NASA CR 62075

Service through Science

GPO PRICE $ ______

CFSTI PRICE(S) $ ______

Hard copy (HC) 3.00

Microfiche (MF) .65

ff 653 July 65

LUNAR EXCURSION MODULE PROPULSION SYSTEMS VALVE ACTUATING TESTS

FINAL REPORT

April 7, 1966 to July 23, 1966

by

RALPH D. GIFT
JACK M. SPURLOCK
JOHN A. SIMMONS
JAYDEE M. MILLER

for

MANNED SPACECRAFT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 9-5937

Control No. 6054039

ATLANTIC RESEARCH CORPORATION
Alexandria, Virginia
July 29, 1966

N68-25108 (ACCESSION NUMBER)
76 (PAGES)
CR 62075 (NASA CR OR TMX OR AD NUMBER)
1 (THRU)
(CODE)
28 (CATEGORY)
FACILITY FORM 602

LIBRARY COPY
OCT 3 1966
MANNED SPACECRAFT CENTER
HOUSTON, TEXAS

ATLANTIC RESEARCH

ATLANTIC RESEARCH CORPORATION
ALEXANDRIA, VIRGINIA

LUNAR EXCURSION MODULE PROPULSION SYSTEMS VALVE ACTUATING TESTS

FINAL REPORT

April 7, 1966 to July 23, 1966

by

RALPH D. GIFT
JACK M. SPURLOCK
JOHN A. SIMMONS
JAYDEE M. MILLER

for

MANNED SPACECRAFT CENTER
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

CONTRACT NAS 9-5937

Control No. 6054039

ATLANTIC RESEARCH CORPORATION
Alexandria, Virginia
July 29, 1966

This report was prepared by the Atlantic Research Corporation under Contract No. NAS 9-5937, entitled "Lunar Excursion Module Propulsion Systems Valve Actuating Tests", for the NASA Manned Spacecraft Center. Work on the overall program was administered under the technical direction of the Propulsion Design Section of the Propulsion and Power Division, Manned Spacecraft Center, with Mr. Oscar Cabra, Jr. serving as project manager.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

This report presents the results of an experimental program to evaluate the performance, in a vacuum environment, of the propellant-valve actuating systems for the Lunar Excursion Module Descent and Ascent Engines. The objectives of the program are two-fold: (1) to determine the extent of adverse effects that could result from evaporatively-frozen propellant in the propellant-valve actuating systems (i.e. pilot valves, actuators and vent lines); and (2) to investigate a few remedial techniques for the reduction of such effects. The Descent and Ascent pilot-valve and actuator assemblies, which were Government supplied, were tested in the Atlantic Research Corporation's high-altitude facility. The working fluid was a 1:1 mixture of hydrazine and unsymmetrical dimethylhydrazine.

Three general types of tests were conducted: (1) normal mission duty-cycle tests, (2) leak tests, and (3) remedial tests. During the normal-mission tests, evaporatively-frozen propellant produced no problems which would have prevented successful completion of the normal LEM Descent and Ascent missions, as presently defined; however, malfunctions, in both the Descent and the Ascent valve-actuating systems were encountered during the endurance (20- and 35-restart) sets of tests. During the leak tests and remedial tests it was determined that a small orifice, positioned at the vent-line exit, can be used effectively to limit the amount of propellant loss in the event of the pilot valve sticking in the half-open position. Such an orifice also can be a deterrent to evaporative freezing of propellant upstream of the orifice; however, the orifice alone is not a panacea for the overall problem of freezing and vent-line plugging.

It was demonstrated during this experimental program that application of heat to the vent line can be an effective deterrent of blockage due to evaporative freezing. Further effort is recommended to determine the amount of heat required to prevent evaporative freezing for various missions and leakage situations. A more detailed valve-leakage study, including an evaluation of overall system performance in a vacuum, also is recommended.

1.0 SUMMARY

This final report describes the results of an 11-week experimental program to evaluate the operation, in a vacuum environment, of the propellant valve actuating systems for the LEM (Lunar Excursion Module) Descent and Ascent engines. The purpose of the program was to determine the extent to which adverse effects could be produced by evaporatively frozen propellant in the vent lines of the LEM propellant valve actuating systems. The test program was divided into two major parts: LEM Descent tests and LEM Ascent tests. The propellant used was a 1:1 mixture of hydrazine and unsymmetrical dimethylhydrazine.

The principal results of this investigation are as follows:

(a) Evaporatively-frozen propellant produced no problems which would have prevented successful completion of the normal LEM Descent and Ascent duty-cycle missions as presently defined, however malfunctions, both in the Descent and Ascent valve actuating systems were encountered during the endurance (20- and 35-restart) sets of tests.

(b) Vent-line blockage, produced by evaporatively-frozen propellant, occurred only near the vent-line exit.

(c) Vent-line exit geometry and immediate surroundings are important design factors because evaporatively-frozen propellant must be able to collect around or lodge against an object (such as a tube end, a plate or piece of structure upon which the venting propellant impinges, etc.) in order to form a rigid plug.

(d) A small orifice positioned at the vent-line exit can be used effectively to limit the amount of propellant loss in the event of the pilot valve sticking in the half-open position.

(e) An orifice at the vent-line also can be a deterrent to evaporative freezing of propellant upstream of the orifice.

(f) No leakage of the LEM Ascent valve actuating system was noted during the tests; however, considerable leakage was experienced past the piston seal in the LEM Descent valve actuating system.

(g) Approximately 13.2 watts of applied heat were required, for the worst case (i.e., where the composition of the freezing propellant mixture is such that the vapor pressure is at the maximum, approximately 26.5 torr, for freezing composition), to prevent evaporative freezing in a vent line containing a 1/16-inch diameter orifice at the vent-line exit.

Based on these results, it is apparent that under certain conditions, evaporatively frozen propellant could prevent a mission from being successfully completed. The controlling factor is the number of cycles the valve actuating systems are required to make. The operation of the actuator system will not be affected as long as the propellant in the actuator can be expelled into the vent line by the spring actuated piston. If, however, blockage of the vent line should occur, the number of cycles that could be successfully completed is a function of the ratio of the volume of the vent line to the volume of the actuator (volume of propellant required to actuate the piston). A recommendation therefore to refine and perhaps supplement the remedies briefly tested in this program, (i.e., application of heat and positioning a small orifice at vent line exit) is justified.

2.0 INTRODUCTION AND DISCUSSION

A recent test program conducted by Aerojet-General has indicated that the failure of the Titan III Vehicle 4C during the Transtage portion of the flight, likely was caused by propellant evaporatively freezing under the influence of its exposure, upon venting, to the vacuum environment of space. Evaporative freezing of propellant leakage through the pilot valve was shown in ground tests to cause blockage of the vent line, which then prevented the valve from operating properly. The Transtage utilizes a fuel-actuated pilot-valve system to operate the engine bipropellant valves.

The fact that the Lunar Excursion Module (LEM) Ascent and Descent engines utilize a fuel-actuated system very similar to that of the Titan Transtage has led to concern regarding problems which possibly could be caused by frozen propellant in the vent ports of these LEM engines. Although an elaborate redundant valving system is employed, blockage of flow by frozen propellant in several vent ports could impair or prevent restart of the LEM Descent or Ascent engines.

This final report presents the results of an 11-week test program conducted to determine the effects of a vacuum environment on the operation of the LEM Ascent and Descent engine pilot-valve and actuator venting systems. Government-furnished Ascent and Descent valves were tested in the Atlantic Research Corporation's high altitude facility. The propellant used was Aerozine-50 (a 1:1 mixture of N_2H_4 and UDMH), for which the pilot valve and actuator system was designed.

The behavior of liquids upon exposure to a vacuum environment involves a variety of phenomena, most of which result directly or indirectly from the suddenly imposed supersaturation(1)*. Volatile liquids exposed either in bulk or by flowing through a port usually boil, and the growth and bursting of bubbles break the liquid up into a cloud of vapor and drop lets. Surface forces and other disturbances created by the flow of the

---

* Superscript numbers in parentheses correspond with numbered references in the Literature Citations at the end of this report.

liquid also contribute significantly to the breakup. Simultaneous (with breakup and dispersal) evaporation occurs from all free surfaces of the liquid. The rate of evaporation depends primarily on the temperature of the surface, or consequently the equilibrium vapor pressure of the surface. Vapor-phase resistance to evaporation is slight unless the ambient pressure is greater than about 10 per cent of the equilibrium vapor pressure. Because of the associated removal of the latent heat of vaporization, evaporation causes cooling of the liquid. In a space environment, the rate of evaporative cooling is very great, and usually exceeds the rate of heating from outside sources, even when the vapor pressure of the liquid at the surface is a small fraction of a mmHg. Consequently, small drops of a pure (single-component) liquid whose triple-point pressure is greater than one mmHg cool, freeze, and sub-cool, all within a second or less after exposure to a space environment. The difference between the value of the triple-point pressure (of a pure liquid) and the vacuum conditions of space produces the driving force for evaporative cooling and freezing of single-component liquids.

Aerozine-50 is not a pure liquid and therefore does not have a triple point, but freezes over a range of temperatures. As the mixture is cooled, the first solid phase, which is pure hydrazine, appears at approximately $18^{\circ}F$ ($-8^{\circ}C$). Freezing-out of hydrazine continues with more cooling, and the liquid phase becomes enriched in UDMH, accompanied by a decrease in the freezing point. Eventually, the liquid reaches the eutectic composition, about 98 per cent (weight) UDMH, which freezes at approximately $-78^{\circ}F$ ($-61^{\circ}C$). If the cooling is caused by evaporation, the entire mixture (solid and solution) is hydrazine enriched, since for solutions with UDMH concentrations greater than 20 per cent (weight), the vapor is nearly pure UDMH. Furthermore, because the heat of vaporization of UDMH is approximately 1.5 times the heat of fusion of hydrazine (based on a unit weight), the hydrazine rapidly freezes such that the remaining liquid solution becomes enriched with UDMH in spite of the loss of UDMH by evaporation. Assuming that the heat of fusion of hydrazine and the heat of vaporization of UDMH from the solutions are the same as for the pure materials, it is estimated that after all the eutectic has been frozen, the over-all composition of the frozen material is approximately 95 per cent (weight) hydrazine. Continued evaporation will cause still more hydrazine enrichment. This brief review describes the type of process by which evaporative freezing of Aerozine 50 was expected to occur in the LEM Ascent and Descent valve-actuator vent lines.

Section 3.0 of this report describes the experimental studies including the test apparatus, test procedure, and safety considerations. The tests were conducted in two parts: (1) with LEM Ascent components, and (2) with LEM Descent components. Results of the tests and their analysis are presented in Section 4.0. Conclusions and recommendations for future work are discussed in Sections 5.0 and 6.0, respectively. The detailed body of data obtained during the experimentation is presented in Appendix A.

3.0 EXPERIMENTAL SYSTEMS AND PROCEDURES

3.1 BACKGROUND

The objective of this experimental program was to evaluate the operation, in a vacuum environment, of the propellant valve actuating systems for the LEM Ascent and Descent engines. The Government-supplied LEM Ascent and Descent pilot valve and actuator assemblies were tested in the Atlantic Research Corporation's high-altitude facility at a pressure of approximately 0.04 torr (230,000 feet altitude). To establish the background for the problem of interest and the experimental approach employed, a brief description of the operation of the LEM engine propellant valves is presented in the following paragraphs.

The ball-type main propellant valves used in the LEM Ascent propulsion system, are operated by a hydraulic actuator sub-system which uses the fuel mixture of hydrazine and unsymmetrical dimethylhydrazine as the working fluid. Briefly, a three-way solenoid valve is energized, allowing the fuel to enter the actuator cylinder and move a piston. The piston provides the necessary reciprocating motion to a linkage which operates two ball-valves (one fuel and one oxidizer). When the solenoid is deenergized, the spring-loaded piston expels the fuel overboard through a long vent line having numerous bends. Four such ball-valves, arranged in a series-parallel flow network (two parallel lines, each containing two ball valves in series) are used for each of the two propellants. Thus four separate vent lines are required to comprise the total propellant (fuel and oxidizer) feed system. This redundancy technique is used to improve the reliability of the system. These eight ball-valves are actuated by four pilot-valve and actuator systems. Only one of the four pilot-valve and actuator assemblies was tested during the LEM Ascent portion of the program. This assembly is shown in Figures 3-1 and 3-2.

The propellant valving system for the LEM Descent propulsion system uses a valve arrangement and principle of operation which are the same as those used in the LEM Ascent valving system (four ball-valves arranged in a series parallel flow network, for each propellant). However, a different

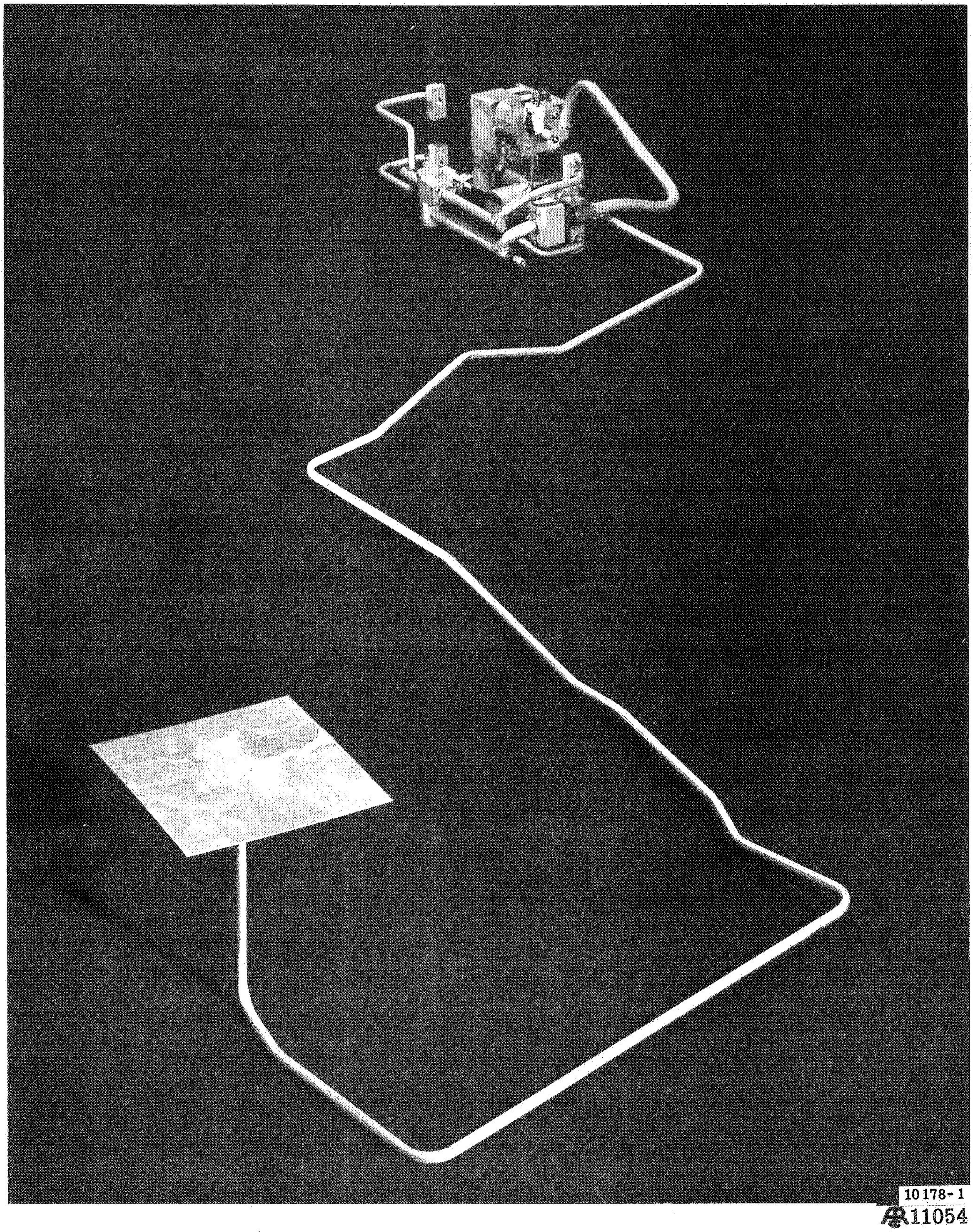


Figure 3-1. LEM Ascent Pilot Valve, Actuator and Vent Line.

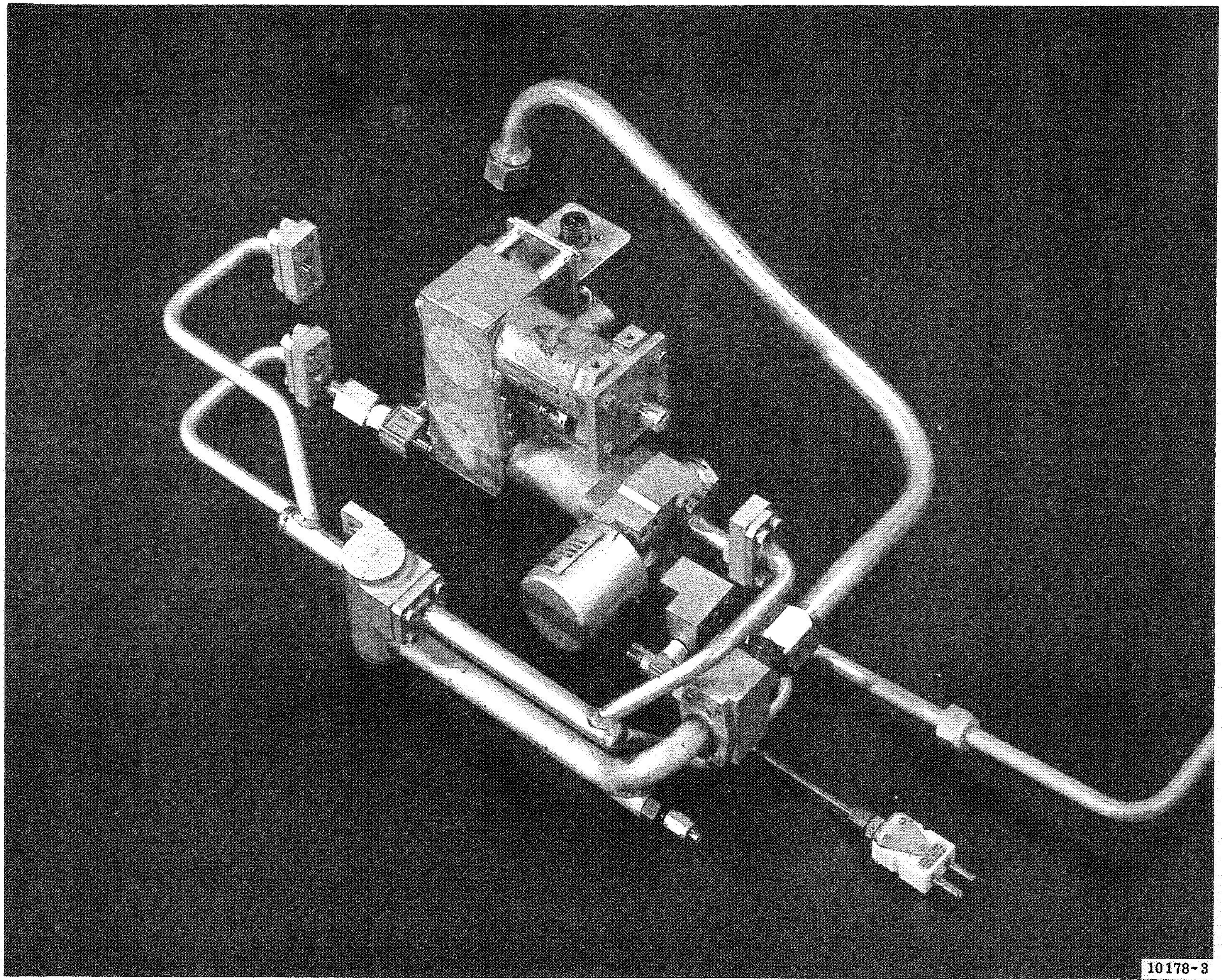


Figure 3-2. LEM Ascent Pilot Valve and Actuator Assembly.

pilot valve and actuator assembly design is used. Whereas the Ascent System uses four individual pilot-valve and actuator assemblies, the Descent system uses only one. This assembly contains four pilot valve and actuator sub-assemblies which can be operated individually. Each sub-assembly operates two ball-valves (one fuel and one oxidizer). Because of this integral type of design, it was necessary to test four vent-line systems rather than a single vent line as in the Ascent tests. Figures 3-3 and 3-4 show the LEM Descent pilot valve and actuator assembly which was tested during this program.

The test program for the Ascent tests is outlined in Table 3-1. The diagnostic program was designed to investigate four different potential problems which might arise from evaporative freezing of propellant in the vent line and pilot valve-actuator assembly: (1) vent-line plugging during normal operation of the system; (2) freezing of the dribble volume (residual propellant) in the system after a normal mission cycle; (3) slow leak of propellant past the pressure seal in the pilot valve, with subsequent freezing; and (4) vent-line plugging arising from pilot valve stuck in half open position during firing. In addition to these diagnostic tests, six remedial tests were conducted. These tests are discussed in detail in Section 4.0.

The test program for the Descent tests is outlined in Table 3-2. This program was designed to investigate the same problems and phenomena of interest in the Ascent tests, described above, except that tests involving a slow leak past the pressure seal of the pilot valve were not included in the Descent program.

3.2 TEST SYSTEMS

3.2.1 High Altitude Facility

The major tool used in performing the experiments of this program was the Atlantic Research Corporation high-altitude tunnel facility. Figure 3-5 depicts this facility and some of its pertinent characteristics.

The test section consists of a cylindrical stainless steel tunnel, 6 feet in diameter and 25 feet long, which is exhausted by a 5-stage steam

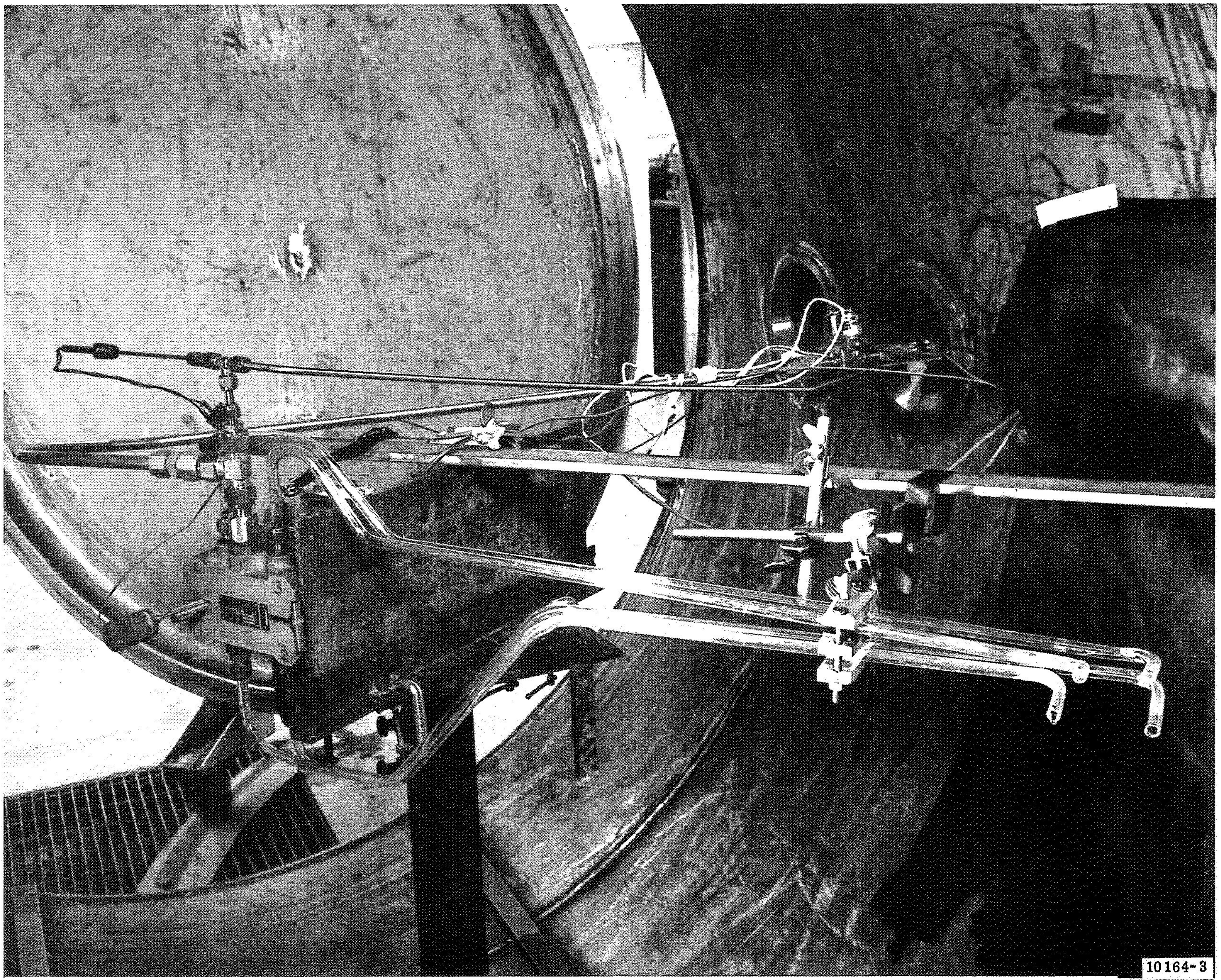


Figure 3-3. LEM Descent Valve Actuator Assembly and Glass Simulated Vent Lines Installed in Vacuum Chamber.

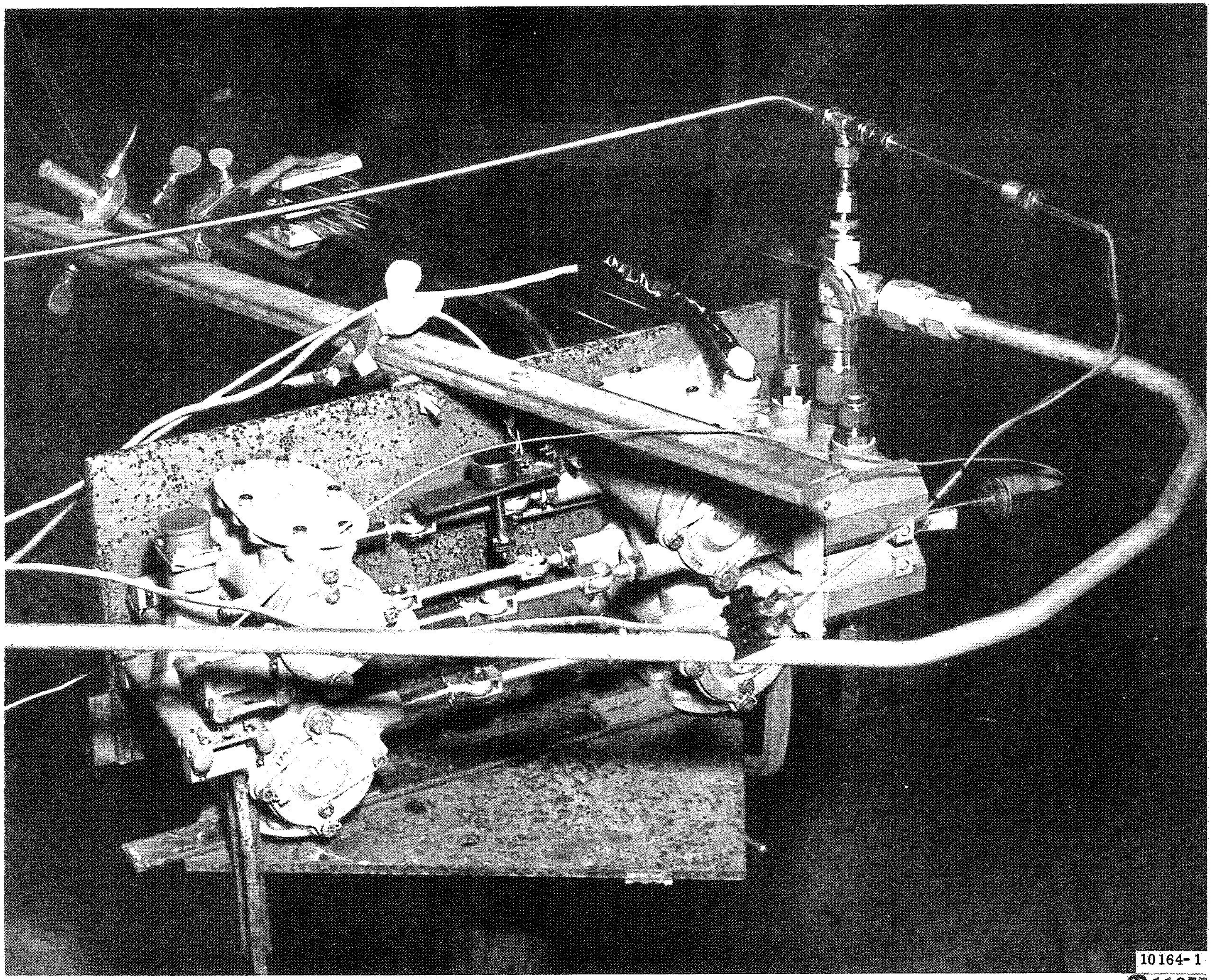


Figure 3-4. LEM Descent Valve Actuator Assembly Installed in Vacuum Chamber.

TABLE 3-1

PROGRAM FOR LEM ASCENT TESTS

1.0 NORMAL MISSION DUTY CYCLE

- 1.1 5 sec (A) - Coast - 400 sec (A) - Coast - 5 sec (H) - Coast - 5 sec (C) (2 runs)
- 1.2 5 sec (A) - Coast - 400 sec (A) - Coast - 5 sec (C) - Coast - 5 sec (C) (2 runs)
- 1.3 430 sec (A) - Coast - 5 sec (H) (2 runs)
- 1.4 430 sec (C) - Coast - 5 sec (C) - Coast - 5 sec (C) - Coast - 5 sec (C) - ......(35 restarts) (2 runs)

2.0 LEAK TESTS

- 2.1 Dribble volume freezing (4 runs)
- 2.2 Slow leak past pressure seat of pilot valve (4 runs)
- 2.3 Pilot valve hung open during firing (4 runs)

3.0 REMEDIAL TESTS (6 runs)

Notes:

1. Coast periods between firings were approximately 5 minutes
2. Propellant temperatures were: (A) ambient, nominal 70°F; (H) hot, nominal 190°F; and (C) cold, nominal 45°F.

TABLE 3-2

PROGRAM FOR LEM DESCENT TESTS

4.0	NORMAL MISSION DUTY CYCLE	
4.1	10 sec (C) - coast - 10 sec (C) ......(20 restarts)	(1 run)
4.2	33 sec (A) - coast - 910 sec (H)	(2 runs)
4.3	33 sec (A) - coast - 910 sec (C)	(2 runs)
4.4	33 sec (C) - coast - 910 sec (C)	(2 runs)
5.0	LEAK TESTS (DRIBBLE VOLUME)	(4 runs)
6.0	REMEDIAL TESTS	(4 runs)

Notes:

1. Coast periods between firings were approximately five minutes.
2. Propellant temperatures were: (A) ambient, nominal 70°F; (H) hot, nominal 105°F; and (C) cold, nominal 37°F.

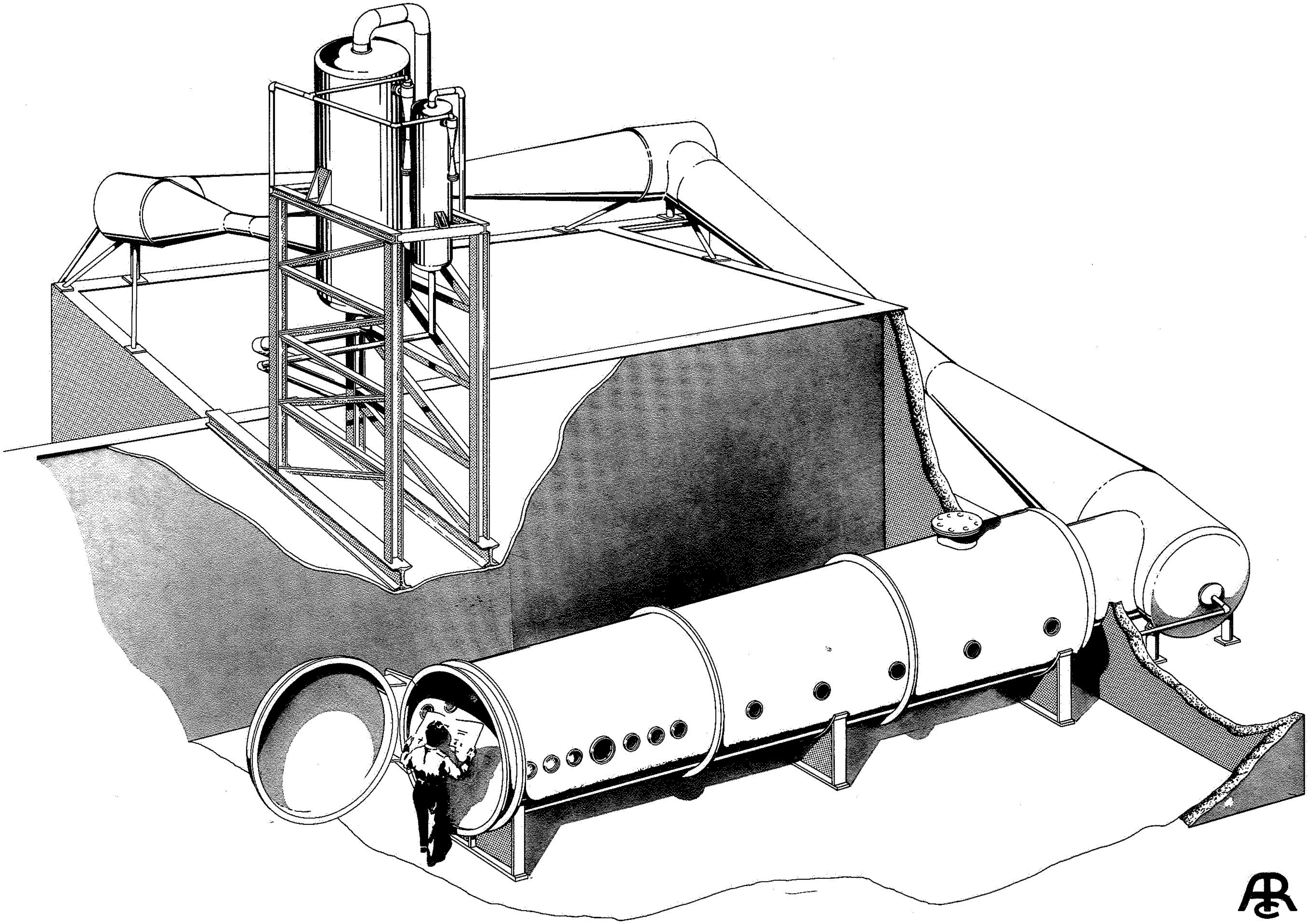


Figure 3-5. High Altitude Research Tunnel.

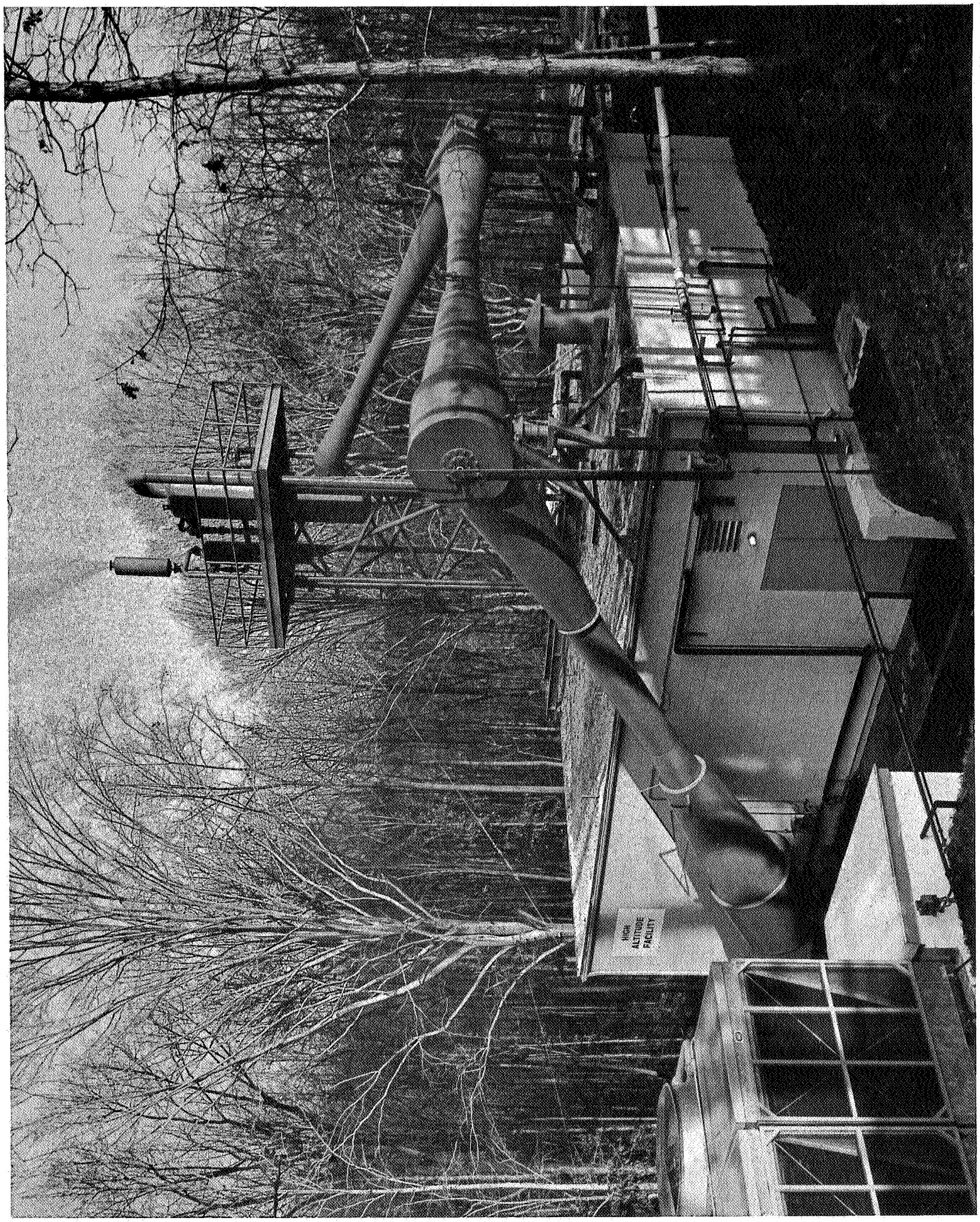
ejector system. The tunnel is housed in a building adjacent to the Atlantic Research Corporation principal laboratories located in Alexandria, Virginia. Figure 3-6 is a photograph of the facility including the cooling towers for the condenser water.

The facility has a design pumping capacity of 71,000 liters of air per second at a pressure of 60 microns of mercury, and a no-load, minimum pressure capability of 20 microns of mercury, which simulates an altitude of approximately 245,000 feet. The ejectors use 9,000 pounds of steam per hour, and the two condensers require 1200 gallons of cooling water per minute. Direct-contact type condensers are located between the third and fourth stages and between the fourth and fifth stages. The condensers are used to reduce the overall steam consumption of the unit. The steam is supplied by a gas-fired, automatic boiler with a rated output of 10.35 MBTU/hr. A preheater using steam as the heat source is used to preheat the boiler feed water to approximately 190°F. The boiler, including the electrical control panel, is shown in Figure 3-7. The tunnel control panel and some of the instrumentation used for the program are depicted in Figure 3-8.

3.2.2 Flow Systems

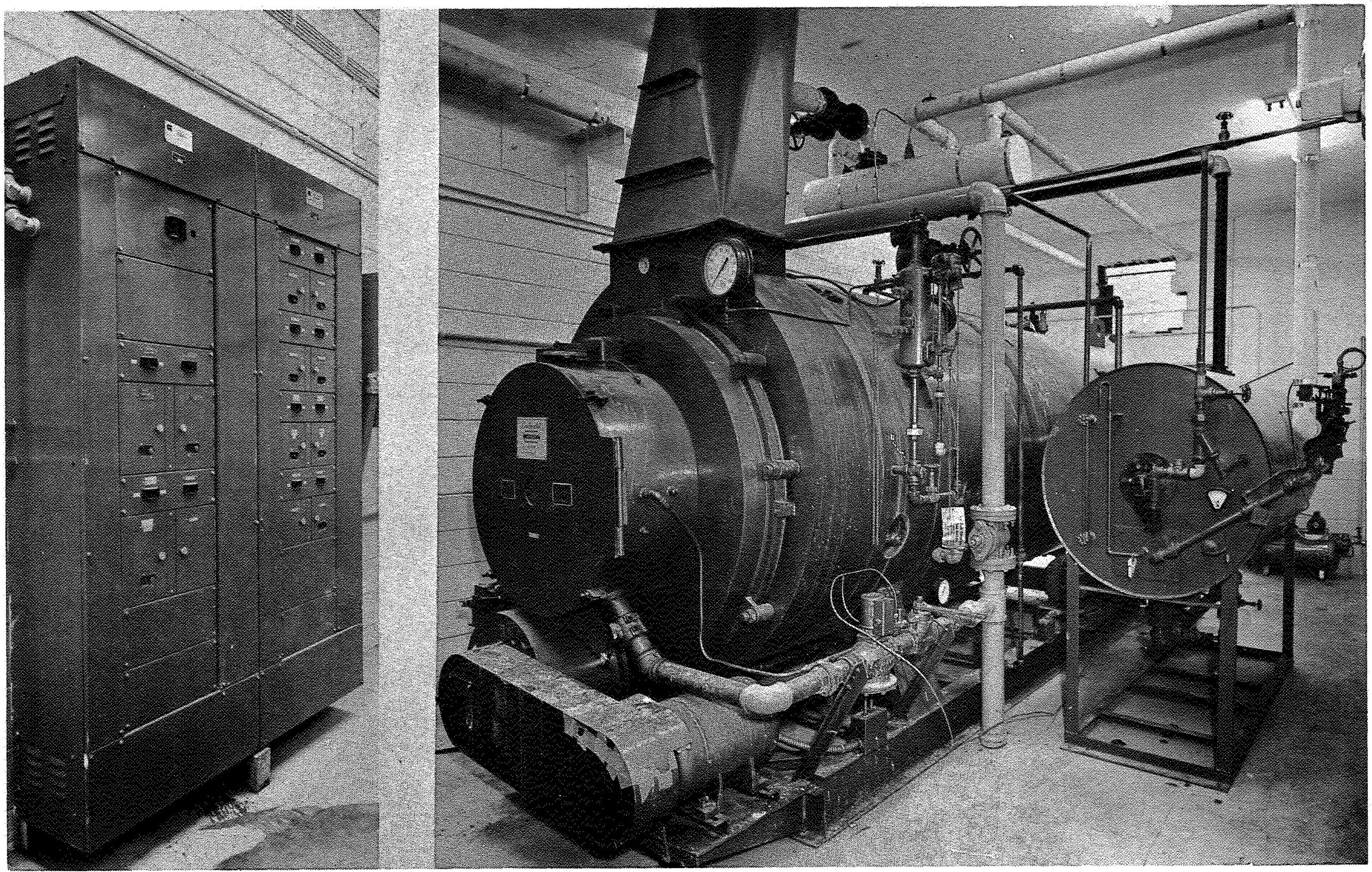
3.2.2.1 Lem Ascent Apparatus

Figure 3-9 is a schematic diagram of the propellant flow system used for the Ascent tests. Two different simulated vent-lines were fabricated and tested. Both lines were fabricated to represent the size and shape of the actual vent line as closely as possible. The first simulated vent-line was made of 10-mm diameter Pyrex tubing, approximately nine feet long. The second simulated vent-line was made of 3/8-inch diameter aluminum tubing and is shown in Figure 3-1. For a particular test series, one of these two was mounted inside the Atlantic Research Corporation's 6-ft-diameter x 25-ft-long vacuum chamber, and the Government-furnished LEM Ascent Valving system was mounted immediately outside the vacuum chamber, as indicated in Figure 3-9. Figure 3-2 shows the valve and manifold system in detail.



AE35048

Figure 3-6. High Altitude Research Facility.



30768

Figure 3-7. Boiler for High Altitude Research Tunnel.

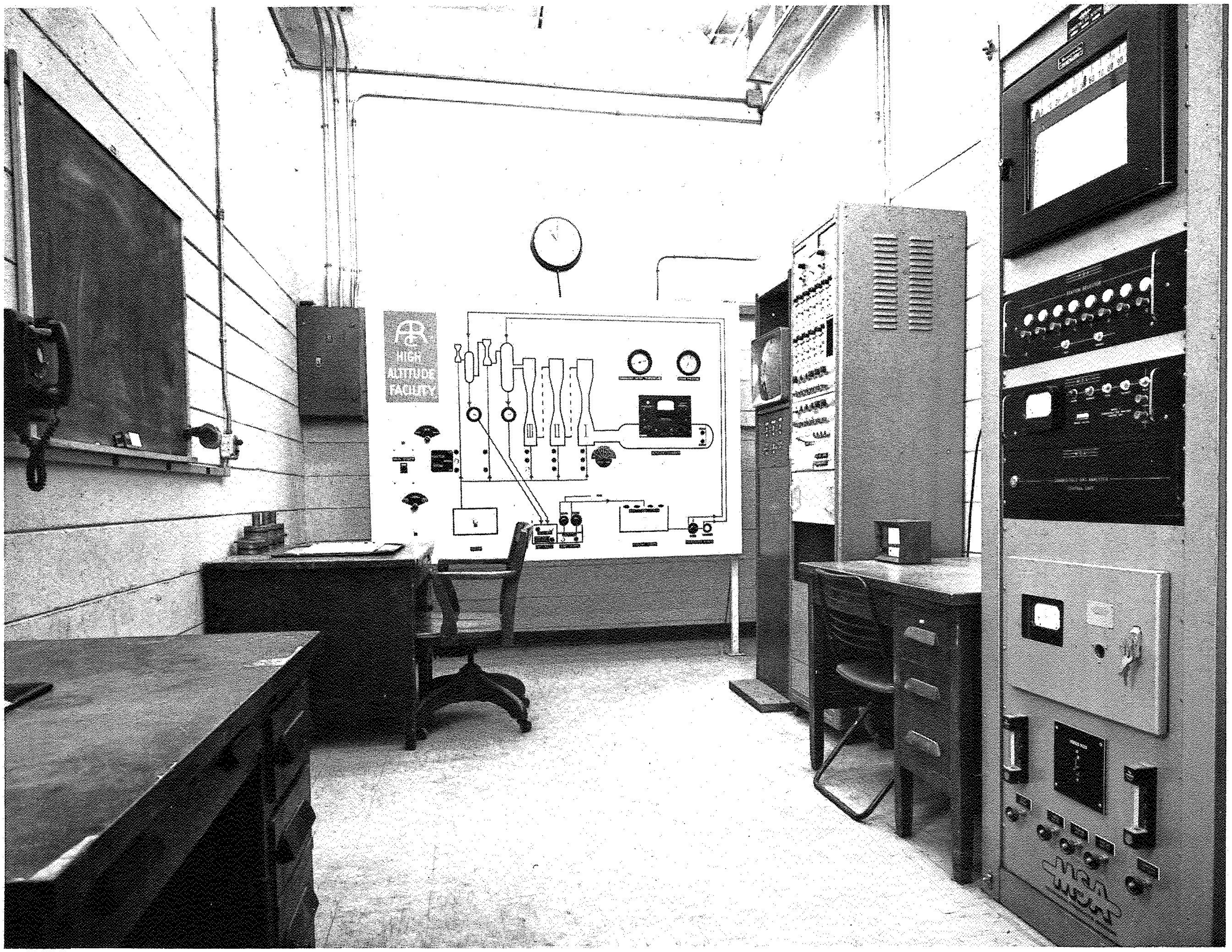


Figure 3-8. Control Panel and Instrumentation for High Altitude Research Tunnel.

9869-3
7682

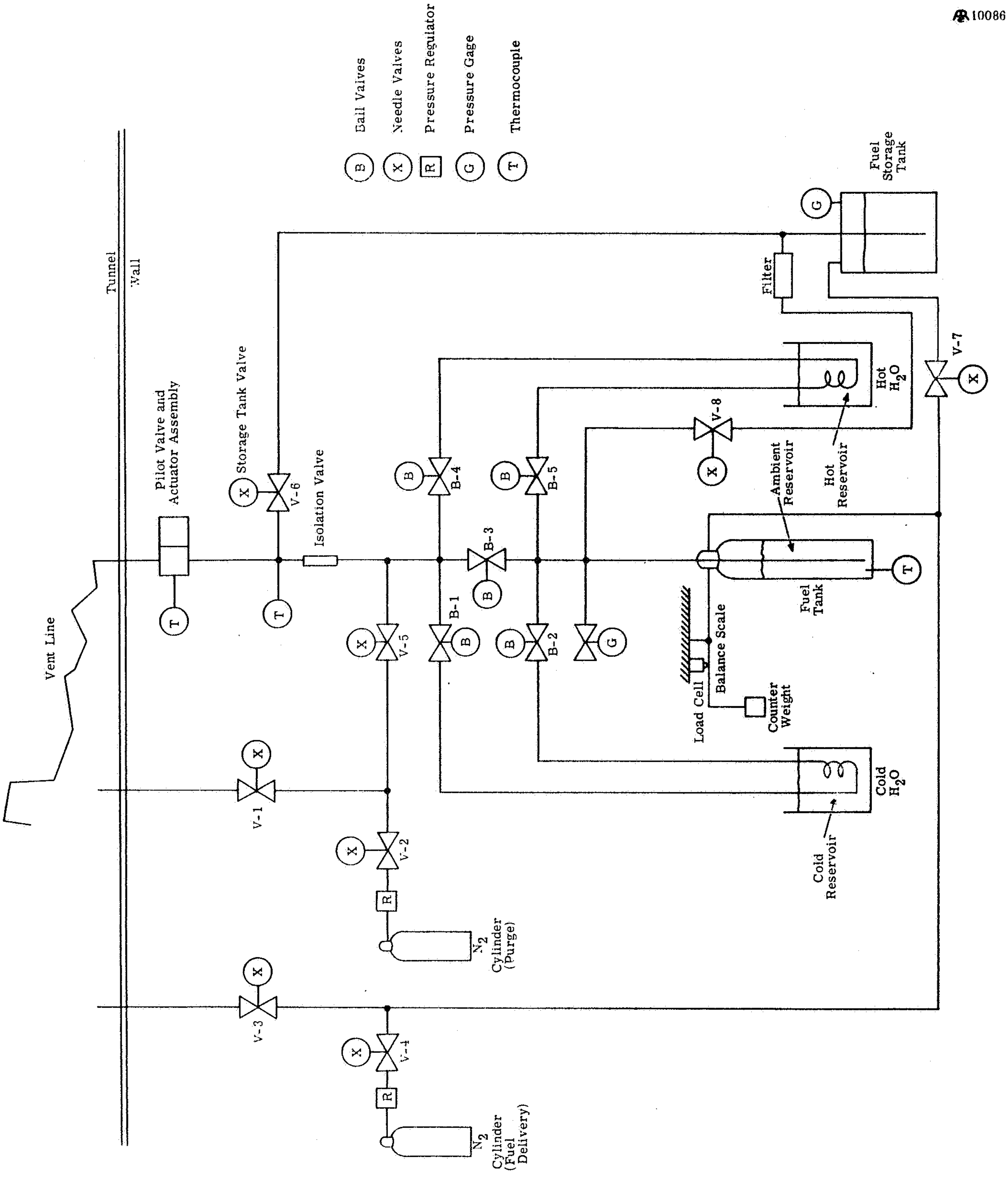


Figure 3-9. Schematic Diagram of Flow System for LEM Ascent Tests.

In order to simulate actual operating conditions as closely as possible, three different propellant temperatures were used. The propellant, at its conditioned temperature, was used to heat or cool the valving system, as required, by using the by-pass system shown schematically in Figure 3-9. Of course under actual conditions, the heat exchange would take place in part by the opposite process because the valving system would be heated by engine heat soak-back after a firing.

The main propellant tank was suspended from a special beam-balance system which was used to measure propellant leak rate. Details of this technique are discussed in Section 3.2.3.

The hot and cold reservoirs were fabricated from 130 feet of 1/2-inch-diameter x .049-inch-wall aluminum tubing, wound into a coil 20 inches in diameter. The hot-fuel reservoir was heated by immersing it (the coil) in a 30-gallon drum filled with water heated, in turn, by direct contact with low-pressure steam. The cold-reservoir coil was cooled by immersing it into a 40-gallon tank filled with water which was cooled by a refrigeration system. Aluminum tubing, 1/2-inch in diameter, was used to connect the heat-exchanger control valves (5 ball valves) to the isolation solenoid valve. A 5/8-inch aluminum tube, bent as closely as possible to the shape used in the actual LEM Ascent configuration, was used to connect the isolation valve and the pilot valve. All tubing between the ambient reservoir and the heat-exchanger control valves was 1/4-inch stainless steel tubing. All flow control valves were stainless steel with teflon packing. Flow of liquid fuel was achieved by applying nitrogen-gas pressure to the vapor space at the top of the ambient reservoir and opening and/or closing the appropriate heat-exchanger control valves to obtain hot, cold or ambient fuel flow.

3.2.2.2 Lem Descent Apparatus

As was discussed in Section 3.1, the LEM Descent valve actuator sub-system is an integral unit consisting of four complete actuator networks. Because of its complexity, the entire Descent valving system was mounted inside the vacuum chamber. The four vent-lines, shown in Figures 3-3 and 3-4, were made of 10 mm Pyrex tubing approximately 3.5 feet long. Figure 3-10 shows four lines made of 3/8-inch-diameter aluminum tubing which were used to replace the glass lines for some of the tests. The lines were fabricated to represent the size and shape of the actual vent lines as closely as possible. The remainder of the propellant flow system used for the Descent tests, as shown in Figure 3-11, was essentially the same as the one used for the Ascent tests.

3.2.3 Instrumentation

A multichannel recording oscillograph was used to record simultaneously the variables that were measured. This recorder provided chart speeds from 0.1 to 80 inches per second. The measured variables included propellant temperatures, pressure and leak rate, and valve-actuator piston travel. Locations of the sensing elements are shown in Figures 3-9, 3-11 and 3-12.

Temperatures were measured with copper-constantan thermocouples. Their signals were conditioned by bridge circuits which allowed pre-run balance and electrical calibration.

Pressure was measured by means of an unbonded strain-gage pressure transducer. It was connected to conditioning circuits which provided the excitation voltage for the strain-gage bridge and allowed pre-run balancing and electrical calibration.

Propellant flow-rate was measured by a specially-constructed beam balance shown schematically in Figures 3-9 and 3-11. The beam was suspended from a carriage by a strip of stainless-steel shim stock which served as the beam fulcrum. The propellant tank was fastened securely to one end of the beam and was counterbalanced by a weight clamped to the opposite end.

The force transducer, electrically connected to a carrier-demodulator, was affixed to the balance carriage such that the transducer button touched the beam when the beam was in a horizontal position. When

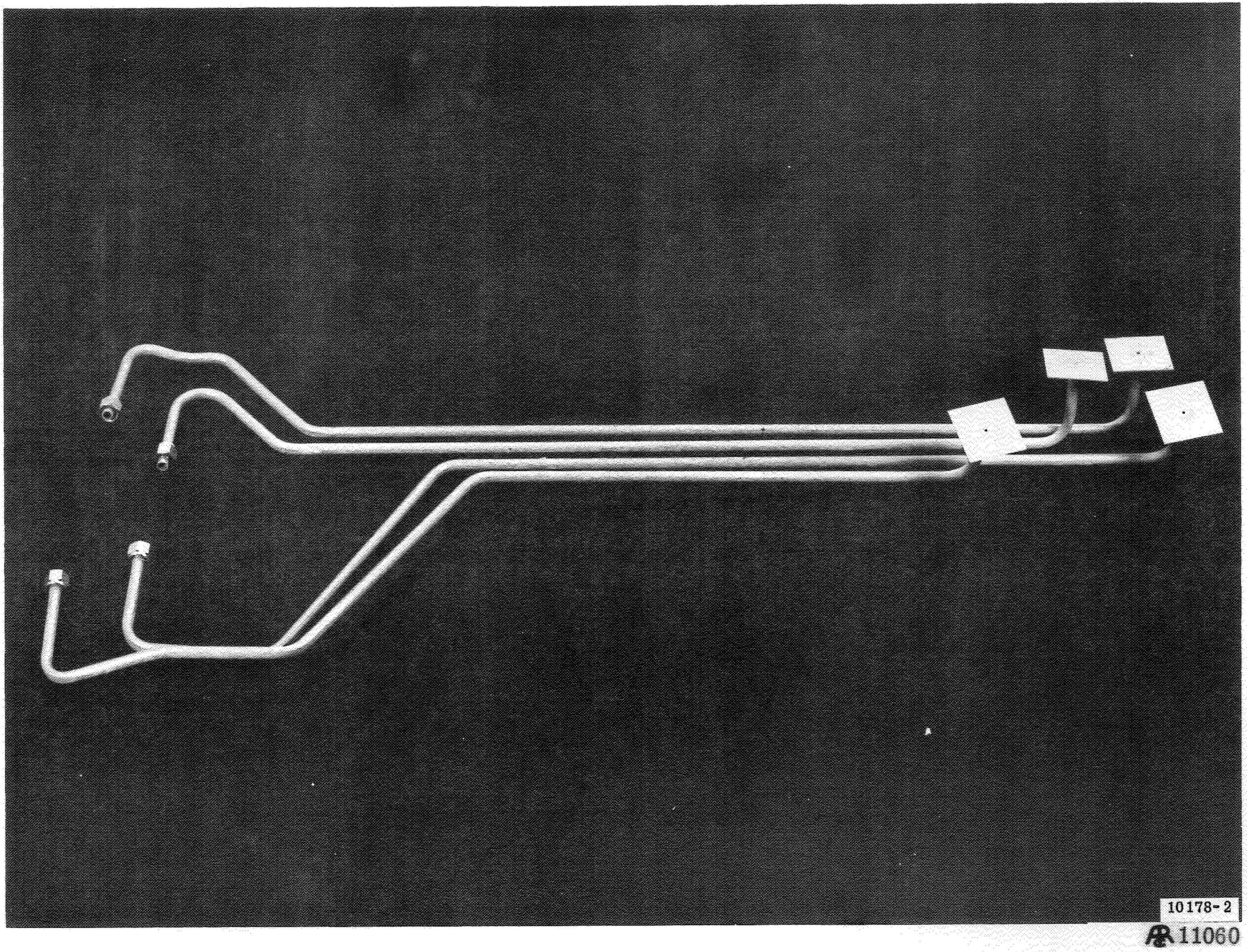


Figure 3-10. Aluminum Vent Lines for Descent System.

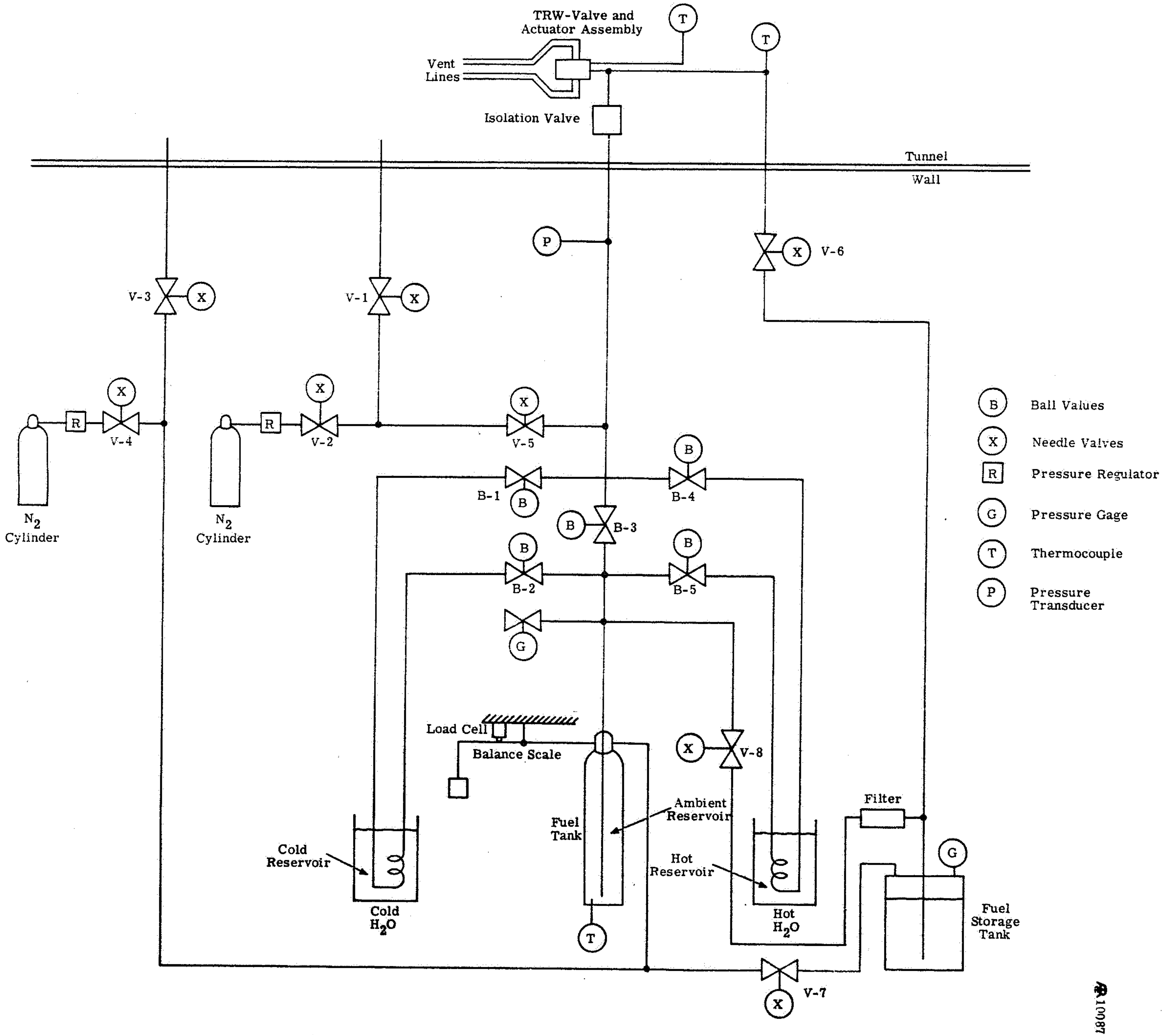


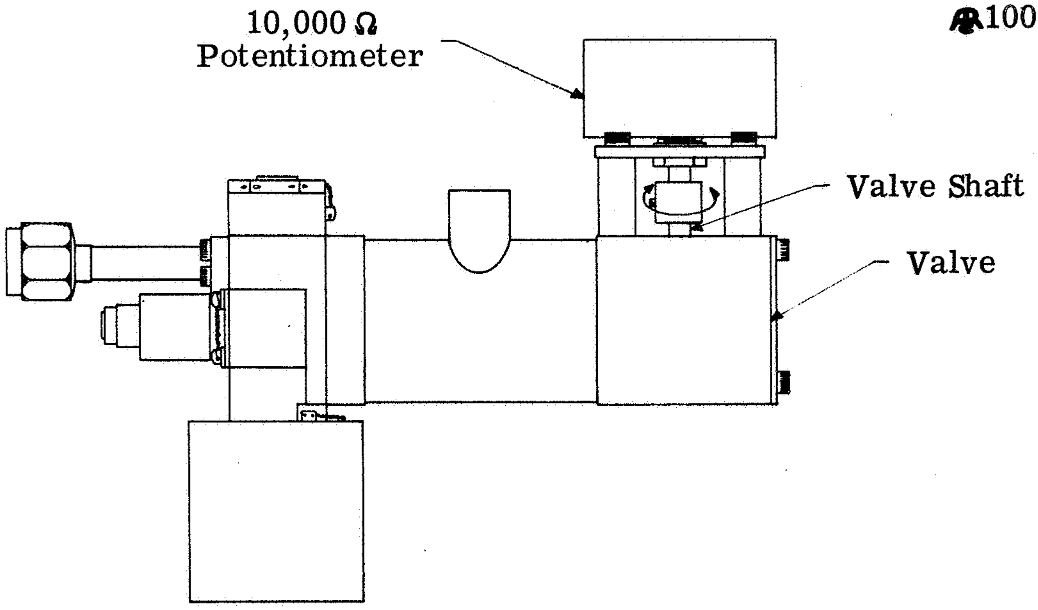
Figure 3-11. Schematic Diagram of Flow System for LEM Descent Tests.

the tank was fully loaded, small counterweights were placed on the beam to position the transducer trace at maximum deflection. The number and size of these weights and their location on the beam were chosen such that when the trace approached zero deflection, due to propellant flow out of the tank, the removal of one of these weights would restore the trace to a nearly full-scale position.

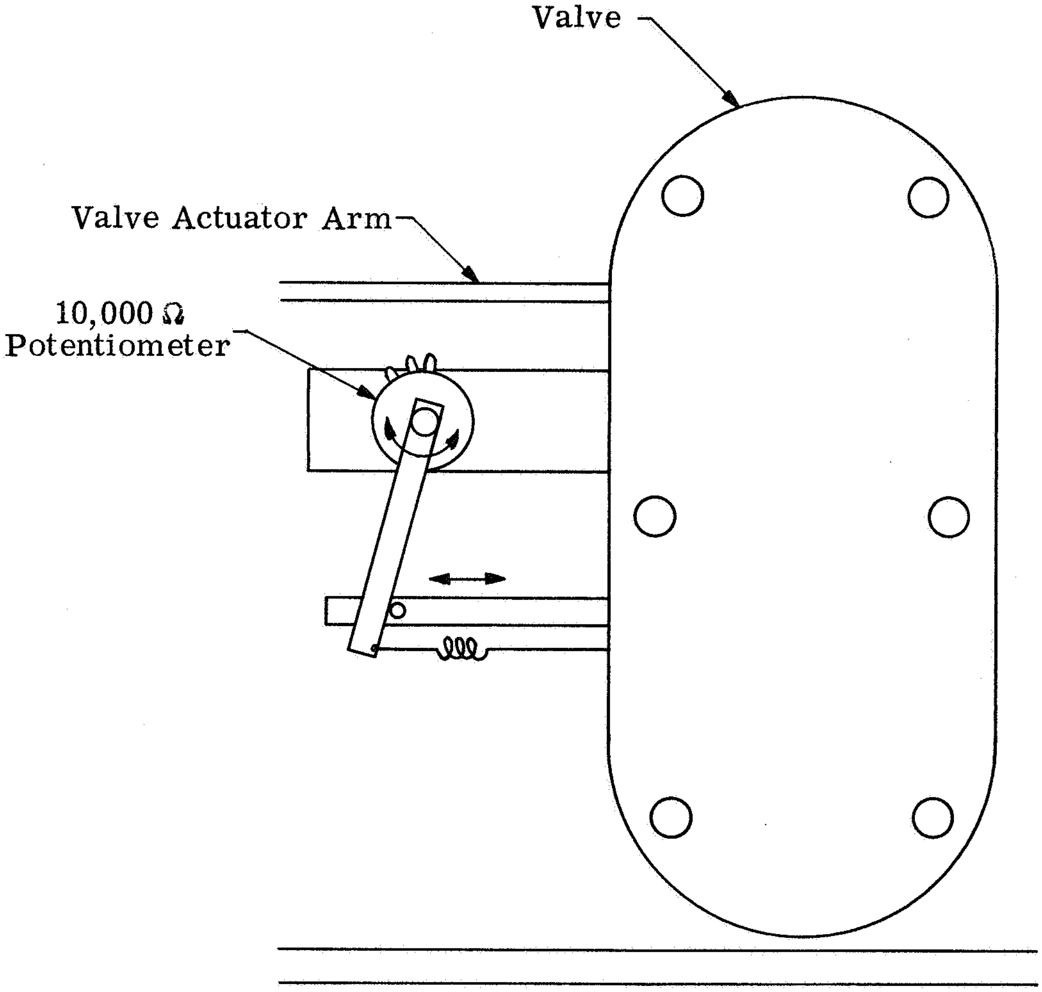
The balance was calibrated by pouring measured quantities of water into the tank and recording the resulting galvanometer deflections. By repeating the process with various amounts of water initially in the tank, it was shown that the calibration did not change significantly with a change in liquid level. The result of this procedure was a constant calibration factor of the dimensional form: grams of weight change per inch of deflection. The magnitude of the factor was determined by the span adjustment in the demodulator circuit and the location of the load cell on the balance beam relative to the balance pivot point. Since the data obtained from the balance were in the form of propellant weight versus time, it was necessary to differentiate these data to obtain flow rates. By dividing the change in weight by the time interval over which the change occurred, the average mass rate for the interval was obtained.

A 10,000-ohm variable resistor was connected to the main ball-valve shaft of the Ascent valve actuator. Rotation of the shaft caused a change in resistance which was proportional to the degree of valve opening. A signal conditioning circuit, consisting of a bridge configuration having the potentiometer (on the actuator shaft) as two legs of the bridge, was used to drive a galvanometer in a recording oscillograph. The Number Three solenoid-actuator sub-assembly of the Descent system was equipped with a similar 10,000-ohm variable resistor. Figure 3-12 shows the method by which these potentiometers were connected to the valve actuators. With this technique, the history of the valve-actuator opening and closing behavior was recorded along with the other types of data.

Normal-speed 16 mm color motion pictures recorded events in the vent lines during all the tests. For some of the Descent tests, movies of



Ascent Valve



Descent Valve

Figure 3-12. Sketch of LEM Ascent and Descent Propellant Valve Systems Showing Potentiometer Mounting Location.

the events that occurred around the outside structure of the actuator assembly also were recorded.

3.3 TEST PROCEDURE

For both the Ascent and Descent phases of this program, the experiments associated with each were divided into three types of tests: normal mission duty-cycle tests, leak tests, and remedial tests. The elements of these tests are outlined in Tables 3-1 and 3-2, and the basis for the selection of these types of tests for the study of freezing effects was discussed in Section 3.1.

3.3.1 Flow System Filling Procedure

Prior to running a test, the ambient reservoir, hot reservoir and cold reservoir (see Figures 3-9 and 3-11) were filled with fuel (Aerozine-50). The procedure for filling the lines was (all component identification codes refer to Figures 3-9 and 3-11):

1. All valves were closed.
2. The tunnel was evacuated with a five-stage steam ejector system.
3. Valves V-1, V-3, V-5, B-1, B-2, B-3, B-4, B-5 and the isolation valve were opened to evacuate the flow system and reservoirs.
4. While the lines were being evacuated, the ambient reservoir on the balance scale was tare-balanced by adding the appropriate counter weights.
5. After the lines were evacuated to tunnel pressure (about 0.04 torr), valves V-3, B-2, B-3 and B-5 were closed.
6. Valve V-8 was slowly opened and fuel was drawn into the ambient reservoir from the fuel storage tank.
7. The quantity of fuel transferred was monitored by use of the balance scale, which had been tared and calibrated previously. Pressure in the ambient reservoir was controlled by adjusting valve V-3.
8. When the ambient reservoir was full, valves V-8 and V-3 were closed and the reservoir was pressurized slightly by

opening valve V-4, opening the fuel delivery N_2 cylinder, and adjusting the regulator.

9. Valves B-1 and V-4 were closed.
10. Ball-valve B-2 was opened slowly, and fuel was transferred from the ambient reservoir into the cold reservoir.
11. Valve B-2 was closed and the ambient reservoir was refilled as described in the appropriate steps above.
12. Valve B-4 was closed and valve B-5 was opened slowly which allowed fuel to be transferred from the ambient reservoir into the hot reservoir.
13. The ambient reservoir was refilled again from the fuel storage tank.

Fuel was then in all fuel lines up to ball-valves B-1, B-3, and B-4. Valves V-1, V-5 and the isolation valve were still open, such that the lines from the valves (ball-valves) in the propellant thermal-conditioning system to the pilot valve remained evacuated.

14. Valves V-1 and V-5 were closed; then valve B-3 was opened slowly and fuel was admitted up to the pilot valve.
15. Finally all valves, including the isolation valve, were closed and the system then was ready for testing to begin.

3.3.2 Normal Mission Duty-Cycle Tests

The normal mission duty-cycle tests were initiated by heating or cooling the fuel as required for the particular test being conducted. During the cooling process valve B-2 was open and during the heating process valve B-5 was open to allow for expansion and contraction of the fuel and tubing. When the required reservoir temperatures were attained, the following test procedure was used:

1. recording equipment was turned on and allowed to warm up;
2. all valves were checked to assure that they were closed;
3. tunnel was evacuated (unless the test followed immediately after the filling operation, in which case the tunnel was already evacuated);

4. instruments were calibrated electronically;
5. the ambient reservoir was pressurized by opening valve V-4 and setting the pressure regulator at the desired value (about 40 psig);
6. appropriate ball-valves were opened to permit delivery of fuel at the temperature desired; for instance, if cold fuel was required valves B-1 and B-2 were opened and valves B-3, B-4 and B-5 were kept closed;
7. the isolation valve was opened;
8. valve V-6 was opened slowly and the fuel temperature was monitored.
9. when the fuel reached the desired temperature, valve V-6 was closed;
10. the vapor space in the ambient reservoir was pressurized to the desired operating pressure (200 to 300 psig);
11. the Visicorder paper supply and desired settings (chart speed etc.) were checked;
12. the movie camera and visicorder were turned on;
13. the pilot valve was opened for the prescribed time interval which constituted the test cycle;
14. the pilot valve and isolation valve were closed simultaneously at the end of the test cycle;
15. the movie camera and visicorder were turned off.

During the "coast" period between cycles the fuel temperature could be changed, if required, by reducing the pressure to about 40 psi and repeating steps 6 through 9. The system was then pressurized again to operating conditions. At the termination of a test series, the pressure was reduced to a value slightly above one atmosphere and all valves were closed.

3.3.3 Leak Tests

Three different types of leak tests were conducted with the LEM Ascent flow system: (1) dribble volume, (2) slow leak past pressure seat of pilot valve and (3) pilot valve hung open during firing.

3.3.3.1 Dribble Volume Tests

The objective of the dribble-volume (residual propellant in the system after "firing") tests was to determine the extent to which the dribble volume remaining in the actuator assembly and vent line would freeze after operation of the system. These tests were conducted in the same manner as for the first cycle of a normal mission duty cycle test. The valves were closed after the first cycle and the dribble volume was exposed to the tunnel pressure through the vent line. After various waiting periods (1 to 30 minutes) the pilot valve was actuated and the opening and closing times recorded by the visicorder were compared with the opening and closing times for the initial cycle. At the end of the tests the pressure in the flow system was vented into the tunnel, the visicorder was turned off and all valves were closed.

3.3.3.2 Slow Leak Past Pressure Seat of Pilot Valve

The slow leak past the pressure seat of the Ascent pilot valve was accomplished by controlling the plunger travel in the pilot valve. A special micrometer-equipped solenoid cover was used for this purpose. Prior to a leak test, the tunnel was evacuated, the instruments were calibrated, the ambient fuel reservoir was filled and tared on the beam balance, and the visicorder was started. With the isolation valve open and the system pressurized up to the pilot valve, the micrometer control was adjusted until the desired leak rate was obtained. The leak rate was determined by measuring the loss in weight of the ambient reservoir over a period of time. This was accomplished by monitoring the output from a load cell which was part of the special beam balance (see Section 3.2.3), and recording this output with the recording oscillograph. When the desired leak was achieved the isolation valve was closed. After the isolation valve was closed the pressure in the line, connecting the isolation valve and the pilot valve, decreased as the liquid leaked past the seals in the pilot valve. This resulted in a decreasing leak rate which could not be measured because the balance scale was located upstream from the closed isolation valve. The leak tests were terminated by opening the isolation and pilot valve for 5 sec and then closing them. (The visicorder chart was turned off, the pressure in the flow system was decreased and all valves were closed). Moving pictures were taken during the leaking and during the opening and closing of the valve. The time required to open the valve actuating system was measured and compared with the time required for the non-leakage case to determine if freezing may have caused sluggish operation of the system.

3.3.3.3. Pilot Valve Hung Open During Firing

The tests for the case of a pilot valve hung open were accomplished by inserting a thin shim under the pilot valve solenoid stem cap. This shim allowed the valve stem to travel only half its normal distance when the valve was energized. The test procedure was as follows: The tunnel was evacuated, the instruments were calibrated, the ambient reservoir was filled and tared, the flow system was pressurized to operating pressure, the visicorder and camera were turned on, and the isolation and pilot valves were opened. The duration of each test was from 5 to 10 sec. The test was terminated by closing the pilot and isolation valves, stopping the visicorder and camera, lowering the flow system pressure and closing all valves.

3.3.4 Remedial Tests

The basic procedure used for conducting the remedial tests was the same as that used for the normal mission duty cycle tests. These tests were conducted with various vent line configurations which are described in detail in Section 4.0.

3.4 SAFETY

Special precautions and handling techniques were required to conduct the tests because of the toxic and high energy nature of the propellants (a 1:1 mixture of hydrazine and unsymmetrical dimethylhydrazine) involved. A completely closed propellant transfer system was utilized and precautions were taken to assure compatibility of all materials. The personnel working on this program all had extensive prior experience with the propellants being used. Protective clothing, including impermeable gloves, boots and body protection were worn to protect against spills. Self contained breathing equipment with full face masks were used for respiratory protection when needed. A safety shower and eye wash are located in the test area. Atlantic Research employees are instructed to wear safety glasses during all hazardous work activities.

4.0 RESULTS AND ANALYSIS

This section of the report represents a summary and interpretation of the test results. Detailed data gathered during these tests are presented in Appendix A. The tests were conducted as described in Section 3.3 and according to the schedule outlined in Tables 3-1 and 3-2.

4.1 ASCENT TESTS

The LEM Ascent valve-actuator system operated properly during the "Normal Mission Duty Cycle" sets of tests (test series 1.1, 1.2 and 1.3). Although an accumulation of frozen propellant formed at the end of the glass simulated vent line after each cycle, no plugging or malfunction of the system was noted. The accumulation of frozen propellant usually fell off during the coast period, but if it survived during the entire coast period (approximately 5 minutes) it was dislodged quickly during the following cycle and a new accumulation was formed. The size of a typical accumulation during these tests was about 1/2-inch in diameter and one-inch long. During each cycle most of the propellant was expelled out the end, but a small amount of propellant usually remained in the vent line, where it boiled and, in some cases, froze evaporatively. Subsequently it either sublimed completely or was washed down-stream and melted by the warmer propellant during the succeeding cycle.

The first set of "35-Restart Tests" (test series 1.4) produced essentially the same results described above for tests 1.1, 1.2 and 1.3. The second set of 35-restart tests, however, resulted in a "hung-open" valve. During this test the intermittent propellant accumulations described above were obtained during the first seven cycles. Beginning with cycle number eight, the accumulation was not dislodged but continued to grow during each cycle until cycle number 19. Subsequently the propellant no longer vented but collected in the glass vent line. The plug had grown to a diameter of about three inches around the vent-line end and extended about three inches inside the line. At the time of cycle number 23, a sufficient amount of propellant had collected in the vent line to allow only 90% of the piston travel. During the next three cycles the piston travel became progressively smaller until, during cycle number 26, the valve remained completely open. Adherence of the propellant accumulation to the exit of the vent line was caused by contraction of the frozen propellant. Unlike water which expands when freezing, the N_2H_4 - UDMH mixture contracts when it freezes. The propellant accumulation grew back along the outside wall of the vent line, and the clamping action around the end of the vent line, caused by contraction of frozen propellant, was sufficient to prevent the accumulation from becoming dislodged during subsequent cycles. Cooling, resulting from sublimation of the frozen propellant, caused continued freezing of the propellant inside the exit section of the vent line.

The "Leak Tests", as listed in Table 3-1, produced results similar to the three "Normal Mission Duty Cycle Tests". Frozen propellant formed at the vent-line exit and a small amount of evaporative freezing occurred in the line. However, normal operation of the system was not prevented by evaporative freezing during this test series.

Based on these results one cannot conclude categorically that leakage could not cause a problem. The very limited scope and time permitted for the performance of these tests allowed only four leak rates to be observed, covering a range from 0.08 to 5.3 grams per second. Since leak-rate is one of the most important parameters governing evaporative freezing phenomena(3,4,5), it is possible that additional tests at different leak-rate values may produce plugging due to evaporative freezing.

Six sets of remedial tests were conducted which were of the 35-restart type, similar to the test series 1.4. For the first set of tests in this series, the exit of the glass vent line was flared to about 30°. After the second cycle of this test the frozen propellant accumulation remained lodged at the exit of the vent line and remained until the 16th cycle when the glass vent line broke as a result of the pressure increase caused by the plug.

For the second remedial test the glass vent line was modified by inserting a 1/16-inch-diameter orifice at the exit of the line. The primary benefit of this modification would be the limiting of the flow, and consequently propellant loss should the pilot valve hang half-open during a firing. Without a restriction of some type this situation would result in too large a loss of propellant and prevent the completion of the mission. The 1/16-inch-diameter orifice allowed a flow of only 60 grams/sec, which was judged to be low enough to allow successful completion of the ascent mission. Five restarts were completed with this configuration and neither freezing nor plugging were experienced inside the vent line. The usual frozen propellant growths were formed at the vent line exit after each cycle, but they were dislodged during the subsequent cycle.

For remedial tests, 3, 4, 5 and 6 the glass simulated vent line was replaced by an aluminum line. The 3/8-inch-diameter aluminum line was fabricated to resemble the actual vent lines of the LEM Ascent propellant-valve-actuating system (See Figure 3-6), except that a 8-inch-square aluminum plate was welded on the exit end and a 1/16 inch diameter hole was drilled in the plate at the centerline of the line. The purpose of the plate was to prevent re-occurrence of the plugging experienced in test series 1.4 as described above. Since the strength of the plug depends on its footing, the growth of a strong plug about the end of the vent tube is precluded by a flat plate having no projecting and convex surfaces which can be grasped by the freezing propellant. Moreover, a plug which grasps the lip of the orifice may not form since evaporative freezing (via the 1/16-inch orifice) of the Aerozine-50 in the tube cannot occur for many circumstances. This point is discussed further in the next section.

Remedial tests 3, 4, 5 and 6 were conducted with this arrangement. The four sets of 35-restart tests were completed without difficulty and with no apparent freezing in the vent line. However, this configuration cannot be regarded as a panacea for the plugging problem caused by evaporative freezing; subsequent testing of the LEM descent propellant-valve-actuating system, with the "remedial" configuration described below, showed otherwise.

4.2 DESCENT TESTS

As described in section 3.2 and shown in Figure 3-11, the descent propellant-valve-actuating system and four glass simulated vent lines were located entirely inside the vacuum test chamber. The first set of tests (set 4.1) in the Descent-actuator test series consisted of 20 restarts, as outlined in Table 3-2. During cycles 1 through 6 of this set of tests, frozen propellant accumulated at the exits of the four vent lines after each cycle, but the accumulations were dislodged during the following cycle. During cycles 7 through 19, random plugging of the four vent lines was experienced but the plugging did not prevent the valves from operating. During cycle 9 and the remainder of the test, frozen propellant discharged into the vacuum chamber through the vent port (which is in the actuator body to relieve the pressure on the downstream side of the four pistons). Also, a similar discharge occurred around the joint between the cylinder housing and main body of the valve. This implied that propellant was leaking past the piston seals. During cycle 20, solenoid Number three opened only partially and allowed a small flow of fuel through the vent line during the entire 10-second firing (solenoid identifications are shown in Figure 3-3). Flow through the vent-line terminated when the solenoid valve was deenergized. During cycle 21, solenoids Three and Four also behaved in this abnormal manner.

The leakage past the piston, experienced during this test, may have been a function of a low fuel-delivery pressure at the pilot-valve inlet during the initial stages of a cycle. Although a tank pressure of 200 psig was used, the large length of tubing (1/2 inch diameter by 100 feet long), used as a heat-exchanger coil between the tank and valve assembly to achieve the required propellant temperature, undoubtedly caused a large temporary pressure drop and a reduced fluid pressure at the pilot-valve inlet. Although not recorded during this test, the inlet pressure to the valve was recorded during subsequent tests, with a pressure transducer especially installed for this purpose. An initial drop of the inlet pressure to as low as 60 psig was recorded. As a result the average valve-opening time recorded was about 650 milliseconds rather than the design value of less than 200 milliseconds.

The normal mission duty-cycle sets of tests 4.2, and the four sets of dribble-volume tests, 4.3 and 4.4, were conducted with the same glass vent-lines that were used for the 4.1 sets of tests. These tests were completed without difficulty. Small amounts of residual propellant froze in the vent-lines between cycles, but the frozen propellant either sublimed or was washed downstream and melted by the warmer propellant during the subsequent cycle.

For the first remedial test, a 1/16-diameter orifice was inserted at the exit end of each of the four glass vent-lines. At the end of the fifth cycle, frozen propellant plugs had formed at the exits of all four lines and the lines began to fill with liquid. Propellant leakage past the piston seals, as experienced in test 4.1 and described above, also was noted during this set of tests. During cycle 7, the plug in line Number Four was blown out the orifice, but the other three vent lines remained plugged. All the valves operated normally except valve Number Three. This valve opened completely; however, during the closing part of the cycle the piston travelled only 47 per cent of the full distance. This set of tests was terminated at the end of the seventh cycle.

For the second remedial test, the four glass vent-lines were replaced by aluminum lines of the same size and configuration as those planned for the actual LEM vehicle. A flat aluminum plate, 2-inches square, was welded to the exit end of each line and a 1/16-inch diameter orifice was drilled in the center of the plate at the tube centerline. Vent-lines One and Two plugged during the second cycle of the test; thereafter all lines plugged for a few cycles and then unplugged, in a random manner, during the remainder of the test. During cycle 17, valve Number Four operated in a sluggish manner, and at the end of cycle 18 the piston remained in the fully open position when the solenoid valve was deenergized. After cycle 20, Pistons Three and Four remained in the open position.

For the third set of remedial tests, the aluminum vent lines were replaced by the same glass vent-lines that were used for the first remedial test. This time, propellant at ambient temperature (70°) was used instead of propellant which had been cooled to about 40°F. This eliminated about 100 feet of 1/2-inch-diameter tubing (heat-exchanger coil) from the propellant feed system. By also increasing the propellant tank pressure from 200 to 300 psig, the valve opening time was reduced from about 650 to 400 milliseconds. These changes did not seem to affect the valve-leakage or vent-line-plugging phenomena. The results during this set of tests, which was terminated at the end of cycle 8, were similar to those of the first set of remedial tests.

For the final set of remedial tests, the glass vent-lines on valves Two and Four were replaced by the aluminum lines and flat plates used for the second set of remedial tests. In addition, a length of insulated heater wire was wrapped around vent-line Number Four. For the first three cycles, a 10-watt heat-flux was applied, and during the remainder of the 53 cycles, a five-watt heat flux was applied. Intermittent plugging and unplugging of the vent lines was experienced during the first 15 cycles on all lines except line Number Four (the heated line) and all the valves opened and closed completely. During cycle number 16, valve Number One stuck open and remained open for the remainder of the test. Lines Two and Three were intermittently plugged and unplugged throughout the test. Finally, on cycle number 53, Number One glass vent-line broke because of excessive fluid pressure created by the plug of frozen propellant at the exit end. Vent-line Number Four (the heated line) was not plugged throughout the test. Excessive leakage past the piston seals was noted throughout the test.

During all the tests with the Descent vent line configurations, it was observed that considerable amounts of frozen propellant (from the discharge of the nearby lines) accumulated on the outside of the vent lines near the exit ends. This condition arose because the propellant discharged from the vents in a conical spray of vapor and freezing liquid. The included angle of the spray cone was nearly 180°. Moreover, as growths of frozen propellant grew at the vent outlets, much of the spray sometimes was deflected in a backward direction. The freezing liquid in these sprays impinged and froze on the outside surfaces of the nearby vent lines. Continuing evaporative cooling from this material refrigerated the line and froze the liquid inside. This occurrence undoubtedly played a major role in the formation of plugs in the vent lines during these tests.

After the scheduled tests were completed, the Descent valve assembly was pressure-tested with nitrogen gas. Three types of tests were conducted. The first test involved applying N_2 gas at a pressure of 160 psig, to the solenoid-valve inlet. The solenoid valves were deenergized and leakage past the solenoid valve seats was checked. No leaks past the solenoids could be detected, and since leaks as low as 10 cc/hr could be measured by the technique used, leakage, if any, must have been less than this value. The same arrangement was used for the second leak test, except that the pressure was increased to 260 psig. Again no leakage was detected. The third type of test involved opening one solenoid at a time and checking leakage past the piston seals at a pressure of 260 psig. No leakage was detected past any of the pistons. However, during this set of tests, solenoid valve Number Three failed to close completely in two of the five tests performed.

The limited scope and time available to conduct the test program did not permit an optimization of the heater requirements to prevent evaporative freezing in the vent lines. During one of the Descent-system remedial tests, a thermal flux as low as five watts, applied to the exit end of one of the vent lines, prevented freezing. This, however, may not have been the worst case. For the worst case, the composition of the freezing fuel mixture (N_2H_4 and UDMH) is that which has the highest vapor pressure, and, hence, produces the maximum evaporative heat flux for freezing mixtures. This condition occurs at approximately $-3.9^{\circ}C$ where the total vapor pressure is approximately 26.5 torr*. Considering flow of the propellant liquid and vapor through the 1/16-inch-diameter orifice, the heat required to prevent freezing in the vent line, can be calculated for this worst-case condition,

---

*Estimated for limited data (cf. Reference 3).

as follows:

$$q_T = K_u A_o \Delta H_u \frac{P_u}{\sqrt{T}} + K_H A_o \Delta H_H \frac{P_H}{\sqrt{T}}$$

For UDMH $q = 552 \times .0198 \times 129.6 \frac{(24.74)}{760 \sqrt{269}} = 2.80 \text{ cal/sec}$

For N_2H_4 $q = 294 \times .0198 \times 429 \frac{(1.76}{760 \times \sqrt{269}} = 0.352 \text{ cal/sec}$

$$q_T = 2.80 + 0.35 = 3.15 \text{ cal/sec}$$

$$= 13.2 \text{ watts}$$

Accordingly, an estimated heat-flux value of 13.2 watts is required to prevent freezing in the vent line for the worst case. The value for the constants K_u and K_H was derived from the data and detailed analysis presented in the Atlantic Research Corporation report entitled "The Study of Valve Leakage in a Vacuum Phase II Report".(4) The subscripts u and H refer to UDMH and hydrazine, respectively. A_o represents the orifice area, ΔH is the heat of vaporization, P is the partial pressure and T is the temperature of the mixture.

5.0 CONCLUSIONS

During the duty cycles of a normal mission (as presently planned) in both the Ascent and Descent tests, no problems were encountered which would have prevented successful completion of the mission. Even when a plug formed at the exit of the vent line during the first cycle, the valves still operated. The reason for this is that the volume of the vent lines is sufficient to contain the entire amount of propellant vented during all the cycles of a normal mission. Of course, this would be true only if very little or no leakage through the valves occurred during the mission. Should a vent line become plugged at its outlet end and completely filled with propellant, the main propellant valves associated with that particular vent line could not be closed.

However, during the 20- and 35-restart sets of tests, both valve systems did malfunction because of evaporative freezing. Plugs of frozen propellant formed at the vent line exits, preventing further venting. Eventually the plugged lines filled with propellant and the valve actuators could not move to the closed position. The table below summarizes the critical event data for the restart tests conducted during the program which resulted in eventual actuator-system malfunctioning. These critical event data are the number of cycles in each restart series after which the freezing-induced malfunction occurred.

	Run No.	System Malfunction (cycle No.)
Ascent Tests	1.4b	23
	3.1a	16
Descent Tests	4.1	20
	6.0a	7
	6.0b	17
	6.0c	7
	6.0d	16

The plugging appeared to have resulted from either of two causes. In one case the spray discharge from one vent line impinged and froze on the outside of another. Continuing evaporation of this material cooled and froze the propellant inside that line and formed a plug.

In the second case, the plug appeared to have built up during one or more cycles. In an initially clean line, most of the propellant was expelled from the exit of the line. That which remained usually froze, especially if it was near the exit. When the liquid managed to freeze around the lip of the end of the vent line, a tight bond between the end of the line and the frozen material was formed (Aerozine-50 shrinks as it freezes). Thus, the footing of the frozen material was sufficiently strong to obstruct the flow of subsequent ventings. In a short time (often within one cycle), enough additional liquid collected about this material, froze and occluded in the end of the line. The necessary condition for plugging of this type to occur is that some protuberance or convex surface (e.g. the lip of the vent line exit) be available for the propellant to freeze around and "grasp".

Although not investigated, another plugging mode is likely to occur when some of the vehicle is in the path of the discharge spray. The propellant will freeze on this part, and after several cycles a stalagmite of frozen propellant will grow back into the vent line and plug the opening. This process has been observed in other experiments.(1)

The experiments described were, of course, performed in a one-g gravitational field. In the absence of gravity (or in a field of low strength), freezing and plugging is expected to be more severe. In the experiments of this program, the axes of the vent lines were orientated more or less perpendicular to gravity. Thus, residual liquid remaining in the lines after a cycle, collected in the low section formed by the bends in the lines. However, in the absence of gravity, this liquid would be carried to the end of the line by the flow of the vapor that is evolved. Since the flow of this liquid would likely be slow, it could easily freeze in the end of the line and enhance plug formation.

Placing a small orifice at the vent-line exit can be used to limit the amount of propellant loss should the pilot valve stick half-open during a firing. Such an orifice, togehter with heat applied to the end of the vent line, also can be used to prevent evaporative freezing within the line. The orifice limits the rate of vapor flow from the vent line, and therefore the rate of evaporative cooling within the line. For the case of the 1/16-inch-diameter orifice tested, it was estimated that a heat flux of approximately 13 watts from a heater would be required to prevent evaporative freezing in the vent line for the worst-case conditions. Even better results could be obtained with a smaller orifice, limited only by the possibility that it could become plugged with some foreign material. A smaller orifice reduces the heat requirements to prevent freezing, and limits, further, the loss of propellant through an accidently stuck valve.

The LEM ascent pilot valve and actuator systems performed satisfactorily during the tests conducted; however, the LEM descent pilot valve and actuator system leaked profusely during some of the tests. Propellant leakage past the actuator piston seals was considerable each time the valve was cycled. The amount of leakage was undoubtedly affected by the fact that the valve-actuation time during the tests was about three times longer than the design value.

6.0 RECOMMENDATIONS

During this brief (11-week) test program, several significant facts were learned concerning the behavior, in a vacuum environment, of the LEM Ascent and Descent propellant-valve actuating systems. Although the primary purpose of this program was the determination of the extent of and adverse effects resulting from the accumulation of frozen propellant in the vent-line of LEM propellant-valve actuating systems, several important side results also were obtained. However, as a result of time and budgetary limitations, the potential difficulties and remedial procedures, suggested by the important test results, could not be explored fully. Therefore, the recommendations discussed below include suggestions for further investigations, as well as suggested procedures that relate directly to vent-line design considerations which were the main objective of this program.

As was discussed in Section 5.0 of this report, one of the principal conclusions derived, which also can be regarded as a recommendation, concerns vent-line design criteria for normal LEM mission duty cycles. In this respect, the present vent-line designs, both for the Ascent and the Descent systems, appear to be adequate notwithstanding the threat of plugging by the accumulation of frozen propellant at their discharge ends. The reason for this, as discussed before, is that their volumetric capacities permit them to accommodate at least the number and intervals of valve-actuation cycles associated with the presently-planned LEM normal mission, even when their exit ends are plugged (assuming, of course, that little or no pilot-valve leakage occurred during the mission). However, the addition of a small orifice at the end of each line, to limit the extent of propellant loss in the event of a pilot valve being stuck in the half-open position, probably would be desirable. The results of testing on this program indicate that these orifices would not alter the propellant freezing and accumulation around the vent-line discharge end, and therefore would not adversely affect the presently-planned LEM normal mission (assuming, again, that significant valve leakage does not occur during the mission). In fact, a properly-designed orifice can actually retard or prevent propellant-freezing inside the vent line.

Although, as stated above, the normal mission could probably be completed without difficulty using the present vent-line design, certain deviations, such as a significant increase in the number and frequency of restarts, could present serious problems. Such mission-plan deviations possibly could occur as a result of emergency situations. Therefore, it is recommended that further investigations be conducted to establish optimum vent-line design criteria to eliminate the threat of vent-line plugging by evaporatively-frozen propellant. Consideration of such factors as (1) vent-line placement and discharge-end designs to prevent the impingement of effluent from one line onto the discharge-end of other lines; (2) location of structural protuberances with respect to the discharge end of the vent-lines; (3) optimum design of heaters; etc., should be included in such an investigation. Although it was demonstrated during the present program that the application of heat to the vent-lines can be an effective deterrent to the accumulation of frozen propellant, program limitations did not permit the determination of the optimum amount of heat flux required for individual vent-lines. This information would probably be very beneficial.

Finally, it appears that the actual performance of the entire valve-actuating systems (Ascent and Descent) in a vacuum environment should be evaluated very carefully. Fortunately, although not part of the principal objective of this program, the performance characteristics of one of these actuator assemblies, in a realistic vacuum environment, were observed. As a result, several possible problem areas were identified. A future program of investigation to thoroughly assess and, if necessary, remedy these difficulties should give particular attention to (1) the minimum value of propellant feed pressure, below which the rate of travel of the actuator piston becomes low enough to permit leakage past the piston, thereby setting up deleterious conditions of propellant freezing inside the actuator cavity; (2) leak tests for a selection of leak rates beyond the leak-rate levels used in the experiments of this program; and (3) additional sources of valve leakage and/or malfunction, in a vacuum environment, as yet unidentified, which possibly could compromise the successful completion of even the normal LEM mission-plan.

LITERATURE CITATIONS

1. Atlantic Research Corporation, "Investigation of the Effects of Vacuum on Liquid Hydrogen and Other Cryogens Used on Launch Vehicles", Final Summary Report by J.A. Simmons, R.D. Gift, and M. Markels, Jr. for Contract NAS 8-11044, December 18, 1964.

2. Bell Aerosystems Company, "Titan II Storable Propellant Handbook", AFFTC TR-61-32, Contract No. AF 04(611)-6079, June 1961.

3. Atlantic Research Corporation, "Study of Propellant Valve Leakage in a Vacuum", Phase I Report, June 7, 1965 to November 24, 1965.

4. Atlantic Research Corporation, "Study of Propellant Valve Leakage in a Vacuum", Phase II Report, January 14, 1966 to March 7, 1966. Contract No. NAS 9-4494.

5. Atlantic Research Corporation, "Study of Propellant Valve Leakage in a Vacuum", Phase IV Report, December 10, 1965 to January 14, 1966.

APPENDIX A

TEST DATA

This appendix contains the detailed test data obtained during the LEM Ascent and Descent tests. The test program is outlined in Tables 3-1 and 3-2. The sets of test runs having the initial numbers one through three were conducted with the ascent valve network, and runs with initial numbers four through six were conducted with the Descent valve network. All tests were accomplished in the Atlantic Research Corporation's high-altitude facility at a pressure of approximately 0.04 torr. The data were recorded as functions of time by a multi-channel recording oscillograph. Test procedures used for both the Ascent and Descent tests are described in Section 3.2.

A comparison of the data in the Valve Response columns yields the elapsed-time intervals between valve-cycling events. These data represent the time into the test (starting at zero) when the electrical solenoids were energized and de-energized. Propellant temperature and pressure were measured just upstream from the pilot valve (see Figures 3-9 and 3-11). The symbol N/A, shown in the tabulated data, indicates that the data point was not available because of a malfunction of the sensing element or because of some other test anomaly.

The propellant-valve position (open or closed) was determined by attaching a potentiometer to the actuator linkage (see Figure 3-12 and the discussion in Section 3). In conjunction with a signal conditioning circuit, where the potentiometer was used as two legs in a bridge configuration, the valve opening and closing was recorded versus time with a recording oscillograph. This measurement was used to determine the extent of completion of valve opening and closing during each cycle. This same measurement also was used to determine the time required to open and close the valves. The column headed "Δt_1" shows the time required to open the valve, and the column headed "Δt_2" shows the time required to close the valve. The data represent the elapsed time from the instant the actuator linkage began to move until the actuator linkage movement was completed.

As discussed in Section 3.1, all four of the Descent pilot valve-actuator sub-assemblies that comprise a typical unit were tested because of the integral construction of the system. Only one of the actuator linkages (number Three as identified in Figure 3-3) was equipped with a potentiometer-valve-position indicator. Consequently, the data column headed "piston travel" refers only to the Number-Three actuator.

During test series 6.0 the average coast period between cycles was five minutes except for the final 38 cycles of test set 6.0d, wherein a coast period of three to four seconds was used.

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED					
1.1a	0		100%	76		215	
		:05	"	76			30
	5:05		"	75		185	
		11:45	"	78			10
	20:45		"	165		245	
		20:50	"	163			30
	31:50		"	66		210	
		31:55	"	67			30
1.1b	0		100%	83		150	
		:05	"	84			70
	5:05		"	83		10	
		11:45	"	85			10
	17:10		"	166		10	
		17:15	"	157			10
	23:10		"	55		60	
		23:55	"	55			70
1.2a	0		100%	65	62	30	
		:05	"	65	61		30
	4:05		"	65	61	10	
		10:45	"	68	73		10
	16:10		"	45	60	50	
		16:15	"	45	59		70
	20:10		"	53	57	60	
		20:15	"	53	57		70
1.2b	0		100%	66	65	50	
		:05	"	66	65		150
	4:05		"	66	61	100	
		10:45	"	69	74		100
	13:40		"	45	66	60	
		13:45	"	46	66		100
	17:45		"	43	55	60	
		17:50	"	44	55		50

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
1.3a	0		100%	83		10	
		8:10	"	86			10
	15:45		"	172		150	
		15:50	"	168			60
1.3b	0		100%	92		10	
		7:10	"	92			10
	21:10		"	173		110	
		21:15	"	172			90
1.4a	0		100%	42	63	10	
		7:10	"	65	76		10
	13:35		"	44	61	60	
		13:40	"	44	62		50
	20:00		"	42	58	50	
		20:05	"	43	59		70
	30:15		"	45	57	50	
		30:20	"	46	57		50
	36:50		"	46	57	60	
		36:55	"	47	57		70
	41:30		"	48	54	50	
		41:35	"	48	54		70
	48:05		"	46	54	50	
		48:10	"	46	55		70
	50:25		"	45	51	80	
		50:30	"	45	51		60
	52:55		"	44	51	50	
		53:00	"	45	51		70
	56:15		"	42	51	50	
		56:20	"	44	51		70
	57:20		"	44	50	40	
		57:25	"	44	50		60
	1:06:35		"	44	53	50	
		1.06:40	"	45	53		50
	1:08:10		"	46	51	50	
		1.08:15	"	46	51		60
	1:10:05		"	44	48	40	
		1:10:10	"	45	49		80
	1:11:45		"	44	48	40	
		1:11:50	"	44	48		50

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED					
1.4a	1:15:00		100%	44	49	40	
(cont.)		1:15:05	"	44	49		60
	1:21:00		"	44	48	50	
		1:21:05	"	44	48		60
	1:23:10		"	45	48	50	
		1:23:15	"	45	48		70
	1:26:05		"	46	47	60	
		1:26:10	"	46	47		60
	1:28:40		"	45	46	50	
		1:28:45	"	46	46		70
	1:31:20		"	45	46	50	
		1:31:25	"	45	46		70
	1:35:15		"	45	47	40	
		1:35:20	"	45	47		70
	1:40:00		"	45	48	40	
		1:40:05	"	45	48		60
	1:41:55		"	45	47	50	
		1:42:00	"	45	47		60
	1:46:25		"	46	48	40	
		1:46:30	"	46	48		70
	1:49:20		"	43	48	50	
		1:49:25	"	44	48		70
	1:54:00		"	44	48	40	
		1:54:05	"	44	48		70
	1:59:00		"	45	47	50	
		1:59:05	"	45	47		70
	2:05:25		"	46	48	50	
		2:05:30	"	46	48		60
	2:07:55		"	46	47	50	
		2:08:00	"	46	47		70
	2:14:30		"	45	47	60	
		2:15:35	"	46	47		70
	2:17:00		"	44	47	50	
		2:17:05	"	45	47		70
	2:22:05		"	49	47	50	
		2:22:10	"	45	47		70
	2:25:25		"	44	46	60	
		2:25:30	"	45	46		80
	2:32:00		"	43	47	50	
		2:32:05	"	44	47		80
	2:37:50		"	44	48	60	
		2:37:55	"	44	48		80
	2:42:35		"	43	47	60	
		2:42:40	"	43	47		70

ASCENT TEST DATA

RUN	VALVE RESPONSE (min:sec)		PISTON TRAVEL	FUEL TEMP.	VALVE TEMP.	Δt_1m sec	Δt_2m sec
NO.	OPEN	CLOSED	%	°F	°F		
1.4b	0		100%	45	63	10	
		7:10	"	64	74		10
	14:10		"	44	66	70	
		14:15	"	45	66		65
	17:00		"	41	59	50	
		17:05	"	43	59		70
	23:00		"	42	55	50	
		23:05	"	43	55		70
	28:05		"	42	52	55	
		28:10	"	43	52		70
	31:40		"	42	51	55	
		31:45	"	43	51		70
	38:30		"	34	47	55	
		38:35	"	35	47		70
	42:55		"	41	51	65	
		43:00	"	42	51		70
	49:05		"	42	52	65	
		49:10	"	43	52		70
	52:40		"	42	50	65	
		52:45	"	43	50		70
	58:20		"	43	48	70	
		58:25	"	43	48		70
	1:02:05		"	41	48	70	
		1:02:10	"	42	48		70
	1:07:25		"	42	47	80	
		1:07:30	"	42	47		70
	1:12:05		"	41	47	65	
		1:12:10	"	42	47		70
	1:17:05		"	38	46	75	
		1:17:10	"	38	46		70
	1:22:05		"	41	46	65	
		1:22:10	"	42	46		70
	1:28:30		"	42	47	60	
		1:28:35	"	42	47		70
	1:32:45		"	44	47	70	
		1:32:50	"	45	47		70
	1:37:10		"	38	45	60	
		1:37:15	"	39	45		75
	1:39:35		"	42	45	50	
		1:39:40	"	43	45		80
	1:42:30		"	43	47	50	
		1:42:35	"	43	47		70

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
1.4b (cont.)	1:46:55		100%	43	49	50	
		1:47:00	"	44	49		90
	1:52:00		"	44	52	55	
		1:52:05	"	45	52		100
	1:56:40		"	44	52	45	
		1:56:45	89.75%	45	52		110
	2:01:05		100%	43	54	40	
		2:01:10	38.5%	44	54		105
	2:05:05		100%	44	52	20	
		2:05:10	5.75%	44	52		30
	2:11:05		100%	45	54	10	
		2:11:10	0.1%	46	54		-
	2:17:00		100%	44	54	-	
		2:17:05	0	45	54		-

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F.	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED					
2.1a	0		100%	42	56	10	
		7:10	"	64	73		10
2.1b	0		100%	45	61	10	
		7:10	"	64	74		10
2.1c	0		100%	45	59	10	
		7:10	"	60	68		10
2.1d	0		100%	47	61	10	
		7:10	"	64	73		10

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F.	Δt_1m sec	Δt_2m sec	LEAK RATE gm/sec
	OPEN	CLOSED						
2,2a	0		100%	72	69	10		5
		7:10	"	75	68		10	
	17:10		"	72	70	440		
		7:14	"	72	70		120	
2.2b	0		100%	66	N/A	10		.08
		7:10	"	68	N/A		10	
	17:06		"	73	N/A	60		
		17:10	"	73	N/A		50	
2.2c	0		100%	67	52	35		5.33
		0:15	"	67	52		10	
2.2d	0		100%	66	59	15		.31
		:05	"	67	59		10	

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec	LEAK RATE gms/sec
2.3a	0		15%	71	65	40		76
		10	100%	68	62		10	
2.3b	0		24%	65	62	310		76
		10	100%	65	58		10	
2.3c	0		100%	63	56	70		76
		10	"	62	54		10	
2.3d	0		100%	63	59	280		76
		23	"	63	58		95	

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
3.0a	0		100%	52	61	40	
		:05	"	53	61		70
	9:30		"	49	59	60	
		9:35	"	51	59		80
	14:50		"	46	57	60	
		14:55	"	47	57		80
	17:20		"	45	53	70	
		17:25	"	46	53		80
	20:25		"	44	50	60	
		20:30	"	44	50		80
	23:40		"	43	49	80	
		23:45	"	44	49		70
	28:50		"	44	49	60	
		28:55	"	45	49		70
	31:55		"	43	48	80	
		32:00	"	44	48		80
	35:35		"	42	47	70	
		35:40	"	43	47		80
	38:55		"	43	47	90	
		39:00	"	44	47		70
	42:40		"	43	48	150	
		42:45	"	43	48		60
	48:50		"	44	49	140	
		48:55	"	45	49		60
	52:20		"	43	51	130	
		52:25	"	44	51		60
	56:40		"	42	52	130	
		56:45	"	43	52		70
	1:00:20		"	41	52	130	
		1:00:25	"	42	52		70
	1:07:20		"	43	53	180	
		1:07:25	"	44	53		80

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED					
3.0b	0		100%	75	72	200	
		7:10	"	77	81		70
	12:10		"	80	81	180	
		12.15	"	80	81		70
	17:10		"	80	78	180	
		17:15	"	80	79		70
	22:20		"	79	76	160	
		22:25	"	79	76		70
	27:25		"	78	75	170	
		27:30	"	78	75		70
	32:30		"	77	74	160	
		32:35	"	77	74		
3.0c	0		100%	72	69	110	
		:05	"	72	70		60
	5:05		"	72	68	-	
		11:45	"	74	77		-
	14:35		"	74	68	180	
		14:40	"	75	68		70
	18:55		"	75	65	180	
		19:00	"	76	64		70
3.0d	0		100%	42	63	100	
		7:10	"	66	74		100
	9:35		"	45	68	50	
		9:40	"	46	68		70
	28:00		"	51	62	50	
		28:05	"	53	63		70
	31:40		"	50	59	50	
		31:45	"	52	59		80
	34:25		"	54	59	50	
		34:30	"	54	59		60

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	VALVE RESPONSE (min:sec) CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
3.0d	41:20		100%	47	57	50	
(cont.)		41:25	"	49	57		60
	44:35		"	46	56	50	
		44:40	"	47	56		60
	48:30		"	45	56	50	
		48:35	"	47	55		70
	52:35		"	45	55	50	
		52:40	"	46	55		80
	55:30		"	45	54	50	
		55:35	"	47	54		70
	58:50		"	45	54	50	
		58:55	"	46	54		70
	1:03:15		"	47	55	50	
		1:03:20	"	48	55		70
	1:07:15		"	45	55	60	
		1:07:20	"	46	55		70
	1:11:15		"	46	55	50	
		1:11:20	"	47	55		55
	1:19:15		"	43	56	50	
		1:19:20	"	45	56		70
	1:23:10		"	45	55	50	
		1:23:15	"	46	55		70
	1:26:15		"	44	55	50	
		1:26:20	"	45	54		70
	1:30:30		"	44	54	50	
		1:30:35	"	45	53		70
	1:35:30		"	43	53	50	
		1:35:35	"	44	53		70
	1:39:30		"	45	54	50	
		1:39:35	"	46	55		70
	1:43:15		"	45	54	50	
		1:43:20	"	46	54		70
	1:47:10		"	45	54	50	
		1:47:15	"	47	54		80
	1:51:15		"	45	54	70	
		1:51:20	"	46	54		80
	1:54:50		"	45	53	70	
		1:54:55	"	46	53		70
	1:59:05		"	43	52	70	
		1:59:10	"	44	52		70
	2:03:15		"	42	52	80	
		2:03:20	"	43	52		70
	2:07:00		"	43	51.5	70	
		2:07:05	"	44	51		70

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED					
3.0d (cont.)	2:12:10		100%	44	52	90	
		2:12:15	"	45	52		70
	2:16:05		"	43	51	80	
		2:16:10	"	44	51		70
	2:19:25		"	43	51	80	
		2:19:30	"	44	51		70
	2:23:30		"	43	51	90	
		2:23:35	"	44	51		70
	2:27:20		"	42	52	90	
		2:27:25	"	44	52		70
	2:30:35		"	45	52	100	
		2:30:40	"	46	52		60
	2:35:35		"	42	52	110	
		2:35:40	"	43	52		70
	2:40:35		"	45	53	120	
		2:40:40	"	46	53		70
	2:45:35		"	45	54	120	
		2:45:40	"	47	54		70
3.0e	0		100%	46	58	10	
		7:10	"	62	68		10
	10:50		"	73	67	140	
		10:55	"	45	66		70
	15:35		"	45	61	160	
		15:40	"	47	61		70
	20:00		"	45	58	150	
		20:05	"	46	58		60
	25:05		"	35	53	170	
		25:10	"	36	53		70
	29:15		"	45	52	160	
		29:20	"	46	52		60
	34:25		"	45	54	65	
		34:30	"	46	54		65
	38:45		"	45	53	170	
		38:50	"	46	54		70
	43:45		"	45	53	180	
		43:50	"	46	53		70
	48:45		"	75	52	175	
		48:50	"	45	52		70
	53:45		"	45	53	195	
		53:50	"	46	53		70

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	VALVE RESPONSE (min:sec) CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
3.0e (cont.)	58:15		100%	43	52	210	
		58:20	"	44	52		65
	1:02:05		"	45	51	200	
		1:02:10	"	45	51		65
	1:07:00		"	45	52	195	
		1:07:05	"	46	52		65
	1:11:00		"	44	53	200	
		1:11:05	"	45	53		75
	1:15:50		"	45	52	205	
		1:15:55	"	46	52		70
	1:19:45		"	45	54	220	
		1:19:50	"	46	54		60
	1:24:20		"	46	55	215	
		1:24:25	"	46	55		70
	1:27:35		"	45	53	200	
		1:27:40	"	47	53		70
			Lost Vacuum				
	0		100%	47	57	205	
		:05	"	48	56		70
	4:30		"	45	56	210	
		4:35	"	47	56		70
	10:30		"	45	57	210	
		10:35	"	47	57		70
	13:40		"	43	56	210	
		13:45	"	45	56		70
	17:40		"	44	55	200	
		17:45	"	45	55		70
	22:10		"	45	56	205	
		22:15	"	46	55		70
	27:50		"	44	56	205	
		27:55	"	45	56		70
	33:00		"	44	56	210	
		33:05	"	45	56		75
	37:25		"	41	54	205	
		37:30	"	42	54		65
3.0f	0		100%	47	67	100	
		7:10	"	68	65		100
	9:35		"	52	69	210	
		9:40	"	54	69		70
	13:55		"	46	66	210	
		14:00	"	47	66		70
	17:35		"	47	64	210	
		17:40	"	48	64		70

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	VALVE RESPONSE (min:sec) CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
3.0f	19:45		100%	45	60	210	
(cont.)		19:50	"	46	59		70
	23:30		"	45	59	210	
		23:35	"	47	59		70
	24:45		"	45	57	210	
		24:50	"	46	57		70
	26:40		"	44	56	200	
		26:45	"	46	56		70
	30:40		"	46	57	210	
		30:45	"	47	57		70
	31:35		"	44	55	20	
		31:40	"	45	54		70
	33:25		"	43	53	20	
		33:30	"	44	53		70
	36:40		"	45	55	210	
		36:45	"	47	55		70
	38:00		"	44	53	210	
		38:05	"	45	53		70
	38:55		"	45	52	220	
		39:00	"	46	52		70
	42:15		"	45	55	210	
		42:20	"	47	55		70
	43:20		"	43	52	200	
		43:25	"	45	52		70
	45:10		"	44	52	210	
		45:15	"	45	52		70
	48:40		"	44	54	200	
		48:45	"	45	54		70
	49:45		"	43	52	210	
		49:50	"	44	52		70
	51:00		"	43	52	200	
		51:05	"	44	52		70
	54:15		"	44	54	210	
		54:20	"	45	54		70
	55:25		"	43	52	200	
		55:30	"	44	52		70
	56:15		"	44	51	200	
		56:20	"	45	51		70
	59:35		"	45	54	200	
		59:40	"	46	54		70
	1:01:25		"	44	52	210	
		1:01:30	"	45	52		70
	1:02:25		"	45	51	210	
		1:02:30	"	46	51		70
	1:05:25		"	43	53	200	
		1:05:30	"	45	53		70

ASCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
3.0f	1:08:45		100%	44	55	200	
(cont.)		1:08:50	"	46	55		70
	1:09:55		"	43	52	200	
		1:10:00	"	44	52		70
	1:13:05		"	44	54	200	
		1:13:10	"	45	54		70
	1:14:25		"	47	52	200	
		1:14:30	"	47	52		70
	1:15:45		"	52	52	200	
		1:15:50	"	45	52		70
	1:18:55		"	44	54	170	
		1:19:00	"	45	54		70
	1:20:25		"	43	52	200	
		1:20:30	"	44	52		70
	1:22:15		"	44	52	200	
		1:22:20	"	45	52		70
	1:23:40		"	44	52	200	
		1:23:45	"	45	51		70

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	VALVE RESPONSE (min:sec) CLOSED	PISTON TRAVEL %	FUEL TEMP. ^{o}F	VALVE TEMP. ^{o}F	Δt_1m sec	Δt_2m sec
4.1	0		100%	38	76	640	
		:10	"	39	76		160
	5:20		"	37	76	660	
		5:30	"	38	76		150
	8:20		"	37	68	990	
		8:30	"	37	68		150
	13:05		"	35	64	830	
		13:15	"	36	64		150
	16:50		"	38	60	760	
		16:60	"	38	60		150
	21:10		"	37	57	770	
		21:20	"	38	57		180
	24:50		"	35	54	840	
		25:00	"	36	55		170
	29:25		"	36	52	740	
		29:35	"	37	52		160
	31:50		"	35	50	620	
		32:00	"	35	50		150
	36:35		"	37	47	590	
		37:45	"	37	47		150
	38:55		"	37	46	700	
		39:05	"	38	46		150
	43:20		"	38	45	700	
		43:30	"	39	45		150
	47:35		"	37	44	690	
		47:45	"	38	44		150
	50:55		"	35	43	670	
		51:05	"	36	43		150
	55:55		"	37	42	560	
		56:05	"	37	42		150
	1:00:45		"	36	41	570	
		1:00:55	"	37	41		150
	1:04:40		"	34	39	620	
		1:00:50	"	35	39		150
	1:07:25		"	34	38	640	
		1:07:35	"	34	38		150
	1:12:40		"	37	37	690	
		1:12:50	"	37	37		150
	1:15:20		No reaction	35	37		
	1:15:29		30%				
		1:15:30	100%	36	38		
	1:25:35		No reaction	36	37		
	1:25:41		100%				
		1:25:45	"	37	37		

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
4.2a	0		100%	91	91	250	
		:33	"	92	91		100
	5:33		"	120	89	500	
		20:43	"	99	102		160
4.2b	0		100%	84	90	300	
		:33	"	84	90		150
	5:30		"	111	89	440	
		20:40	"	99	102		150

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	VALVE RESPONSE (min:sec) CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
4.3a	0		100%	84	92	400	
		:33	"	84	92		150
	5:22		"	43	88	400	
		20:32	"	61	94		160
4.3b	0		"	81	93	200	
		:33	"	81	93		100
	4:03		"	37	112	500	
		19:13	"	51	94		150

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (min:sec) OPEN	CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	Δt_1m sec	Δt_2m sec
4.4a	0		100%	41	76	600	
		:33	"	43	75		150
	6:40		"	42	71	600	
		21:50	"	59	81		160
4.4b	0		"	39	78	600	
		:33	"	43	78		150
	5:40		"	38	74	600	
		20:50	"	59	83		160

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	FUEL PRES. psig	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED						
5.0a	0			35	73	203		
	150					63		
	550					93		
	600		100%			203	480	
		33,000	"	37	68	203		150
5.0b	0			35	68	202		
	100					76		
	550					104		
	600		100%			202	500	
		33,000	"	37	68	202		150
5.0c	0			45	82	305		
	150					83		
	570					111		
	600		100%			305	470	
		33,000	"	47	82	305		150
5.0d	0			39	77	304		
	150					84		
	550					111		
	600		100%			304	470	150
		33,000	"	43	78	304		

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	FUEL PRES. psig	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED						
6.0a	0			41	82	304		
	150					85		
	570					112		
	600		100%			304	470	
		5,000	"	43	82	304		150
	0			43	77	304		
	120					80		
	580					100		
	600		100%			304	480	
		10,000	"	44	77	304		150
	0			42	75	304		
	130					83		
	570					111		
	600		100%			304	470	
		10,000	"	42	74	304		150
	0			42	68	304		
	120					83		
	540					110		
	580		100%		68	304	470	
		10,000	"	43		304		150
	0			52	61	305		
	100					80		
	530					110		
	580		100%			305	470	
		10,000	"	51	61	305		150
	0			47	52	304		
	100					83		
	530					110		
	600		100%			304	470	
		10,000	"	48	52	304		150
	0			45	46	304		
	140					83		
	530					109		
	580		100%			304		
		10,000	47%	47	46			-

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m. sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	FUEL PRES. psig	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED						
6.0b	0			39	55	305		
	180					82		
	570					109		
	630		100%			305	500	
		10,000	"	42	55	305		150
	0			43	51	305		
	200					83		
	580					111		
	630		100%			305	490	
		10,000	"	44	51	305		150
	0			37	48	304		
	130					76		
	580					110		
	630		100%			304	480	
		10,000	"	38	48	304		150
	0			40	44	304		
	140					78		
	590					111		
	650		100%			304	480	
		10,000	"	41	44	304		150
	0			37	43	307		
	100					83		
	500					111		
	600		100%			304	410	
		10,000	"	38	43	304		1290
	0			37	40	306		
	100					83		
	520					111		
	590		100%			306	450	
		10,000	"	38	41	306		150
	0			36	39	305		
	150					83		
	500					110		
	600		100%			305	450	
		10,000	"	36	39	305		150

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	FUEL PRES. psig	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED						
6.0b	0			36	39	304		
(cont.)	160					85		
	540					122		
	610		100%			305	480	
		10,000	"	34	39	305		10 sec
	0			33	39	305		
	170					85		
	560					120		
	630		100%			305		
		10,000	"	31	39	305	470	140
	0			34	38	305		
	150					83		
	550					120		
	610		100%			305	470	
		10,000	"	32	38	305		150
	0			35	38	305		
	160					83		
	550					120		
	600		100%			305	480	
		10,000	"	32	38	305		150
	0			28	38	330		
	150					77		
	600					120		
	670		100%			305	460	
		10,000	"	23	38	305		280
	0			35	37	305		
	140					83		
	530					118		
	600		100%			305	490	
		10,000	"	33	38	305		150

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m sec)		PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	FUEL PRES. psig	Δt_1m sec	Δt_2m sec
	OPEN	CLOSED						
6.0b (cont.)	0			34	37	305		
	120					83		
	540					122		
	630		100%			305	490	
		10,000	"	32	37	305		250
	0			35	37	306		
	120					81		
	540					118		
	630		100%			306	490	
		10,000	"	34	37	306		140
	0			35	37	304		
	130					80		
	510					119		
	610		100%			306	490	
		10,000	"	33	37	306		140
	0				36	305		
	90			32		79		
	560					117		
	650		100%			305	480	
		10,000	"	29	36	305		150
	0			34	37	305		
	110					83		
	510					125		
	590		100%			305	430	
		10,000	"	33	37	305		140
	0			35	37	305		
	110					87		
	430					126		
	520		100%			305	380	
		10,000	90%	33	37	305		140
	0			35	37	304		
	170					92		
	400					124		
	490		100%			305	370	
		10,000	0	33	37	305		

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m sec) OPEN	CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	FUEL PRES. psig	Δt_1m sec	Δt_2m sec
6.0c	0			69	N/A	223		
	100					72		
	600					108		
	650		100%			221	510	
		10,000	"	69	N/A	221		150
	0			69		304		
	80					76		
	440					111		
	460		100%			304	450	
		10,000	"	69		304		140
	0			69		305		
	60					78		
	440					113		
	470		100%			305	400	
		10,000	"	69		305		150
	0			73		305		
	40					79		
	420					114		
	480		100%			305	400	
		10,000	"	73		305		200
	0			73		306		
	70					78		
	440					114		
	470		100%			306	390	
		10,000	"	73		306		200
	0			70		308		
	60					83		
	360					114		
	460		100%			308	400	
		10,000	"	70		308		140
	0			69		308		
	70					78		
	300					120		
	520		92%			308	430	
		10,000	1 sec to close	70		308		150

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m sec) OPEN	CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	VALVE TEMP. °F	FUEL PRES. psig	Δt_1m sec	Δt_2m sec
6.0c (cont.)	0			72		308		
	50					80		
	380					114		
	580		97%			308	400	
		10,000	100%	72		308		160

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m sec)		PISTON TRAVEL %	FUEL TEMP ^{o}F	FUEL PRES. psig	HEATER TEMP.	Δt_1 m sec	Δt_2 m sec
	OPEN	CLOSED						
6.0d	0			62	216	178		
	100				83			
	600				110			
	670		100%		207		450	
		10,000	"	61	207	179		150
	0			61	210	173		
	90				78			
	600				109			
	650		100%		208		450	
		10,000	"	61	208	174		150
		+ 100 sec				152		
	0			63	214	162		
	90				77			
	600				111			
	650		100%		209		560	
		10,000	"	63	209	163		150
		+ 120 sec				144		
	0			64	214	141		
	90				75			
	600				109			
	670		100%		210		550	
		10,000	"	64	210	140		150
		+ 140 sec				121		
	0			65	211	124		
	80				76			
	600				111			
	640		100%		211		550	
		10,000	"	65	211	125		150
		+ 180 sec				109		
	0			65	212	115		
	60				76			
	550				111			
	620		"		209		560	
		10,000	"	65	209	116		150
		+ 170 sec				101		
	0			65	213	107		
	70				77			
	640				111			
	600		100%		209		510	
		10,000	"	65	209	107		150
		+ 130 sec				96		

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m sec) OPEN	VALVE RESPONSE (m sec) CLOSED	PISTON TRAVEL %	FUEL TEMP. °F	FUEL PRES. psig	HEATER TEMP.	Δt_1m sec	Δt_2m sec
6.0d (cont.)	0			64	214	101		
	90				78			
	500				112			
	50		100%		209		450	
		10,000	"	64	209	102		140
		+ 100 sec				90		
	0			63	214	99		
	60				84			
	350				110			
	480		100%		209	100	340	
		10,000	"	63	209	87		140
		+ 160 sec						
	0			63	212	88		
	100				77			
	460				107			
	570		100%		209		440	
		10,000	"	63	209	88		140
		+ 80 sec				85		
	0			62	213	85		
	60				77			
	510				117			
	530		100%		208		470	
		10,000	"	61	208	85		140
		+ 60 sec				81		
	0			58	211	81		
	60				76			
	500				107			
	560		100%		208			
		10,000	"	58	208	81	510	
		+ 60 sec				80		260
	0			58	211	80		
	50				82			
	460				105			
	510		100%		208		400	
		10,000	"	57	208	80		140
		+ 60 sec				78		
	0			55	209	78		
	40				81			
	430				113			
	500		100%		208		400	
		10,000	"	55	208	77		140
		+ 80 sec				unchanged		

DESCENT TEST DATA

RUN NO.	VALVE RESPONSE (m sec)		PISTON TRAVEL %	FUEL TEMP. °F	FUEL PRES. psig	HEATER TEMP.	Δt_1 m sec	Δt_2 m sec
	OPEN	CLOSED						
6.0d	0				211	77		
(cont.)	50				86			
	400				116			
	440				208			
		10,000	100%	55	208	77	360	
		+ 50 sec	"			76		130

38 additional rapid recycles of 3 to 4 seconds each - no plugging of heated vent.