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VIBRATION EFFECTS ON THE SPACE SHUTTLE MAIN ENGINE HIGH PRESSURE OXIDIZER TURBOPUMP BELLOWS

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16. ABSTRACT

A welded metal bellows was subjected to a series of vibration tests in a 400 psi oxygen environment to evaluate the effects of the bellows convolutes rubbing on the damper ring in the High Pressure Oxidizer Turbopump of the Space Shuttle Main Engine.

The bellows was subjected to approximately 2 million cycles at 0.007 in. double amplitude displacement during this series of tests, at a frequency of 400 Hz.

Instrumentation of the test specimen revealed no significant heat buildup caused by the rubbing of the bellows convolutes on the damper ring.

A final destruct test was made to determine if a fire would result if the bellows ruptured in the 400 psi oxygen environment, thus exposing a fresh metal surface. The vibration input was changed to 0.8 in. double amplitude displacement at 20 Hz to intentionally rupture the bellows. Failure occurred after 2.5 sec (50 cycles); no fire or heat buildup was encountered.

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The success of this test program is attributed to the excellent cooperation of the many MSFC personnel that took part in the design, manufacture, and assembly of the test apparatus and the persons who helped in the conduct of the tests.

The Mechanical Division of the Propulsion Laboratory, EP31, is recognized for their cooperation in the design of the test apparatus.

The Fabrication Division of Test Laboratory, the Process Engineering Division, and the Engineering Physics Division of Materials and Processes Laboratory all provided excellent support in precision machining of the parts for the test fixture.

The Process Engineering Division also provided welding support and the Fabrication Division of Test Laboratory provided the required support in cleaning and pressure test.

The Dynamics Test Branch of Test Laboratory provided and operated the vibration test facility.

Precision alignment equipment was provided and operated by the Equipment Installation Branch of Test Laboratory.

Instrumentation was provided and operated by the Laboratory Support Branch of the Engineering Physics Division, Materials and Processes Laboratory.

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VIBRATION EFFECTS ON THE SPACE SHUTTLE MAIN ENGINE HIGH PRESSURE OXIDIZER TURBOPUMP BELLOWS

SUMMARY

An investigative test program was accomplished which involved subjecting a Space Shuttle Main Engine (SSME) High Pressure Oxidizer Turbopump (HPOTP) primary seal bellows assembly to vibration levels simulating that which would be encountered in the engine. The test bellows was enclosed in a test chamber and was pressurized to 400 psig with gaseous oxygen.

A total of over 2 million cycles were put on the unit which was equivalent to approximately 83 min of flight time. The objective of these tests was to determine if sufficient heat would be generated by the rubbing of the bellows convolutes against the damper to cause the bellows to ignite in the highly concentrated oxygen environment.

At no time during these tests did the temperature of the bellows exceed 112°F. There was no indication of excessive friction nor any indication of the bellows rubbing against the damper.

After it had been determined that normal vibration levels (400 Hz at 0.007 in. double amplitude) had no detrimental effect on the bellows, it was subjected to vibration at 0.8 in. double amplitude displacement at 20 cycles/sec. This test was made to intentionally rupture the bellows to see if a fire would result from the fresh fatigued metal surface coming in contact with the 400 psig oxygen.

The bellows ruptured after only 2.5 sec of vibration at full vibration levels (50 cycles). The 400 psi oxygen vented through the ruptured bellows. No fire or heat buildup was encountered. The bellows failed from fatigue in the heat affected zone next to the weld, on the second convolute from the end of the bellows which was attached to the shaker table drive rod.

The results of this series of tests proved that the damped bellows was not the cause of the fire in the SSME HPOTP which occurred during test no. 901-110 at the National Space Technology Laboratory, Bay St. Louis, Mississippi, on March 24, 1977.

I. INTRODUCTION

Friction, combustible material, and oxygen combined in proper proportions can result in a fire. Metal in the presence of a high concentration of oxygen becomes combustible provided sufficient friction to generate energy is present.

A bellows with a damper ring operating in an environment with vibration and high pressure oxygen could be a hazard because the rubbing of the bellows convolutes against the damper ring might generate sufficient heat to cause a fire.

The SSME employs a damped metal bellows in the HPOTP. A comprehensive test program was conducted utilizing an actual flight bellows, S/N 014. and a vibration test facility. A test chamber was designed and built in-house to allow the test specimen to be pressurized to 400 psig with oxygen and at the same time subject it to vibration.

A fire was encountered in the SSME HPOTP during test no. 901-110 at the National Space Technology Laboratory, Bay St. Louis, Mississippi on March 24, 1977. The fire completely consumed the HPOTP primary carbon seal bellows and damper ring. An investigative program was implemented to determine if the bellows/damper friction in the HPOTP could have caused the bellows to ignite. Responsibility for this investigative test program was accepted by the Materials and Processes Laboratory, George C. Marshall Space Flight Center, Huntsville, Alabama.

II. SEAL BELLOWS ASSEMBLY DESCRIPTION

The seal bellows assembly utilized for these tests was taken from spares stock at the SSME manufacturer's plant (Rocketdyne Division of Rockwell International). The assembly P/N D59030, S/N 014, was considered representative of those in the engines. The assembly is shown pictorially in Figure 1 and the drawing is shown as Figure 2.

The metal bellows was made by Sealol Inc., Engineered Products Division, Warwick, Rhode Island, and is a tungsten inert gas (TIG) welded 5 to 6 mil Inconel 718 material with a spring rate of 275 lb/in. ± 10 percent. It consists of 13 convolutes. One end is welded to the flanged housing and the other end is welded to the static seal ring. The bellows convolutes are made in the shape of an "S" so as to transfer the stress concentration areas away from the welds and distribute them throughout the bellows convolutes.

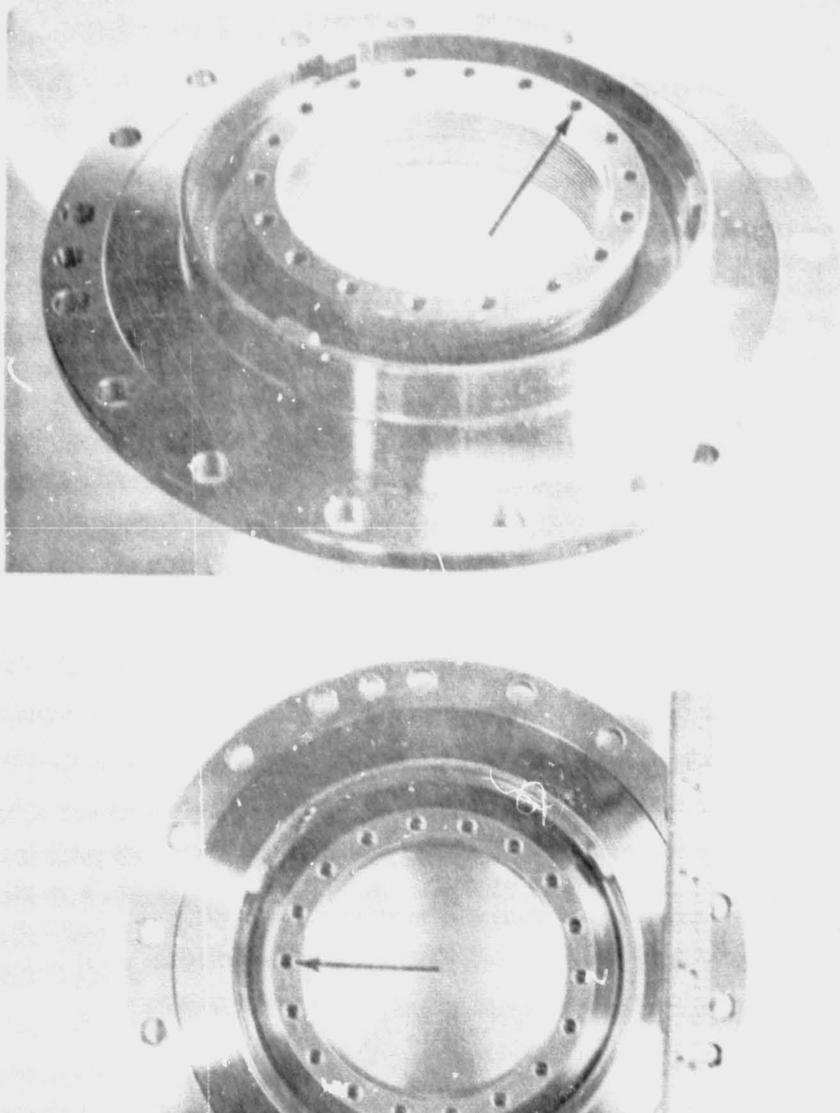


Figure 1. Photographs of test bellows.

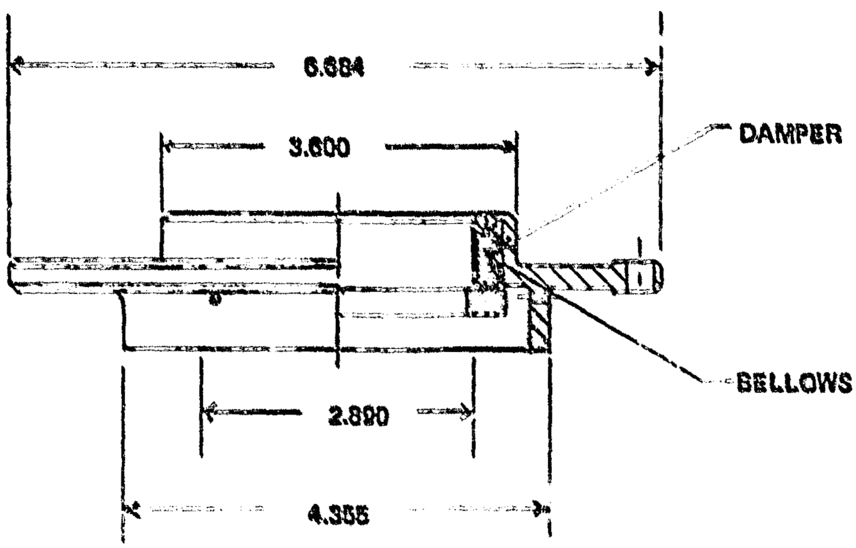


Figure 2. Scale drawing of test bellows.

The damper ring employed in the unit is 5 mil stamped Inconel 750 material which contacts the middle six convolutes. The purpose of the bellows assembly is to provide a preload to the turbopump shaft carbon seal and allow for slight lateral movement of the turbopump shaft caused by the thrust of the pumping action. The bellows also allows the seal to lift off after the speed of the pump shaft is sufficient to achieve an aerodynamic film between the carbon seal and the seal ring. This liftoff feature is provided by lift pads machined into the carbon seal rub face. The purpose of the liftoff feature is to prevent excessive heat buildup and wear of the mating surfaces of the carbon seal and the seal ring. Figure 3 is a concept drawing of the bellows seal assembly.

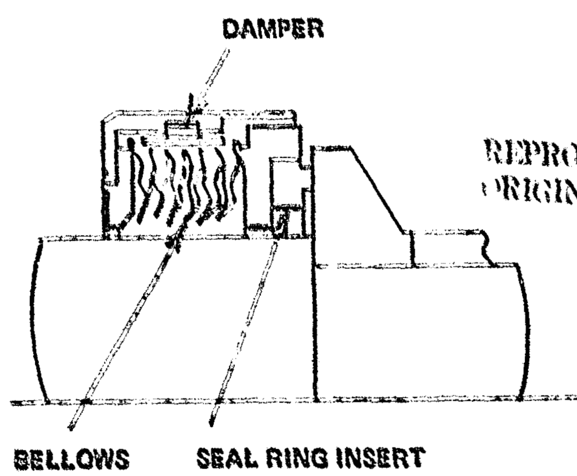


Figure 3. Concept schematic of test bellows.

In preparing the bellows assembly for test, the seal ring was drilled and tapped for eighteen No. 8-36 screws (Fig. 1). These holes were utilized to affix the movable end of the bellows to the vibration input shaft. The flanged bolt circle of the bellows assembly was bolted to the stationary portion of the test fixture. The fixture and test item are shown in a cutaway view in Figure 4.

III. TEST EQUIPMENT

Standard laboratory test equipment was utilized for these tests. The test setup and instrumentation are shown in Figures 5 through 10.

A. Prime Mover

The prime mover utilized was a Ling Model A-249 vibration test machine with associated instrumentation and controls. The machine is located in Room 160 of Building 4619 at MSFC, and the associated control room is Room 159. This vibration machine is a massive and powerful apparatus. The force capability of the shaker table is 30 000 lb force with 1100 amps armature current capability. The vibration plate and armature are supported on springs which have a spring rate of 11 000 lb/in. The vibration equipment was provided and operated by Test Laboratory personnel of the Dynamics Test Branch.

B. Pressure Chamber

In an effort to simulate as near as practical the actual SSME HPOTP environmental conditions, a test chamber was designed and built with approximately 890 in.^{3} of volume. The chamber was made of heavy steel so that it could withstand the 400 psi operating pressure. (It was proof tested at 800 psi.) A feed-through tube was provided to allow the inside of the bellows to be vented, thus accomplishing 400 psid across the bellows convolutes. The vent tube also served as an instrumentation access to the inside of the bellows. Thermocouple wires, a fiber optics bundle, and strain gage wires were connected to instruments inside the bellows. The vent tube also served as a means for venting the oxygen from the chamber in case of bellows rupture. It was connected to piping which was vented to the outside of the building.

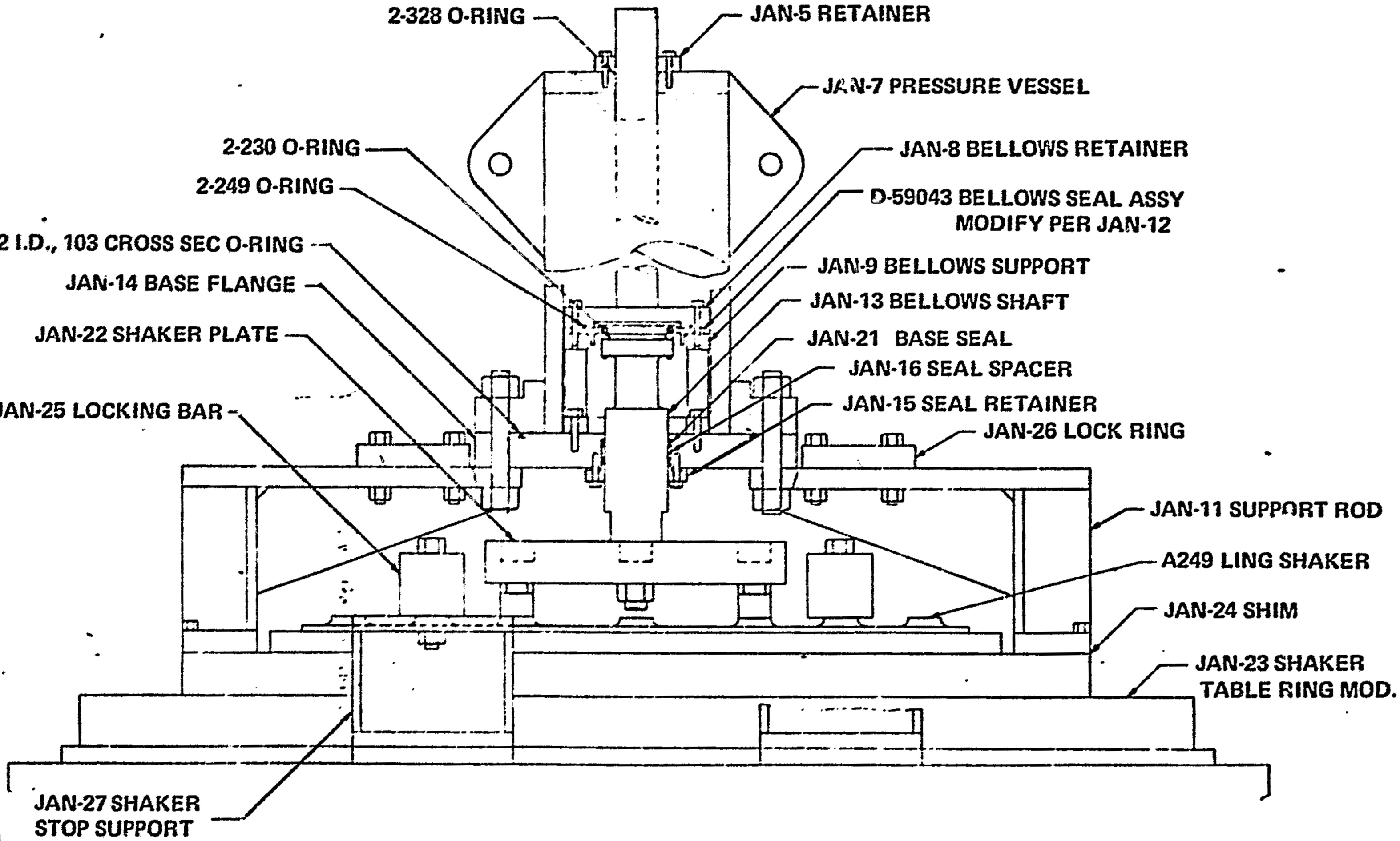


Figure 4. Cutaway drawing of test apparatus.

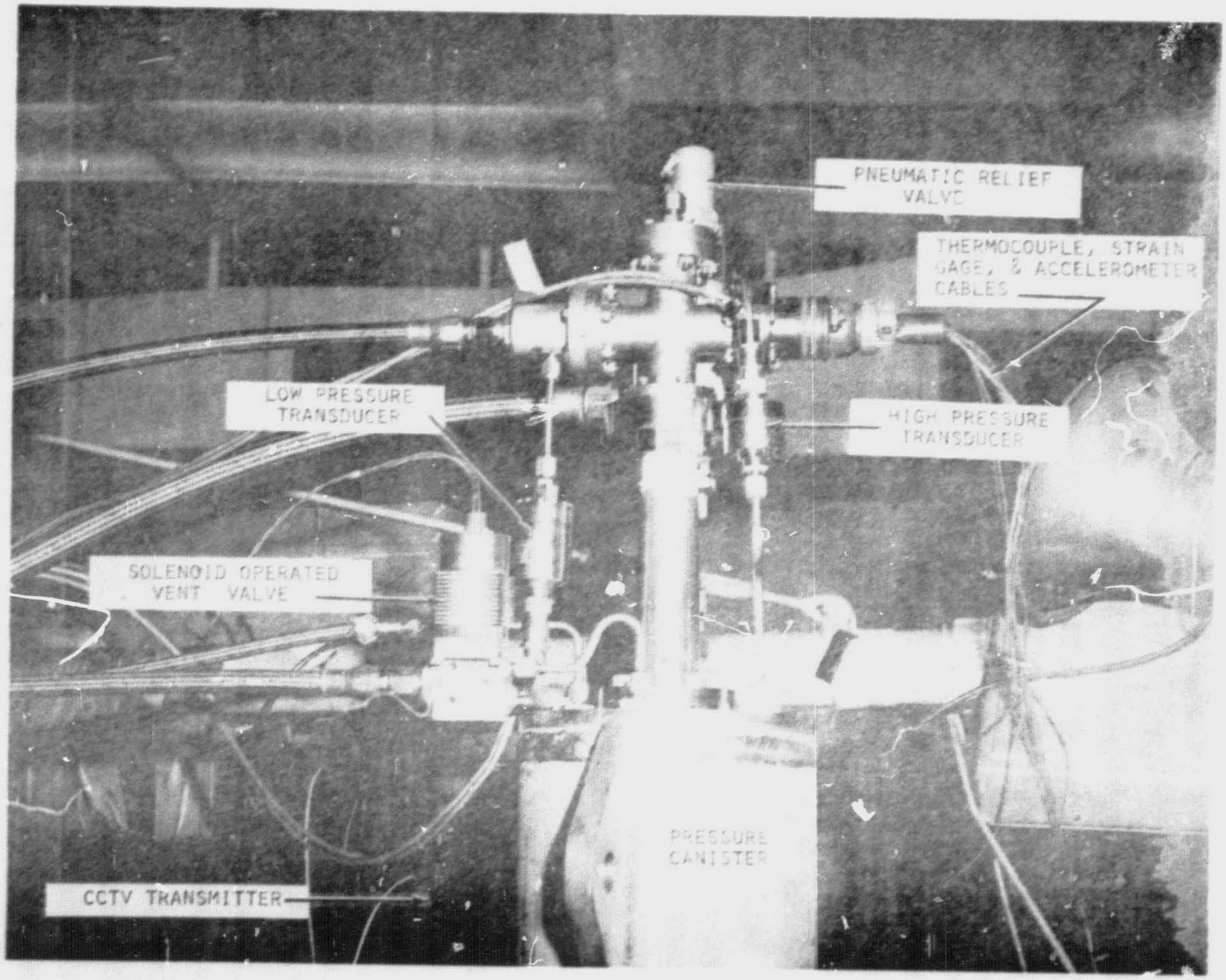


Figure 5. Photograph of pneumatic control.

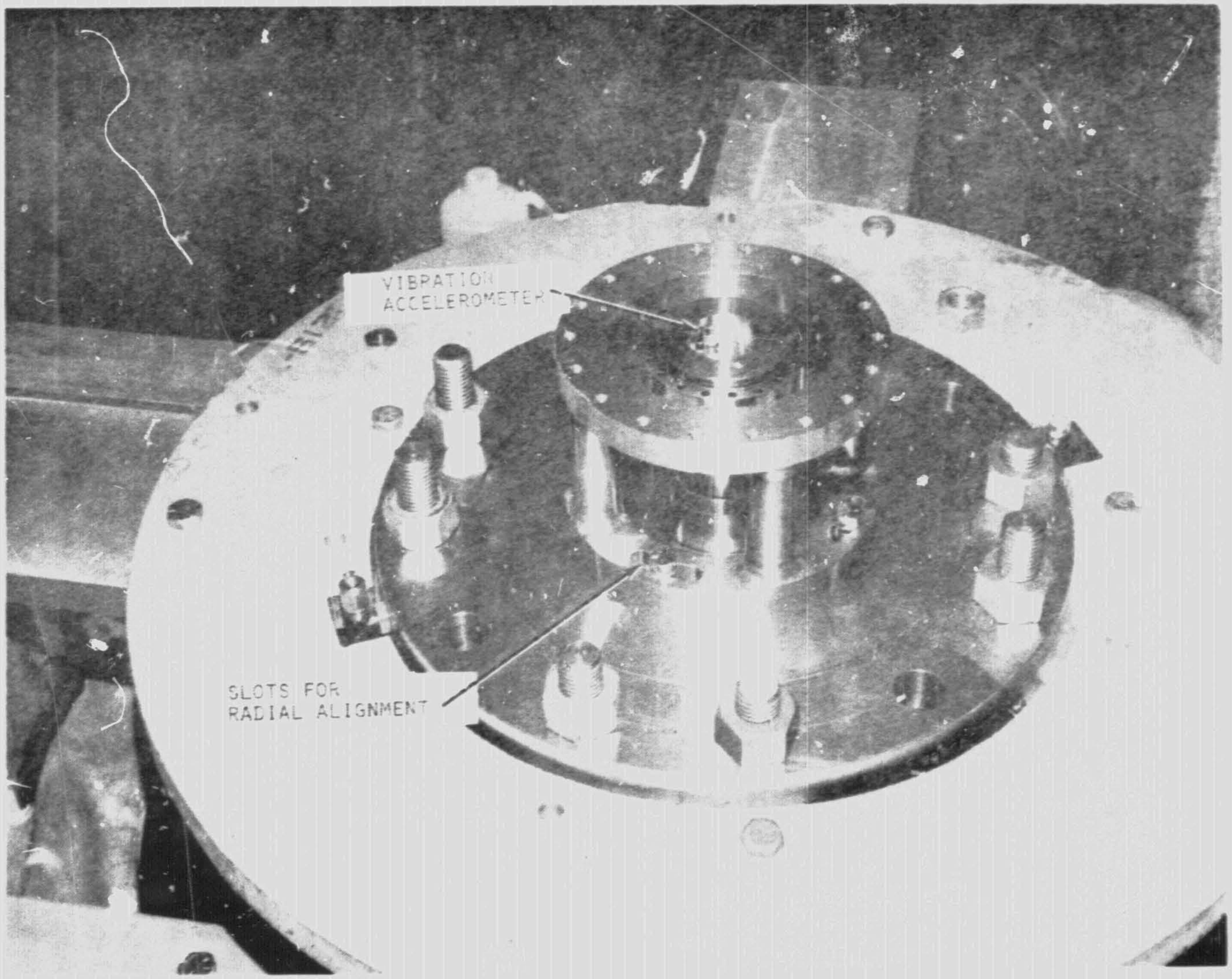


Figure 6. Instrumentation system accelerometers and slots for radial alignment.

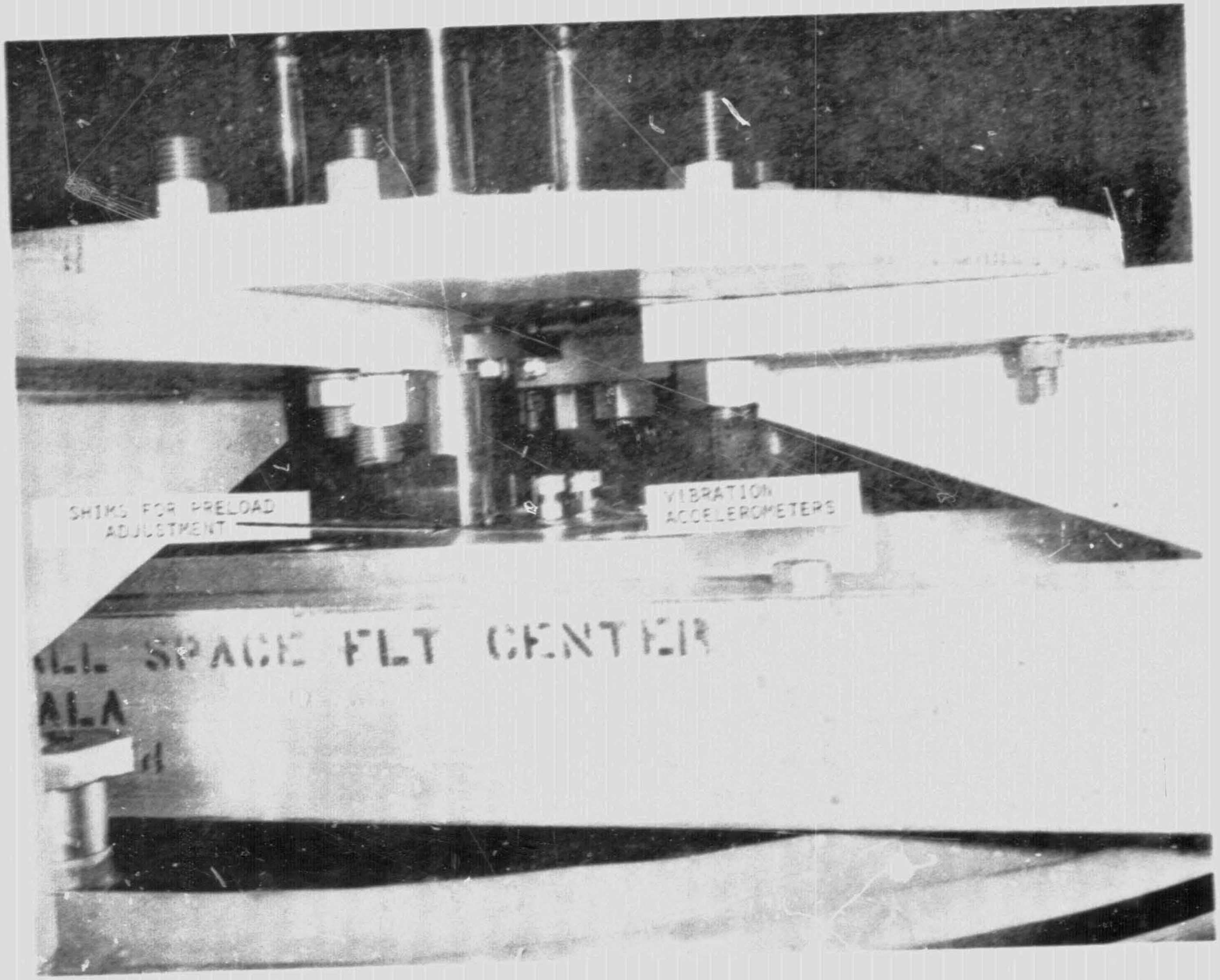


Figure 7. Instrumentation system accelerometers and shims for preload adjustment.

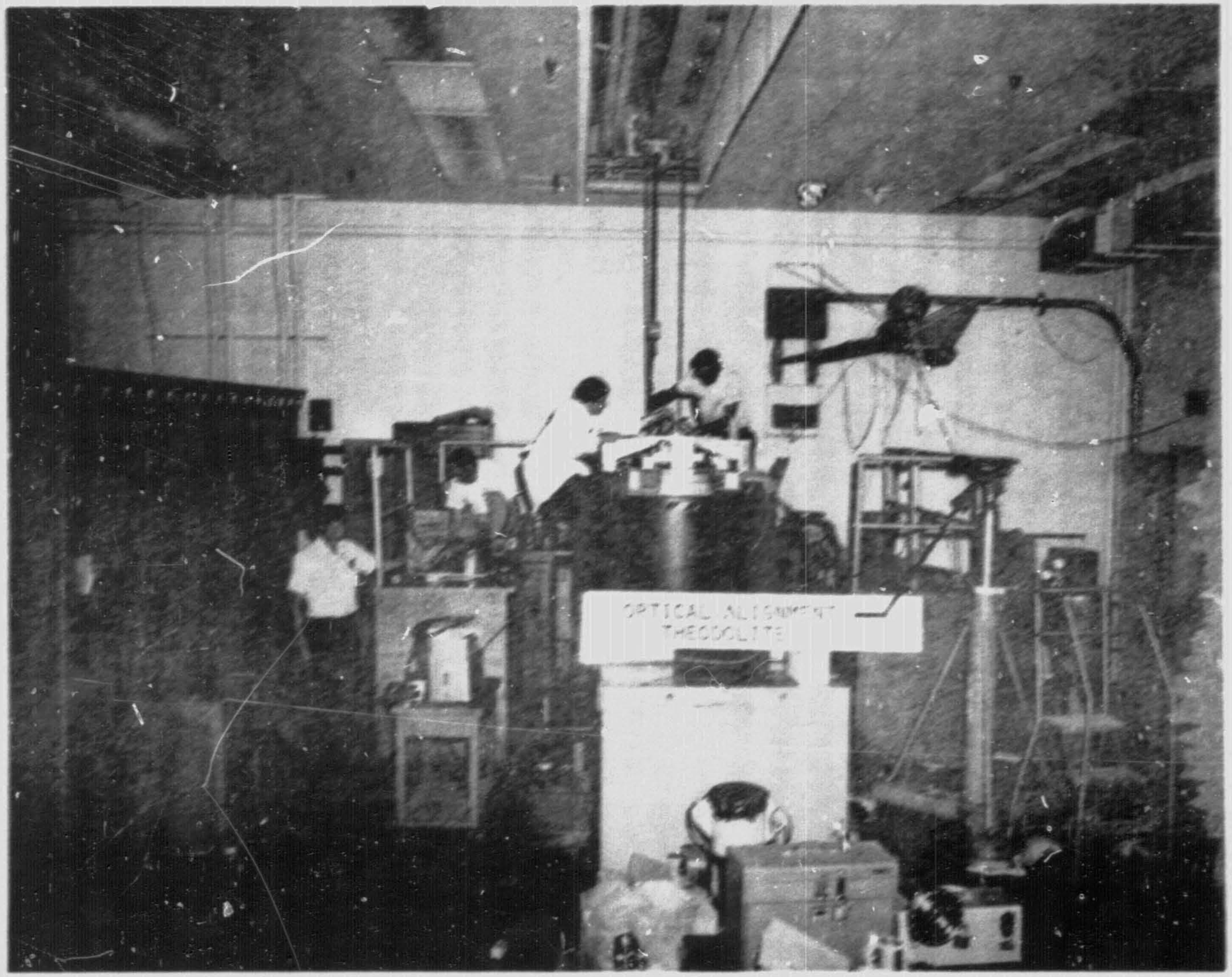


Figure 8. Vibration equipment being prepared.

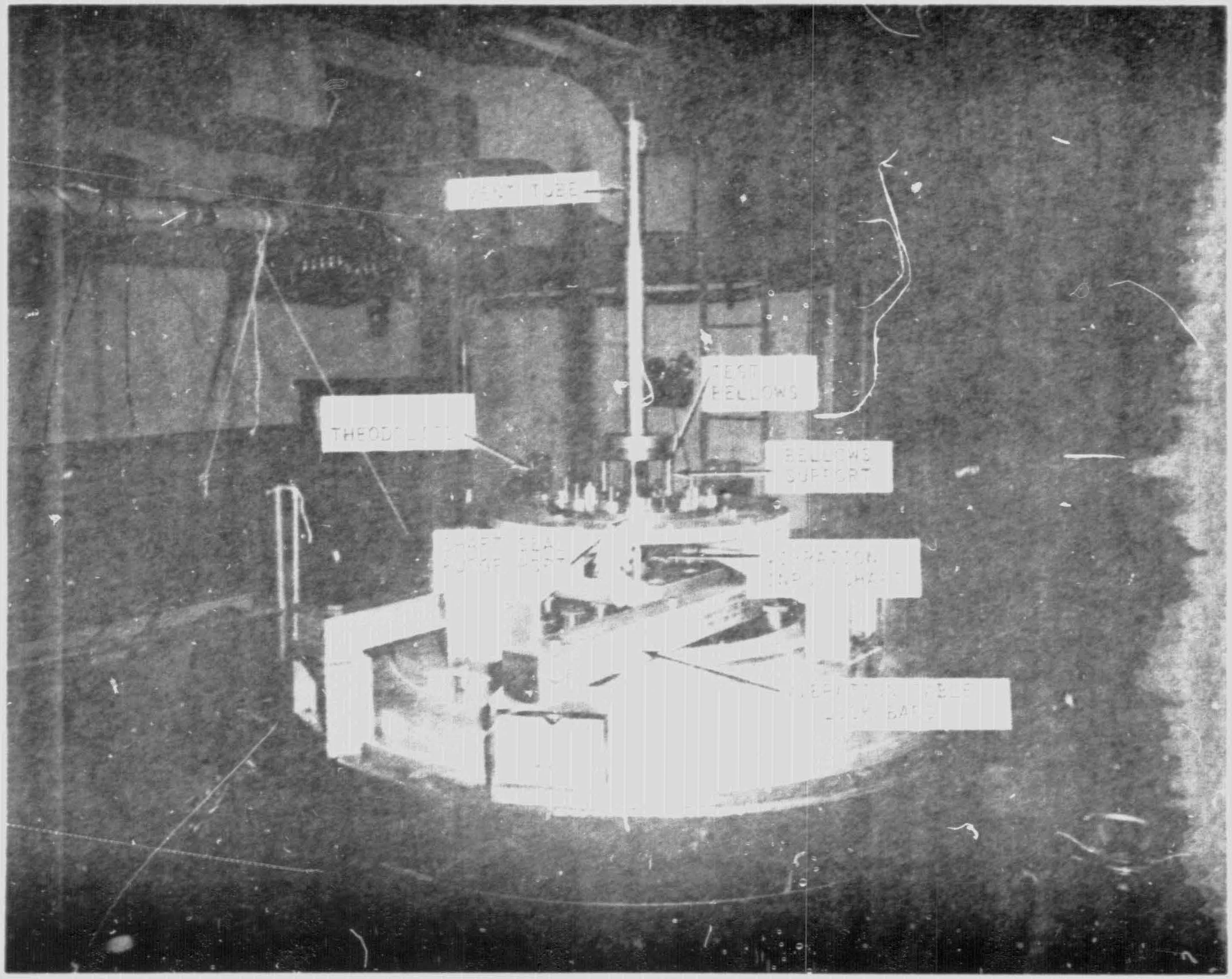


Figure 9. Bellows assembly installed on vibration machine without pressure canister.

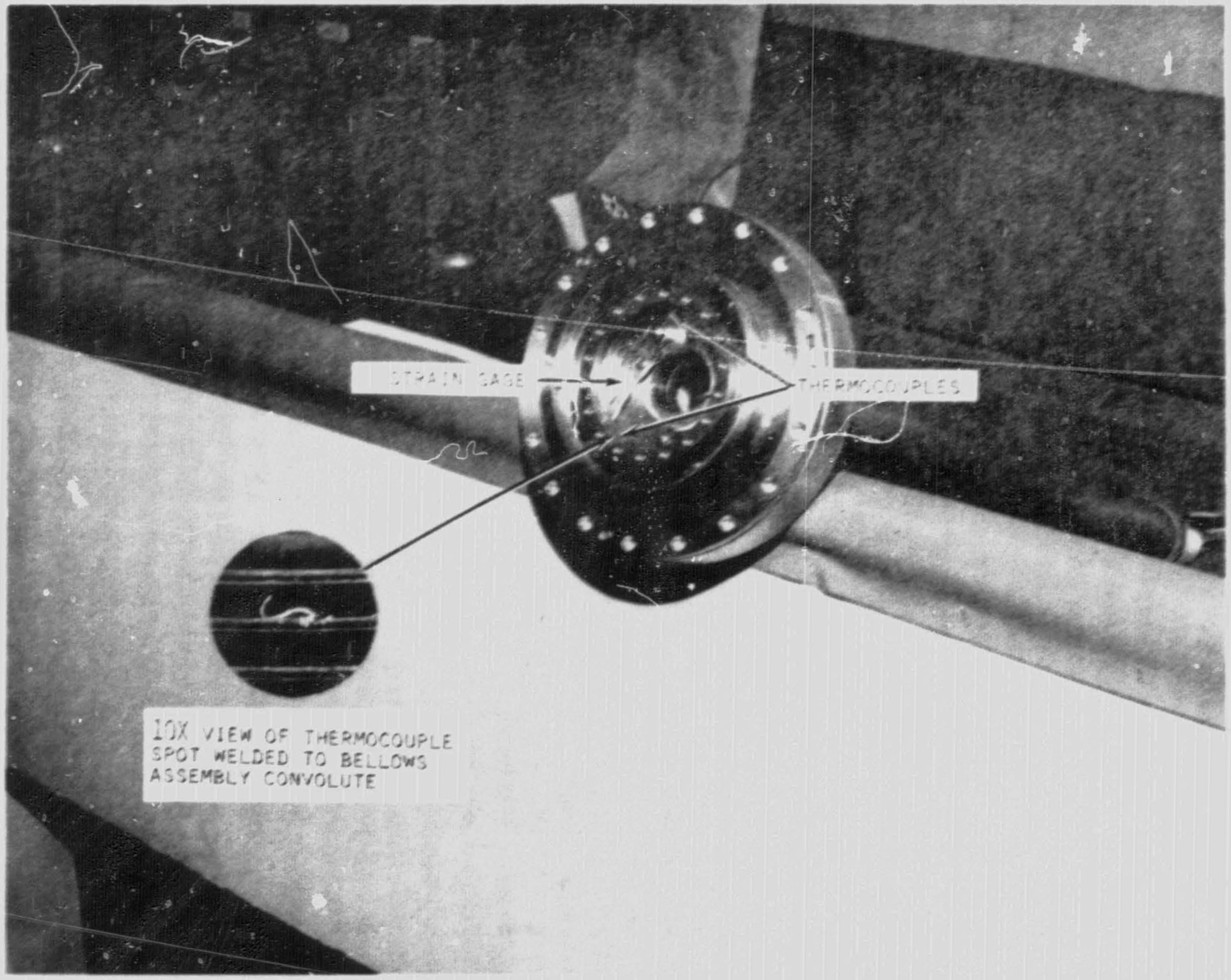


Figure 10. Photograph of strain gage and thermocouple mounting.

The test chamber was also equipped with holding fixtures which allowed transmission of the vibration to the test item through the vibration input shaft. The test chamber and apparatus are shown schematically in Figure 1 of Appendix A.

IV. DESIGN OF THE TEST APPARATUS

A. Design Requirements

The test apparatus was designed to simulate as near as practical the actual SSME HPOTP environments and conditions.

A pressure chamber was built with a volume of approximately 890 $in.^3$ and with capability to withstand 400 psig oxygen. It was provided with a feed-through shaft so that the test item could be subjected to vibration and 400 psig oxygen simultaneously. Instrumentation feed-throughs were also provided. A cross section view of the test apparatus is shown as Figure 4. Photographs of the overall test setup are shown as Figures 5 through 10.

Materials used in the test apparatus were selected to be compatible with gaseous oxygen. Most of the piece parts were made of 304 stainless steel because it had to be welded in several places.

B. Pressure Balancing

Extreme care was taken in design of the vibration transmitting shaft to assure that when 400 psi oxygen was applied, a pressure differential was not produced sufficient to cause the vibration table zero position to change. This would change the preload on the bellows.

Originally it was planned to do the vibration tests on a smaller vibration machine; however, it was found that the springs which support the armature and vibration plate were only 1000 lb/in. spring constant flexure springs.

The original design of the vibration transmitting shaft was 2.00 in. in diameter. This was changed and a new 2.9374 in. diameter shaft was made to eliminate pressure differential forces.

By utilizing the larger vibration machine with a flexure assembly with 11 000 lb/in. and the redesigned shaft, the effects of differential pressure across the bellows were negated.

C. Shaft Seal Cooling

A packing gland and teflon seal were used to prevent excessive oxygen leakage past the shaft. It was anticipated that the rubbing of the shaft against the seals would generate heat. This was kept from developing into a problem by making the seal a two part teflon seal with a steel separator and drilling the base flange so that a LN_2 purge flow could pass between the two seals and vent overboard. The LN_2 purge served a dual function: it cooled the shaft and seals and also served to dilute any oxygen leakage and carry it off where it could be vented to a nonhazardous area.

Considerable experimenting was required to arrive at the optimum torque to apply to the shaft seal retainer bolts. Too much torque caused excessive vibration transmission to the test fixture and excessive shaft seal temperature, resulting in accelerated deterioration of the seal. If the seal retainer bolts were not torqued enough, shaft seal leakage was high. It was determined that the optimum torque for the seal retainer bolts was just finger tight plus one-quarter turn. The seal retainer bolts were retorqued before each vibration test. The checkout procedure provided a means for verifying shaft seal leakage before the vibration tests.

D. Oxygen Purge

The oxygen purge is included in the test procedure (Appendix A). The pressure chamber was pressurized with oxygen to 30 psig and vented three times before the final pressurization to 400 psig. This was done to assure that all residual air in the chamber had been purged and an oxygen environment was left surrounding the exterior of the test bellows simulating SSME HPOTP conditions.

V. TEST SETUP

A. Installation of Bellows in Tester

Precautionary measures were taken to insure that the test bellows was not damaged during installation into the test apparatus. A dummy bellows was made to simulate the test item. It was machined of solid aluminum but was made with the same external configuration and interface connect points as the flight item. This dummy bellows was used to set up the test rig and assemble it onto the shaker table. Alignment and bellows preload adjustments were accomplished by using the dummy bellows instead of taking a chance on damaging the flight type bellows during the setup and alignment process. The dummy bellows was removed, and the actual flight type test bellows was installed immediately before the start of the tests.

B. Alignment

Vertical positioning of the fixed flange of the test item was very critical because the fixed position determined the preload on the bellows. The fixture was designed to permit shims to be added or removed to adjust the preload on the bellows.

Personnel from the Equipment Installation Branch of Test Laboratory utilized a theodolite to determine vertical positioning. The position was checked at various times throughout the test to assure that the bellows was not subjected to overstress movements.

Alignment measurements were used to determine that the position after shutdown was within a few thousandths of an inch of the position before startup.

C. Bellows Preload

From the drawing of the bellows assembly it was determined that the spring constant of the bellows was 275 lb/in. ± 10 percent. The preload conditions of the bellows seal assembly in the engine which burned was determined to be 18 lb. Therefore, shims were added to the test fixture between the vibration input shaft and the vibration plate. This caused the bellows to be compressed 0.0654 in. from the free position, thus accomplishing the 18 lb preload on the test item. Vibration displacement was effected ± 0.0035 in. from the starting point; consequently, the preload varied from 17 to 19 lb during the actual vibration test.

Preload was changed for the 0.8 in. double amplitude displacement tests so that the bellows would not be stacked metal to metal. A 0.320 in. spacer was added between the base flange and the bellows support. This actually caused a negative preload or a tensile load on the bellows of approximately 70 lb (0.320 × 275-18).

D. Protection of the Bellows

The SSME HPOTP primary seal bellows assembly is a delicate mechanism and would be highly susceptible to damage if not properly protected from being overextended, stacked, or subjected to torsional forces.

The vibration equipment used to conduct these tests is massive and powerful and is subject to erratic movements if the supply voltage varies.

All testing was done after normal working hours to minimize the possibility of problems caused by varying supply voltage as a result of personnel in other parts of the building turning equipment on or off.

Shaker table locks were designed and built which locked the vibration table to the frame of the machine when the test item was installed but testing was not actually in process (Fig. 9).

Torsional forces on the bellows were avoided by providing slotted holes in the test fixture to allow for clocking the bellows during assembly to align the mounting holes in the flange with respect to the mounting holes drilled in the static seal ring used to attach the bellows to the vibration transmitting shaft (Fig. 6).

VI. INSTRUMENTATION AND CONTROLS

A. Instrumentation

Standard laboratory instruments were utilized for this test program. Variable data monitored are as follows:

a. Temperature — Thermocouples were attached to weld beads on the test bellows convolutes (Fig. 10) and to the vibration transfer rod. The test chamber temperature was also monitored by means of thermocouple in the area of the test specimen.

b Time — Duration of the tests was controlled by an electronic timer. Data from this counter together with other data from the vibration equipment were used to determine the number of cycles to which the bellows was subjected.

c. Vibration — Instrumentation associated with the vibration facility was utilized to monitor frequency, displacement, acceleration, etc. Recording equipment was located in the control room which received input data from accelerometers mounted at various places on the test fixture and on the vibration transmitting shaft (Fig. 6).

d. Pressure — Pressure transducers were utilized in conjunction with strip chart recorders to monitor and display the pressure of the O_2 inside the chamber and also to monitor the differential pressure across the bellows (Fig. 5).

e. Displacement — A cantilever beam with strain gage was used to monitor the movement of the bellows. It was planned to use the data from this system to arrive at the total speed of the test item and also the total amount of movement (Fig. 10).

f. Closed circuit television (CCTV) monitor — A CCTV monitoring system was employed in combination with a fiber optics bundle to monitor the inside of the bellows during the vibration tests. A tape recording system was also used to record the video events for future analysis and reference.

B. Controls

Figure 2 of Appendix A is a schematic drawing of the gas purge and pressurization test setup and control system. Instrumentation was fixed so as to provide automatic shutoff of the oxygen supply if the bellows failed. This was accomplished by use of a low pressure (5 psig) transducer in the vent tube which was adjusted to sense a pressure buildup in the vent tube which would be evident if the bellows ruptured. This automatic shutoff activated when the bellows was intentionally ruptured during the last test. Operation of the gas purge and pressurization system is better explained in the test procedure, Appendix A. Figure 5 is a photograph of the major components of the pneumatic control system.

VII. TEST PLANS AND PROCEDURES

This test program consisted of the following tests: (a) a low-level sine sweep was run for 60 sec to determine system resonance, (b) a 75 sec vibration test was made at 400 Hz and 0.001 in. double amplitude displacement, (c) a third test was made at 400 Hz, 0.007 in. double amplitude, and 740 sec duration, (c) five consecutive tests each consisting of 740 sec were made at 400 Hz, 0.007 in. double amplitude displacement. These tests were made without stopping. This made the accumulated vibration cycles 1.8 million cycles. It was determined advantageous to continue under steady-state conditions to accumulate a total of 2 million cycles; this was accomplished. The previously mentioned tests completed the originally planned series of tests and are covered in detail in Appendices A and B.

A final destructive test was made to intentionally rupture the bellows to determine the effects of exposing the freshly fatigued metal surface to the 400 psi oxygen. To accomplish this, a test was made at 0.8 in. double amplitude displacement and 20 cycles/sec. This test lasted approximately 2.5 sec or a total of 50 cycles before the bellows ruptured.

After the test item was intentionally ruptured, it was subjected to a thorough metallurgical analysis by personnel of the Materials and Processes Laboratory, Metallurgical and Failure Analysis Branch. This analysis showed evidence of tensile overload but no fatigue striations. Welds on this bellows had oxide stringers at the outer edge of the welds. The initiation site of the material separation coincided with the location of the oxide stringers in the welds.

VIII. DESCRIPTION OF TESTS

A. V-0

The first test made on the flight type bellows designated as V-0 is described in detail in Appendices A and B. It was a random sweep vibration from 200 Hz to 400 Hz at 0.0001 in. double amplitude displacement, 1 g peak acceleration. The duration of the test was 60 sec. It was made to determine if the test bellows had any resonant frequencies in that range. Further testing was planned at the natural frequency of the bellows if it fell within the 200 to 400 Hz range. However, no resonance was detected; thus, all further tests were made at 400 Hz. The pressure chamber was purged and back filled with O_2 at 400 psig for this test.

B. V-1

This test consisted of 75 sec vibration at 400 Hz, 0.001 in. double amplitude displacement, 8.15 g peak acceleration. The pressure chamber was pressurized to 400 psig O_2 for this test. Test V-1 was made immediately following the sine sweep test, V-0. The vibration table was set for standby while the data from V-0 was analyzed and adjustments were made to change vibration parameters for V-1. Occurrences during the test and results of the test are discussed in Section IX.

C. V-2

Vibration testing at 400 Hz, 0.007 in. double amplitude displacement, 57.12 g peak, was accomplished for a duration of 740 sec. This test simulated the vibration input to the test bellows that would occur during a normal full duration static firing on the SSME HPOTP. This test also was accomplished during the same day that V-0 and V-1 were made. The oxygen supply bottles were replenished and the O_2 purge and repressurization procedure was accomplished between tests V-1 and V-2.

D. V-3 Through V-7

Tests V-3 through V-7 were planned as identical tests to be accomplished one at a time with shutdown of the vibration equipment and data evaluation after each 740 sec test. Analysis of data from test V-2 revealed an apparent steady-state condition, and it was determined that if steady-state conditions were achieved in test V-3, a decision would be made to let the vibration equipment continue to operate until all of the tests through V-7 were accomplished, until failure of the bellows occurred, or until shaft temperature or seal leakage became excessive. All of these tests were made at the same vibration levels as test V-2.

E. Additional Tests

Steady-state conditions were achieved during the V-3 through V-7 test series; therefore, the decision was made to continue the vibration another 6.75 min and, thus, accomplish a total of approximately 2 million cycles on the bellows, including all tests from V-0 and on. This made the total vibration time on the test unit 4980 sec. This additional test is not mentioned in Appendix A or B, but the vibration levels used were the same as for tests V-2 through V-7.

F. Destruct Test

The primary objective of this test program was to determine if the vibration and pressure differential across the bellows would cause it to rupture and, secondly, if it did rupture, would it cause a fire or explosion. Since none of the originally planned tests caused the bellows to rupture, the first objective was accomplished, but it still was not known if a fire would result if the bellows ruptured. A test was devised to intentionally overstress the bellows and cause it to rupture exposing the newly fatigued metal surfaces to the high pressure oxygen. This was accomplished by adjusting the vibration table displacement to 0.8 in. double amplitude displacement with an input frequency of 20 Hz. Normal shutdown of the vibration and gas pressurization system was accomplished when the bellows ruptured after 2.5 sec from the time steady-state vibration levels were achieved.

G. Preliminary Development Tests

Since the test fixture was a completely new and unproven device, there was some concern about the shaft seal. If a tight fitting shaft seal were used, friction would be high causing excessive heat and also excessive transmission of vibration into the stationary portion of the fixture. If the shaft seal is too loose, excessive leakage would occur making it more hazardous and also more difficult to maintain proper chamber pressure. A development test was devised to evaluate the effect of shaft seal retainer bolt torque versus vibration transmissibility and leakage. All of these development tests were made before the test bellows was installed in the fixture.

IX. DISCUSSION OF TEST RESULTS

A. V-0

Data analysis revealed no resonant frequencies in the 200 to 400 Hz range. A slight problem surfaced during this test; the pressure chamber relief valve opened and reseated allowing the chamber pressure to drop to 320 psig momentarily. The valve relieved because the vibration apparently excited the valve spring. This was not considered to be a serious problem and no action was taken to alter the situation before the next test series. Actual test data are not given because all temperatures remained constant throughout the test. Pressure variations were only encountered when the relief valve opened and the vibration data showed no anomalies.

B. V-1

The relief valve activation problem became more prominent during this test. The value opened four times, allowing chamber pressure to vary from 345 to 410 psig. The shaft temperature remained constant at 70°F throughout the test. Bellows temperatures remained constant at room temperature.

C. V-2

At the end of test V-1, the relief valve was removed from its hard line mounted position on top of the pressure chamber and installed in the flex line leading to the outside vent area. This seemed to help; however, the valve still relieved three times during V-2 test and allowed the chamber pressure to drop to 320 psig. Temperature changes were more prominent during V-2 than had been noted on any previous tests. Shaft temperature was more pronounced with an increase of from 60°F at the start of vibration to 100°F when the test was stopped after 740 sec. The temperature thermocouple on the bellows indicated an increase from 68°F at the start of the test to approximately 90°F when the test was stopped. These temperatures continued to climb to approximately 120°F on the bellows and 130°F on the shaft after the test was stopped. It was concluded that the bellows temperature increase was caused by heat being transmitted from the shaft which heated up from the shaft seal friction. There was no indication of bellows rupture or even any deterioration at this point in the test program.

D. V-3 Through V-7 Plus Additional Testing

The relief valve was removed and readjusted to open at 425 psig before starting test V-3. This completely resolved the pressure regulation problem. Tests V-3 through V-7 were accomplished without incident and steady-state conditions were achieved at approximately 1600 sec into the test. Shaft temperature increase was the most dynamic parameter, increasing from 80°F at the start of the vibration test to 136°F at 1600 sec. The test bellows temperature followed the shaft temperature because of the heat being transmitted from the shaft caused by seal friction to the bellows through the mounting interface. Maximum temperature of the bellows was 112°F and this occurred at 3200 sec into the test. Variable data recorded during V-3 through V-7, plus the additional vibration test at steady-state conditions, are presented in Table 1. As was previously mentioned, the decision was made to continue the test under steady-state conditions to achieve approximately 2 million cycles. This required an additional 6.75 min of testing. There was no change in any variable data parameter during this additional testing. Shaft temperature remained constant at 134°F, mid bellows temperature remained constant at 110°F, and the end convolute of the bellows remained at 112°F throughout this test period.

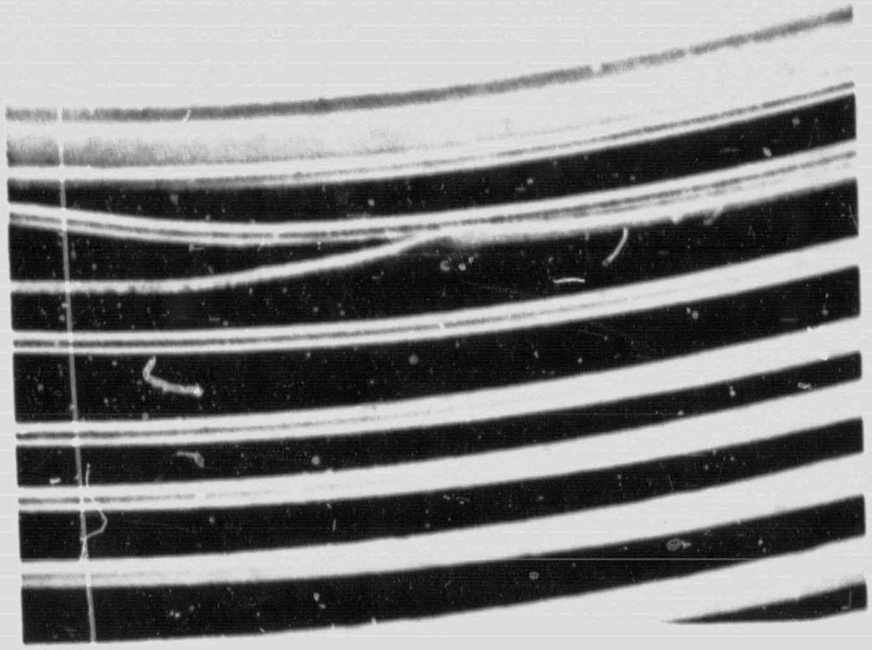
The bellows was removed from the fixture and subjected to a thorough visual analysis after these tests. No damage or evidence of any problem was visible.

TABLE 1. VARIABLE TEST DATA

Time (sec)	Temperature (°F)			Chamber Pressure (psig)
	Mid Bellows	Lower Bellows	Top of Shaft	
Before Test	81	80	88	0
After O_2 Purge	74	75	80	30
Vibration Start	75	75	82	400
400	80	79	87	403
800	94	94	115	402
1200	102	105	131	400
1600	105	109	136	400
2000	107	110	136	402
2400	108	110	135	402
2800	109	110	135	400
3200	109	112	135	401
3600	110	112	135	401
End of Test 4105	110	112	134	401

E. Destruct Test

The final vibration test was made to determine what would happen if the bellows failed allowing oxygen to be exposed to the freshly fatigued metal surfaces. It was determined that the vibration table capability was 0.8 in. double amplitude displacement at 20 Hz. This displacement greatly exceeds the design capability of the bellows imposing considerable overstress in the convolutes. It was calculated that the bellows would fail within the first 150 cycles. It failed after approximately 50 cycles. The failure mode was rupture of the bellows convolute second from the seal end where the vibration transmission shaft was attached. The bellows material separated in the weld heat affected zone adjacent to the weld (Fig. 11). The bellows convolute separated approximately 40 percent of the circumference.



10X VIEW OF RUPTURED BELLOWS ASSEMBLY

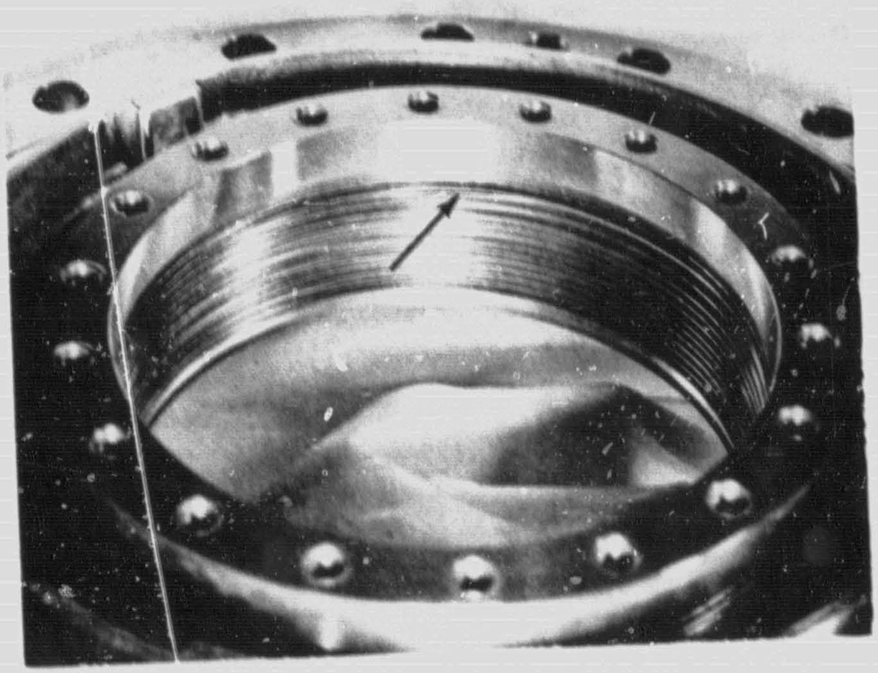


Figure 11. Photographs of ruptured bellows assembly.

When the bellows ruptured, the 400 psig O_2 vented through the rupture causing a buildup of pressure in the overboard vent line which activated the automatic O_2 supply shutoff valve. No indication of a fire or explosion was detected. Vibration equipment was shut down normally, and the chamber was purged with GN_2 before personnel entered the test area.

X. SAFETY

Since the primary objective of this test program was to try to cause a fire, it was evident that safety should be involved.

All plans and procedures were reviewed and approved by representatives of the MSFC Safety Office. A representative from the MSFC Safety Office also was present to witness the tests.

Firemen with their extinguishing equipment were at the test site at all times when oxygen was being used in the test chamber. The firemen were briefed on the planned events and facility layout before each series of tests.

A section of the test procedure was provided as a checkoff list for assuring that all test personnel and firemen knew their assignments in case a fire did occur.

Evacuation plans and diagrams were provided for all test personnel and were brought to their attention by the Test Conductor before each test.

The test area was roped off and guards were posted to assure that no unauthorized persons entered the hazardous areas during the test time.

All tests were made after normal working hours to eliminate the possibility of voltage transients caused by turning off or on high current usage equipment and also to cut down on the number of people who might be in the test area who were not needed for the actual conduct of the test.

APPENDIX A. TEST PROCEDURE[1]

1. This appendix is the test procedure EH14-PROC-007-77 titled, "Test Procedure for SSME Bellows Seal Assembly Vibration Test." This document contains details of the tests and provides space for recording variable data during the conduct of the test. The procedure was approved by all responsible disciplines before implementation of the test program.

EH14-PROC-007-77

TEST S/N ____________________

TEST DATE ____________________

TEST PROCEDURE

FOR

SSME

BELLOWS SEAL ASSEMBLY

VIBRATION TEST

By

MATERIALS & PROCESSES LABORATORY

SCIENCE & ENGINEERING

GEORGE C. MARSHALL SPACE FLIGHT CENTER

MARSHALL SPACE FLIGHT CENTER, AL 35812

The signatures below constitute approval of Test Procedure EH14-007-77 for an investigative type vibration test of the high pressure oxidizer turbopump seal bellows assembly with damper ring installed.

APPROVED BY: [illegible] DATE 5-3-77
M&P

APPROVED BY: [illegible] DATE [illegible]
Design

APPROVED BY: [illegible] DATE [illegible]
Safety

APPROVED BY: [illegible] DATE 5/3/77
Test

Test Procedure for SSME Bellows Vibration Test

1.0 Objective

To perform an investigative type of vibration test on an SSME metal bellows assembly as defined in the "Test Plan for the SSME Bellows Vibration Test."

2.0 General

This test will be conducted in Building 4619 with the test hardware described in the Test Plan installed on the Vibration Table in Room 160 according to the procedure given in Section 3.

3.0 Test Procedure

3.1 Pre-Test Facility Checkout

3.1.1 Verify test article installation per Figure 1. ________

3.1.2 Instrumentation and gas control system verification. ________

3.1.2.1 Stripchart Recorder (verify measurement hookup).

Channel	Measurement	Range	
1	Vent Pressure	0-15 psig	________
2	Chamber Pressure	0-500 psig	________
3	T/C-1 Mid Bellows	0-250°F	________
4	T/C-2 Lower Bellows	0-2500°F	________
5	T/C-3 Lower Bellows	0-250°F	________
6	T/C-5 Shaft	0-250°F	________

3.1.2.1.1 Verify chart speed set for 1.0 mm/sec. ________

3.1.2.2 Video Recorder and Fiber Optic Verification.

3.1.2.2.1 Verify CCTV camera mated to fiber optics and T/C-1 (if possible) displayed on TV monitor. Otherwise, display clear view of bellows. ________

3.1.2.2.2 Verify that recorder is operational by record and playback of CCTV picture. ________

3.1.2.2.3 Verify audio channel #1 of video recorder by input of signal generator set at 400 Hz and playback on oscilloscope. ________

3.1.2.2.4 Verify hookup of strain gage balance to CCTV tape recorder and audio channel #1. ________

3.1.2.3 Gas Control System Verification.

3.1.2.3.1 Verify gas control system functional operation per Figures 2 and 3 and as follows:

	ACTION	RESULT	
a.	Vent SW-ON	Vent VLV OPEN	________
	Vent SW-OFF	Vent VLV CLOSED	________
b.	O_2 SW-CLOSED	GOX VLV (Green IND LT)	________
c.	O_2 SW-CLOSED & Actuate O_2 FILL PUSHBUT" ON	GOX VLV (Amber IND LT)	________
d.	Verify vent line pressure switch de-activates GOX VLV by de-energizing relay R-1		________

3.1.2.3.2 Verify relief valve certification of operation. ________

3.1.2.3.3 Verify GOX monitor in place and operational. ________

3.1.3 Calibration of Accelerometers

3.1.3.1 Patch accelerometer circuits through to recorders and log appropriate information on instrumentation data sheets. ________

3.1.3.2 Mount accelerometers on shaker. ________

3.1.3.3 Record charge amplifier calibration voltage on instrumentation data sheets. ________

3.1.3.4 Set charge amplifier for 10 g peak. ________

3.1.3.5 Set oscillator frequency at 44.3 Hz. ________

3.1.3.6 Bring shaker up to 0.1 inch D.A.D. as indicated by a displacement wedge. ________

3.1.3.7 Set each charge amplifier to its calibration voltage.

3.1.3.8 Turn shaker off. ________

3.1.3.9 Record charge amplifier gain settings. ________

3.1.4 Vibration Facility Checkout

3.1.4.1 Test Engineering verify test requirements. ________

3.1.4.2 Mount master control and backup accelerometer on shaker. ________

3.1.4.3 Insert sine test patch panel in control system (4619). Position sine/random switches to sine. ________ ________

3.1.4.4 Set up and run sine tests prescribed. Record shaker amplifier and charge amplifier settings.

	Sine Evaluation	Vehicle Dynamics
Shaker Amplifier Setting	________	________
Charge Amplifier Setting	________	________
Charge Amp. Servo Switch Setting	________	________

3.1.4.5 Mount test specimen on shaker per TSS. ________

3.1.4.6 Install specimen accelerometers per TSS. ________

3.1.4.7 Excite accelerometers and verify continuity through to recorders and control system. ________

3.2 Test Preparation

3.2.1 N_2 Purge of Chamber and Gas System

3.2.1.1 Close HOV-1. ________

3.2.1.2 Remove POV-3 from Port 2 (Fig. 4). ________

3.2.1.3 Disconnect O_2 line from O_2 supply. ________

3.2.1.4 Connect GN_2 bottle to O_2 press line (inlet of POV-2). ________

3.2.1.5 Set purge pressure to 100 psig. ________

3.2.1.6 Open HOV-1 to full open position. ________

3.2.1.7 Open POV-5 and verify flow at Port #2 of chamber. ________

3.2.1.8 Flow purge gas for 15 minutes - monitor chamber pressure on T-1 (100 psig Redline). ________

3.2.1.9 Close valve POV-5. ________

3.2.1.10 Replace POV-3 in Port 2. ________

3.2.2 <u>Chamber Leak Test</u>

3.2.2.1 Close POV-3. ____________

3.2.2.2 Open valve POV-5. ____________

3.2.2.3 Monitor pressure on T-1 (ensure 100 psig). ____________

3.2.2.4 Allow pressure to stabilize for 3 minutes. ____________

3.2.2.5 Audibly and visually check for gross leakage. ____________

3.2.2.6 Close valve POV-5. ____________

3.2.2.7 Monitor T1 for five minutes - record pressure decay rate. ____________psi/minute.

3.2.2.8 Adjust GN_2 pressurization system to 400 $\pm$ 5 psig. ____________

3.2.2.9 Open POV-5. ____________

3.2.2.10 Repeat steps 3.2.2.4 through 3.2.2.7. ____________

3.2.2.11 Increase chamber pressure to 475 psig or until relief valve RV-1 opens. Record relief pressure. ____________psig

3.2.2.12 Re-adjust chamber pressure to 400 $\pm$ 5 psig and lock off pressure. ____________

3.2.2.13 Check vibration table alignment relative to the zero position. Record position and direction. ____________

3.2.2.14 Loosen vibration table lock bars one bolt at a time and record alignment changes

a. Inside Bolt #1 ____________________

b. Inside Bolt #2 ____________________

c. Inside Bolt #3 ____________________

d. Inside Bolt #4 ____________________

e. Outside Bolt #1 ____________________

f. Outside Bolt #2 ____________

g. Outside Bolt #3 ____________

h. Outside Bolt #4 ____________

3.2.2.15 Open POV-3, reduce chamber pressure to ambient. ______

3.2.2.16 Repeat step 3.2.2.13 alignment check. Record position and direction. ____________

3.2.2.17 Re-torque vibration table lock bars. ______

3.2.2.18 Repeat step 3.2.2.13 alignment check. Record position and direction. ____________

3.2.2.19 Disconnect and remove GN_2 pressurization system from Port #4 and reconnect O_2 supply system. ______

3.2.3 <u>Cold GN2 Purge Initiation</u>

3.2.3.1 Connect cold GN_2 purge system to dynamic seal purge Port #5. ______

3.2.3.2 Open HOV-6 and ensure flow from overboard vent. ______

3.2.3.3 Close HOV-6. ______

3.2.4 <u>Pre-Gox Pressurization Safety Precautions</u>

3.2.4.1 STOP ALL ACTIVITIES AND INSURE THAT ALL CRITICAL PARAMETERS ARE ASSIGNED TO MONITORS. RECORD NAMES BELOW.

Channel 1.	Vent Pressure	0 - 15 psig	____________
Channel 2.	Chamber Pressure	0 - 500 psig	____________
Channel 3.	T.C. #1 Mid Bellows	0 - 250°F	____________
Channel 4.	T.C. #2 Lower Bellows	0-2500°F	____________
Channel 5.	T.C. #3 Lower Bellows	0 - 250°F	____________
Channel 6.	T.C. #5 Shaft	0 - 250°F	____________

3.2.4.2 Assign valve activation and recorder operational personnel.

POV-3	________
POV-5	________
HOV-1	________
POV-1	________
POV-2	________
HOV-3	________
HOV-2	________
HOV-6	________
CCTV RECORDER	________
STRIP CHART RECORDER	________

3.2.4.3 Assure that an emergency exit plan is understood by all test personnel. ______

3.2.4.4 Assure that firemen and safety personnel understand assignments. ______

3.2.4.5 Verify all communications channels. ______

3.2.4.6 Verify firemen readiness. ______

3.2.4.7 Clear hazardous areas of all personnel. ______

3.2.5 <u>Gox Purge and Pressurization</u>

3.2.5.1 Adjust O_2 supply pressure to 30 psig. ______

3.2.5.2 Open HOV-1 to full open position. ______

3.2.5.3 Open POV-5 and POV-1 and monitor T-1 for chamber pressure. Verify 30 psig. 1 ______

3.2.5.4 Open vent valve POV-3 and reduce chamber pressure to 5 psig. ________

3.2.5.5 Close vent valve POV-3 and increase chamber pressure to 30 psig. Verify. 2 ________

3.2.5.6 Open vent valve POV-3 and reduce chamber pressure to 5 psig. Verify. ________

3.2.5.7 Close vent valve POV-3 and increase chamber pressure to 30 psig. Verify. 3 ________

3.2.5.8 Open vent valve POV-3 and reduce chamber pressure to 5 psig. Verify. ________

3.2.5.9 Close vent valve POV-3 and increase chamber pressure to 30 psig. Verify. 4 ________

3.2.5.10 Open HOV-6 and start cold GN_2 purge of seal cavity. Verify flow at overboard vent. ________

3.2.5.11 Increase chamber pressure to 400 $\pm$ 5 psig. Verify. ________

3.2.5.12 Adjust HOV-1 and POV-2 as necessary during vibration testing to maintain chamber pressure at 400 $\pm$ 5 psig.

3.2.5.13 Adjust HOV-6 as necessary during vibration testing to maintain shaft temperature below 85°F. If shaft temperature reaches 450°F notify test conductor and prepare for normal shutdown.

4.0 Vibration Test Operations

4.1 Assure that vibration equipment is set up for operation at 400 Hz, .007 in. D.A. ________

4.2 Turn on instrumentation calibration switches listed in Instrumentation Data Sheet. ________

4.3 Record all calibrations on recorders. ________

4.4 Turn off all calibration switches. ________

4.5 Set range on instrumentation amplifiers and record range on recorder data sheet. ________

4.6 Set control accelerometer charge amplifier range and servo switch to positions determined during pretest checkout. Record range on recorder data sheet. ________

4.7 Set close loop switch to open, and, if shaker is hooked up to team tables, turn on hydraulic pump. ________

4.8 Turn shaker amplifier gain to position determined during pretest checkout. ________

4.9 Turn compressor switch to STBY position and turn OUTPUT full open. ________

4.10 Turn compressor switch to AUTO. ________

4.11 Turn on all appropriate recorders. ________

4.12 Activate X-Y recorder. ________

4.13 Start test V-3. (Go to 5.0). ________

4.14 At end of test, turn the compressor switch to STBY -- and the OUTPUT off. ________

4.15 Turn shaker power amplifier off. ________

4.16 Fifteen seconds after end of test, turn off all recorders. ________

4.17 Visually inspect test specimen for damage or degradation. ________

4.18 Wait until bellows temperature stabilizes at the initial temperature and return to III, 1-18. ________

5.0 Controlling Test Criteria

5.1 Monitor T-1, to be maintained at 400 psig (+5, -2), regulate by adjusting HOV-1. ______

5.2 Monitor TC-1, if temperature reaches 300°F (+0, -10) TERMINATE TEST. ______

5.3 Monitor vent tube pressure, if pressure reaches 10 psig, TERMINATE TEST. ______

6.0 Test Termination

6.1 At end of each 740 second test notify the Test Conductor. ______

6.1.1 If Test Conductor's decision is to proceed continue steady state operation until all tests through V-7 have been accomplished. ______

6.1.2 If decision is to terminate test, go to 6.2. ______

6.2 Termination of O_2 and N_2 Systems

6.2.1 Slowly reduce chamber pressure by adjusting O_2 supply valve to zero psig. ______

6.2.2 Allow GN_2 purge systems to continue for 5 minutes after O_2 has been vented. ______

7.0 Contingency (In Case of Fire)

7.1 Close POV-5 (shuts off O_2). ______

7.2 Open POV-3 (vents chamber). ______

7.3 Notify all personnel and firemen. ______

7.4 Turn off servo and down cycle power amplifiers. ______

7.5 Evacuate all personnel. ______

7.6 Firemen inspect and secure test cell as required and notify electrician to remove power if necessary at sub-station. ______

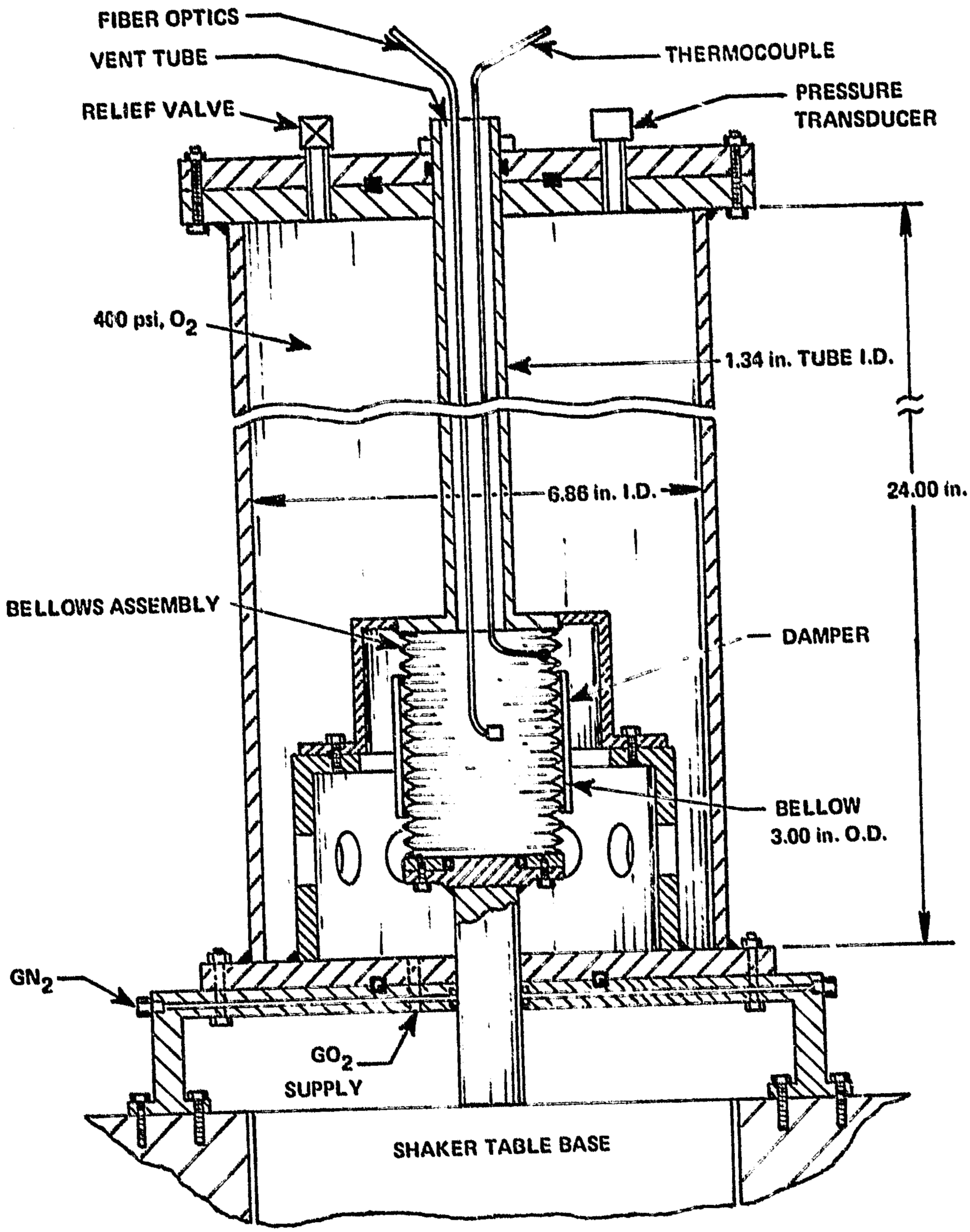


Figure 1. Bellows vibration test.

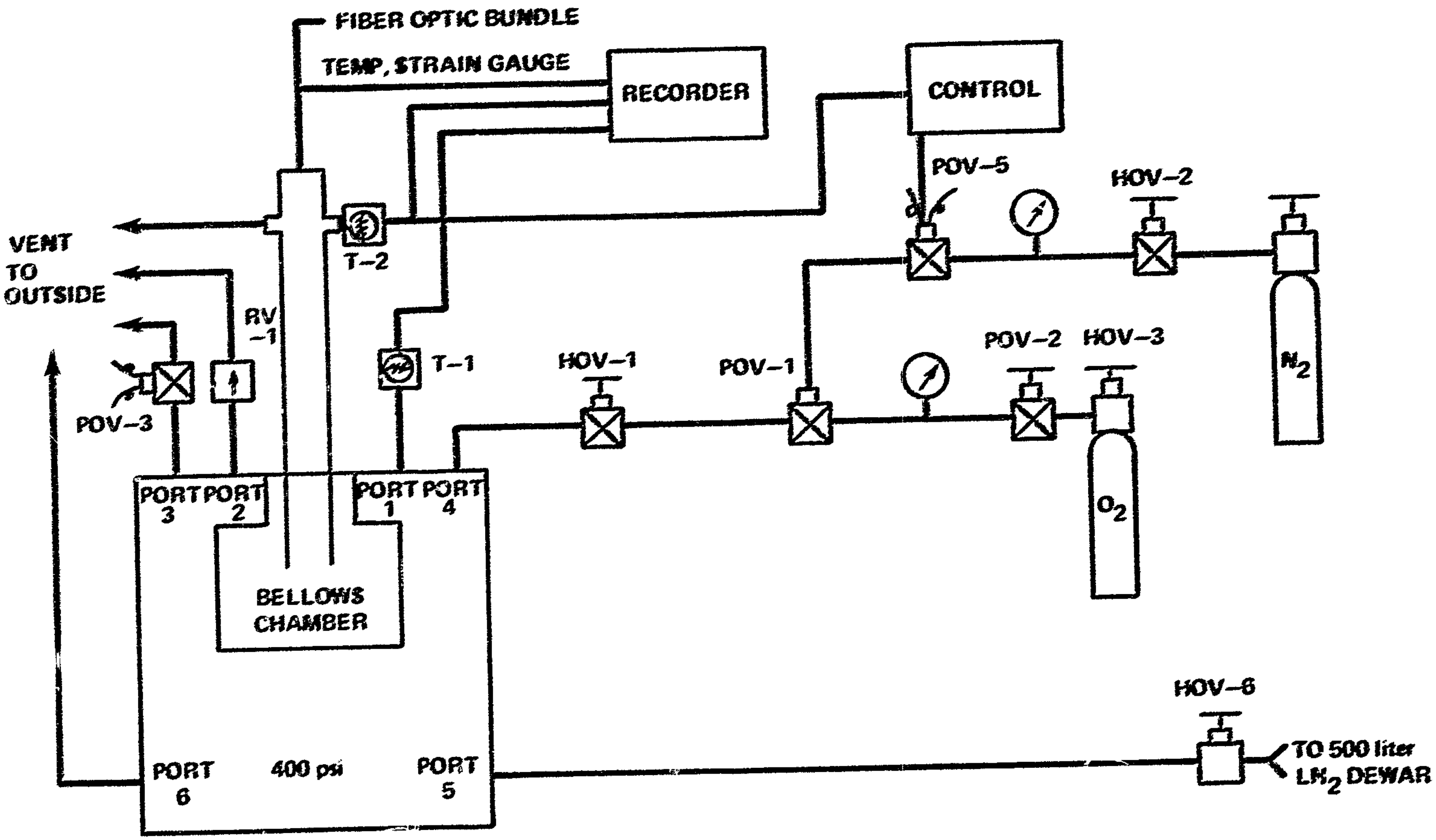


Figure 2. SSME bellows test instrumentation and gas control schematic.

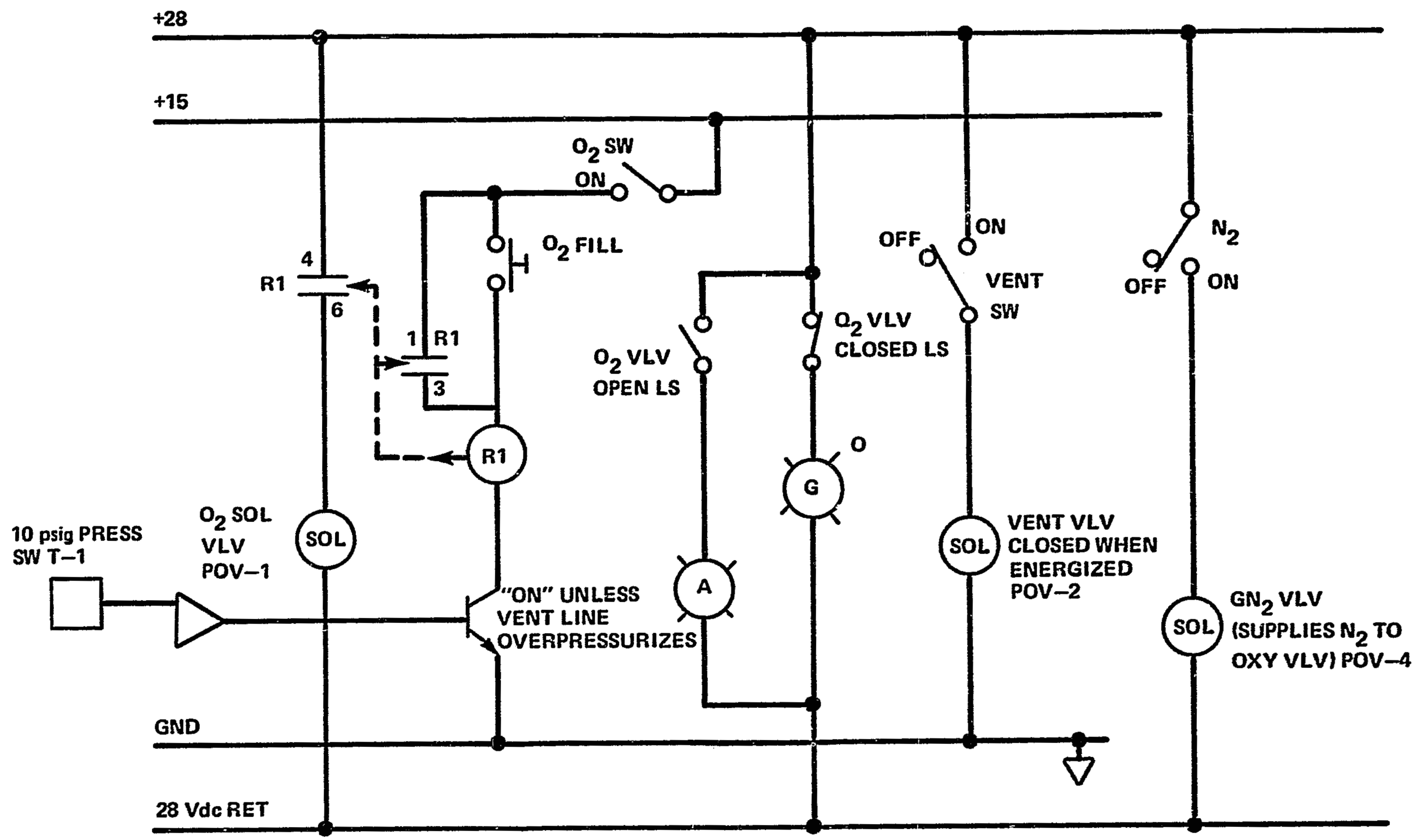


Figure 3. SSME bellows test valve electrical control schematic.

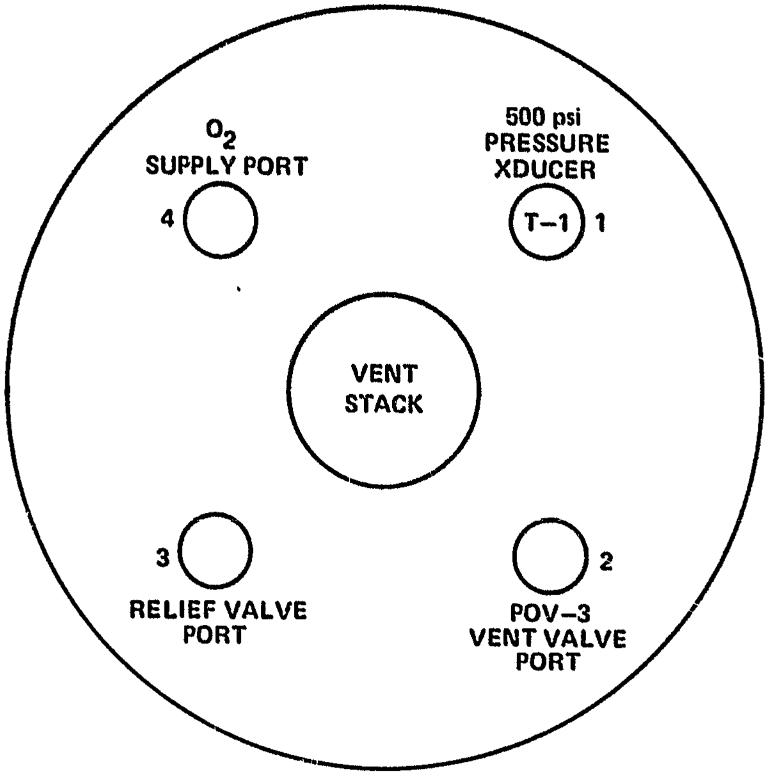


Figure 4. Top view of pressure chamber.

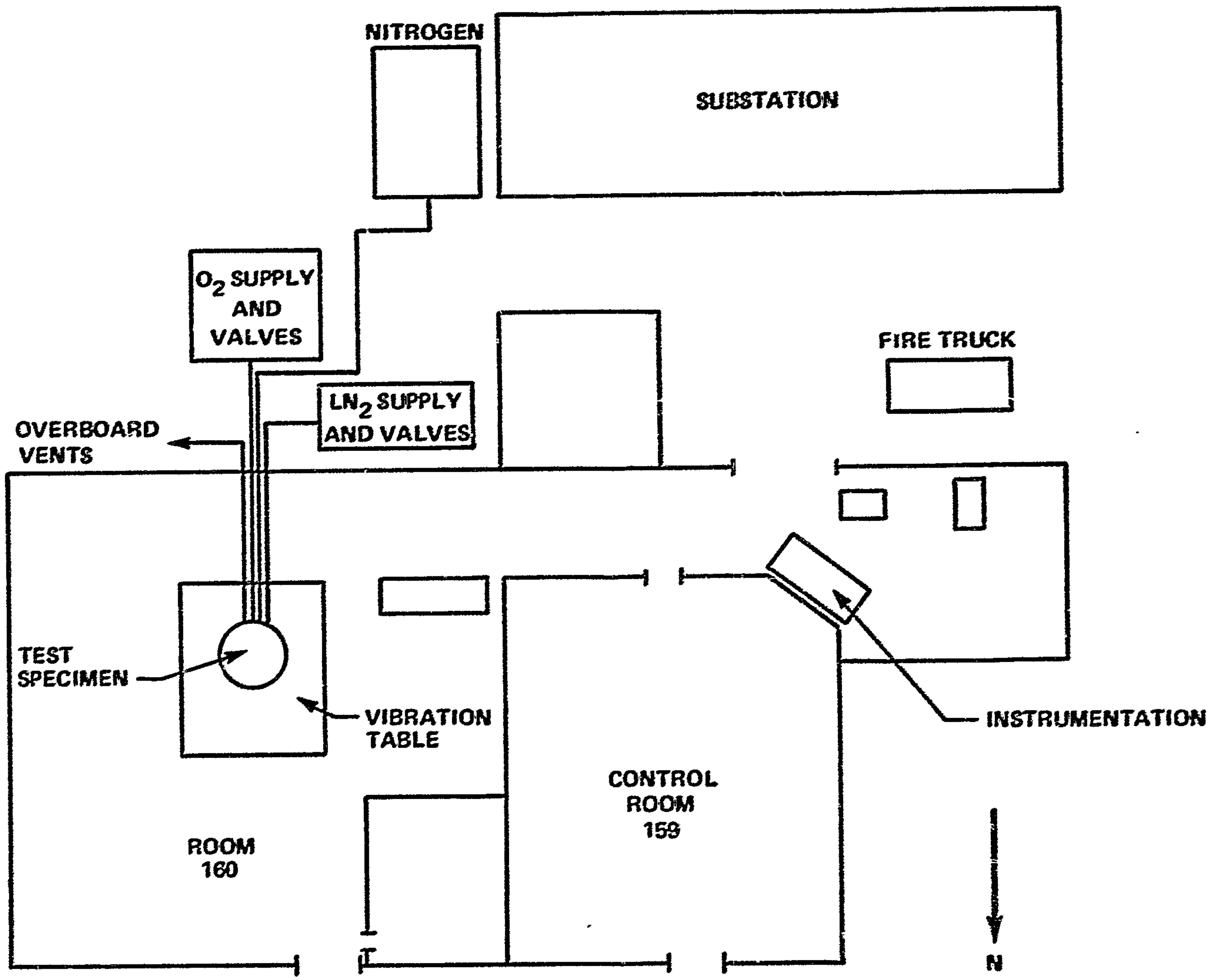


Figure 5. Test area layout.

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APPENDIX B. TEST PLAN[2]

2. This appendix is the test plan which was prepared at the onset of the program to provide general guidelines and objectives. This document was also approved by all responsible disciplines before implementation of the test program.

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TEST PLAN

SSME BELLOWS VIBRATION TEST

PREPARED BY: ENGINEERING PHYSICS DIVISION
MATERIALS & PROCESSES LABORATORY

APPROVAL: R. J. Schwinghamer

R. J. Schwinghamer
Director
Materials and Processes Laboratory

Alex A. McCool
Director
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Director
Test Laboratory

Donald L. Hartley

Donald L. Hartley
Safety Office

TEST PLAN FOR SSME BELLOWS VIBRATION TEST

1.0 Introduction

1.1 Purpose

The purpose of this plan is to define the objectives of the SSME bellows vibration test and the means by which these objectives will be accomplished.

1.2 Test Objectives

1.2.1 Primary - To investigate the SSME bellows assembly as an ignition source under simulated SSME high pressure oxygen turbopump gox pressure and vibration conditions.

1.2.2 Secondary - Determine bellows fatigue life and the effects of bellows failure in a high pressure gox environment.

2.0 Test Program

2.1 Test Program Management

Management of the test program is the responsibility of the Materials and Processes Laboratory and includes (a) the definition of test requirements and equipment; (b) establishment of test schedule; (c) coordination of all test hardware design, fabrication, and checkout; and (d) the planning of test activities.

2.2.1 Test Performance Responsibilities - The organizations responsible for the various activities associated with the technical aspects of this test effort are given below:

Function	Responsible Organization
Test Hardware Design	S&P Laboratory M&P Laboratory
Hardware Fabrication	Test Laboratory M&P Laboratory
Test Operations	Test Laboratory M&P Laboratory
Safety	Safety Office

2.2 Description of Test Hardware

2.2.1 Pressure Chamber and Bellows Assembly - Figure 1 attached shows the configuration of the bellows assembly and the method by which it is attached to the vibration source and the pressure chamber.

2.2.2 Instrumentation and Gas Control Systems - Figure 2 attached shows the schematic of the plumbing and valves necessary to control the pressurization and venting of the gox and the instrumentation necessary to provide the required test data.

2.3 Test Description

2.3.1 Vibration Induced Temperature Tests - These tests will be made by exciting the bellows assembly at a designated vibration frequency and displacement for a period of time determined by the temperature level induced in the convolutes by the rubbing of the convolutes with the damper or for a predetermined period of time. The test will be terminated when the prescribed time is achieved, when the temperature attains redline, when the vent tube pressure reaches 10 psig, or when an ignition is obtained. All tests will be made at a gox pressure of 400 $\pm$ 25 psi and a bellows preload of 18 pounds. The following test sequence will be followed:

Test No.	Redline Temp, °F	Frequency (Hz)	Amplitude (mils D.A.)	Time Sec
V-0	Low level sweep to determine system resonance			75
V-1	300	400	0.001	75
V-2	300	400	0.007	740
V-3	300	400	0.007	740
V-4	300	400	0.007	740
V-5	300	400	0.007	740
V-6	300	400	0.007	740
V-7	300	400	0.007	740

Results of 2.3.1 will be carefully reviewed prior to proceeding with 2.3.2.

2.3.2 Fatigue Life and Failure Effects Tests - This test will be initiated after the completion of 2.3.1. The bellows assembly will be vibrated with maximum preload applied to determine the fatigue life of the bellows in a 400 $\pm$ 25 psi gox environment. The input vibrational frequency, displacement, and preload shall be TBD Hz, TBD inch, and TBD lbs., respectively. When a fatigue crack is formed, a fresh metal surface will be exposed to a flow of high pressure gox and a determination will be made as to whether this type of failure can result in ignition of the bellows material.

2.4 Post Test Destructive Analysis

Following completion of all scheduled testing, the bellows assembly will be removed from the test chamber and made available for such destructive testing as may be deemed necessary.

2.5 Test Procedures

The detailed procedures required to conduct the tests described in 2.3 shall be prepared and approved by the Materials and Processes Laboratory, the Structures and Propulsion Laboratory, the Test Laboratory, and the Safety Office prior to test initiation.

3.0 Safety

To insure the safe conduct of the high pressure gox tests the following special precautions and safety measures must be implemented.

3.1 Proof Test

The pressure chamber shall be proof tested to twice the maximum operating pressure.

3.2 Cleaning

All parts exposed to the gox environment shall be cleaned according to standard procedures required for the gox service.

3.3 Materials Compatibility

Materials used in the test hardware which will be exposed to gox shall be gox compatible.

3.4 Gox Gas Control

The system of valves and plumbing required for the pressurization and venting of gox shall be designed so that the supply of gox can be shut off and the chamber can be vented quickly in the event of ignition. The design of this system shall be reviewed and approved by the Safety Office.

3.5 Contingency Procedures

A special set of procedures shall be prepared which define the specific actions to be taken in the event of ignition and subsequent burning of the bellows assembly or any associated test hardware during the performance of these tests.

4.0 Test Report

At the conclusion of these tests, a comprehensive test report shall be written describing the tests made, the test hardware used to make the tests, and the results obtained.

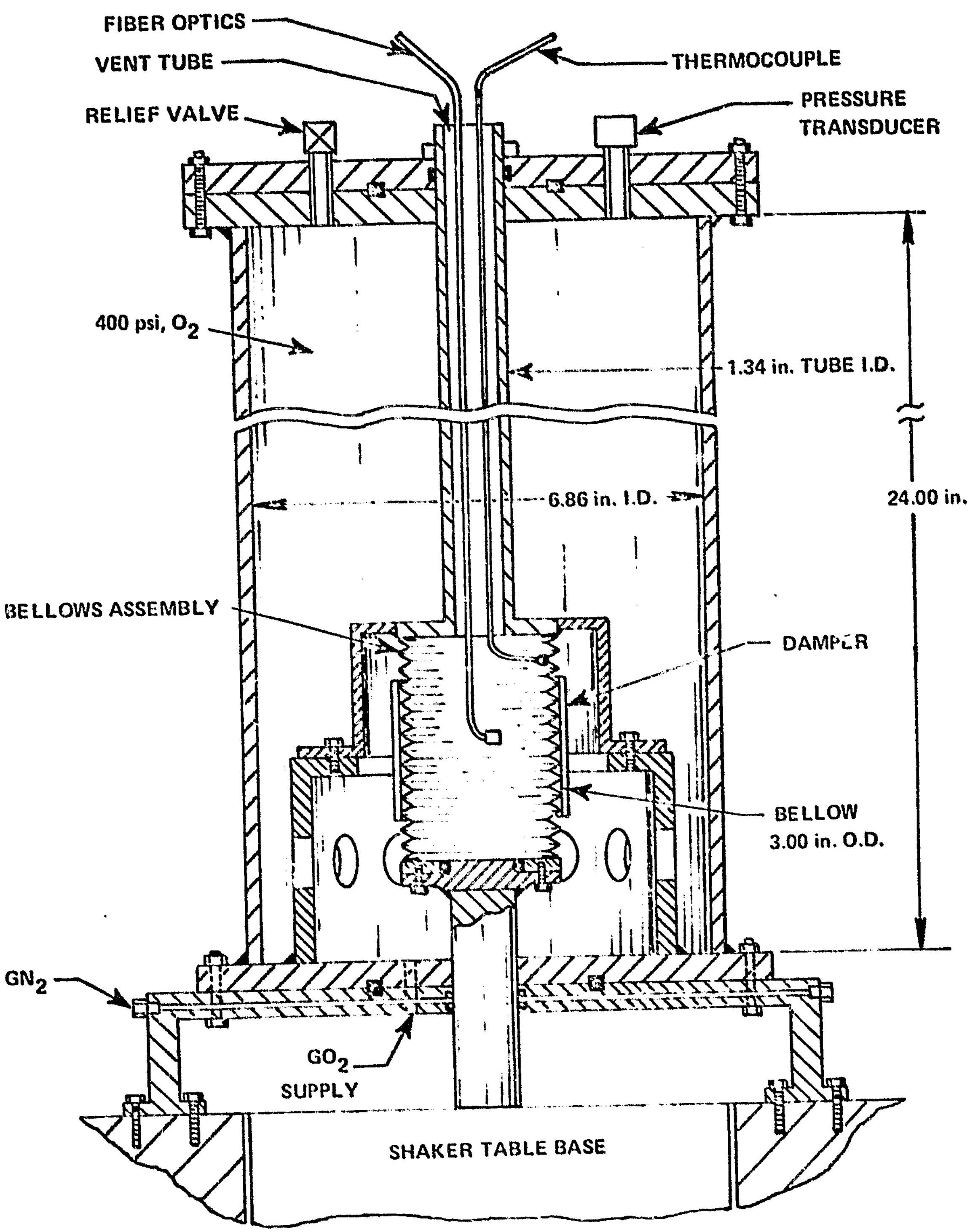

Figure 1. Bellows vibration test.

APPROVAL

VIBRATION EFFECTS ON THE SPACE SHUTTLE MAIN ENGINE HIGH PRESSURE OXIDIZER TURBOPUMP BELLOWS

By James A. Harp

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

R. J. SCHWINGHAMER
Director, Materials and Processes
Laboratory

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