	Lowered voltage
		102	200	7500	
		194	178	7750	
		243	178	7900	Off and restarted
		279	78	7900	
		381	175	7940	
		544	179	8000	
		714	180	8000	
		809	179	7920	
		881	182	7920	
		982	181	8000	
G-2	EG-509 Grease	1048	183	8000	Completed test
		0	99	7800	
		5	140	7800	
		76	182	7800	Lowered voltage
		103	201	7800	
		194	180	7800	

Table 3-13 (Cont.)

Bearing Pair	Lubricant System	Elapsed Time (hr)	Temp (° F)	Speed (rpm)	Remarks
		243	180	7940	Off and restarted
		279	78	7940	
		381	178	7950	
		544	180	8000	
		623	184	8000	
		809	182	7940	
		881	185	7940	
		982	185	8000	
		1048	186	8000	Completed test

Table 3-14

RESULTS OF LIFETIME TESTS - PHASE E

Bearing Pair	Material	Lifetime (hr)	Results
		<u>Solid-Film Lubricant</u>	
5A-1	Electrofilm 2008P	1	Bearing failure; rear bearing was jammed. Lubricant film pushed aside by balls running in same band of raceways. Balls still shiny. Retainers satisfactory.
5A-2	Electrofilm 2008P	239	Bearing failure; front bearing had side play, allowing the rotor to rub on stator and its retainer to wear. Lubricant film was largely removed from raceways. Balls pitted with a satin finish.
8A-1	Electrofilm 4306	984	Bearing failure; wear debris present in ends of motor. Raceways of both bearings are badly worn. Rear bearing retainer is broken and twisted. Balls are badly pitted and worn.
8A-2	Electrofilm 4306	894	Bearing failure; wear debris present in ends of motor. Raceways of both bearings are badly worn. Front bearing retainer is broken and twisted. Balls of front bearing are badly pitted and worn.
10A-1	Everlube Inlox 44	178	Bearing failure; front bearing was jammed from metal wear debris. Lubricant film completely removed from raceways which are worn and pitted. Ball pitted and brinelled. Rear retainer is broken in two places.
10A-2	Everlube Inlox 44	0.5	Bearing failure; front bearing has side play, allowing rotor to rub against stator. Lubricant film largely removed from raceways which have wear bands and some metal debris. Balls still shiny. Retainers satisfactory.

Table 3-14 (Cont.)

Bearing Pair	Material	Lifetime (hr)	Results
12A-1	Everlube 811	988	Bearing failure; metal wear particles inside motor and bearing housings. Lubricant film pushed aside by balls running in same band of raceways. Balls in rear bearing are pitted with bits of retainer material cold welded to surface. Retainer bent and broken in several places.
12A-2	Everlube 811	191	Bearing failure; front bearing has side play, allowing rotor to rub against stator. Rear bearing housing filled with metal wear debris. Lubricant film pushed aside and removed from raceways. Inner race of front bearing has excessive wear from retainer rubbing. Balls pitted with minute particles cold welded to surface. Retainers indicate some wear.
16A-1	General Magna-plate Drilube	2	Bearing failure; bearings jammed from wear debris. Lubricant film is completely removed from raceways which are worn. Balls shiny but pitted. Retainers satisfactory.
16A-2	General Magna-plate Drilube	10	Bearing failure; rear bearing jammed from wear debris. Front bearing still satisfactory.
17A-1	General Magna-plate Hi-T-Lube	843	Bearing failure; raceways and balls have a sand blasted surface appearance. Retainers were severely worn and broken.
17A-2	General Magna-plate Hi-T-Lube	581	Bearing failure; lubricant film was pushed aside from ball rolling band in raceways. Balls shiny with slight pitting. Rear retainer was broken from rubbing on inner race of bearing.

Table 3-14 (Cont.)

Bearing Pair	Material	Lifetime (hr)	Results
21A-1	Lubeco 905S	126	Bearing failure; both bearings jammed. Balls pitted and brinelled. Lubricant film largely removed from raceways with small metal particles cold welded to surface. Retainers satisfactory.
21A-2	Lubeco 905S	4	Bearing failure; rear bearing jammed. Ball lightly pitted. Lubricant film largely removed from raceways. Retainers satisfactory.
<u>Special Retainer Materials</u>			
3B-1	Ilkaloy AFIL-M10	185	Bearing failure; front and rear bearing housings filled with black metallic wear debris. Balls still shiny. Raceways have satin worn appearance. Front bearing retainer is broken and completely worn out. Ball pockets of other retainer are worn in a radial direction.
3B-2	Ilkaloy AFIL-M10	111	Bearing failure; both bearing retainers shattered and worn out.
8B-1	Vespel SP-3	407	Bearing failure; both bearing retainers shattered and worn out.
8B-2	Vespel SP-3	434	Bearing failure; same as 8B-1.
9B-1	Nylafil G1/30/MS/5	275	Bearing failure; inner raceways highly worn and badly pitted. Balls deeply pitted. Retainers still in excellent condition. Bearings had the appearance of being run clean and dry with very little lubricating aid from the retainer.
9B-2	Nylafil G1/30/MS/5	1000	Completed life test satisfactorily; wear debris from retainer present in ends of motor. Raceways and balls of both bearings indicate heavy wear. Retainers still in excellent condition.

Table 3-14 (Cont.)

Bearing Pair	Material	Lifetime (hr)	Results
18B-1	Rulon C	1001	Completed life test satisfactorily. Raceways and balls have wear bands and deposits of lubricant particles from retainer. Retainers show very little wear.
18B-2	Rulon C	1001	Same as 18B-1.
23B-1	MB Bronze-Filled Teflon	1005	Completed life test satisfactorily; wear debris from retainers present in ends of motor. Raceways heavily worn. Surface of balls have a minor sand blasted appearance. Retainer ball pockets are still round and indicate very minor wear.
23B-2	MB Bronze-Filled Teflon	1005	Completed life test satisfactorily; same as 23B-1 except rear bearing has a large amount of bronze particles cold welded to the raceways.
26B-1	Bar Temp	1022	Completed life test satisfactorily. Raceways and balls in excellent condition and coated with minute particles of lubricant from retainers. Retainers are in excellent condition. Particles from the retainers deposited around surfaces inside the bearings for good lubricating qualities.
26B-2	Bar Temp	1008	Completed life test satisfactorily; same as 26B-1.
<u>Oil and Grease</u>			
O-1	FS-1265 Oil	1010	Completed life test satisfactorily; both bearings still in original condition with no wear. Oil still present within bearings and retainer.
O-2	FS-1265 Oil	1010	Same as O-1
G-1	EG-509 Grease	1048	Completed life test satisfactorily; both bearings still in original condition with no wear. Grease still present within bearings.
G-2	EG-509 Grease	1048	Same as G-1.

Table 3-15

SUMMARY OF LIFETIMES IN ULTRAHIGH VACUUM - PHASES B, C, D, AND E

Lubricant	Lifetimes at 8000 rpm in Ultrahigh Vacuum (hr)			
	Phase B (Vibrated at R. T.)	Phase C (Vibrated at -200° F)	Phase D (Vibrated at 200° F)	Phase E (No prior vibration)
Solid-Film Lubricants				
Electrofilm 2008P	2	—	—	1
	—	—	—	239
Electrofilm 4306	243	180	134	984
	2	41	24	894
Everlube Inlox 44	467	1	5	178
	6	535	30	0.5*
Everlube 811	330	618	481	988
	6	301	175	191
General Magnaplate Drilube	8	—	—	2
	103	—	—	10
General Magnaplate Hi-T-Lube	1000	1013	1001	843
	1000	510	1001	581
Lubeco 905S	162	599	141	126
	384	1013	477	4
Special Retainer Materials				
Ilkalo AFIL-M10	291	—	—	185
	154	—	—	111
Vespel SP-3	502	474	*	407
	562	457	211	434
Nylafil G1/30/MS/5	1005	1010	1041	275
	1005	103*	1036	1000
Rulon C	1004	1010	1003	1001
	1004	1010	1003	1001
MB Bronze-Filled Teflon	1000	1067	1003	1005
	1000	1093	1003	1005
Bar Temp	1002	1009	1001	1022
	1002	1009	1000	1008
Oil and Grease				
FS-1265 Oil (250 c. s.)	1000	1080	1000	1010
	1000	1080	1000	1010
EG-509 Grease	1000	9	1011	1048
	13*	1080	1011	1048

*Failure due to fixture difficulties, not due to lubricant

(General comments continued from page 3-38.)

- The motor coast time generally increased as a result of vibration; the changes varied with the specific coating, but typically was from 1 min before vibration to 3 min after vibration; in one extreme case the increase was from 0.12 to 5.20 min. In several cases where the initial coast time was longer than average, it decreased after vibration.

Failures with bonded solid-film lubricants have been due primarily to wear-through of the lubricant film and to the resultant wear of retainer and raceways. When this occurs, there is a build-up of metallic wear debris, thus jamming the bearing and in many cases breaking the ribbon retainer, as illustrated in Fig. 3-1.

Bearings lubricated with solid-film lubricants had erratic lifetimes regardless of whether or not they had been subjected to vibration before lifetime testing. In several cases, bearings that were vibrated before lifetime testing had longer operating lifetimes in vacuum than bearings that were lifetime tested without prior vibration. Nevertheless, despite the scatter in lifetime test results, many bearings lubricated with solid-film lubricants operated successfully for more than 100 hr after vibration.

Hi-T-Lube gave the best performance of the solid-film lubricants tested; all eight pairs of bearings with Hi-T-Lube operated for more than 500 hr and five of these survived the full 1000 hr of lifetime testing in vacuum.

3.2.2 Special Bearing Retainer Materials

Generalizations on the behavior of special bearing retainer materials are difficult because of the variety of materials and the diversity of their behavior. Six of the materials could not be machined satisfactorily into retainers, despite repeated attempts with different techniques and tools. Some of the materials wore badly; boron nitride is an extreme example of this condition, in which the accumulation of wear debris during run-in was sufficient to stall the motor. The most successful retainer materials were those that wore just enough to provide a thin transfer film that minimized wear on the balls and races.

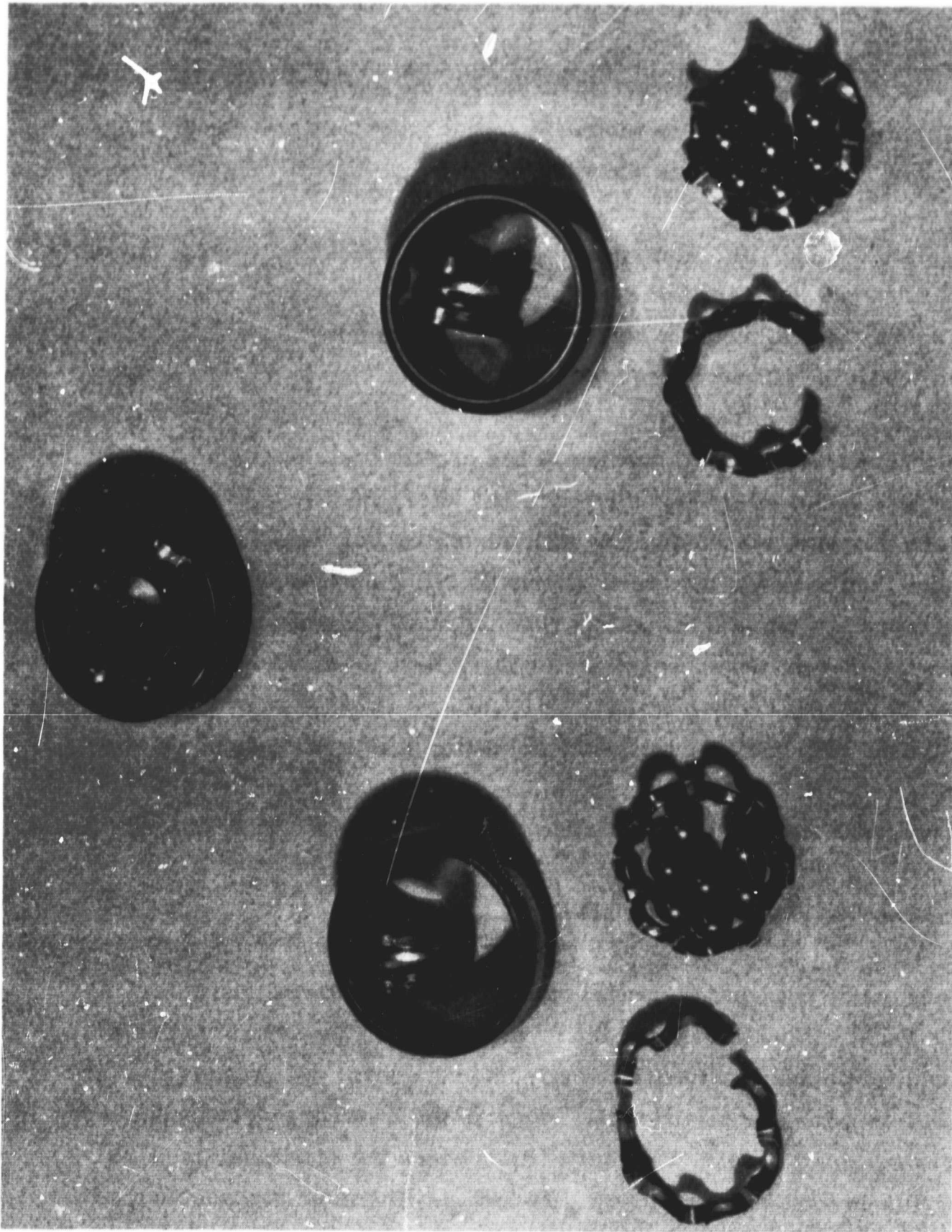


Fig. 3-1 Failed Solid-Film Lubricated Ball Bearings

Bearings with retainers of filled Teflon (i. e., Rulon C, Bar Temp and MB Bronze-Filled Teflon) gave the best performance of those with special retainer materials. All of these bearings completed the 1000-hr lifetime tests successfully and appeared to be capable of additional operation.

Metal-matrix composite materials generally gave poor performance. As discussed in subsection 3.1.1, five of those that had been selected for evaluation could not be machined into satisfactory retainers. The ball pockets of the remaining metal-matrix retainers were badly worn as a result of vibration in Phase A, and in one case the retainers were broken into small pieces. Of those metal-matrix retainers that survived vibration in Phase A, Ilkaloy AFLL-M10 appeared to be in the best condition and was the only one evaluated in lifetime tests. However, it provided only relatively short lifetimes, ranging from 111 to 291 hrs for the four bearings tested.

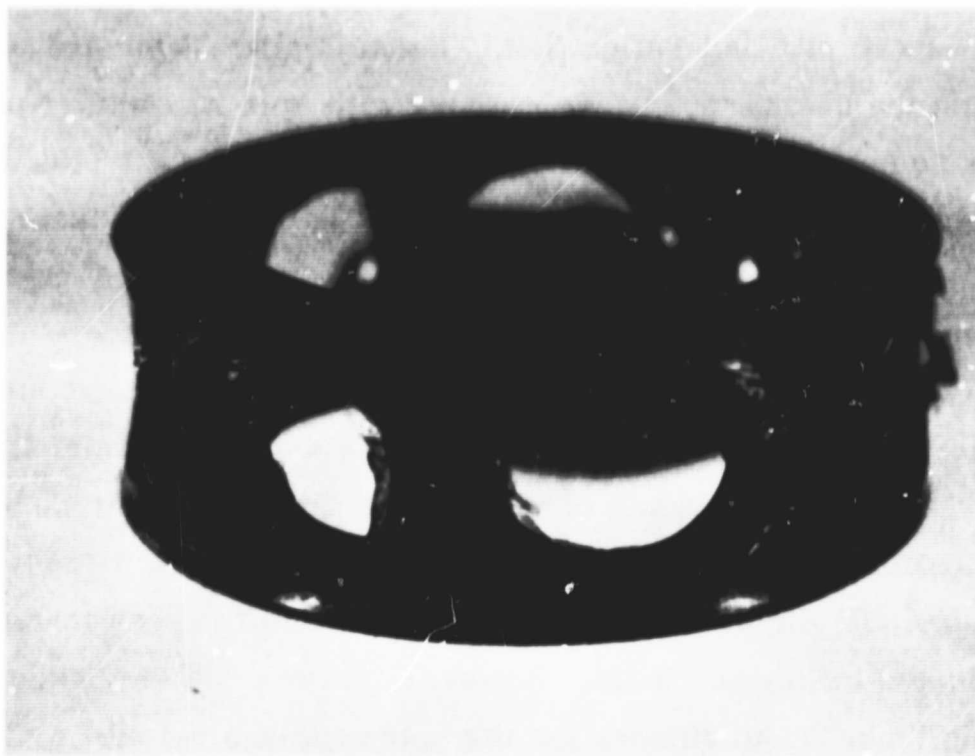
Failures with special retainer materials have been due primarily to the enlargement of ball pockets caused by wear, which in turn causes the retainer to crack, break, or completely wear out on one side, as illustrated in Fig. 3-2.

3.2.3 Oil

All bearings lubricated with FS-1265 fluorosilicone oil completed the 1000-hr lifetime tests successfully and appeared to be capable of additional operation.

3.2.4 Grease

Most of the bearings lubricated with EG-509 silicone grease also completed the 1000-hr lifetime tests successfully, but one pair of them failed in a shorter time.



ENLARGED BALL POCKETS



COMPLETE WEAROUT OF ONE SIDE OF RETAINER

Fig. 3-2 Ball Bearing Retainers After Test

Section 4 CONCLUSIONS

- (1) Some solid-film lubricants and self-lubricating retainer materials can survive extreme conditions of vibration and temperature in vacuum and provide useful operating lifetime thereafter. The same is true for the oil and grease tested.
- (2) Of the solid-film lubricants tested, HI-T-Lube gave the best performance. All eight bearings provided lifetimes longer than 500 hrs in vacuum, and five of these completed the full 1000 hrs of lifetime testing without failure, despite prior vibration. Although several of the other solid-film lubricants performed well in a few tests, their performances were erratic and there was considerable scatter in their lifetimes.
- (3) Of the self-lubricating retainer materials tested, three proprietary grades of reinforced Teflon (i. e., Rulon C, Bar Temp, and MB Bronze-Filled Teflon) gave the best overall performances, with all bearings completing the full 1000 hrs of lifetime testing in vacuum without failure. A reinforced and filled nylon (Nylafil G1/30/MS/5) also performed well.
- (4) None of the powder-metallurgy self-lubricating composite materials performed well as ball bearing retainers. Several of them could not be machined satisfactorily into ball-bearing retainers.

Section 5

RECOMMENDATIONS FOR FUTURE WORK

Additional testing should be conducted with a larger sample size of selected solid-film lubricants and self-lubricating retainer materials. These tests should be concerned with:

- Extending the range of operating variables (i. e. , vibration level and duration, bearing speed and load etc.)
- Establishing statistically valid minimum lifetimes under service conditions

Appendix A

EXPERIMENTAL FIXTURE DIFFICULTIES

The very severe conditions of vibration and temperature in this investigation required several special equipment modifications. These included:

- Isolating the vacuum seal from the severe vibration by means of a special bellows
- Redesigning the fixtures to eliminate base plate resonance
- Redesigning the vacuum seal for use at - 200° F
- Increasing the pumping capacity to take care of outgassing

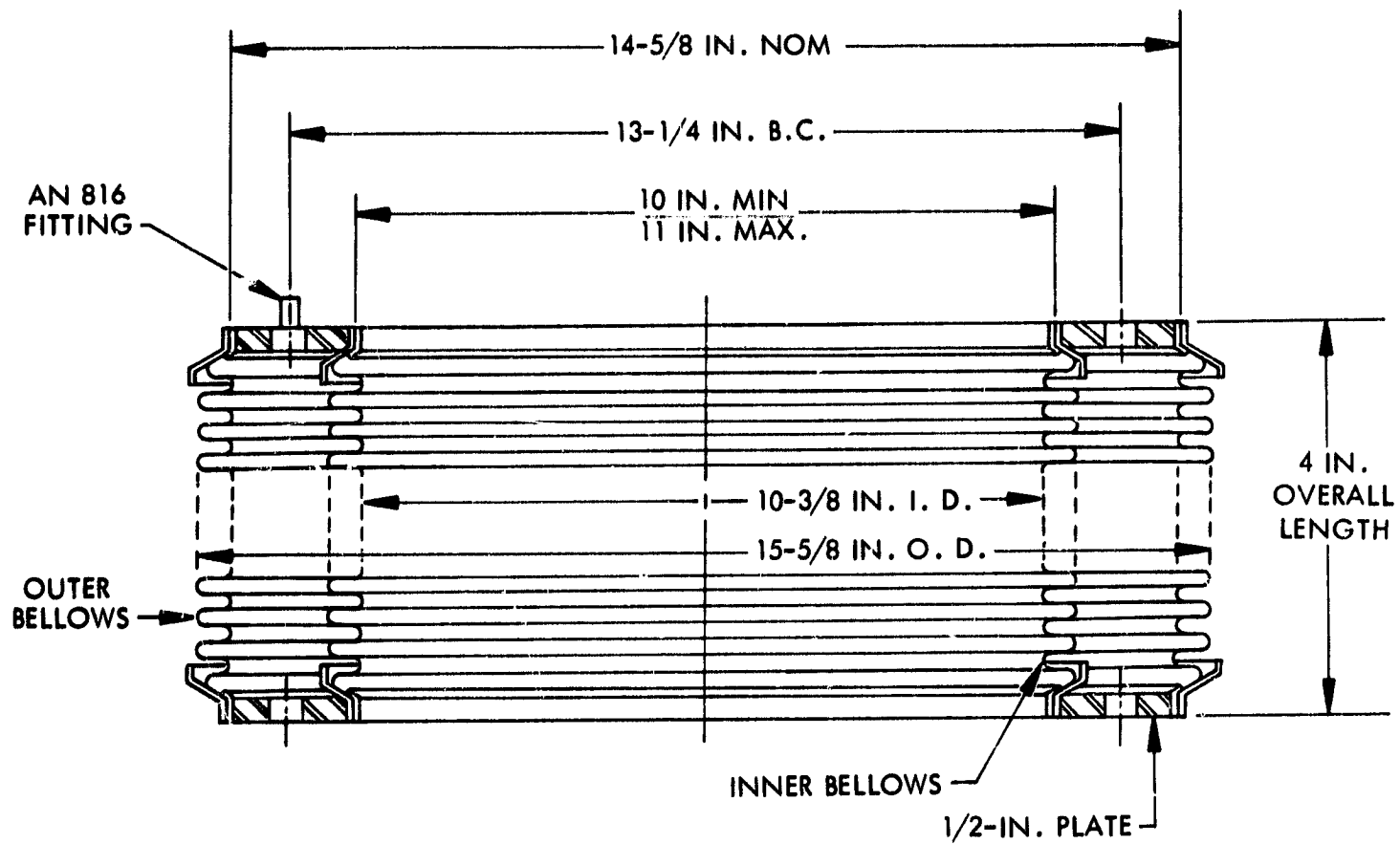
A.1 VIBRATION ISOLATION OF VACUUM CHAMBER

The original design of the test fixture for vibration test required the vacuum chamber to be mounted directly to the vibration fixture. This is normal vacuum testing practice. The 3/8-in. cover plate was placed on top of the chamber to allow easy access to change the motor mounting block contained within. During the initial vibration tests the welds fractured under the stress of $28g^2$ rms random vibration of the motor mounting block. The weld fractures were repaired but again failed in three consecutive trial runs.

As a result of the failures it was decided to isolate the chamber from the vibration fixture. The fixture was redesigned to:

- Mechanically isolate the chamber
- Counteract the force of the air across the bottom of the fixture
- Maintain the vibrator armature in a neutral position

The redesign consisted of a concentric double-wall bellows assembly (Fig. A-1). The inner bellows contained the vacuum and offered mechanical isolation of the chamber from the vibration fixture. The outer bellows enclosed a space that was pressurized with air to counteract the air pressure across the evacuated surface of the fixture.



NOTES:

1. MATERIAL: 347 STAINLESS STEEL
2. ALL INERT GAS WELDED
3. AN 816 FITTING SPACED BETWEEN BOLT HOLES
4. 1/2-IN. PLATE: EIGHT BOLT HOLES EQUALLY SPACED ON 13-1/4 IN. B.C., TAPPED 3/8-16
5. INNER BELLOWS: ANGULAR AREA TEST-60 PSIG, INNER BELLOWS TEST - 1×10^{-9} MIN 10 1/8 IN.
6. OUTER BELLOWS: 15-5/8 IN. OD FOR 50 PSIG
7. MOVEMENT: 1-IN. TOTAL AXIAL-NO LATERAL OR RADIAL

Fig. A-1 Bellows Assembly for Vibration/Vacuum Test

For stabilization, the chamber was mounted on a stand-off connected to the vibrator seismic mass.

The complete assembly was placed in service with satisfactory results.

A.2 VIBRATION TEST FIXTURE REDESIGN

The initial design of the vibration test fixture incorporated the following features:

- Interchangeable motor mounting block to reduce time that chamber is open to air
- Bolted assembly for ease of fabrication to reduce cost

This method of manufacture caused a problem of low frequency resonance when the fixture was vibrated with the motors installed.

A redesign was initiated to fabricate the test fixture from one piece of material. Also included in the redesign were stand-offs and a damping plate to clamp the motors in the fixture. The fixture was held to a minimum thickness of four inches, with the motor holding block on top giving the fixture an overall height of eight inches. The resonance frequency of the fixture was in excess of 2,000 cps.

The new design also included simplified porting for the heat exchange media.

A.3 SEAL REDESIGN FOR LOW TEMPERATURE

During the initial checkout of the temperature servo at low temperature, leaks developed in the vacuum system. Leak checking revealed several small leaks across the seal. Further reduction in temperature resulted in gross loss of pressure across the Viton A seal between the magnesium fixture and the steel bellows flange. Several synthetic material seals were tried including a Teflon O-ring. The Teflon O-ring was installed and the vacuum was maintained at a lower temperature than previously experienced; however, the seal was unsatisfactory at temperatures below -125°F.

Upon recommendation of a Tec-Seal Corporation representative, the special cryogenic vacuum seal described in Section 2.3.6 was used. The difference in coefficient of expansion of the materials caused the stainless steel coil spring to tighten and force the Teflon against the seal surfaces. This seal maintained the vacuum at a lower temperature than previously possible, but not to the required temperature of -200°F .

The complete vibration fixture was delivered to Research Devices Inc who tried the following methods to seal the leakage:

- Use of indium
- Use of differentially pumped indium seal
- Use of gold-indium alloy

Sealing was not accomplished with the indium seal or the gold-indium seal due to metal shearing caused by the difference in coefficient of expansion of the materials.

Seal was finally accomplished by use of a dual differentially-evacuated Tec-Seal (Fig. A-2).

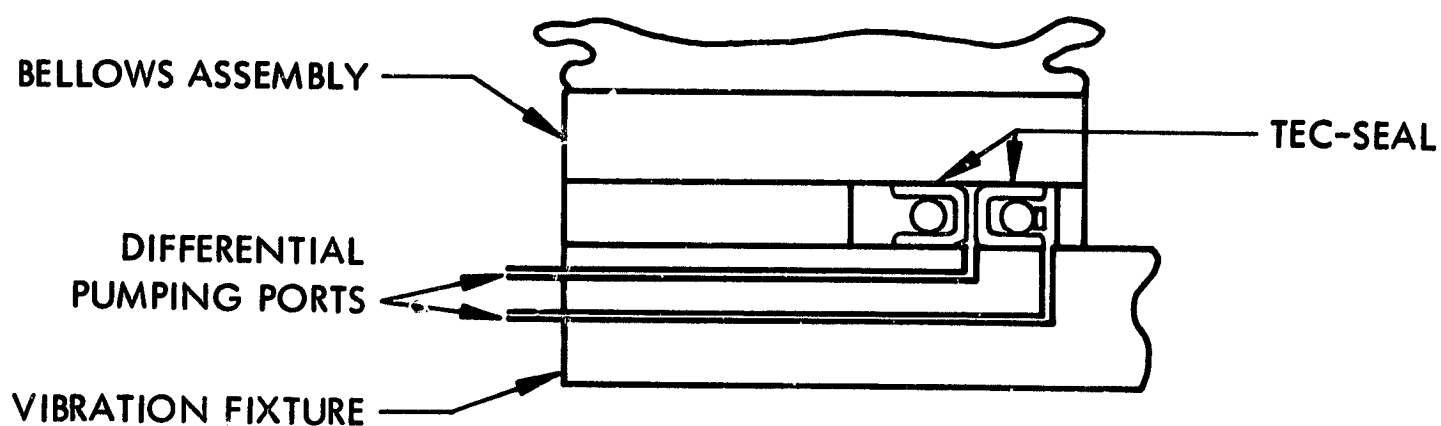


Fig. A-2 Dual Differentially-Evacuated Tec-Seal

A.4 VACUUM PUMPING SYSTEM REDESIGN

During the room temperature tests the vacuum system required 36 to 48 hr to pump down to the specified vacuum of 5×10^{-7} torr. For the high temperature tests at +200°F the calculated outgassing rate was estimated to be 4000 liters/sec. The available pumping speed of the existing vacuum system was about 400 liters/sec. It was concluded that the required vacuum could not be attained in a reasonable time without increased pumping capability.

A vacuum system design was executed which utilized titanium sublimation pumping on a liquid nitrogen chilled surface to achieve the required high pumping speed. The design also permitted maximum use of the existing vacuum equipment. Other improvements were incorporated in the design so that downtime would be kept to a minimum during the test program.

The design target for pumping speed was 5100 liters/sec at the work chamber. In operation the specified pressure of 5×10^{-7} torr was achieved in an average time of 6 hours with the test specimens at +200°F.