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SUBCRITICAL CRYOGENIC STORAGE DEVELOPMENT AND FLIGHT TEST

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Houston, Texas

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ABSTRACT

A subcritical cryogenic nitrogen system was aboard Apollo-Saturn flight 203 on July 5, 1966. This flight completed development of this particular subcritical system.

This paper contains the development history, ground-test results, and flight-test results of a subcritical cryogenic storage system which is designed to supply warm vapor regardless of the liquid orientation. A two-phase development program resulted in delivery of ground-test units and flight units. The successful flight test culminated development efforts with this subcritical system and demonstrated its feasibility.

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SUBCRITICAL CRYOGENIC STORAGE DEVELOPMENT
AND FLIGHT TEST

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SUMMARY

The NASA Manned Spacecraft Center experiment 13 was conducted during the Apollo-Saturn 203 flight on July 5, 1966. This experiment was the culmination of a program to develop a cryogenic dewar which would deliver vapor from two-phase storage in low gravity. The purpose of the experiment was to demonstrate this capability in a low-gravity field using liquid nitrogen as the stored fluid. The basic dewar design required that the delivered fluid be throttled in a control valve and vaporized in a heat exchanger which was brazed to the pressure vessel.

The objectives of the experiment were to demonstrate positive pressure control of the storage volume and pressure stability in the system, to identify the state of the delivered fluid, and to verify operation of a cubical wire matrix used to determine the quantity remaining in the storage vessel. Satisfactory performance of the system in these areas was obtained, providing the confidence needed to use this concept in programs requiring high-reliability subsystems.

Utilizing pressure and temperature data accumulated during the mission, vapor was shown to be consistently present at the heat-exchanger outlet and at the downstream delivery port. Flight data also indicated only minor pressure fluctuations in the delivery circuit which proved satisfactory operation of the heat exchanger and regulator. The average storage vessel capacitance was measured with the wire matrix. This value, which is proportional to the mass of the stored fluid, showed a steady decrease in the mass remaining throughout the mission.

INTRODUCTION

In 1963, the Power Generation Branch of the Propulsion and Power Division at NASA Manned Spacecraft Center (MSC) initiated an effort to develop a reliable cryogenic storage system capable of low-gravity operation in the two-phase (subcritical) region. This mode of storage provides several potential advantages over single-phase storage. Some of these advantages are as follows.

1. Relief of storage dewar thermal design limits

2. A substantial weight savings as a direct result of lower operating pressures which permit lighter components

3. High-density liquid delivery for refilling portable environmental systems on the lunar surface

Analytical and development efforts during the program concentrated on the following topics important to the development of subcritical systems.

1. Measurement of the quantity of stored fluids

2. Vessel internal heat transfer

3. Vessel pressure control

4. Use of available refrigeration in the exiting fluid to reduce heat leak to the inner vessel

The development program was conducted as two distinct phases. The objective of Phase I was to design and fabricate operational prototypes for ground test.[1] Extensive ground testing was performed and the success of the tests determined the advisability of proceeding with Phase II. The objective of Phase II was to evaluate the performance of follow-on subcritical hardware in earth orbit.[2]

Both Phase I and II storage systems were instrumented to show temperatures and pressures of the heat exchanger, storage volume, and delivered gas. Heater currents, flow rates, and fluid quantity were also instrumented to provide a comprehensive parametric view of system behavior. The Phase II experiment package contained signal conditioners to allow telemetry measurements of the system parameters. Launch vehicle instrument-unit broadcast channels were used for this purpose.

The ground-test data and experimental data from earth orbit, operation and description of the systems, and data analysis are presented. Examination of the flight data indicates that the fluid exiting the heat exchanger and delivery port was consistently vapor. This was a prime requirement. The objectives of the development program, which culminated with the orbital test, were fulfilled.

SYMBOLS

h	enthalpy, Btu/lb
J	mechanical equivalent of heat, 778 ft-lb/Btu

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[1] Work performed under contract NAS 9-1065.

[2] Work performed under contract NAS 9-1065.

k	constant
m, M	mass, lb
p, P	pressure, psia
Q_{htr}	heat input by electrical heaters to the pressure vessel, Btu/hr
Q_{hx}	heat removed by the phase-control heat exchanger, Btu/hr
Q_L	ambient heat leak, Btu/hr
T	temperature, °F or °R
t	time increment, hr
t_0	initial time, hr
u	specific internal energy, Btu/lb
v	specific volume, ft^3/lb
x	quality

Subscripts:

1, 2	sequential state points
f	liquid state
g	gaseous state

DESCRIPTION

In subcritical storage, fluid is maintained at a pressure below critical pressure (that pressure below which the fluid may exist as a liquid-vapor mixture and above which it exists as a single-phase fluid). The storage vessel is filled with liquid cryogen at 1 atm and then pressurized by heat leakage or by heaters. When the system is at operating pressure, fluid is withdrawn and throttled in a delivery circuit. The throttling process allows fluid expansion and temperature reduction. To insure delivery of vapor only, the delivery circuit has a phase-control heat exchanger designed to transfer the heat required to vaporize any liquid being delivered. The throttling valve is also designed to maintain constant pressure in the heat exchanger. Therefore, with a nearly constant state point at the heat-exchanger outlet, delivery is achieved at a constant flow rate. Thermodynamic operation of the system is represented in figures 1 and 2. The numbers in parentheses in the following paragraphs correspond to fluid state points shown in these figures.

The filling operation is carried out at atmospheric pressure. Initially at point (1), the thermodynamic state point moves to point (2) as the vessel cools, and to point (3) as filling progresses. After disconnecting service lines and capping the fill and vent fittings, pressure buildup starts. During buildup, the state point moves along path (3) to (5). At (4), the vapor phase disappears, and the tank is filled with compressed liquid. This does not occur unless the fill percentage is high. At (6), which is above the normal operating pressure, venting occurs through the safety relief valve.

Fluid delivery from the storage vessel occurs when demand creates a drop in the delivery line pressure. An internal valve senses this pressure decrease and opens, allowing fluid delivery from the storage vessel into the phase-control heat exchanger. When the tank is full, compressed liquid enters the valve at some point between (5) and (7) and undergoes constant-enthalpy throttling to the corresponding point on path (8) to (8'). As additional fluid is removed, the overall state point moves to the right, along path (5) to (9), until the vapor phase appears at (7). When this occurs, two different throttling processes become possible. When the liquid phase covers the valve inlet, throttling occurs along path (7) to (8'). When the vapor phase is adjacent to the inlet, the path is (9) to (11). Under low-gravity conditions it is nearly impossible to predict which phase will be adjacent to the valve at any given time.

Fluid leaving the internal valve at (8') is a mixture of liquid and vapor at a temperature below that in the storage vessel. The fluid passes through a heat exchanger which is brazed to the inner vessel, where the temperature difference transfers heat from the storage vessel. Liquid remaining in the exchanger vaporizes, and the state point moves to (10).

Fluid leaving the internal valve at (11) is single phase (vapor) at a temperature below that in the storage vessel. Upon passing through the exchanger, the vapor is heated slightly, moving the state point along the path (11) to (12). The internal heat exchanger is sized for liquid delivery. In either case, vapor leaves the exchanger at a temperature no higher than the storage-vessel temperature. External heating is therefore required to supply vapor at 70° to 80° F.

If pressurization of the storage volume is required, an internal regenerative exchanger utilizing the warm vapor is used. The fluid in this exchanger traverses the path (12) to (13) and is then reheated externally to (12) prior to delivery.

System Operational Concepts

Operational concepts are essentially the same for the Phase I and II systems, except for a vapor-cooled radiation shield needed for the low-temperature requirements of the Phase I liquid hydrogen system. The cryogen is stored under pressure in the inner vessel. The inner shell is insulated from the vapor-cooled radiation shield (Phase I hydrogen only) and from the outer shell by means of an evacuated annulus and is supported by low-conductivity support pads. Fill and vent valves permit filling of the inner container. Figure 3 is a representative system schematic.

Phase control. - In a low-gravity environment and in a symmetrically shaped vessel, it is almost impossible to predict whether liquid or vapor will exit the internal regulator valve during two-phase operation. However, because the pressure in the delivery line and phase-control exchanger is below the storage pressure, the boiling point of the fluid in the phase-control exchanger is lower than that of the stored fluid. Because of this temperature difference, heat from the stored fluid is transferred to the fluid passing through the phase-control exchanger. Liquid exiting the internal regulator valve is therefore evaporated in the phase-control exchanger and leaves the phase-control exchanger as a gas. Not only is vapor delivery from the phase-control exchanger insured, but heat is removed from the stored fluid. The overall thermodynamic effect of the phase-control exchanger is essentially equivalent to obtaining vapor withdrawal from the inner container.

During delivery, when a stored fluid is in the compressed liquid state, the same phenomenon occurs, and the exiting liquid is evaporated in the phase-control exchanger.

Filling. - The vessel is filled by passing cryogenic fluid through the fill valve. Initially, most of the liquid is vaporized as it enters the inner shell and vapor is vented through the vent valve. As the temperature of the inner shell drops, the liquid level rises. The fill line enters the inner shell at the bottom of the vessel, and the vent line leaves the inner shell close to the top at a point corresponding to the design fill level. Thus, when the liquid in the inner shell reaches the fill level, excess cryogen overflows through the vent line. The appearance of liquid at the vent valve indicates that the inner container has been filled to the correct level. No restrictions are present in the vent line, and the stored fluid at the end of the filling operation is at atmospheric pressure.

Standby. - Standby is the period, following the filling operation, between closing of the fill and vent valves and the initiation of delivery. During the standby period the storage pressure rises because of the expansion of the liquid phase caused by heat input. Eventually the liquid phase completely fills the inner shell, and the fluid is then in the compressed liquid region.

Delivery. - Delivery is initiated by opening a solenoid valve in the delivery line. When the pressure in the delivery line drops below normal, the internal regulator valve opens to allow flow into the phase-control heat exchanger and thus increases the delivery line pressure. The function of the phase-control heat exchanger is to vaporize any liquid exiting the inner vessel. The absolute-pressure regulator in the delivery line controls the pressure of the fluid as it leaves the system.

The fluid then enters the primary heat exchanger, which heats the exiting fluid to ambient temperature before it enters the bypass control valve (Phase I only). The bypass control valve, used in the Phase I system, bypasses a portion of the ambient-temperature fluid through the pressure-control heat exchanger and reheat exchanger. The Phase II system employed an electrical heater to fulfill this function. The bypass and main streams recombine and pass through a solenoid valve, an absolute-pressure regulator, and a flow-control orifice or needle valve before delivery. An electric heater is provided to assist in pressurization of the stored fluid. Instrumentation is provided at various locations in the system, including a matrix-capacitance gage to measure the quantity of cryogen in the inner container.

End of delivery. - At the end of two-phase operation, the temperature of stored fluid increases, until only a small percentage of the original stored mass is still present in the vessel and the temperature reaches the point at which it is no longer efficient to heat the gas. This stage is considered to be the end of delivery.

Phase I and II System Description

The first cryogenic storage system demonstrated design feasibility through ground tests and was designated Phase I. The second was a design qualification system for testing in space and was designated Phase II. Both systems utilized the typical double-wall dewar design.[3]

Phase I. - Two subcritical cryogenic storage vessels were fabricated and tested during Phase I of the program. Figures 4 to 8 depict the liquid oxygen dewar showing the external components cross-referenced to a schematic (fig. 8) of the oxygen system. The schematic of the liquid hydrogen system is shown in figure 9.

Both of the Phase I systems employed regenerative heat exchangers for pressure control and electrical heaters for rapid depletion. The storage vessels and delivery lines were instrumented for pressure and temperature monitoring. Figure 10 is a photograph of the Phase I oxygen system which was cut away to expose the wire matrix quantity gage. External hardware was removed from the dewar before photographing. A transparent model of the system is shown in figure 11.

A complete description of the major components used in the Phase I hardware is given in appendix A.

Phase II. - The Phase II subcritical cryogenic storage and supply system is a self-contained package. All components necessary to store cryogenic nitrogen for extended periods and to deliver the vapor phase or convert the liquid phase for vapor delivery under the environmental conditions of orbital flight are included. Conditioned signal outputs are provided from each of the monitored parameters for telemetry during flight or for direct transmission during ground tests.

Two systems were fabricated, one for space-flight evaluation in the nose cone of an uprated Saturn I and one for qualification testing and flight system backup. Ground handling carts for each system, a ground checkout console with wiring harness, and ground halves of fill and vent quick-disconnect valves were also fabricated.

The experiment package consisted of two major subsystems, the storage vessel and the signal-conditioner plate. The signal-conditioner plate was mounted horizontally above the storage vessel, as shown in figure 12. All external flight components not attached to the storage vessel girth ring were mounted on the signal-conditioner plate.

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[3] These systems were fabricated by the AiResearch Manufacturing Division of the Garrett Corporation.

In addition, all interfaces between the subcritical system and the launch vehicle or ground service equipment were located on the signal-conditioner plate. Connections between the plate and storage vessel consisted of fill, vent, and delivery fluid lines and electrical harnesses. Because of limitations on the amount of electrical power available during flight, two power supplies were provided to the signal-conditioner plate. The first was 28 V dc from the launch vehicle instrumentation unit (IU). The second was 28 V dc from the launch pad and was available only before lift-off. All power consuming components not required during flight were connected to ground power to conserve IU power during flight. A schematic of the experimental system is presented in figure 13. The internal pressure regulator is again employed and is shown in the lower right pressure-vessel wall. The internal relief valve used in the Phase I hardware is replaced by a safety relief valve shown at the top of the figure.

An electrical heater replaces the one- and two-pass regenerative heat exchangers used on the Phase I systems. The regenerative heat exchangers were replaced to minimize system complexity. Figure 13 also depicts the signal-conditioner plate, shown vertically on the right of the figure.

Because the experimental hardware did not employ regenerative pressure-control exchangers, the pressure-enthalpy and temperature-entropy diagrams do not show the 13th state point which does appear in the Phase I diagrams (figs. 1 and 2).

The system used for qualification testing is shown in a handling cart in figure 12. The location of the system in the nose cone and vehicle is shown in figures 14 and 15. The flight system being checked out at Kennedy Space Center through a nose-cone access door is shown in figures 16 and 17.

Instrumentation impedance, weight, and power requirements are presented in tables I and II. Location of instrumentation points appears in figure 18, and sensor ranges are listed in table III. Table IV contains the performance requirements for the Phase II hardware. Appendix B contains detailed component information.

PROCEDURE

This section deals with the testing which was performed on the Phase I and II systems. Step-by-step verification testing was used to qualify the system and validate system design for a space environment.

Subcritical Cryogenic Storage System Design Verification Testing

Phase I systems thermodynamic testing.[4] - The primary objectives of this program were to evaluate pressure-control and vapor-delivery characteristics, to evaluate the capacitance matrix quantity-gaging system, and to evaluate the effectiveness of the vapor-cooled shield (Phase I liquid hydrogen dewar only).

The results of this testing indicated that the system design concept warranted verification in low gravity; thus, experiment 13 was initiated. Both Phase I dewars were thoroughly evaluated in a gimbaled test stand which permitted sloshing and random liquid-vapor orientation to simulate variable gravity conditions. The purpose of this test was to demonstrate the capability of the internal regulator and heat exchanger to throttle and vaporize any liquid entering the exchanger.

A photograph of the Phase I oxygen system is shown on test in figure 19.

Phase I oxygen system vibration test. - The philosophy of the subcritical development program was to test and verify each piece of hardware before continuing. Upon completion of thermodynamic testing of the subcritical oxygen storage system (Phase I), a test of behavior in a launch vehicle vibration environment was initiated. A vibration specification was chosen by the MSC Power Generation Branch Personnel which was considered to be representative of an uprated Saturn I launch vehicle (payload area 16). The vibration test was conducted by the MSC Structures and Mechanics Division personnel during the third quarter of 1965. The Phase I vessel was vibrated in order to troubleshoot any design deficiencies prior to final fabrication of the flight hardware.

The storage vessel was mounted in a four-pylon vibration fixture and tested on a 30 000 force-pound shaker. Photographs of the test setup appear in figures 20 and 21. The vessel was filled with 300 lb of distilled water, and the capacitance quantity-gaging grid was monitored to determine any possible breakdown in the structural integrity of the grid. Since the quantity gage was not activated with its linearizing bridge, the plot in figure 22 does not agree with the data of figure 23. The latter trace, liquid oxygen weight versus capacitance, reflects the behavior of the gage when it is operated correctly.

A low- and high-level sine sweep vibration test was run on the mounted vessel. The test levels are shown in figure 24. A random-vibration test was performed to the levels shown in figure 25. Upon completion, the only visible degradations were hairline cracks in the girth-ring paint and a minor separation of the girth ring from the vacuum jacket.

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[4] Power Systems Test Facility personnel conducted thermodynamic testing of the Phase I subcritical storage systems (June 15 to August 31, 1964). This testing was performed at an MSC interim test facility at Ellington Air Force Base, Houston, Texas.

The results of this test provided a high confidence level in this type of design with respect to dynamic launch environment.

Flight system vibration qualification. - The addition of the experiment to the launch vehicle nose cone required that NASA Marshall Space Flight Center (MSFC) qualify the nose cone with a mockup or experiment installed. A mockup of the Phase II subcritical nitrogen storage system was designed and fabricated by MSC for use in nose-cone vibration qualification. The mockup was identical to the actual filled system in weight, center of gravity, size, and mounting provisions. A photograph of the model appears in figure 26.

The anticipated vibration levels were transmitted to NASA MSC on May 5, 1965, and were incorporated into the experimental hardware specification. These levels were subsequently redetermined at higher values, and elastomeric vibration isolators were incorporated into the mounting provisions to compensate for the higher levels. Vibration isolators were also incorporated into the mockup design, and qualification of the nose cone with the mockup was attempted. It was found from this test that the actual values were still higher than anticipated because of the high degree of transmissibility through the nose cone and the dewar supports. These levels caused the isolators to fail, and the mockup and supports were badly damaged. From this test, it was possible to determine accurately new and more stringent vibration levels. Isolators were designed and procured, based upon the actual test levels. The required delivery date of the actual flight system was January 31, 1966. However, the increased severity of the dynamic environment prohibited the Phase II system manufacturer from completing qualification. Accordingly, a decision was made to qualify the Phase II storage system simultaneously with qualification of the nose-cone test article. The flight hardware installation date had been met prior to successful qualification of all test articles in March 1966 at the Wyle Laboratories, Huntsville, Alabama (ref. 1).

Quality Assurance for Phase II Hardware

A quality assurance plan was written by the hardware vendor and was approved. This plan is described in references 1 to 3. Qualification testing not discussed in this section was performed by the vendor and witnessed by NASA or USAF inspectors appointed by MSC personnel. This testing is discussed in detail in reference 4.

Phase II System Servicing

The storage system parameters were monitored during manual servicing with liquid nitrogen. Servicing was performed from the service structure using a portable dewar, until the specified percentage of fill was attained. Several hours before launch, the pressurization heater was activated and monitored from the blockhouse. In the event of a dangerous malfunction, the instrumentation switch could have been opened when power was transferred from the launch complex to the onboard batteries. This would have caused the delivery valve to open and thereby shut off all power to the experiment. This function was controlled from a blockhouse console.

RESULTS

The results of each phase of the subcritical cryogenic storage system development effort determined the advisability of continuing development.

Phase I

The tests of the Phase I liquid oxygen and liquid hydrogen dewars demonstrated that the basic design was suitable for use in a low-gravity space environment. These dewars were tested on a gimbaled stand and vapor was delivered as required. The gimbaled test stand permitted the test dewars to be inverted to expose the internal regulator alternately to vapor and liquid. Representative plots of the data obtained from this testing are presented in figures 27 and 28 and are marked "regulator up" or "regulator down." Figure 29 is representative of ground-test data obtained from the quantity gage.

Phase II

The pressure stability exhibited during the orbital test was excellent as evidenced by the system pressure data in figure 30. The calculations for quality of the fluid entering the regulator during flight indicate that the mass of liquid entering the regulator was small. Since the ground tests of the Phase I hardware permitted pure liquid to enter the valve, the system vaporization capability was taxed most severely during ground tests.

The saturation temperature of the stored fluid coincided with T_2 flight data except at 13 and 94 minutes into the mission. The rapid decrease at these times is attributed to stratification in the liquid bulk. Throughout most of the mission, the temperature just downstream of the internal regulator (T_3) remained well above the saturation temperature. A short duration decrease of T_3 to saturation temperature is evident in figure 31 at 8 and 285 minutes into the mission and are of interest. During the first decrease of T_3 at 8 minutes into the mission, the upper and lower tank temperatures $(T_1$ and $T_2)$ were close together and very near saturation temperature. Because of storage temperatures near saturation, no appreciable amount of liquid need enter the valve to allow the observed low exit temperature. During the second decrease of T_3 at 285 minutes into the mission, a much larger difference existed between upper and lower tank temperatures. Since the valve is relatively close to the upper temperature sensor, a relatively lower inlet quality was expected in order to provide suitable conditions for a lower valve-exit temperature (T_3). A small slosh wave which missed the temperature sensor could account for the small increase in liquid in the valve inlet region. Utilizing an analytical technique (discussed in the next section) to compute quality at the valve inlet, good correlation is shown between the lower quality ($x = 0.90$) calculated at this point and conditions which must have existed to obtain saturated fluid entering the valve.

In comparison with the plot of internal heater cycles versus time (fig. 32), it is seen that the storage pressure, varying as expected because of fluid withdrawal, was well controlled by the internal electrical heater.

Although the method of gaging is not optimum for all subcritical systems, a uniform depletion of the stored fluid was evidenced by the capacitance matrix quantity-gage (fig. 33). The internal temperatures encountered during the mission were nominal. Temperature T_1 departed from nominal at approximately 145 minutes into the mission (fig. 34). This departure indicates that liquid bulk was apparently in the hemisphere opposite the withdrawal valve.

The primary purpose of experiment 13 was to demonstrate that vapor could be withdrawn from two-phase cryogenic storage while in a low-gravity environment. This objective was fulfilled and the operation of several important components was verified since the heat exchanger and delivery port exit temperatures T_4 and T_5 were always well above saturation temperatures for the respective pressures, P_2 and P_3.

DISCUSSION AND ANALYSIS

Single-phase cryogenic storage is currently used for fuel-cell reactant and environmental gas-supply systems on all manned spacecraft. The delivery of fluid is assured because the cryogen occupies the entire storage volume throughout the period of delivery. As fluid is expelled, the density decreases and the average temperature increases. In a storage vessel containing a two-phase fluid the average temperature and liquid density remain relatively constant. The amount of energy required to expel a given fluid mass is dependent upon the phase withdrawn. The required energy is relatively high if this phase is vapor and is relatively low if the withdrawn phase is liquid. However, subcritical storage systems tend to be operationally more complex. The increased complexity primarily results from the fact that the orientation of the liquid and vapor phases of the two-phase fluid under zero-gravity conditions is not predictable. Thus, it is not possible to determine whether liquid or gas will exit the inner container. To overcome this problem, the subcritical vessels contained phase-control heat exchangers. The function of these heat exchangers was to evaporate any liquid exiting the inner container and to insure vapor at the exit from the phase-control heat exchanger.

The Phase I and MSC experiment 13 (Phase II) configurations were so arranged that the delivered fluid was throttled into a line which was in contact with the pressure vessel. Any liquid moving through this line is vaporized as a result of heat transfer from the environment and from the pressurized contents. As the liquid is vaporized, the stored fluid is refrigerated. The net heat required for vapor expulsion from this system is, therefore, greater than that required for vapor expulsion from supercritical storage. Because state-of-the-art insulation schemes are of limited capability, the increased allowable heat for pure-vapor removal from two-phase storage assists in alleviating thermal design limits. Thus, subcritical, or two-phase, storage is desirable, provided dependable vapor delivery rates are assured. The reduced operating pressure provides a weight savings in plumbing, in valve bodies, and possibly in the pressure vessel. This reduced pressure reduces the system leakage tendencies.

An analysis was conducted to determine the quality (vapor mass/total mass) of the stored fluid entering the internal regulator at several points in the mission. A determination of the severity of the test on the internal regulator and internal heat exchanger could be made since their function was to vaporize any liquid entering the regulator. The calculation of quality of the fluid entering the valve supplemented the data obtained from the orbital experiment. Comparison of the flight data temperatures with fluid saturation temperatures permitted a judicious selection of points in the mission timeline where quality could be correlated with test results. It should be noted that the information derived from this analysis is not required to assure a successful experiment (that is, vapor expulsion) but is of interest and is discussed under results.

Neglecting potential and kinetic energy changes and heat transfer, mass transfer across the internal regulator valve is isenthalpic. From the first law of thermodynamics

$$m_1h_1 = m_2h_2 \tag{1}$$

and

$$h = u + \frac{144pv}{J} \tag{2}$$

$$m_1\left(u_1 + \frac{144p_1v_1}{J}\right) = m_2\left(u_2 + \frac{144p_2v_2}{J}\right) \tag{3}$$

The mass entering the valve is equal to the mass exiting during time period t ($t = t_0 + \Delta t$).

$$\left.m_1\right]^{t_0} = \left.m_2\right]^{t_0} \tag{4}$$

Therefore,

$$u_1 + \frac{144p_1v_1}{J} = u_2 + \frac{144p_2v_2}{J} \tag{5}$$

The function of the valve is to maintain a constant, or nearly constant, pressure in the heat-exchanger line downstream from the regulator valve. In order to formulate an actual operating equality, the enthalpy change at m_1 with time must be evaluated because of tank heat-transfer conditions. The influence of the heat leak, electrical heater, and heat removed by the heat exchanger (to the total mass M) on m_1 is of the general form

$$\frac{m_1}{M}\left(Q_L + Q_{htr} - Q_{hx}\right)$$

The operating equality over the time increment t is then rewritten as

$$m_1\left(u_1 + \frac{144p_1v_1}{J}\right)\Bigg]^{t_0} + \frac{tm_1}{M}\left(Q_L + Q_{htr} - Q_{hx}\right)\Bigg]^{t} = m_2\left(u_2 + \frac{144p_2v_2}{J}\right)\Bigg]^{t} \tag{6}$$

If the heat-exchanger inlet temperature is greater than the saturation temperature at P_2, then

$$v_2 = v_g \tag{7}$$

The specific volume and internal energy at 1 (immediately adjacent to the upstream side) are dependent upon quality in the same form

$$v_1 = x\left(v_g\right) + (1 - x)v_f \tag{8}$$

$$u_1 = x\left(u_g\right) + (1 - x)u_f \tag{9}$$

From equations (4), (8), and (9) and substituting in equation (6), the rearranged equality is

$$u_2 + \frac{144p_2v_{g_2}}{J}\Bigg]^{t} - \frac{t}{M}\left(Q_L + Q_{htr} - Q_{hx}\right)\Bigg]^{t} = x\left(u_{g_1}\right) + (1 - x)u_{f_1}$$

$$+ \frac{144p_1\left[x\left(v_{g_1}\right) + (1 - x)v_{f_1}\right]}{J}\Bigg]^{t_0} \tag{10}$$

Utilizing flight data, the quality of the fluid m_1 just upstream of the internal regulator valve may be found directly.

CONCLUDING REMARKS

MSC experiment 13 was flown aboard Apollo mission AS-203 on July 5, 1966. This experiment was the final portion of a program to develop a subcritical liquid/vapor cryogenic storage and delivery system capable of operation in a low-gravity environment.

The primary objective of the experiment was to demonstrate that vapor could consistently be delivered from subcritical storage. The development program consisted of two phases. Extensive ground tests were performed on Phase I liquid oxygen and liquid hydrogen dewars. The success of Phase I indicated that the follow-on experiment (utilizing liquid nitrogen as the stored medium) should be pursued. The ultimate success of the program indicated that the "building block" philosophy was warranted.

During the earth orbital mission, the system exhibited good pressure control and stability. The heat-exchanger outlet temperature and the delivery temperatures were significantly above saturation for the pressures at those points. Vapor was delivered at a constant pressure and the capability of the internal regulator (flow proportional) valve and internal heat exchanger to operate within the design limits was verified.

A three-dimensional wire matrix, measuring the average capacitance throughout the storage volume, was employed to monitor the quantity of stored fluid. This was the first successful orbital test of this device.

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National Aeronautics and Space Administration
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TABLE I. - INSTRUMENTATION IMPEDANCE AND POWER REQUIREMENTS

Description	Power requirement, A[a]	Output impedance, Ω
Pressure transducer, P1	0.009	300
Pressure transducer, P2	.009	300
Pressure transducer, P3	.009	300
Temperature system, T1	.100	400
Temperature system, T2	.100	400
Temperature system, T3	.100	400
Temperature system, T4	.100	400
Temperature system, T5	.100	400
Current sensor, I1	.015	500
Current sensor, I2	.015	500
Flowmeter, F1	.080	500
Quantity sensor signal conditioner, Q1	.040	250

[a]Amperage measured at 28 V dc.

TABLE II. - WEIGHT AND POWER SUMMARY

Description	Weight, lb	Power, W
Subcritical oxygen system	-	(a)
System support stand	-	-
Instrumentation assembly (packaging)	[b]12.00	-
System wiring (schematic and hardware)	[b]9.00	-
Wiring harness, system to test equipment	-	-
Wiring harness, matrix gage	-	-
Vent valve	[b].44	-
Safety relief valve, storage vessel	.30	-
Pressure transducer, storage vessel, P1	.60	0.25
Pressure regulator, liquid-gas	.31	-
Temperature sensor, heat-exchanger outlet, T4	-	-
Temperature sensor, heat-exchanger inlet, T3	-	-
Temperature sensor, vessel, upper, T1	-	-
Warmup heat exchanger, supply system	.50	70.0 ± 3.0
Temperature sensor for warmup heat exchanger	.10	2.8
Controller, warmup heat exchanger	.74	10.00 maximum
Power monitor, supply system heater	[b].50	.84
Pressure transducer, supply system	.60	.25

[a]Nil or zero.

[b]Plate-mounted.

TABLE II. - WEIGHT AND POWER SUMMARY - Continued

Description	Weight, lb	Power, W
Safety relief valve, supply system	0.25	-
Solenoid valve, supply system	.22	[c]19.5 maximum
Absolute-pressure regulator, supply system	.50	-
Temperature sensor, supply system, T5	.20	-
Pressure transducer, supply system	[b].60	.25
Flow transducer	[b]1.25	2.3
Flow restrictor	.10	-
Temperature sensor, storage vessel, lower, T2	-	-
Heater, electric, storage vessel	.50	50.0 ± 5.0
Power monitor, storage vessel heater	(b)	-
Pressure switch, vessel heater control	.20	-
Storage vessel assembly	70.00	-
Signal conditioner, temperature sensor, T4	[b]1.26	2.8
Signal conditioner, temperature sensor, T6	[b]1.26	2.8
Signal conditioner, temperature sensor, T2	[b]1.26	2.8

[b]Plate-mounted.

[c]GSE power only.

TABLE II. - WEIGHT AND POWER SUMMARY - Concluded

Description	Weight, lb	Power, W
Signal conditioner, temperature sensor, T1	[b]1.26	2.8
Signal conditioner, temperature sensor, T5	[b]1.26	2.8
Signal conditioner, matrix	[b]1.26	2.8
Fill valve	[b].44	-
Matrix gage assembly	2.00	-
Wiring harness, current monitors	-	-
Wiring harness, pressure and temperature sensor	-	(a)
Radio noise filter	[b]5.00	-
Heater, electric, ground buildup	.50	[c]180.0 + 18.0
Vibration isolators	6.50	-
Total for instrumentation plate	36.79	
Total for tank	84.12	
Total weight	120.91	
Total power		158.69 maximum (flight) 217.8 maximum (GSE)

[a]Nil or zero.
[b]Plate-mounted.
[c]GSE power only.

TABLE III. - INSTRUMENTATION RANGES AND DESCRIPTIONS

Name	Span
Tank temperature, upper, T1	130° to 230° R
Tank temperature, lower, T2	130° to 230° R
Heat-exchanger inlet temperature, T3	130° to 230° R
Heat-exchanger outlet temperature, T4	130° to 230° R
Measurement supply temperature, T5	460° to 560° R
Quantity, Q1	0 to 100 percent
Tank pressure, P1	20 to 250 psia
Tank outlet pressure, P2	20 to 250 psia
Supply pressure, P3	0 to 100 psia
Flow rate, F1	0 to 1.5 lb/hr
Internal heater current, I1	0 to 3 A
Warmup heater current, I2	0 to 3 A

TABLE IV. - PERFORMANCE REQUIREMENTS

Parameter	Performance value
Weights	
Usable fluid weight:	125-lb maximum
Maximum filled system weight:	275 lb[a]
Pressures	
Operating storage pressure:	150 ± 20 psia
Operating delivery pressure:	60 ± 5 psia
Relief pressure:	220 ± 20 psia
Proof pressure:	1.5 times maximum relief pressure
Burst pressure:	2.0 times maximum relief pressure
Flow rate	
Nominal operating flow rate:	2 ± 1 lb/hr (constant within ±10 percent)
Vessel configuration:	Spherical
Times	
Heater pressurization of stored fluid at ambient pressure to 150 ± 20 psia:	4-hr maximum
Pressure buildup without heater (ambient heat leakage):	30-hr minimum at 80° ± 10° F
Fill time:	Minimum achievable with initial equipment stabilized at 80° ± 10° F ambient
Safety considerations:	Electrical hardware shall be explosion-proof No system failure shall propagate sequentially
Cleanliness level:	In accordance with the levels specified in NASA-MSFC Specification 164, latest revision

[a]Includes instrumentation, lines, valves, and so forth.

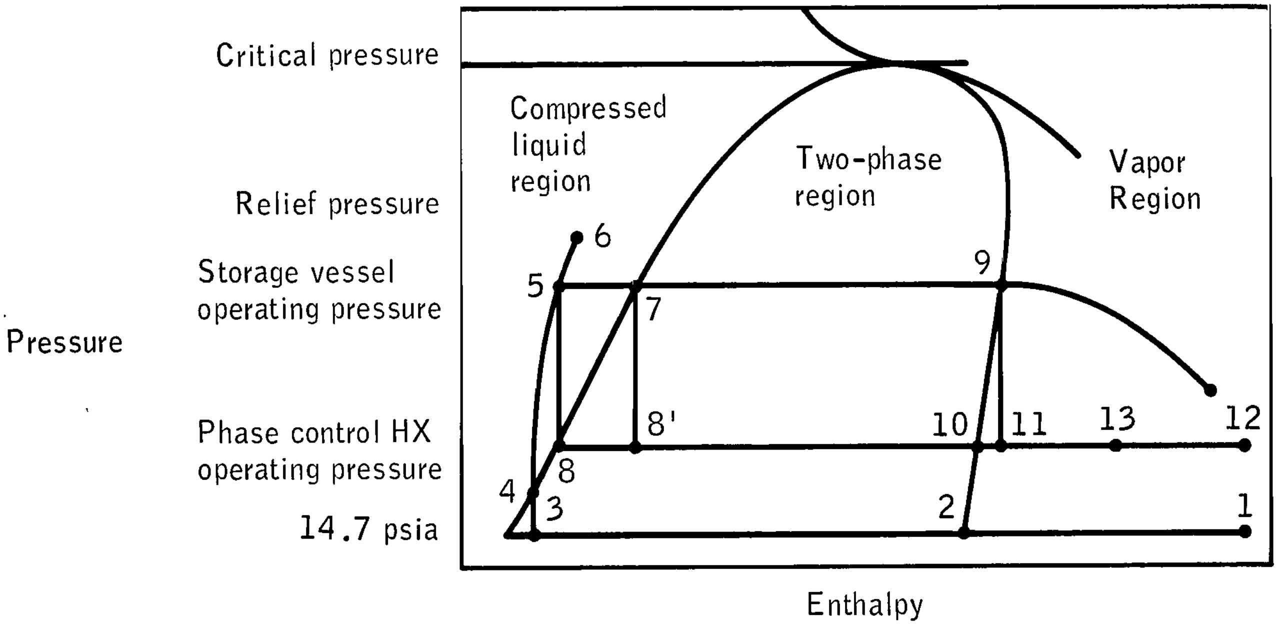

Figure 1. - Thermodynamic operation of subcritical storage systems, pressure-enthalpy diagram.

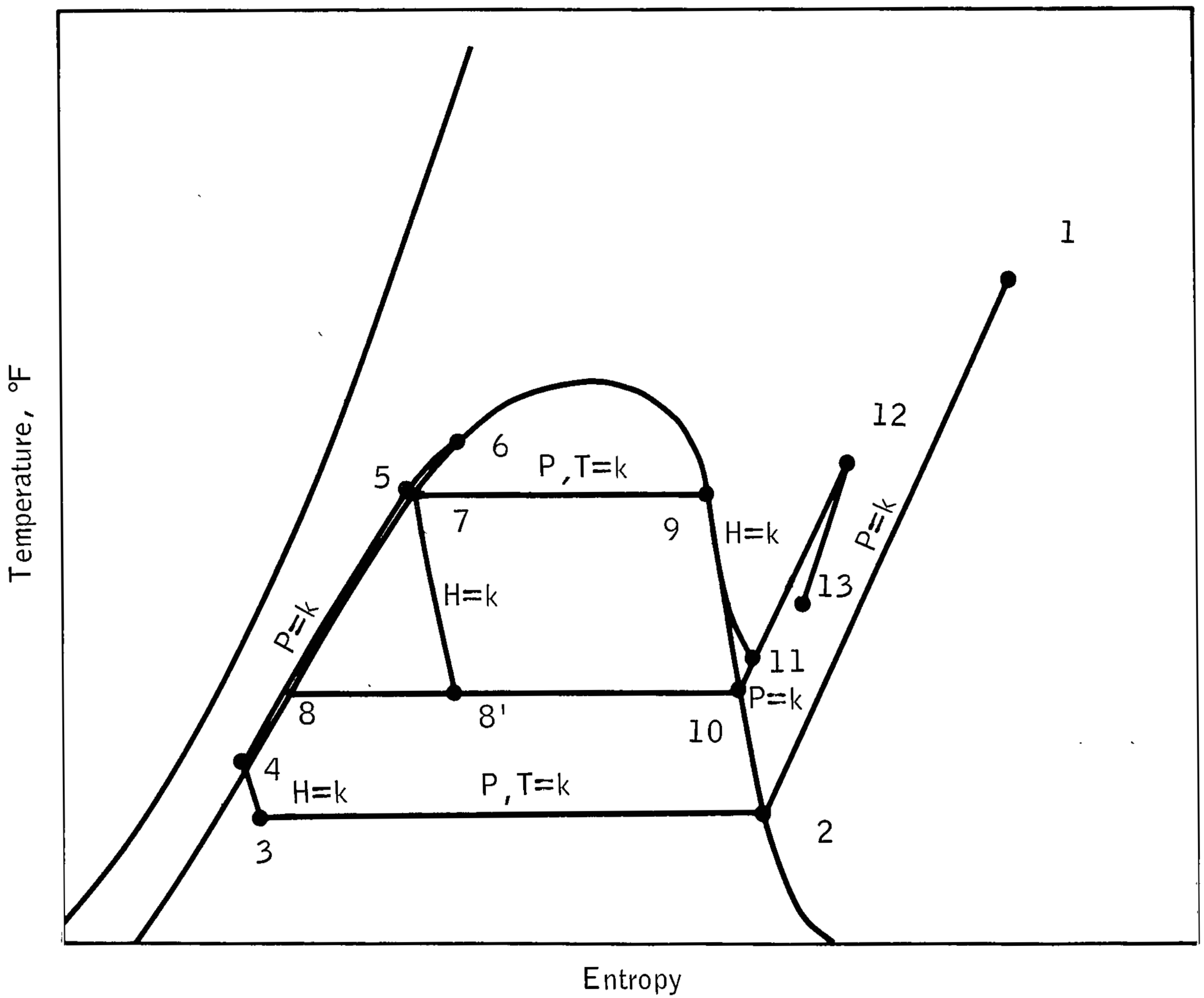

Figure 2. - Thermodynamic operation of subcritical storage systems, temperature-entropy diagram.

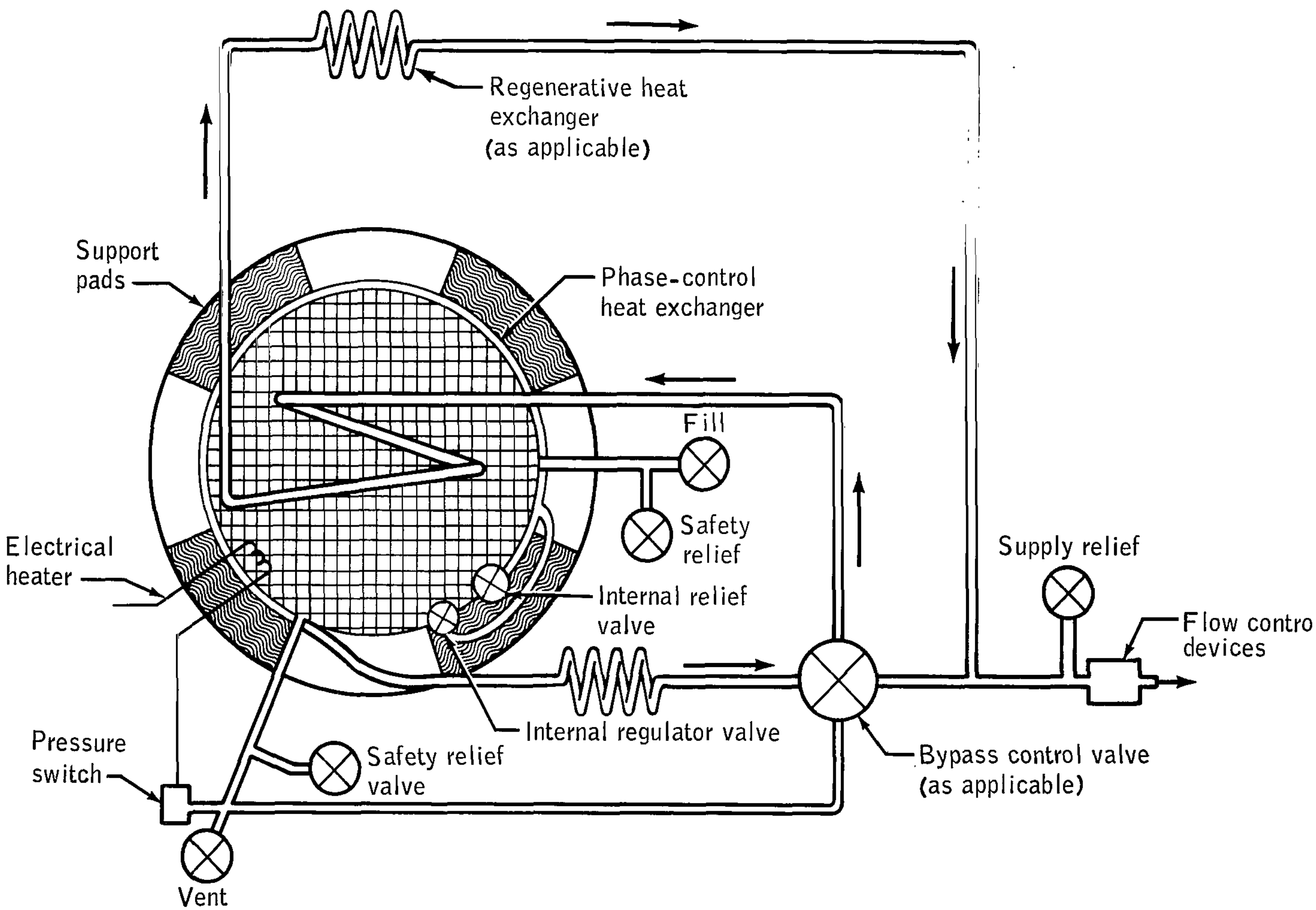

Figure 3. - Generalized schematic of subcritical storage system.

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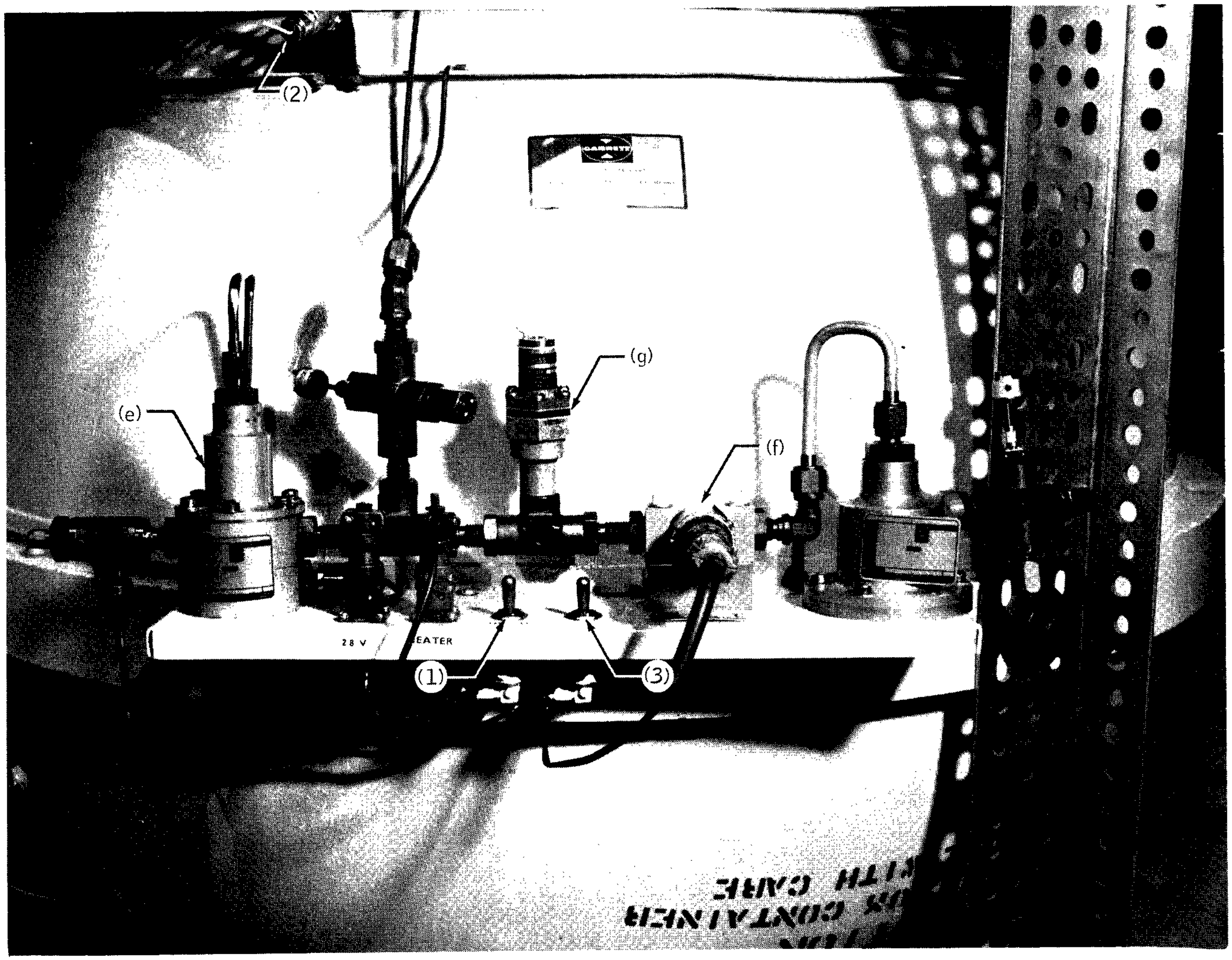

Figure 4. - Oxygen system as delivered to NASA MSC.

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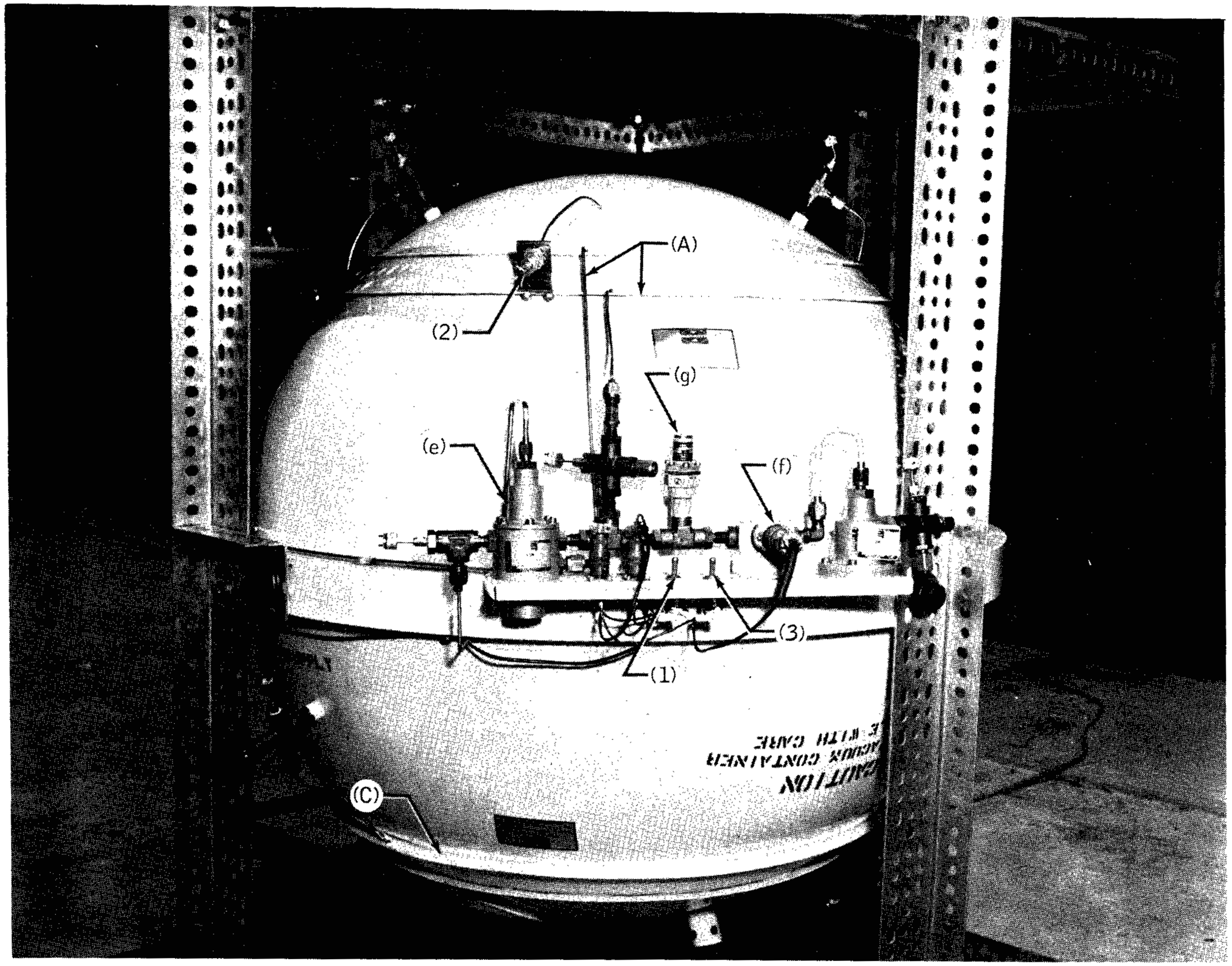

Figure 5. - Oxygen system as delivered to NASA MSC.

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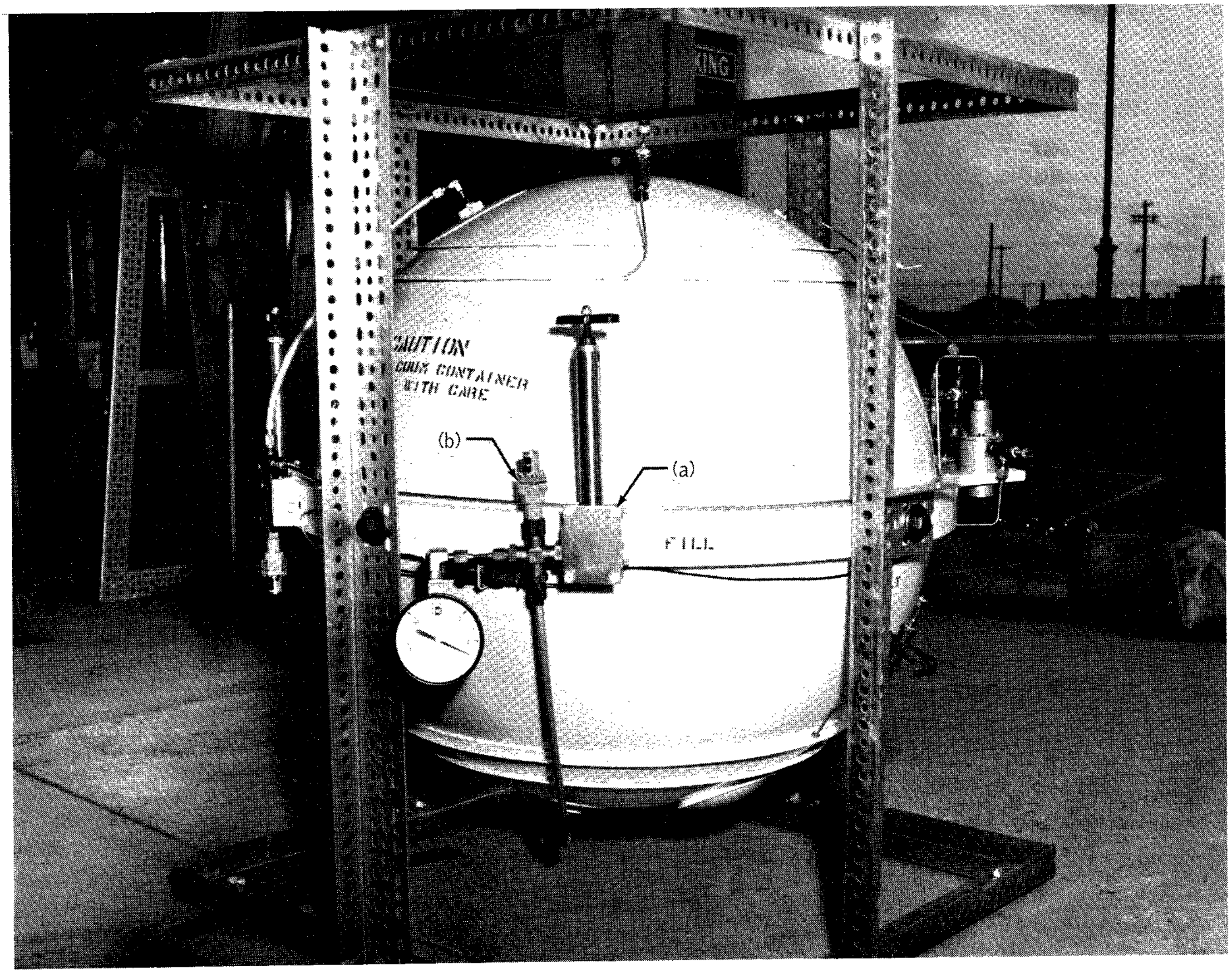

Figure 6. - Oxygen system as delivered to NASA MSC.

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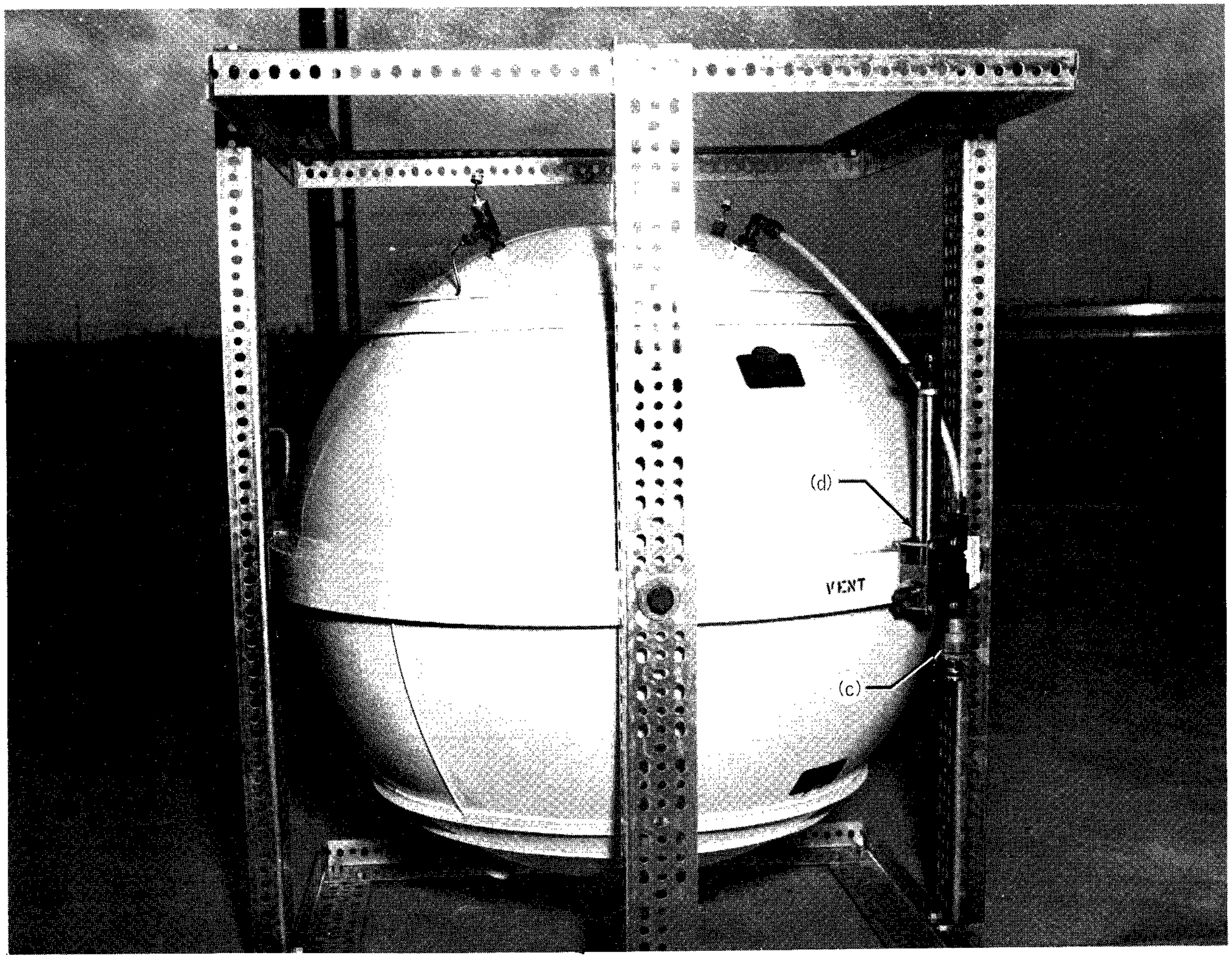

Figure 7. - Oxygen system as delivered to NASA MSC.

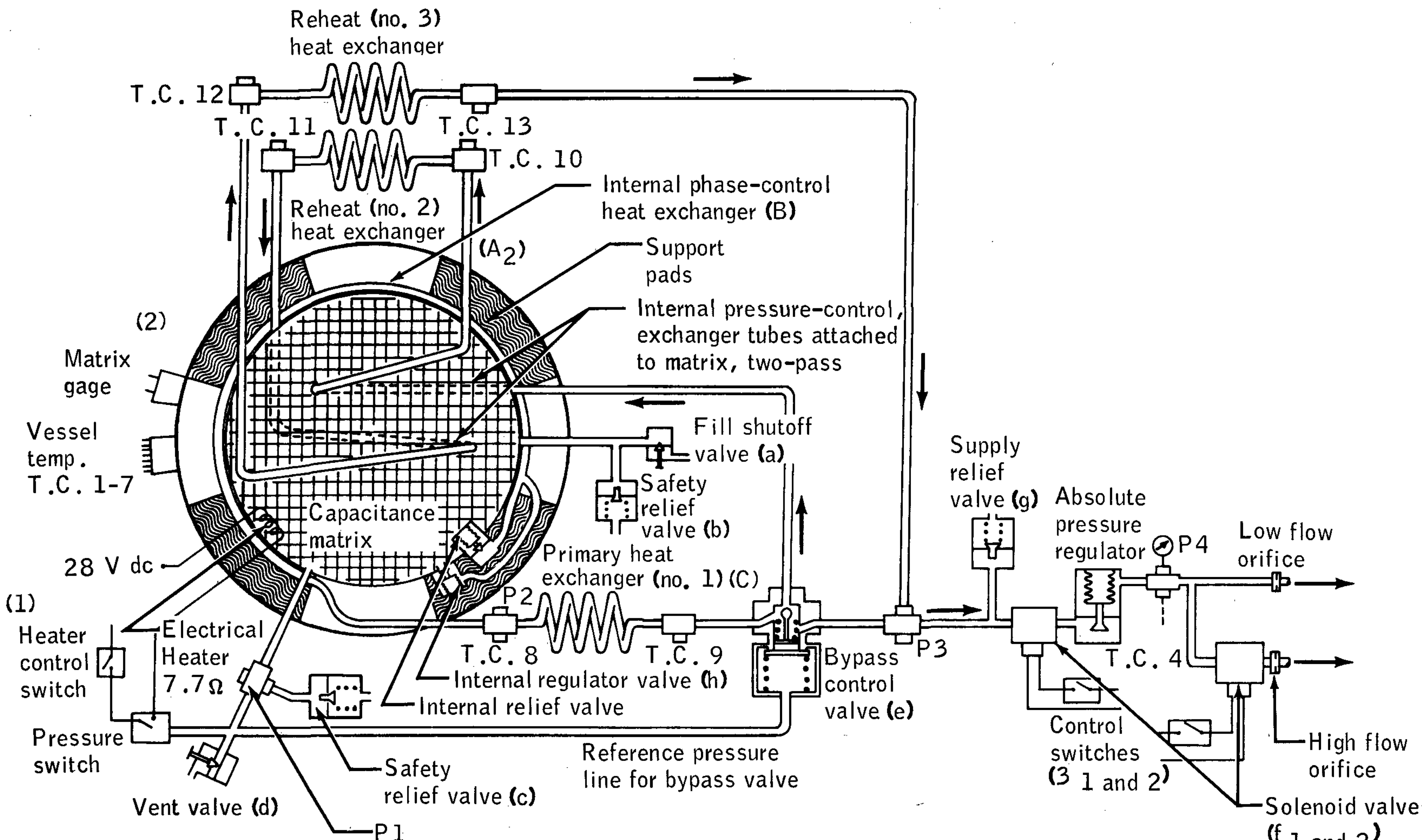

Figure 8. - Oxygen subcritical storage system.

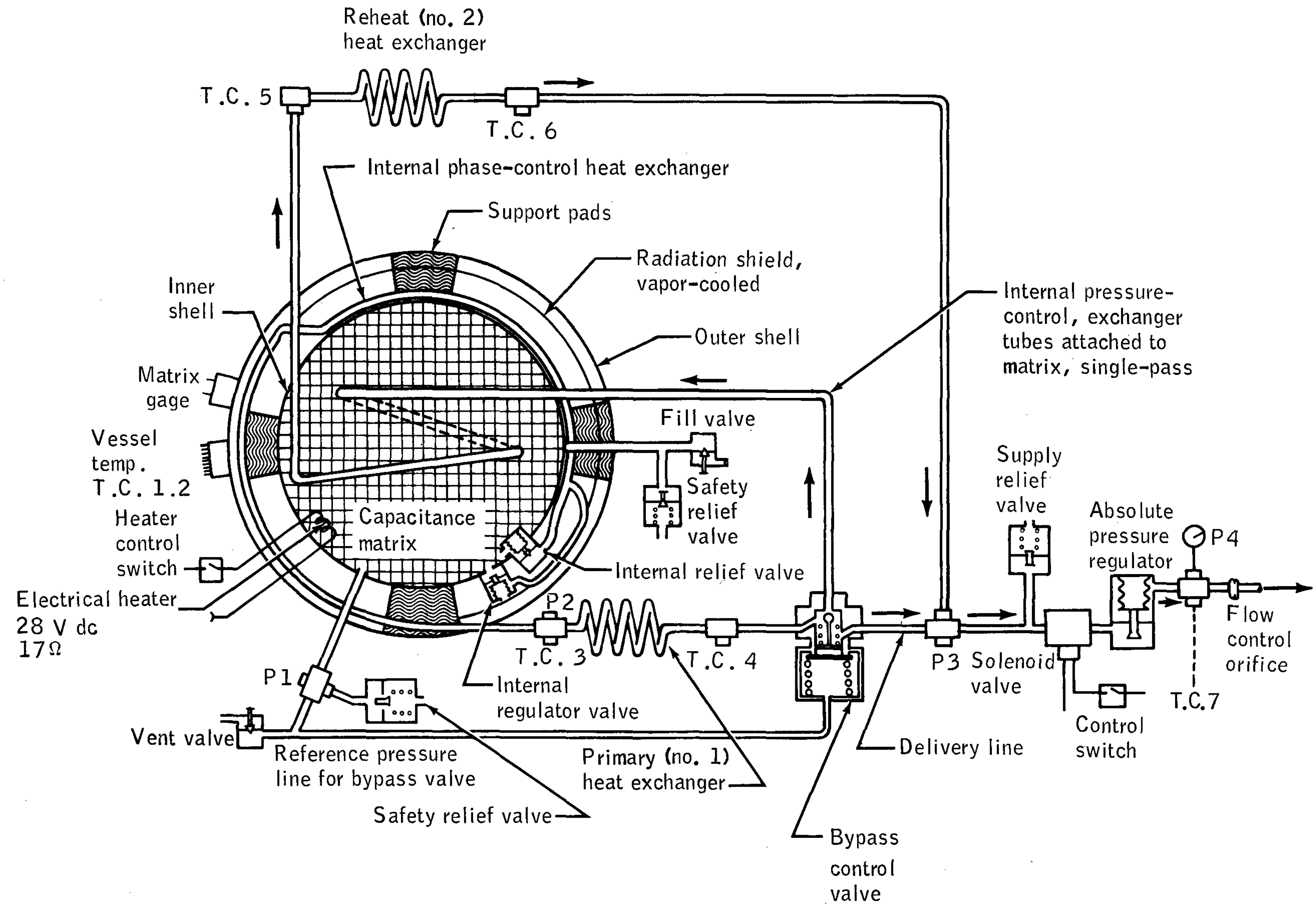

Figure 9. - Phase I hydrogen subcritical storage system.

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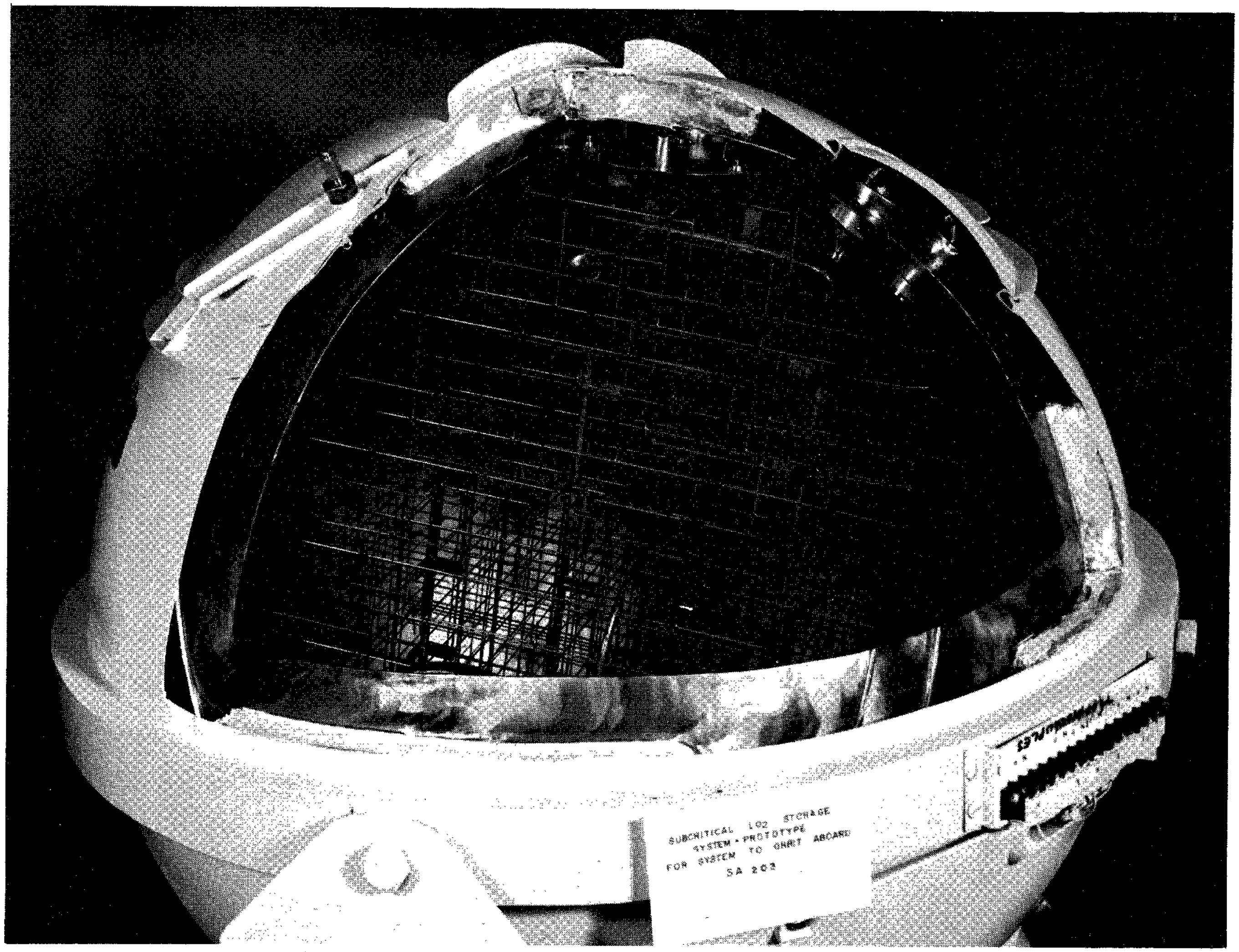

Figure 10. - Cutaway of completed Phase I oxygen system.

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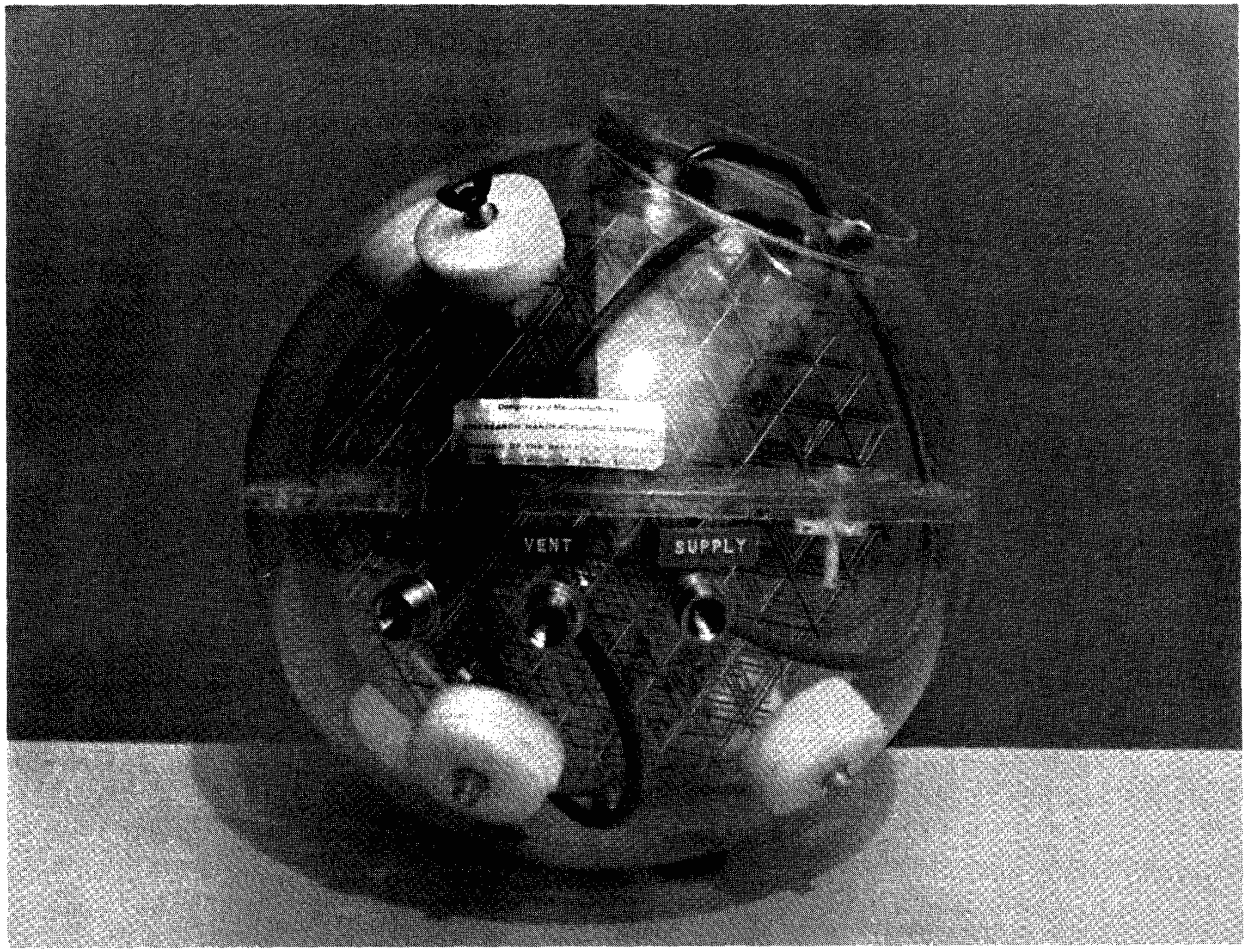


Figure 11. - Model of Phase I liquid oxygen system.

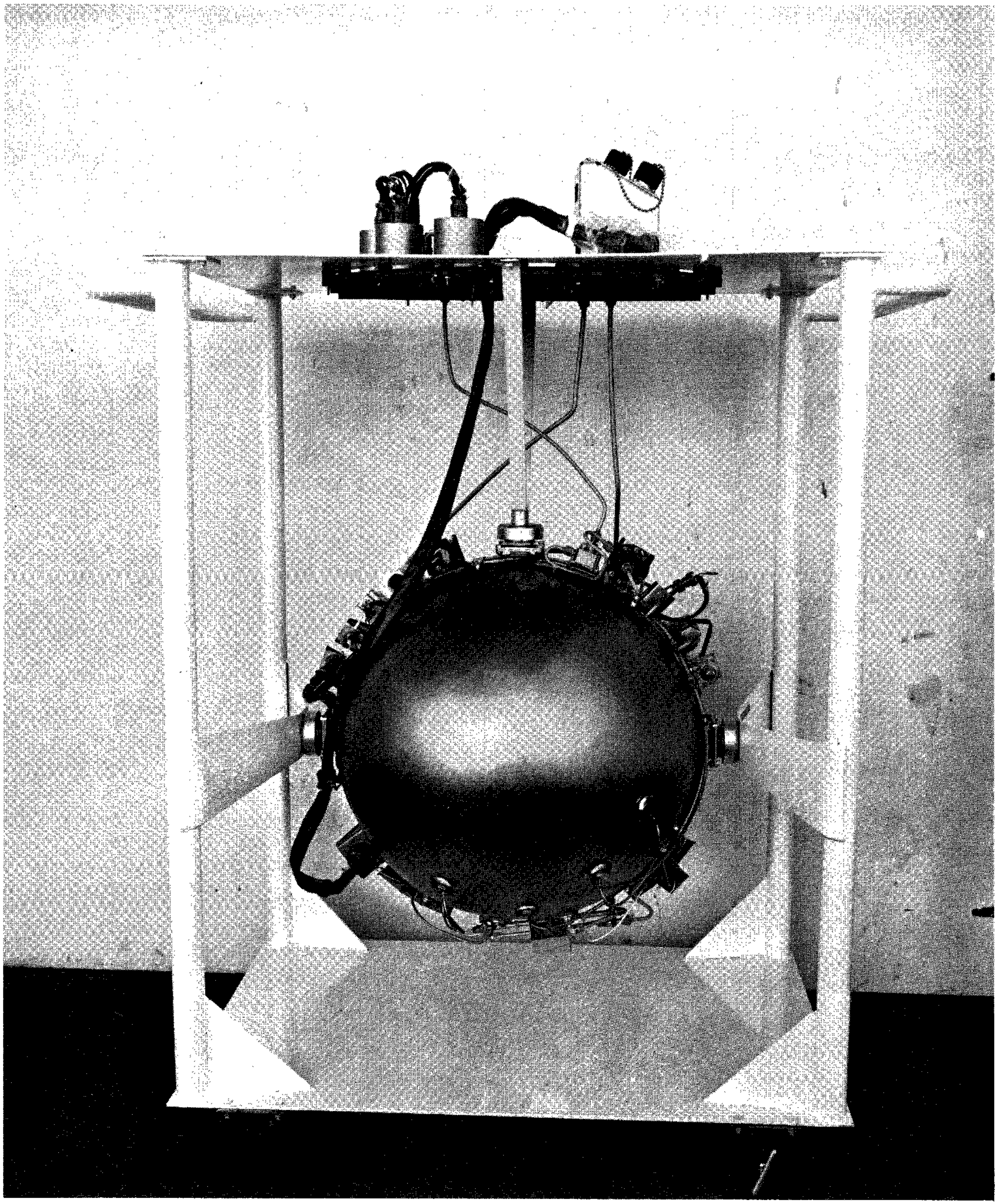
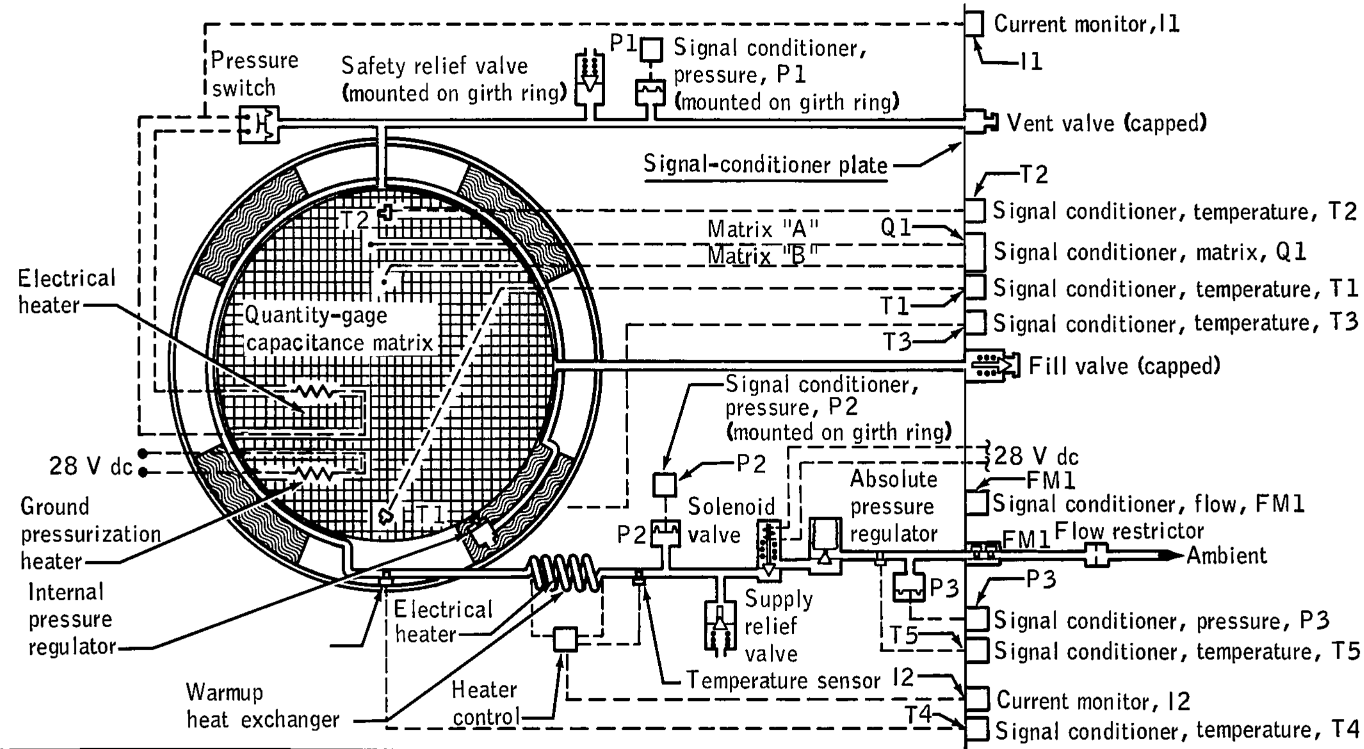


Figure 12. - Storage vessel with signal-conditioner plate mounted.



Design parameters

Operating pressure range	130 - 170 psia	Ambient temperature range	-65 to + 160°F
Delivery pressure	60 ± 5 psia	Delivery rate	1.25 ± .13 lb/hr
Relief pressure	220 ± 20 psia	Total electrical power available, prelaunch	28 V dc, 400W
Proof pressure	360 psia minimum		
Burst pressure	480 psia minimum	Total electrical power available, postlaunch	28 V dc, 174W
Maximum filled weight	275 lb		
Liquid nitrogen capacity	128 lb	Shelf life	1 year
Standby time, nonvented, at 160°F	30 hr	Radio noise specification	MIL-I-26600 (USAF)

Figure 13. - Phase II subcritical nitrogen system.

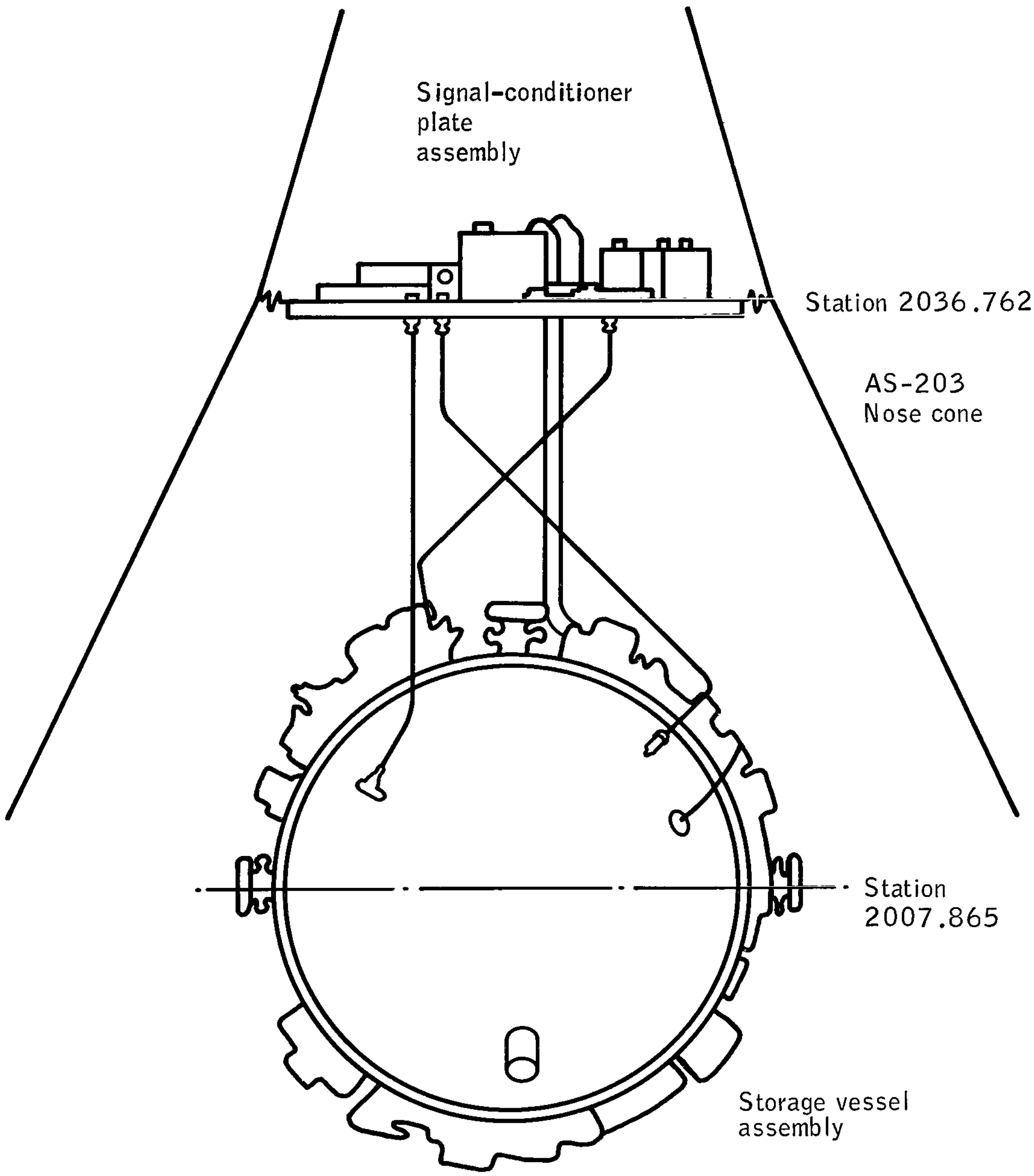


Figure 14. - Location of the system in the nose cone.

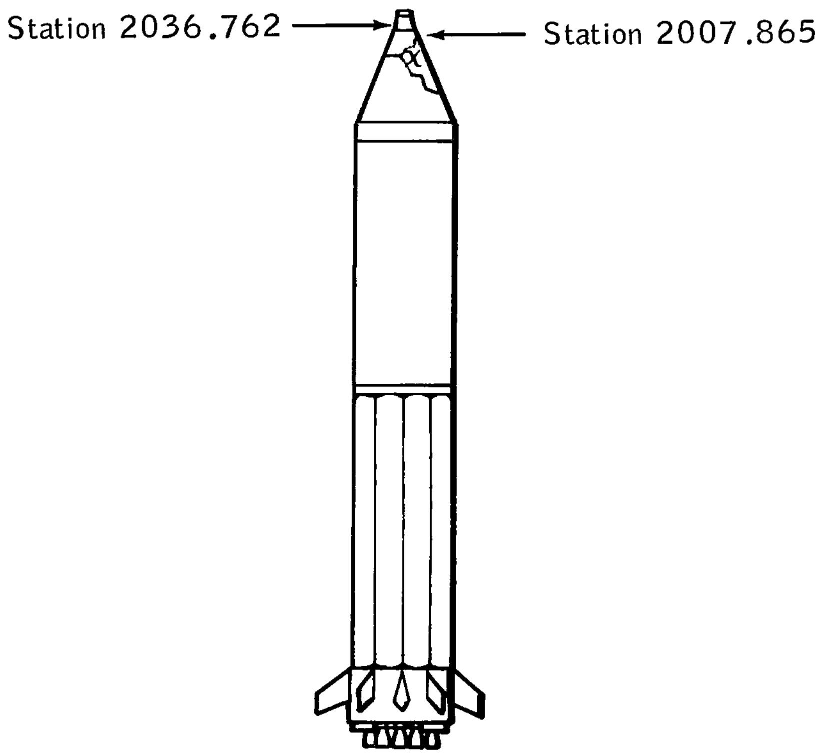


Figure 15. - AS-203 experiment 13 system location in the vehicle.

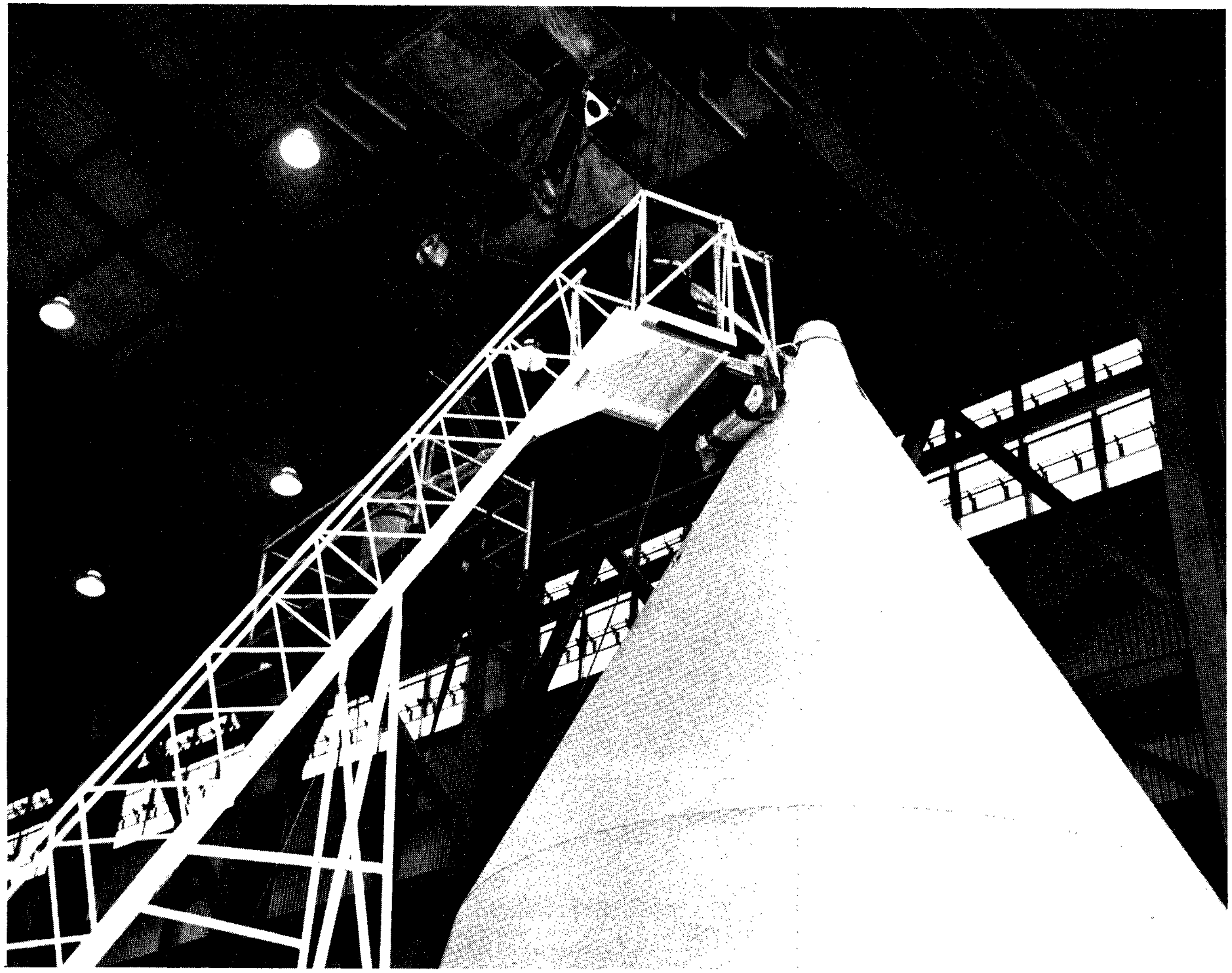


Figure 16. - Flight system being checked.

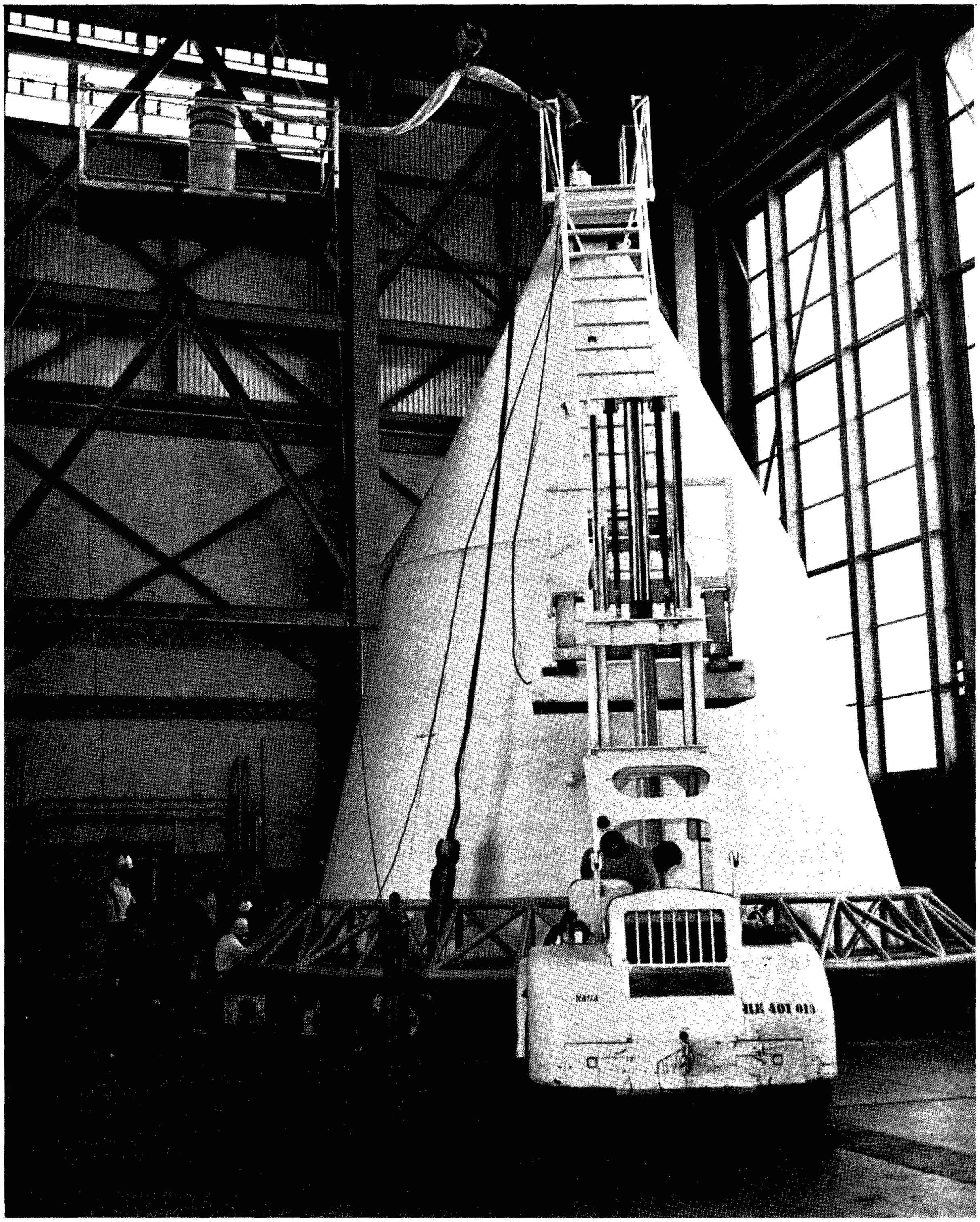


Figure 17. - Flight system being checked.

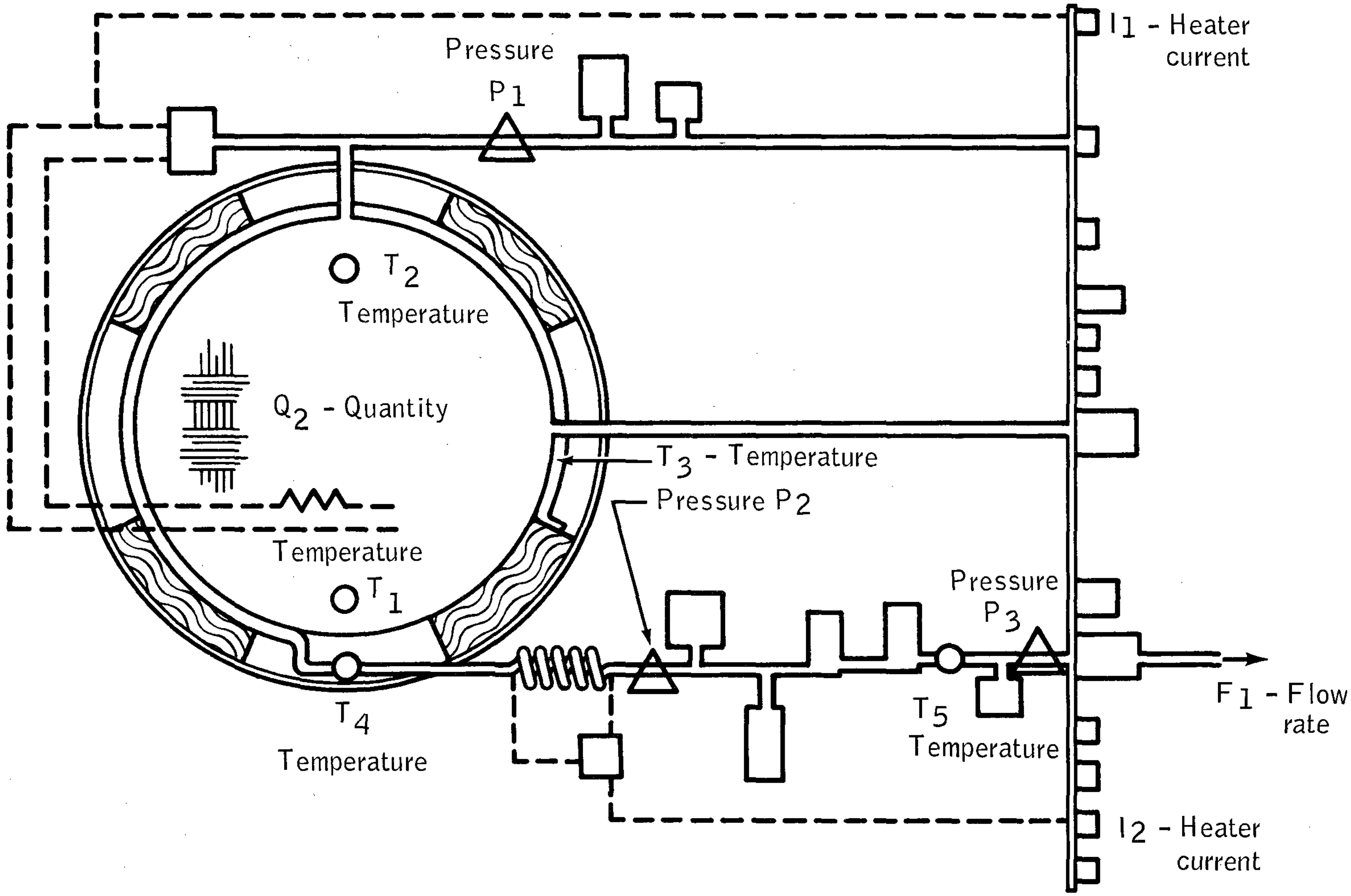


Figure 18. - Instrumentation location.

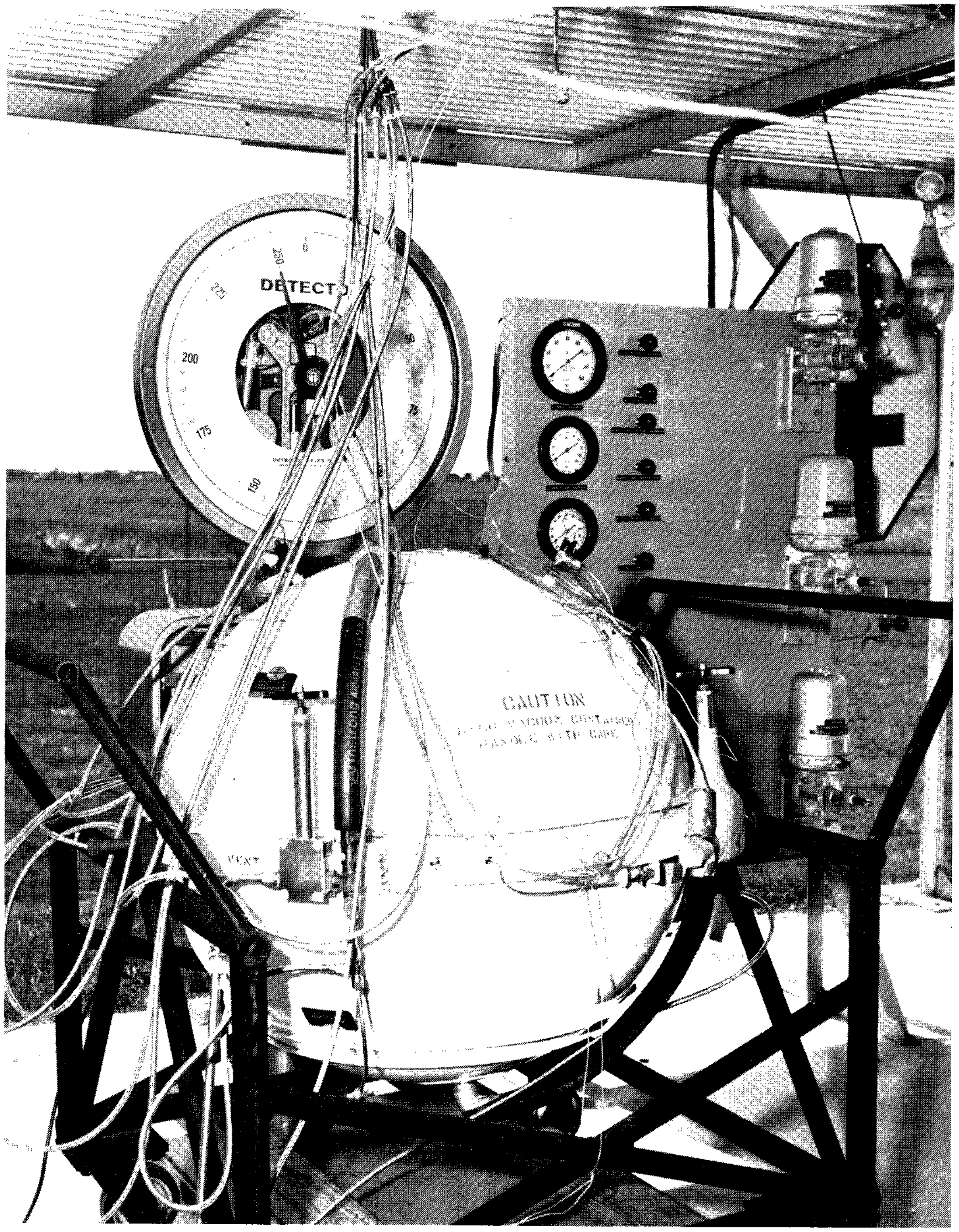


Figure 19. - Completed Phase I liquid oxygen storage system.

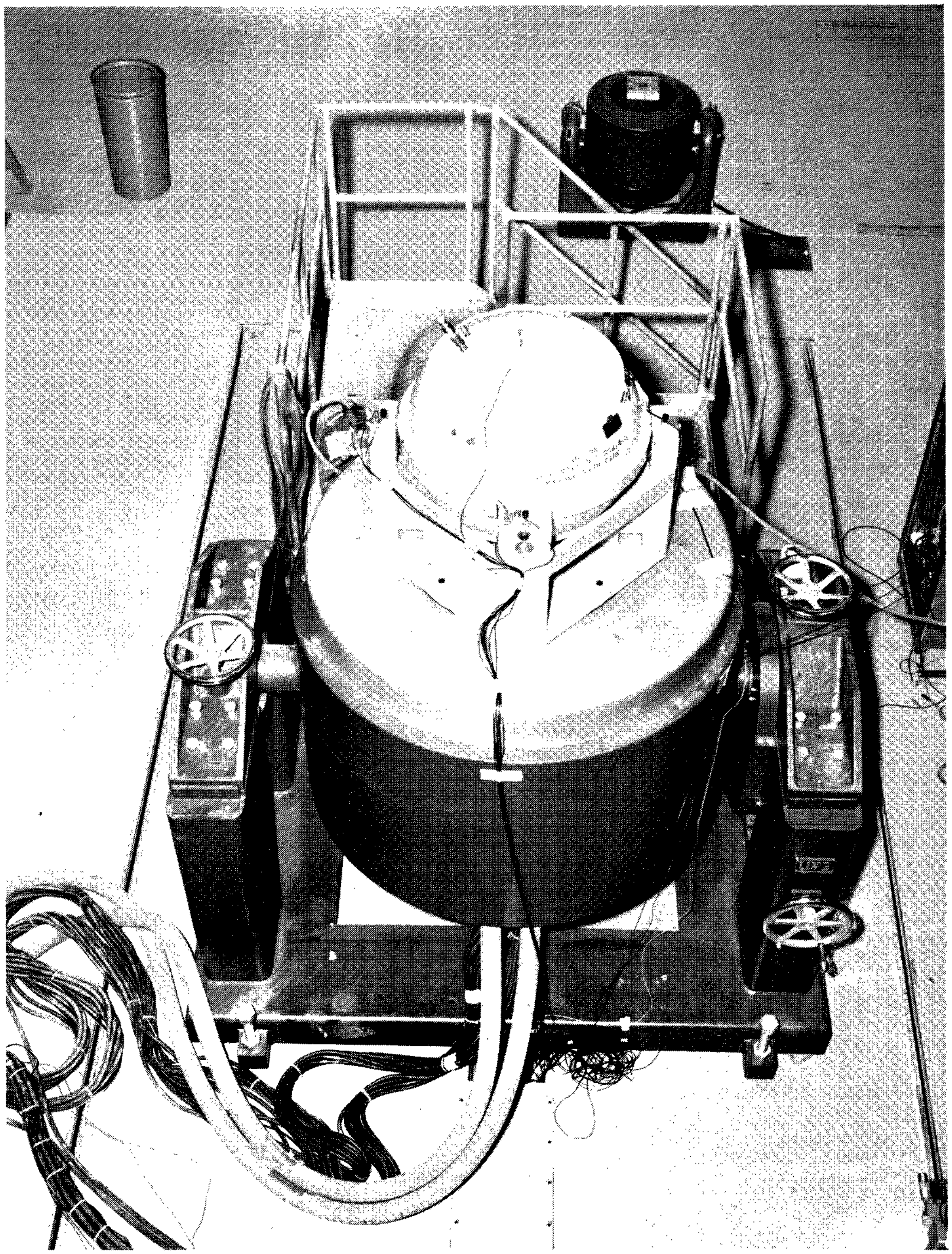


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Figure 20. - Phase I oxygen dewar vibration test setup.

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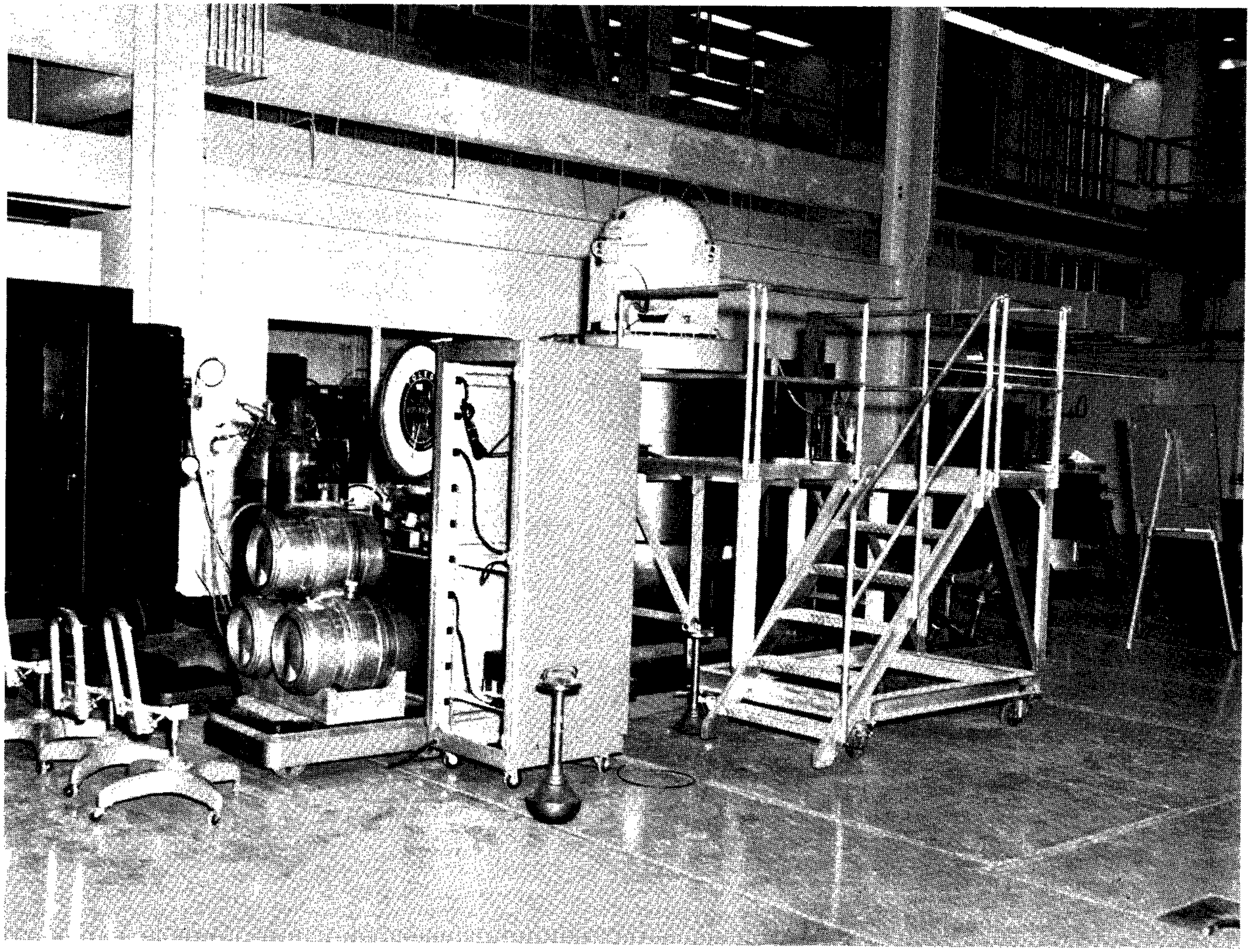

Figure 21. - Phase I oxygen dewar vibration test setup.

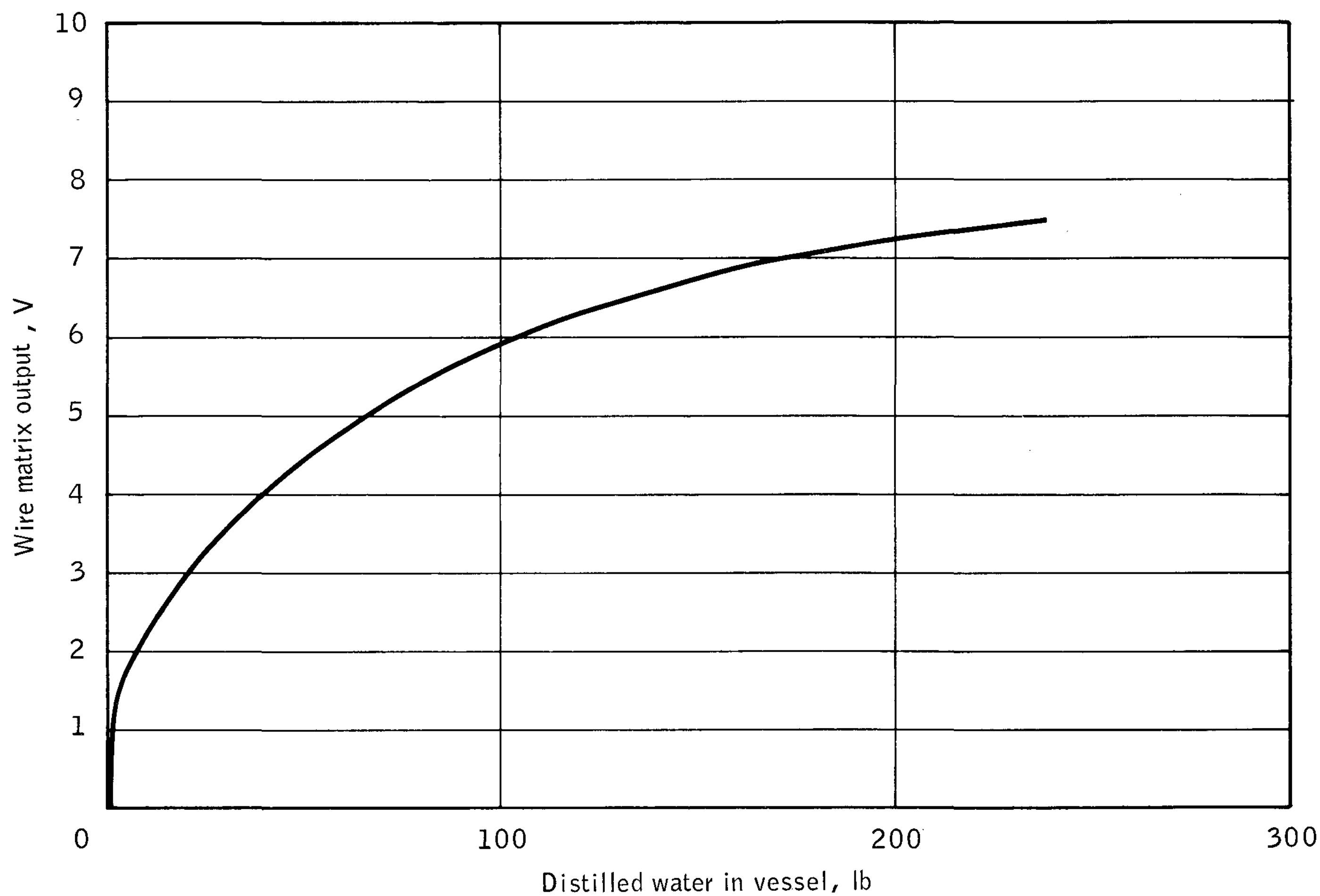

Figure 22. - Liquid oxygen dewar, Phase I quantity gage behavior during vibration.

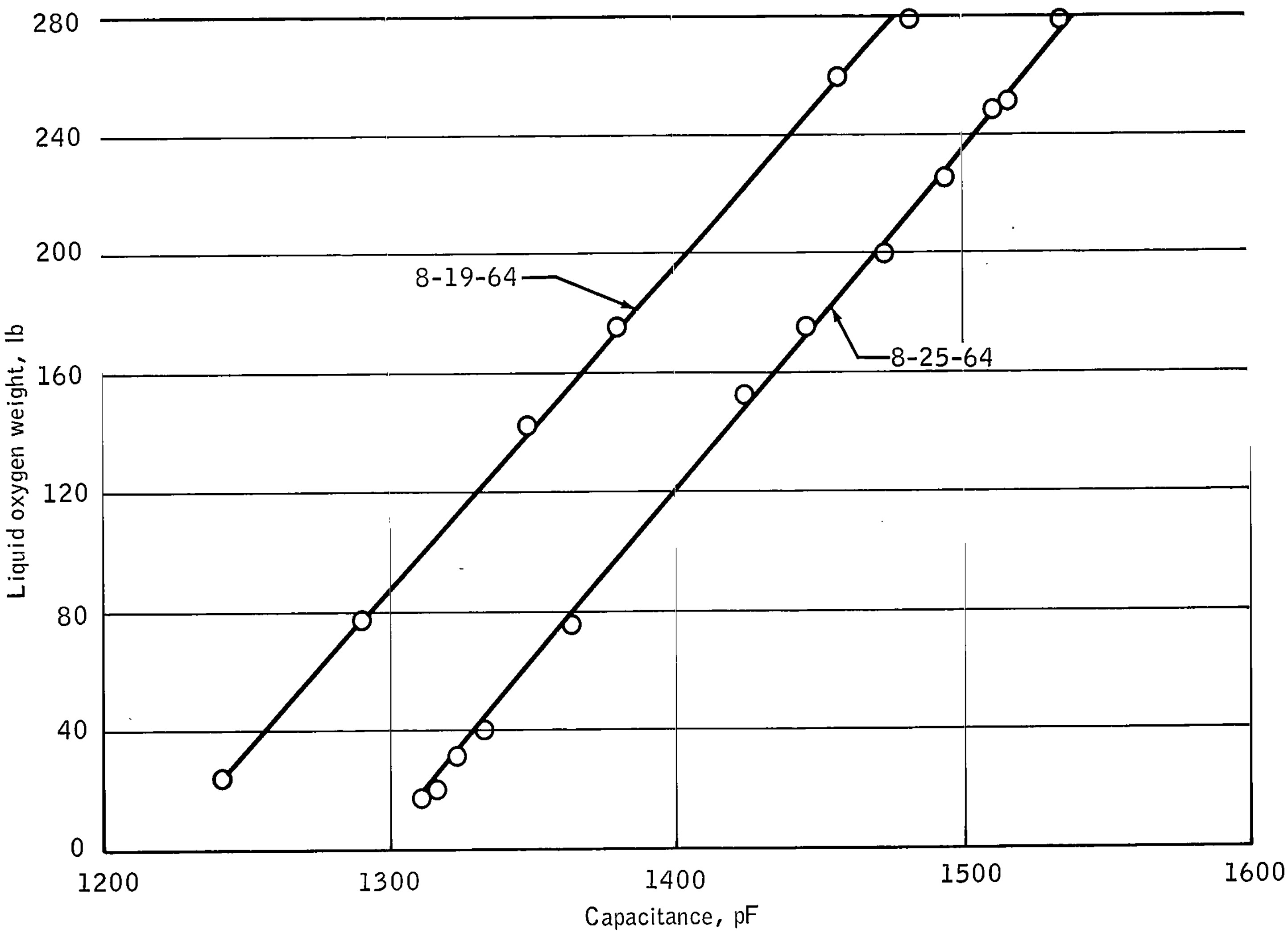

Figure 23. - Liquid oxygen, Phase I quantity gage verification.

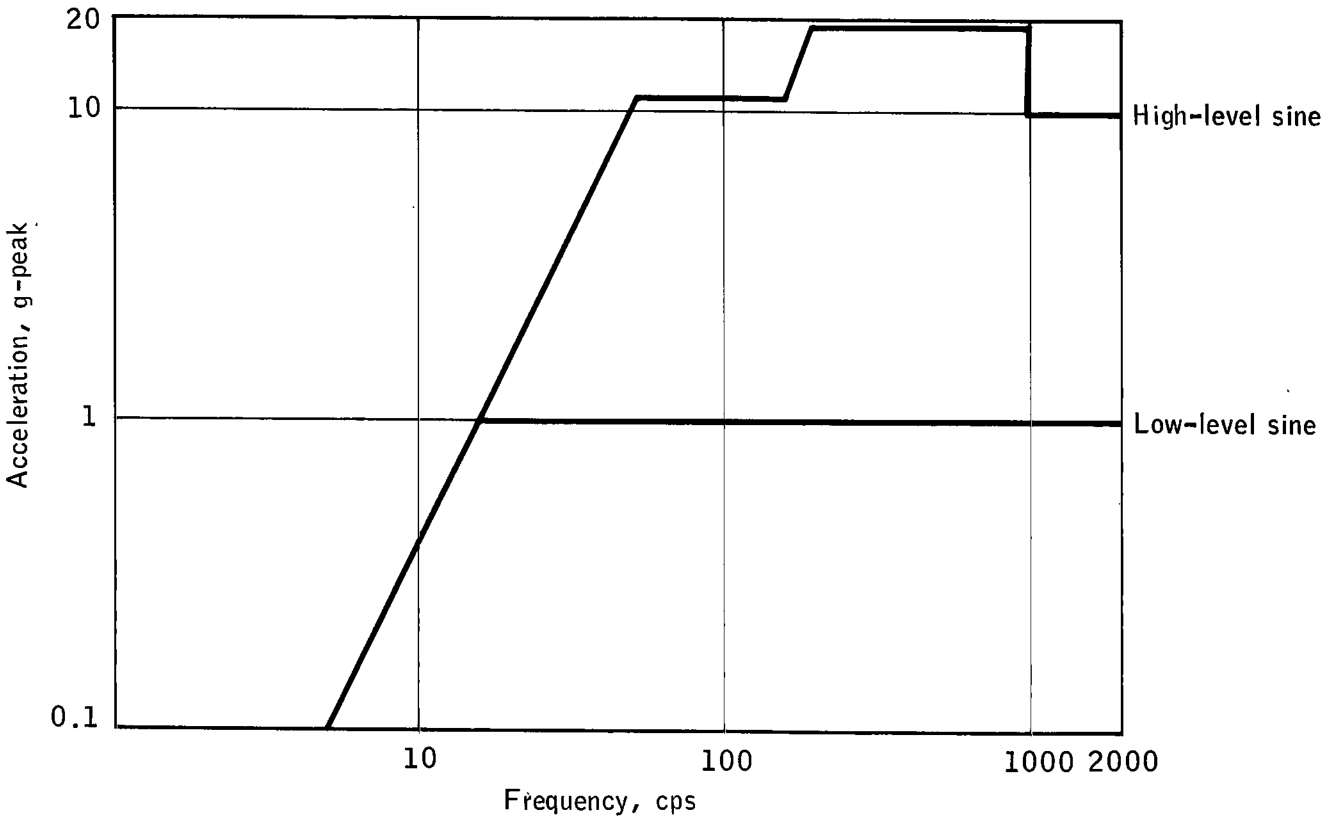

Figure 24. - Liquid oxygen, Phase I vibration test levels (sine).

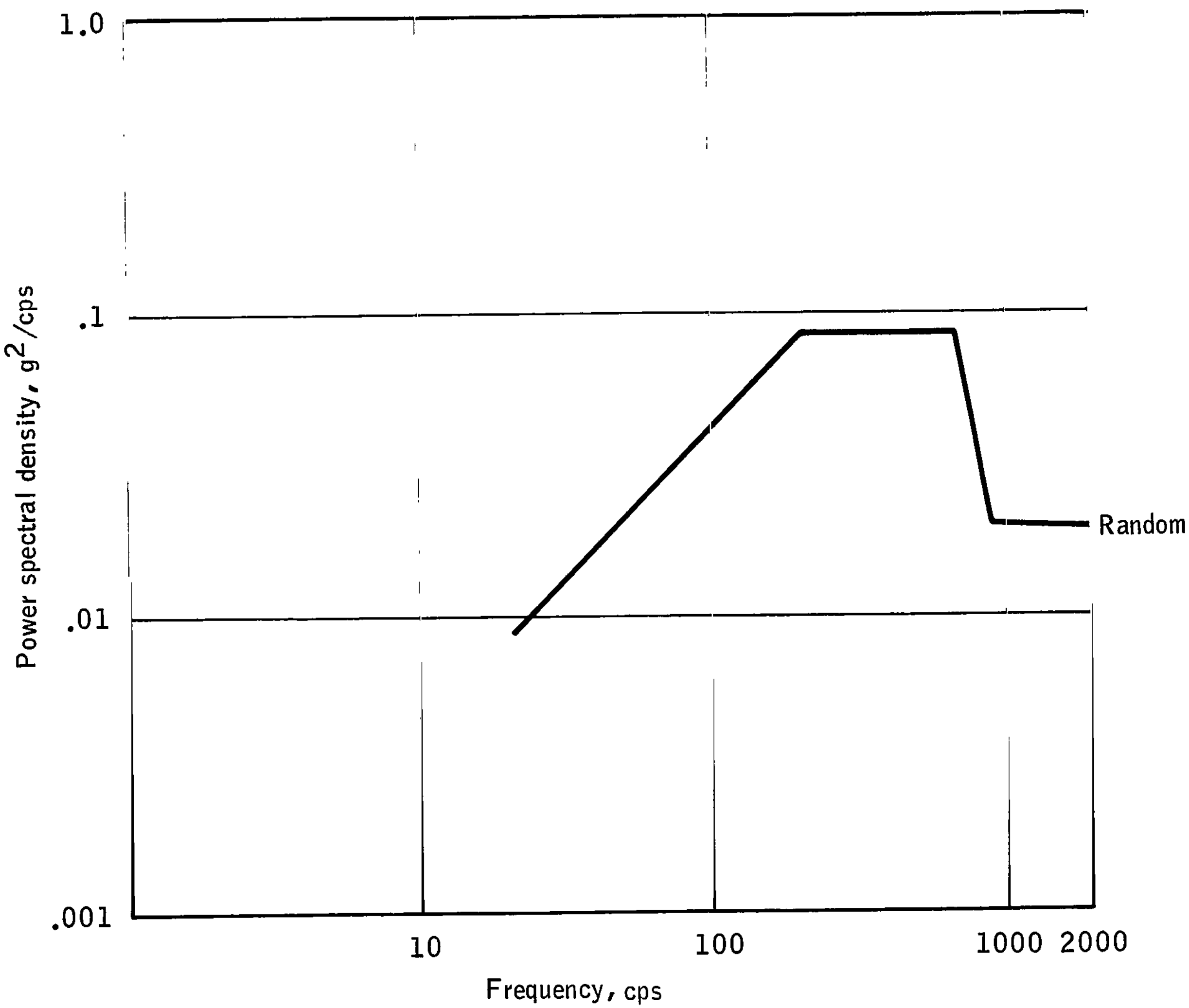

Figure 25. - Liquid oxygen, Phase I vibration test levels (random).

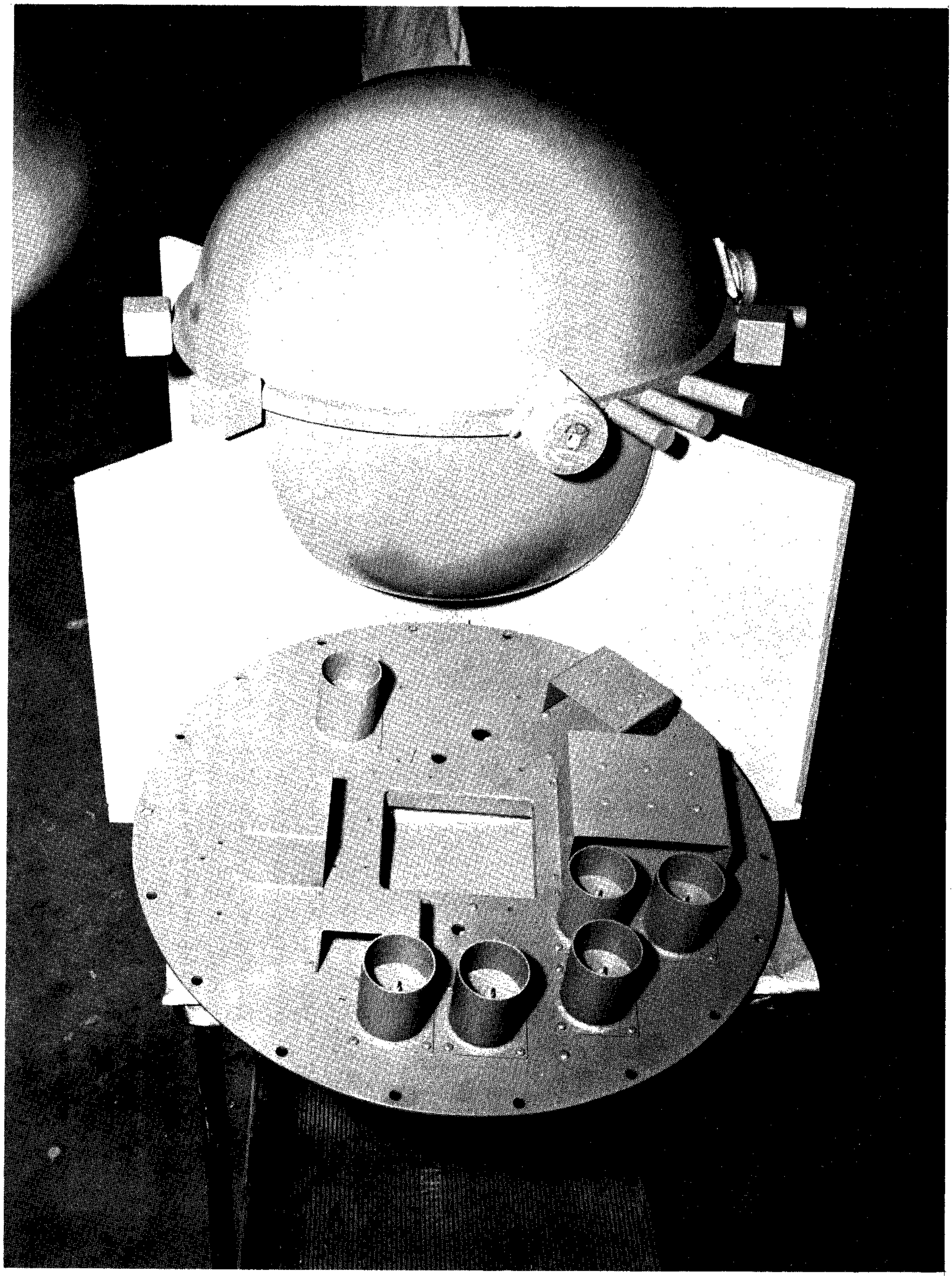

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Figure 26. - Model of Phase II liquid nitrogen subcritical storage system.

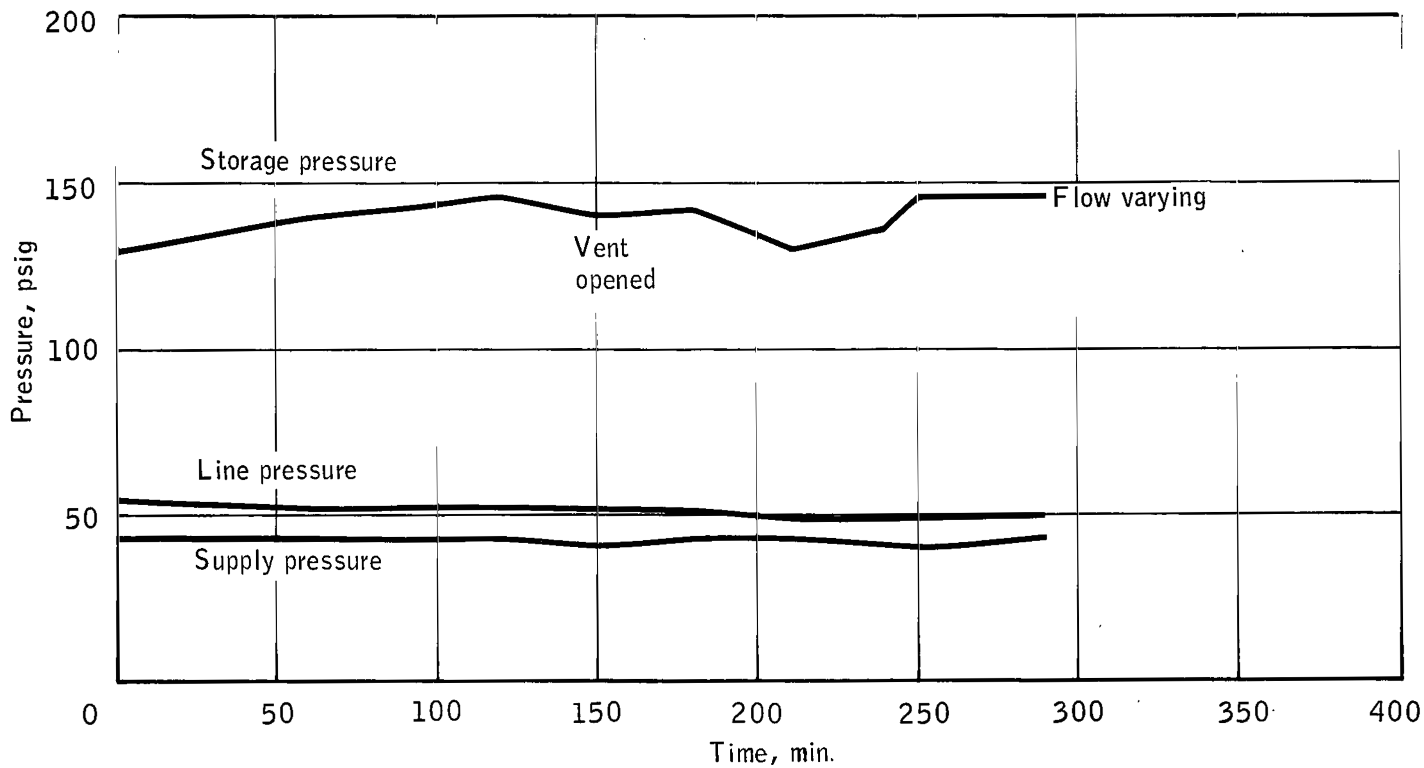


Figure 27. - Liquid oxygen system, Phase I ground-test pressures, regulator up.

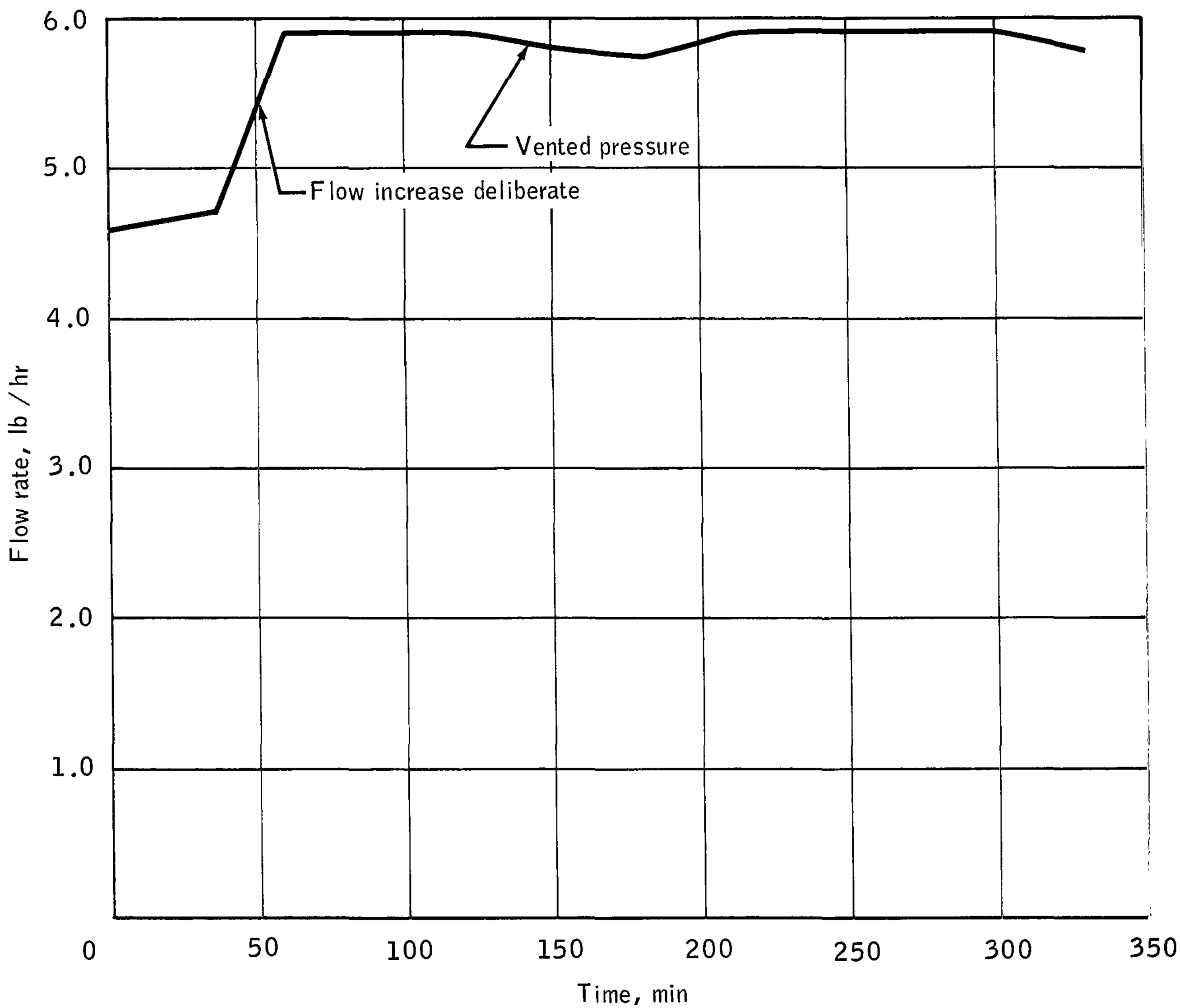


Figure 28. - Liquid oxygen dewar, Phase I ground-test flow rates, regulator down.

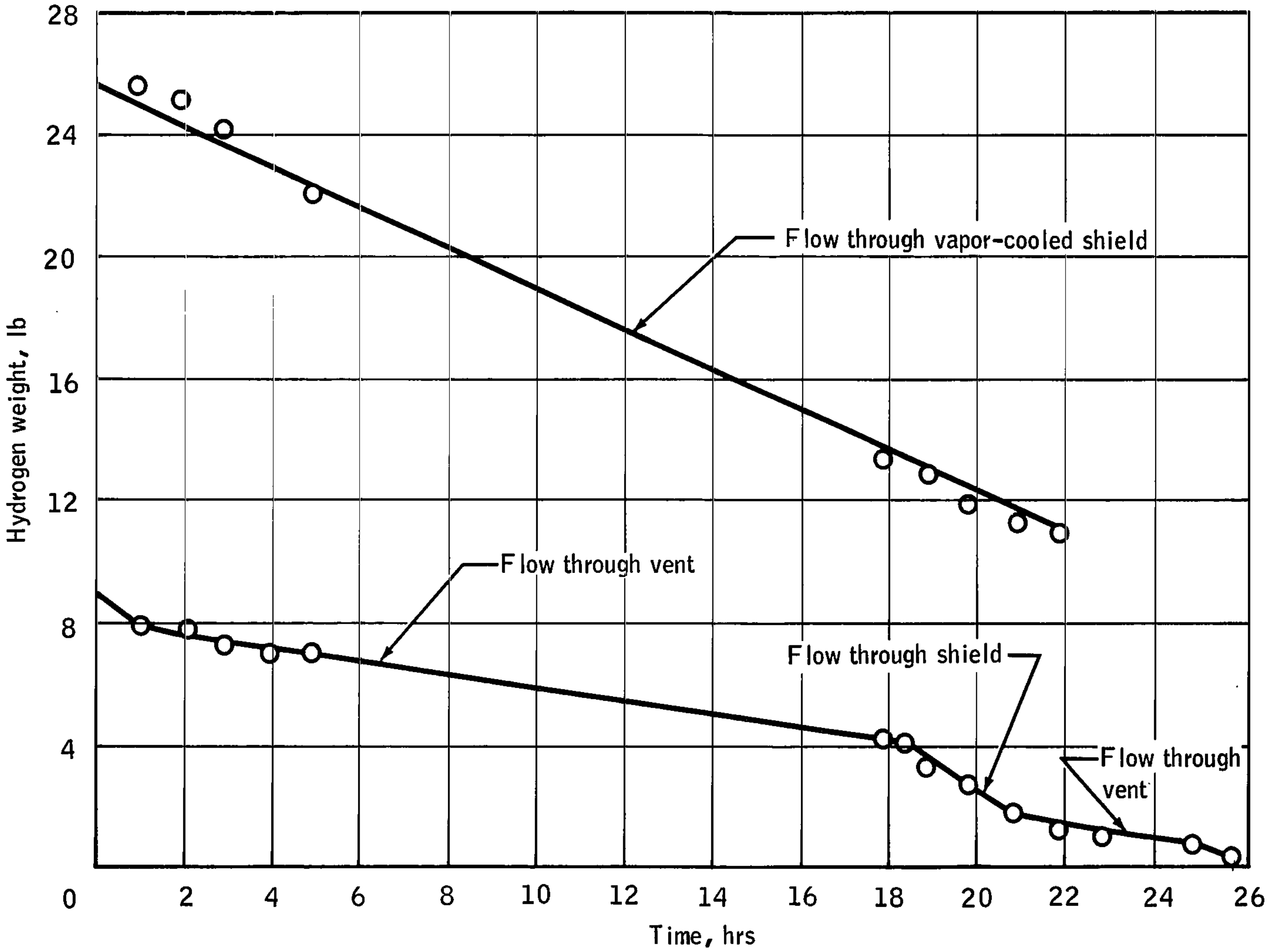


Figure 29. - Liquid oxygen dewar, Phase I ground-test depletion.

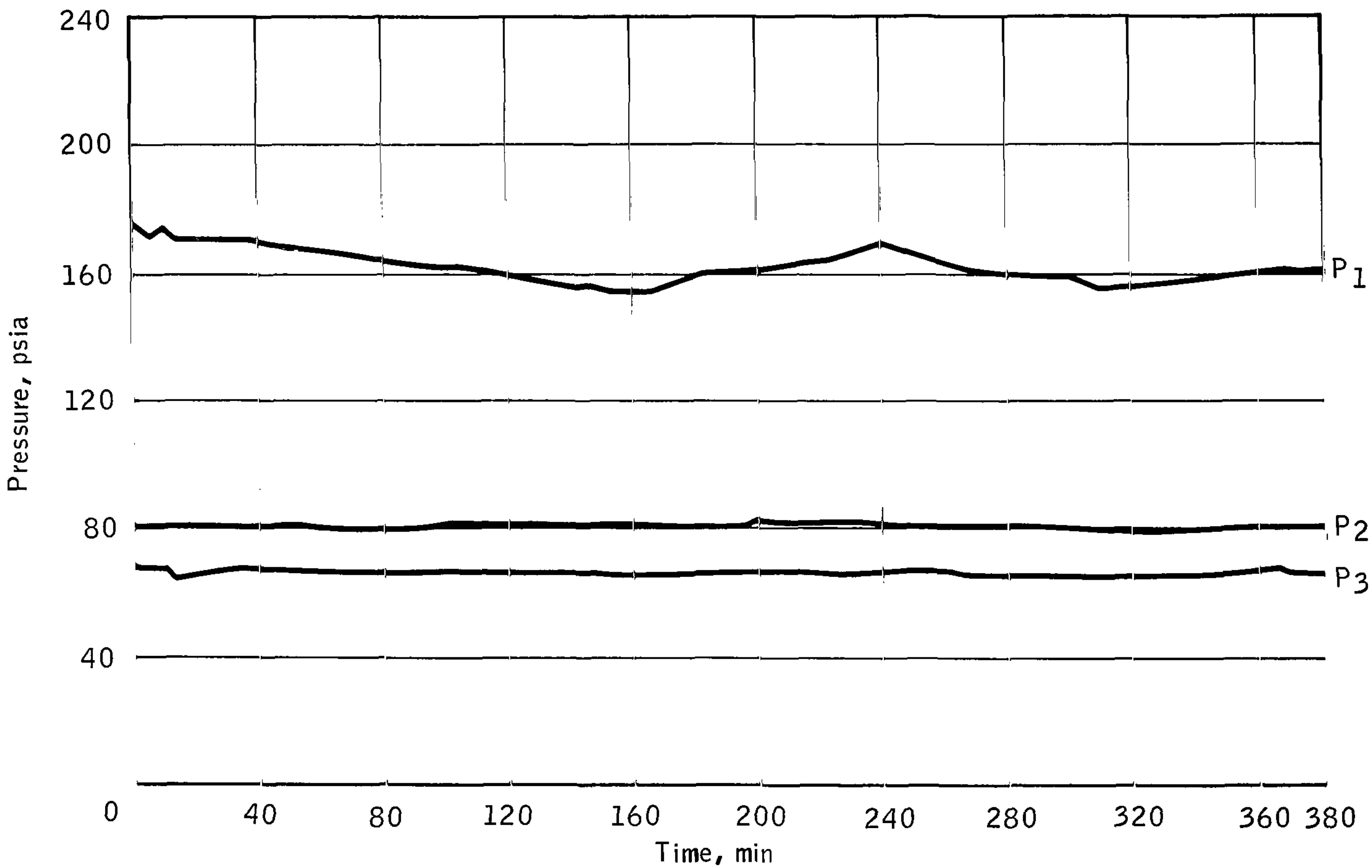


Figure 30. - Orbital test data, pressures.

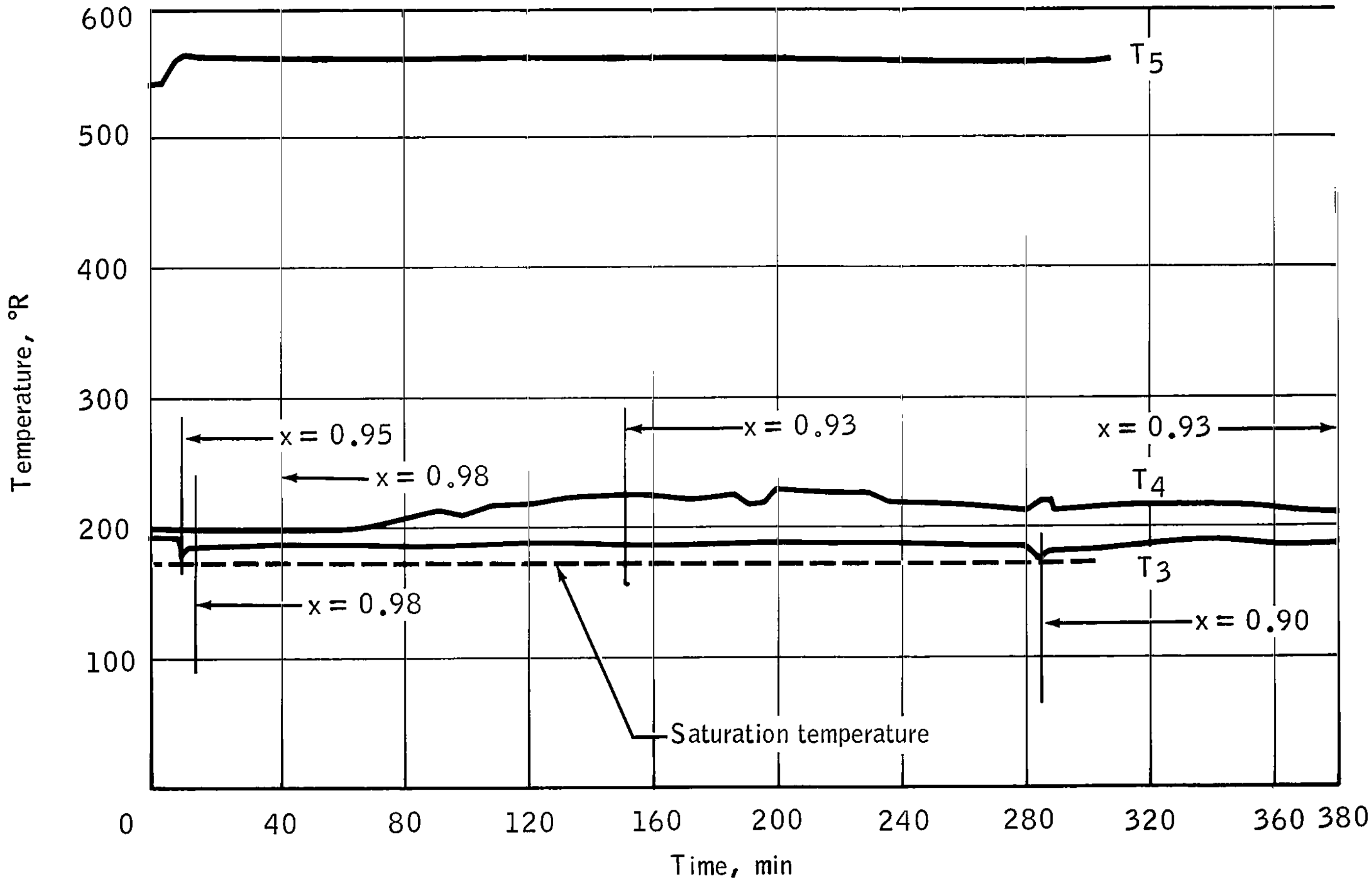


Figure 31. - Orbital test data, plumbing temperatures.

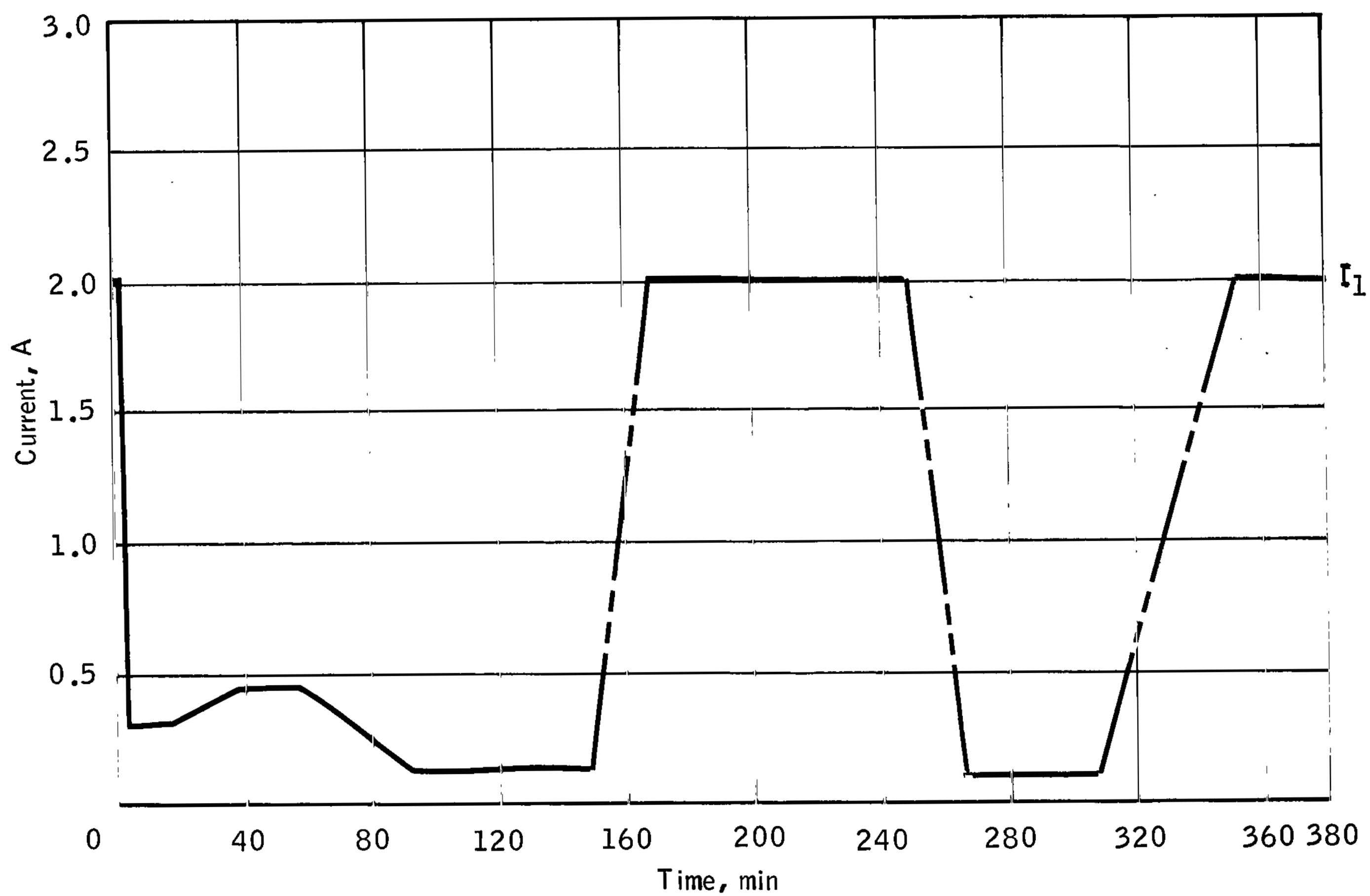


Figure 32. - Orbital test data, electrical heater current.

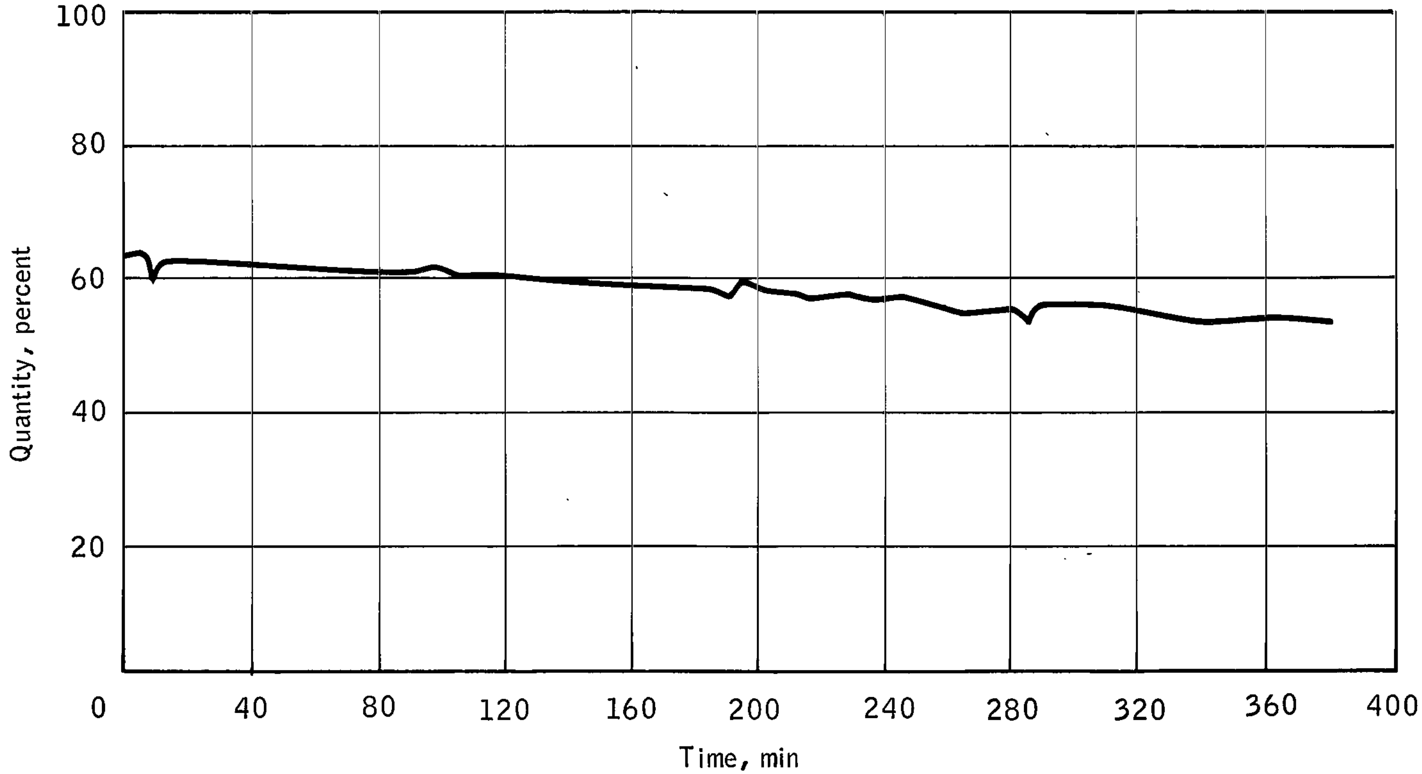


Figure 33. - Orbital test data, percent fill.

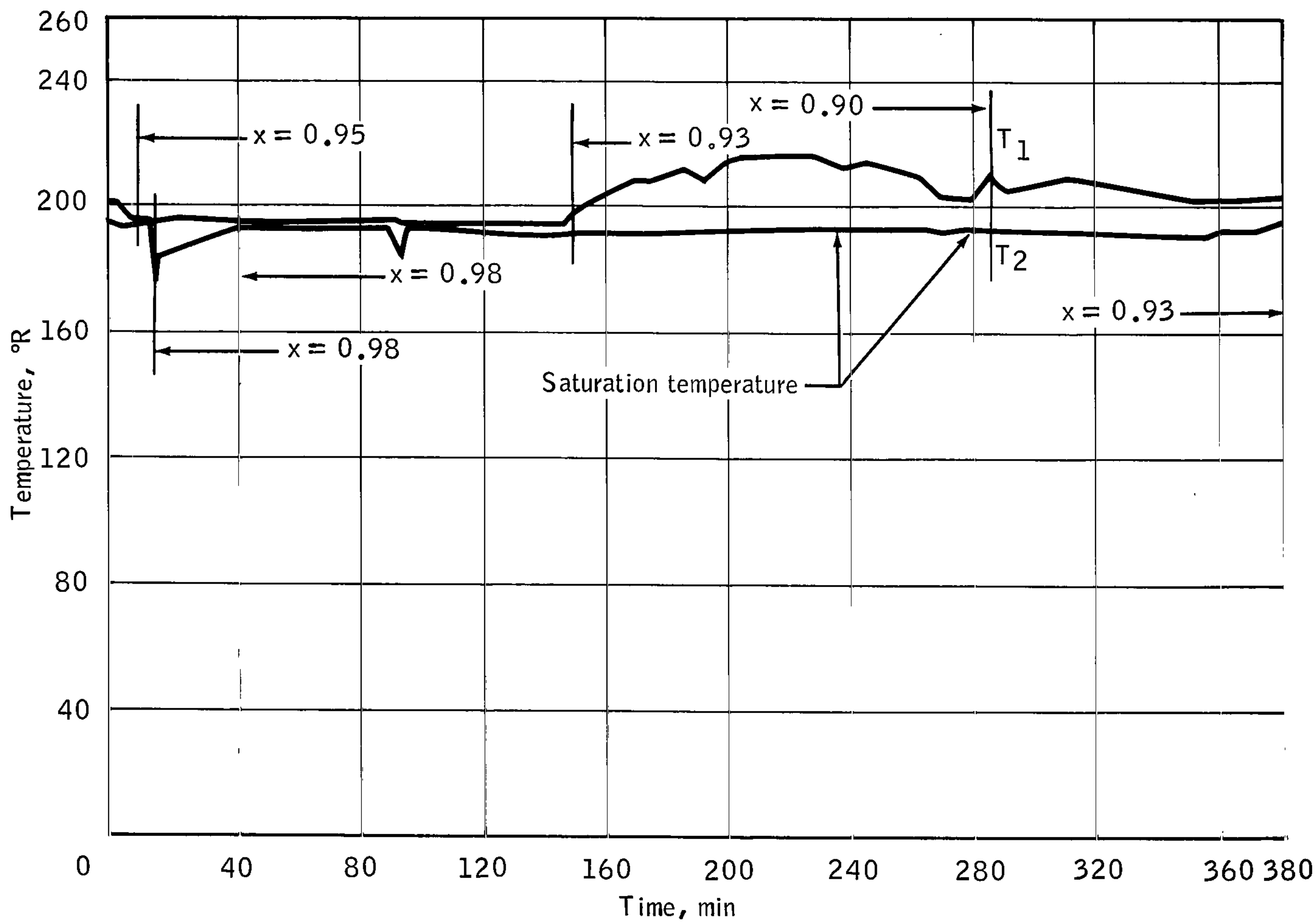


Figure 34. - Orbital test data, stored fluid temperatures.

APPENDIX A

PHASE I COMPONENT DESCRIPTION

Hydrogen System

External components. -

Heat exchangers: The system employs two external heat exchangers to provide sources of heat for staged energy addition to insure maintenance of system pressure and delivery of ambient temperature fluid. These heat exchangers are thin-walled stainless-steel tubes which are both brazed and epoxy-bonded to the outer container surface.

Bypass control valve: The bypass control valve is located in the delivery line circuit to provide a means of diverting the warmer delivery flow through the internal heat exchangers to maintain the stored fluid pressure. This valve contains four ports: the inlet port, the bypass return port, delivery through-flow port, and container reference pressure port. The poppet is a two-position device normally positioned to permit flow through the bypass return port only by means of a spring and a container reference pressure-loaded piston. When container pressure increases sufficiently, as a result of bypass circuit flow, to sustain delivery, the piston is forced to move the poppet to close the bypass return port and to permit all flow directly through the delivery port.

Relief valves: The system employs three relief valves: one in the fill line; one in the vent line; and one in the delivery line. The fill- and vent-line relief valves provide redundant vessel pressure relief, while the delivery-line relief valve protects the delivery system against excessive pressure in this circuit during extensive nonuse periods. All three relief valves contain an unbalanced, spring-loaded, ambient-pressure-referencing poppet; they are of minimum internal complexity and provide means for relief-pressure-point calibration.

Solenoid-operated flow valve: The solenoid-operated valve is utilized in the delivery circuit for normal (low flow) delivery through a calibrated orifice. This valve operates on 28 V dc (normal) or 17 V dc (minimum threshold power) and is a single-poppet, normally closed, powered-to-open unit. An individual on-off control switch is used to apply power to the valve as desired. The valve will seal against a maximum applied pressure of 120 psig before leakage occurs through the seat.

Flow orifice: The flow orifice is employed in the system to simulate the demands of a system being supplied with the fluid, such as a fuel cell. Each orifice consists of an AND union, plugged in one end, with a hole of precisely calculated diameter drilled through the plug.

Fill and vent valves: These valves are manually operated, standard cryogenic needle valves of minimum complexity. They are employed during the filling operation to open the fill and vent lines of the container. The valves have standard tube fitting openings for connecting the fill and vent lines to the servicing equipment. Plug fittings are provided for redundant seals, and they preclude entry of contaminants following completion of the filling operation.

Delivery pressure regulator: The delivery pressure regulator contains a fully balanced poppet maintained in the open position by an evacuated, precisely calibrated bellows. The bellows is referenced to the downstream pressure in the delivery line. When the pressure rises above the calibrated limit, the bellows is compressed to retract the poppet onto its seat. The flow, and subsequently the pressure through the regulator, is reduced until the downstream pressure stabilizes at or below the bellows calibration point. This action returns the poppet to its normal operating position.

Fluid temperature sensors: Fluid temperature sensors are located throughout the plumbing and internally in the container to monitor the fluid temperature at each position deemed necessary to observe the system performance. The sensors are copper-constantan thermocouples, mounted in standard tube fittings in external locations and mounted in insulated sheaths for intramural mounting transversing to internal locations.

Hydrogen storage container and its internal components. -

Container shells: The hydrogen storage is a double-walled spherical container with a radiation-shield sphere between the inner and outer walls. The inner sphere is supported from the radiation-shield sphere by six compressed fiber-glass pads, and the outer sphere is similarly supported from the radiation-shield sphere. The inner sphere is the pressure vessel and the outer sphere is the vacuum vessel. The inner sphere, the radiation-shield sphere, and the outer sphere are fabricated from type 304 stainless steel.

Insulation: The insulation of the hydrogen container is accomplished by four methods. The intramural annulus area is evacuated to minimize heat transfer by convection between the spheres. For low emissivity, the inner surface of the outer sphere is copper plated and highly polished, and the outer surface of the inner sphere is highly polished. The use of these fiber-glass pads minimizes the transfer of heat at the points of support. The radiation shield is discussed in the following paragraph.

Radiation shield: The hydrogen storage container also employs a radiation shield between the inner and outer spheres to minimize the heat leakage into the storage container. This radiation shield is copper plated and electropolished. The tubing of the internal phase-control heat exchanger is brazed to and passes around the inner sphere of the storage container. At the end of one complete pass around the inner sphere, this tube extends outward through the radiation shield and is brazed to the radiation shield in a manner similar to the method by which the phase-control heat exchanger is attached to the inner sphere. When cold vapor is passed through the discharge line, this vapor acts as a refrigerant, absorbing the heat from the radiation shield, which thus acts as an extended heat-transfer surface. Obviously, the greater the quantity of vapor flowing through the discharge line, the greater the heat absorption. When there is no flow through the discharge line, the radiation shield simply reflects the radiant heat from the environment away from the stored fluid.

Inner sphere support: The compressed fiber-glass pads between the inner and outer spheres perform the support function. They are designed to meet the requirements of a typical spacecraft mission profile including vibration and acceleration loads encountered during launching.

Capacitance gage matrix: The quantity-of-fluid measurement device is located inside the inner sphere. This device consists of a cubical matrix arrangement of two electrically isolated lattice grids. One grid is fabricated from stainless steel; the other is made from copper-plated stainless steel. When an electric potential is applied to each grid, the two grids act as plates of a capacitor. As the capacitance of the stored fluid varies with the bulk density of the stored fluid (which is dependent upon the proportion of vapor and liquid in the vessel), the capacitance between the grids is measured and translated into a readout; this readout indicates the density of fluid remaining in the container. The matrix grids permit the measurement of the fluid capacitance throughout the volume of the storage space. The use of the matrix grids is required by both the zero-gravity and the all-attitude application. The lack of predetermined phase orientation for all attitudes prevents the use of the cylindrical capacitance device normally used in supercritical applications.

Phase-control heat exchanger: The phase-control heat exchanger is a critical component of the storage container which utilizes the inner-sphere shell as an extended heat-transfer surface. This effect is accomplished by passing the throttled cold fluid through a tube brazed to the outer surface of the inner-sphere shell. This configuration has several advantages over an internally located heat-transfer surface. The weight saving is self-evident, because the surface of the sphere must exist independent of the heat-transfer considerations. The extended heat-transfer surface is adequate to meet the heat-transfer requirements; therefore, the only weight penalty associated with the phase-control heat exchanger is the weight of the extra length of tubing and the brazing material required to attach the tubing to the shell. Utilizing the inner-sphere surface as an extended heat-transfer surface results in the interception and conduction of a part of the ambient heat directly to the throttled fluid. This method is inherently more efficient than absorbing the ambient heat leakage within the stored fluid and then transferring this heat from the stored fluid to the throttled fluid through an internal heat exchanger. This greater efficiency is a consequence of the fact that this method eliminates one step in the heat-transfer process.

Pressure-control heat exchanger: The pressure-control heat exchanger is a device used to transfer heat to the stored fluid in order to maintain the desired pressure inside the storage container. The pressure-control heat-exchanger tubing is attached to the grounded side of the capacitance gage matrix and uses the matrix as an extended heat-transfer surface.

Heater: The heater is an electrical heating device manually controlled by the heater control switch to provide the required heat to build up to the initial operating pressure. The heater is thermally attached to the grounded side of the capacitance gage matrix in order to use the matrix as an extended heat-transfer surface.

Internal-pressure relief valve: The internal-pressure relief valve is positioned in a boss in the inner sphere of the storage container. The internal-pressure relief valve is absolute-pressure referenced by means of an evacuated bellows which also senses the internal storage container pressure. This relief valve relieves the storage container pressure at a preset value. This relief valve has a single spring-loaded ball, normally in the closed position. If the preset relief calibration is exceeded, the valve discharges fluid into the phase-control heat exchanger and consequently conserves the stored fluid by boiling any liquid that may be expelled, thus removing energy and reducing pressure.

Internal-pressure regulating valve: The internal-pressure regulating valve is fabricated entirely from stainless steel. This valve consists principally of a single-poppet, spring-loaded ball positioned by the relationship between the absolute pressure in the bellows, the spring tension, and the downstream supply pressure. The inlet port is located inside the inner sphere of the storage container. The outlet (supply) port is brazed to the phase-control heat-exchanger tube. The internal-pressure regulating valve is positioned in a boss located in the inner sphere of the storage container. This regulating valve senses only the absolute pressure (from the evacuated annulus between the inner and outer spheres) and the downstream (supply) pressure, and is insensitive to the storage container pressure. As the supply pressure decreases below the valve presetting, the ball lifts off its seat and permits the fluid to flow into the phase-control heat-exchanger tube. Conversely, when the supply pressure increases to the preset calibration point, the ball moves closer to its seat and partially or completely shuts off fluid flow. The regulating valve is capable of handling either liquid or gaseous flow. If the flow is liquid, the liquid is warmed in the downstream line. It is then reduced in density and converted into vapor, thus increasing the downstream pressure, which causes the valve to close and shut off the flow of liquid. This sequence of events insures that the required flow rate is not exceeded, as it normally would be for liquid delivery.

Oxygen System

External components. - The oxygen system components are similar to or identical with the hydrogen system components, with the exception of the following items.

Heat exchanger: The oxygen system employs an additional external-reheat heat exchanger. This reheat heat exchanger is required by the second pass of the internal pressure-control heat exchanger.

Pressure-controlled heater switch: This unit controls the application of power to the vessel electrical heater elements. The unit consists of a hermetically sealed electrical switch, the contact arm of which is maintained in the closed position by a force-member assembly, which comprises a piston connected to a Belleville spring-loaded diaphragm that is referenced to the container pressure on its other side. When the container pressure exceeds the diaphragm-positioning force of the calibrated Belleville spring, the diaphragm is repositioned, forcing the piston to retract from the switch contact arm and permitting the switch to open and interrupt current flow.

Solenoid-operated flow valves: The oxygen system employs two solenoid-operated flow valves. The second solenoid-operated valve is used to control the flow of gas to the high-flow orifice.

High-flow orifice: The high-flow orifice is used to measure the high-flow conditions required by the oxygen system.

Oxygen storage container and its internal components. -

Radiation shield: No radiation shield is required for the oxygen system.

Internal pressure-control heat exchanger: The internal pressure-control heat exchanger for the oxygen system is a two-stage, two-pass heat exchanger instead of the single-stage, single-pass internal pressure-control heat exchanger like that used in the hydrogen system.

Overall performance and a physical description of vessels, and the associated characteristics, of Phase I oxygen and hydrogen subcritical storage systems are given in table A-I.

TABLE A-I. - CHARACTERISTICS OF PHASE I OXYGEN AND HYDROGEN SUBCRITICAL STORAGE SYSTEMS

(a) Overall performance

Characteristics	Oxygen	Hydrogen
Time		
Nominal mission duration, days	14	14
Nominal mission duration, hr	336	336
Nonvented standby time, hr	79	40
Design percent liquid fill at 1 atm	95	88
Operating time at nominal flow rate (after standby)		
Compressed liquid region, hr	36	33
Two-phase region, hr	295	264
Vapor-phase region, hr	6	33
Total operating time, hr	337	330
Total standby plus operating time, hr	416	370
Additional standby time (beyond the nonvented standby time listed above) if vented standby and 100-percent, 1-atm liquid fill is used, hr.	NA[a]	95
Weights		
Weight delivered during operation in:		
Compressed liquid region, lb	34	2.8
Two-phase region, lb	280	22.4
Vapor-phase region, lb	6	2.8
Total operating weight delivered	320	28.0
Nondeliverable weight, lb	6	1.3
Total weight of fluid at end of fill, lb	326	29.3
Weight of complete systems when empty, lb	87	146.0
Total weight of system plus fluid at design fill percent, lb	413	175.3
Usable weight as percentage of total weight of system plus fluid, percent	77.5	16
Pressures		
Nominal storage pressure, psia	150	100
Nominal pressure before downstream regulator, psia	65	65
Nominal pressure after downstream regulator, psia	60	60
Flow rates		
Nominal operating flow rate, lb/hr	.95	.085
Maximum operating flow rate, lb/hr	5.0	.085

[a]Not applicable.

TABLE A-I. - CHARACTERISTICS OF PHASE I OXYGEN AND HYDROGEN SUBCRITICAL STORAGE SYSTEMS - Continued

(b) Physical description of vessels

Characteristics	Oxygen	Hydrogen
Shell materials		
Inner shell	Stainless steel type 304, ELC	Stainless steel type 304, ELC
Outer shell	Stainless steel type 304, ELC	Stainless steel type 304, ELC
Shield	NA[a]	Stainless steel type 304, ELC
Shell dimensions		
Inner shell inside diameter, in.	25.15	29.20
Outer shell outside diameter, in.	27.35	31.89
Inner shell volumes		
Internal volume including fittings, ft^3	4.82	7.54
Estimated volume of fittings, ft^3	.02	.02
Volume of fluid, ft^3	4.80	7.52
Number of lines and sizes in annular spaces		
Fill, stainless steel, in.	1 of 3/8	1 of 3/8
Vent, stainless steel, in.	1 of 3/8	1 of 3/8
Heat exchanger, stainless steel, in.	4 of 1/4	2 of 1/4
Delivery, stainless steel, in.	1 of 1/4	1 of 1/4
Electrical connections		
Heater, two copper leads in stainless-steel sheath	22 gage	22 gage
Capacitance gage, Kovar lead and sheath	24 gage	24 gage
Thermocouple constantan-copper leads in stainless-steel sheath	26 gage	26 gage
Heater		
Design conditions:		
Current at 28 V dc, A	3.57	1.64
Power at 28 V dc, W	100	46
Power at 28 V dc, Btu/hr	341	157
Resistance, Ω	7.7	17
Maximum power required, W	486	157
Maximum power required, Btu/hr	142	17
Voltage at maximum power	33.3	28

[a]Not applicable.

APPENDIX B

PHASE II SYSTEM DESCRIPTION

Storage Vessel Assembly

The general description of the Phase II flight dewar is the same as already discussed for Phase I. Remarks concerning minor departures from the Phase I design are given in this section. Table B-I contains the dewar assembly specification.

Phase-Control Heat Exchanger

The phase-control heat exchanger for the flight system was sized for the worst case, flow of pure liquid at 1.25 lb/hr. Orientation and spacing of tube passes on the inner vessel were selected to remove all heat entering the vessel under this condition. Temperature probes were located at each end for telemetry of flight-test data. Design specifications of this heat exchanger are tabulated as follows.

Material:	Stainless steel
Tube dimensions:	0.125-in. o.d. by 0.012-in. wall
Spacing:	12 in. nominal between passes
Fluid:	Nitrogen, liquid or vapor
Operating pressure:	70 to 80 psia
Proof pressure:	360 psig
Burst pressure:	480 psig

Quantity Sensor

The quantity gage was again a capacitance device, consisting of two intermeshed, cubical matrices filling the inner tank. Quantity is measured by sensing the change in capacitance between the matrices when a 5-kHz square-wave signal is applied. Capacitance varies with the dielectric constant of the stored fluid, which varies with the average density of the stored fluid. Thus, sensor output is proportional to fluid quantity, regardless of the ratio of liquid to vapor or regardless of the orientation of phases. Design specifications for pressure sensors are shown in table B-II.

Concentric-cylinder capacitors used in current manned spacecraft are not suited for subcritical systems because of the presence of two phases in a zero-gravity environment. Design specifications are as follows.

Rod size:	0.045 and 0.093 in.
Spacing:	The centerline spacing of all rods of each matrix is 2.5 in. The centerline distance of each matrix rod from its nearest parallel rods in the mating matrix is 1.77 in.
Fabrication:	Tack-weld and furnace-braze
Matrix leads:	Number 77 wire
Matrix lead sheath:	0.125-in. o.d. by 0.012-in. wall by 18-in. minimum length

Pressure Maintenance Heater

Design specifications for the pressure maintenance are as follows.

Voltage:	28 ± 0.3 V dc
Power output:	50 ± 5 W
Resistance at 70° to -320° F:	$15.8 \pm 1.2\ \Omega$
Operation:	To operate while submerged in liquid nitrogen at 14.7 to 170 psia or in equilibrium-state vapor at the conditions listed
External proof pressure:	360 psig
External burst pressure:	480 psig
Maximum allowable sheath temperature:	1800° F

Pressure Sensors

Three pressure sensors (fig. B-1) were used on the subcritical system. Two are mounted on the storage-vessel girth ring and one on the signal-conditioner plate. Designated P_1 and P_2 on the schematic diagram, the first two units measure pressure in the storage vessel and in the phase-control heat exchanger, respectively. Delivery pressure is measured by P_3.

The design incorporates a sealed aluminum case, welded sensing element, and welded electronic circuitry.

Pressure Switch

The pressure switch controls application of power to the pressure-maintenance heater. It contains a hermetically sealed, normally closed electric switch. The contact arm is maintained in the closed position by a spring-loaded diaphragm. The opposite side of the diaphragm is exposed to storage vessel pressure. When this pressure exceeds the spring force, movement of the diaphragm opens the switch and interrupts power to the heater. Specifications are given as follows.

Environmental conditions

Operating pressure, actuation:	170 psig maximum
Operating pressure, deactuation:	130 psig minimum
Proof pressure:	360 psig
Burst pressure:	480 psig
Fluid temperature:	-65° to 160° F
Ambient temperature:	-65° to 160° F
Leakage:	0 at 170 psig

Electrical conditions

Input voltage:	18 ± 0.3 V dc
Current capacity:	6 A maximum

Connections

Pin-connected to system

Sensor and vent ports per Military Specification MIL-MS-24385-4

Relief Valves

Two relief valves are used in the subcritical system, one in the vent line for protection of the storage vessel and one for protection of the delivery line. The relief valves are identical in design and operation. Specifications are given as follows.

Valve material:	Type 303 stainless steel
O-ring material:	Teflon
Operating temperature:	-65° to 160° F

Relief pressure:	240 psig maximum
Reseat pressure:	200 psig minimum
Minimum flow rate at 260 psig:	4 lb/min nitrogen
Allowable external leakage:	None
Allowable leakage past poppet:	0.0002 lb/hr nitrogen at 190 psig, -65° F

Solenoid Valve

A solenoid valve was required to initiate delivery after the storage vessel reached operating pressure. However, no control channel was available in flight to activate the solenoid. Therefore, the subcritical system used a normally open, powered-to-close valve which was connected to the ground support equipment (GSE) power circuit. When the GSE umbilical was disconnected shortly before launch, the solenoid valve opened and remained open thereafter. Thus, the system delivers gaseous nitrogen at a single flow rate from launch until the storage vessel is empty. The solenoid valve was a single poppet device. Design specifications are as follows.

Power requirement:	17 to 30 V dc, 0.32 A at 28 V dc and 70° to 80° F, continuous
Equivalent orifice:	0.035-in. diameter where the discharge coefficient is 0.65
Leakage, internal:	10 cc/hr maximum (O_2) at 250 psig, 70° to 80° F
Leakage, external:	None, 0 to 250 psig
Pressures:	Operating 0 to 250 psig, proof 275 psig, and burst 625 psig
Temperatures:	Ambient and effluent, 70° to 80° F
Qualification:	Military Specifications MIL-S-4040A, except paragraph 3.3.1

Absolute-Pressure Regulator

The absolute-pressure regulator (fig. B-2) contains a balanced poppet, maintained in the open position by a calibrated bellows. One side of the bellows, open to the ambient, causes the unit to act as an absolute regulator in the vacuum of space. The other side of the bellows is referenced to downstream pressure in the delivery line. An increase in pressure compresses the bellows, which retracts the poppet and reduces flow. The resulting pressure reduction allows the poppet to return to its normal operating position. Design specifications are given as follows.

Flow rate:	1.0 to 1.5 lb/hr nitrogen vapor
Fluid temperature:	-50° to 50° F
Ambient temperature:	-65° to 160° F
Inlet pressure:	70 to 170 psia
Discharge pressure:	55 to 65 psia
Operating pressure:	70 to 80 psia
Proof pressure:	360 psig
Burst pressure:	480 psig
External leakage, nitrogen:	10 cc/hr at 150 psig

Design specifications for the pressure buildup heater are as follows.

Input voltage:	18 ± 0.3 V dc
Heating power:	180 W
Resistance at 70° to -320° F:	4.39 ± 0.35 Ω
External proof pressure:	360 psig
External burst pressure:	480 psig
Maximum allowable sheath temperature:	1800° F
Heater lead (2):	0.125-in. o.d. by 0.012-in. wall by 18-in. minimum length (number 22 conductors)

Temperature Probes

System instrumentation included five temperature-measuring probes. These probes were platinum resistance thermometers sealed in stainless-steel jackets. Mating signal conditioners were mounted on the signal-conditioner plate to provide 0- to 5-V dc output signals proportional to the temperature-probe outputs.

Designation	Location	Range
T_1	Storage volume top	130° to 230° R
T_2	Storage volume bottom	130° to 230° R
T_3	Phase-control exchanger inlet	130° to 230° R
T_4	Phase-control exchanger outlet	130° to 230° R
T_5	Vapor delivery, signal-conditioner plate	460° to 560° R

Design specifications for all temperatures probes are given as follows.

Accuracy: ±1.5° R

Sheath dimensions: T_1 to T_4: 5/32-in. o.d. by 0.028-in. wall by 18-in. length

Delivery Temperature Controller

A delivery temperature controller was used to assure vapor delivery in the event of an accidental liquid delivery from the phase-control heat exchanger. Specifications are given in table B-III.

Vibration Isolators

Cryogenic storage vessels are customarily designed for rigid attachment to the launch vehicle structure. The outer shell and external components are designed for full-vibration input levels. This is practical since the mass of the outer shell and components is only a small fraction of the filled system weight.

However, redetermined vibration requirements by MSFC exceeded the limiting resonance input levels of fiber-glass pads used in the Phase II system. To avoid a major design change, elastomeric vibration isolators were installed between the outer shell and the support structure mounted in the launch vehicle. The storage vessel then became a dynamic system with two degrees of freedom. The natural frequency of the new isolators was specified at 20 cps so that they would be attenuating the input at resonance for the fiber-glass pads. This represented the first attempt to mount a large cryogenic storage system on isolators for space flight.

Vibration test requirements were redetermined a second time by MSFC during November 1965. Fabrication of both systems had been completed and qualification testing was in progress. Information obtained at MSFC showed that low-frequency amplitudes in the new specification bottomed-out the elastomeric isolators and caused failure of the mounting pins.

The new vibration requirement imposed the need for custom-made vibration isolators. A secondary design target for the new isolators was to remain within the dimensional envelope of the previous isolators so that redesign of the launch-vehicle attachment struts would not be required. New vibration isolators (fig. B-3) were successfully designed and procured on an accelerated schedule for delivery with the subcritical systems. These isolators were designed to have a natural frequency of 20 cps and to transmit less than 3.5 cps at resonance. Also, the isolators were designed to prevent metal-to-metal contact, regardless of amplitude. The elastomeric core was also restrained to prevent complete separation from the outer cap in the event of failure.

The qualification system was shipped to MSFC, where the storage vessel was successfully qualified with the new isolators under the supervision of MSC personnel. Design specifications are given as follows.

Ambient temperature:	-65° to 250° F
Maximum excursion before snubbing:	0.25 in. radial or axial
Material:	Mild steel, cadmium-plated per QQ-P-416 and silicone-base elastomer
Dynamic loading	
Radial direction:	900 lb
Axial:	900 lb

Description of Signal-Conditioner Plate

The signal-conditioner plate design required a reinforced aluminum plate which served as a mounting platform for signal conditioners and other components not mounted on the storage-vessel girth ring. These components included five temperature signal conditioners, two electrical current monitors, the quantity-gage signal conditioner, two pressure transducers, one flowmeter and signal conditioner, one flow restrictor, one electromagnetic interference (EMI) filter, the fill and vent valves, and electrical interface connectors for the subcritical system.

The plate was mounted to the nose-cone framework in a horizontal position, directly above the storage vessel. Connections between the plate and storage vessel consisted of one 0.25-in. o.d. by 0.035-in. wall tube for vapor delivery and two 0.313-in. o.d. by 0.035-in. wall tubes for filling and venting. All tubes were of type 5052-0 aluminum. Following qualification of the storage vessel at Huntsville, Alabama, tubing was modified to type 6061-T6 aluminum having a thicker wall. Electrical connections were routed through a harness between the EMI filter and the storage-vessel girth ring.

Components in the subcritical system were designed to operate in a maximum environmental temperature of 160° F. Analysis of aerodynamic heating of the nose cone was carried out by MSC personnel early in the program. This analysis showed that the nose-cone skin would experience a peak temperature of 625° F approximately 170 seconds after lift-off (fig. B-4). The inner surface of the nose cone was covered with a low-emissivity coating. To reduce heat transfer by conduction, the signal-conditioner plate was mounted on thermal isolators. Details of the thermal isolators are shown in figure B-5.

The signal-conditioner plate was qualification tested during November and December 1965 by the contractor. Tests were carried out with thermal isolators in place on the plate and with all hardware installed and operating.

Flowmeter

The flowmeter is a device capable of measuring mass flow rates independent of minor changes in fluid pressure and temperature. It operates by determining temperature variations between calibrated resistance thermometers. Although this device was mounted and qualified on elastomeric isolators, the measurement was lost during orbital injection. Design specifications are tabulated as follows.

Fluid:	Oxygen or nitrogen
Flow:	0 to 1.5 lb/hr
Line pressure:	0 to 100 psi
Proof pressure:	150 psi
Pressure drop:	0.65-in. H_2O at 1-atm line pressure and full-scale flow rate
Flow size:	0.18 in.
Output (single-ended):	0- to 5-V dc linear with mass flow
Impedance:	Less than 100 Ω
Accuracy:	± 2 percent of full scale
Time constant:	<0.07 sec

Operating temperature range	
Signal conditioner:	0° to 200° F
Flow medium:	40° to 110° F
Power requirements	
Voltage:	28 ± 4 V dc
Current:	80 mA
Physical characteristics	
Size	
Transducer:	1.375-in. hexagon by 3.06-in. length, excluding fittings
Signal conditioner:	3.12 by 4.5 by 1.5 in.
Weight	
Transducer:	8 oz
Signal conditioner:	12 oz

Power Monitors

The subcritical system included a dual instrument to monitor power supplied to both the pressure-maintenance heater and the warmup heater. This instrument was a dc differential amplifier and its input was power to the electrical heaters. Two separate and distinct amplifiers were packaged in one housing. In addition, the equipment included two separate internal current shunts. Each of the current shunts handled approximately 2.5 to 3.0 A dc and produced a voltage drop of approximately 50 mV for application to the input terminals of the dc amplifiers. The overall temperature characteristics of the current shunt-amplifier combination were such that a maximum of 1 percent full-scale error was introduced over the temperature range and other environmental conditions.

The data-pass band of each amplifier is 0 to 1000 cycles. Wave shapes appearing at the input terminals of the dc amplifier may be dc, sine wave, or square wave. The square-wave response is given among the following specifications for the monitors.

Maximum current to be monitored:	3.25 A
Rise and fall time:	350 μsec
Pulse overshoot:	0.25 percent maximum

Pulse ringing:	0.25 percent maximum
Maximum power consumption:	0.42 W
Maximum allowable weight:	2.25 lb
Input voltage:	28 ± 0.3 V dc
Noise immunity:	Per EMI specification MIL-I-26600 (USAF) plus NASA Addendum MSC-ASPO-EMI-10A, October 17, 1963
Ambient temperature range:	-65° to 160° F
Humidity:	All electrical components moisture-proof per MIL-E-5272

Fill and Vent Valves

In-line manual ball valves were used to service the system. The quick-disconnects were difficult to service through the available 4- by 6-in. door in the nose cone.

Temperature Signal Conditioner

The signal-conditioner plate contained five temperature signal-conditioning amplifiers. Each conditioner was associated with a matching temperature sensor in the storage vessel or in the delivery system.

The signal-conditioning amplifier provided an isolated 0- to 5-V dc signal output for a temperature signal input. It consisted of a regulated dc excitation source, a drift-free amplifier, and a suitable bridge circuit for the specific sensor application. The case was hermetically sealed. Design specifications are as follows.

Output signal level:	0 to 5 V dc for the specified input signal
Output impedance:	Less than 400 Ω
Lead resistance:	25 000 Ω minimum
Gain value:	Fixed gain of 100 ± 0.25 percent
Temperature coefficient:	Less than ± 0.005 of fixed gain value per °F, -65° to 212° F
Zero stability:	± 20 mV for all effects of voltage and temperature

Output limits:	Limited internally to -0.7 V to 6.8 V
Isolation:	Power input in signal output isolation will exceed 100 MΩ at 50 V dc
Insulation resistance:	100 MΩ at 50 V dc between any connector pin and case ground with dry external surfaces
Power requirements	
Power input:	28 ± 4 V dc, 100 mA maximum
Polarity reversal:	Input power polarity reversal will not cause damage
Transients:	Transients 1.5 times rated input voltage will not damage unit
Conducted interference:	Will meet MIL-I-6181D, paragraph 4.3.4.1

Electromagnetic Interference Filter

The subcritical nitrogen system was designed and fabricated to comply with EMI specifications MIL-I-26600 (USAF), plus NASA Addendum MSC-ASPO-EMI-10A, dated October 17, 1963. A major criterion in the selection of components was interference control. Where possible, low-interference or interference-free components were selected. Mechanical discontinuities, such as covers and inspection plates, were treated to effect a continuous low-impedance path. All surfaces between components and mounting structures were free of insulating finishes. Coupling was further reduced by the strategic location of components and by the segregation of wires and cables, and shielded wires were used to provide isolation where necessary.

In addition to the steps just described, both completed systems were operated in the contractor's Radio-Noise Laboratory for EMI testing. Filters were custom-made at this time and installed in a housing on the signal-conditioner plate. These filter housings were then hermetically sealed.

Quantity-Gage Signal Conditioner

The quantity-gage signal conditioner was designed to receive an input current determined by the storage-vessel capacitance probe and to produce a 0- to 5-V dc output signal, which varies linearly with the quantity of cryogen in the tank. For a nonpolar gas or liquid, the capacitance of the probe varies nonlinearly with density. Negative feedback is applied to obtain a linear output voltage as a function of quantity.

A block diagram of the conditioner is shown in figure B-6. The system consists of an amplitude-controlled square-wave oscillator, which drives the probe capacitor, and a reference capacitor. Currents in the two capacitors are summed by the operational amplifier. The output of the operational amplifier is a square wave with amplitude proportional to the ratio of excitation voltage to the capacitance difference between probe and reference. This signal is then demodulated and filtered to become the output voltage. A fraction of the output voltage is summed with the reference voltage and fed into the regulator. The regulator output is then used to control amplitude of the square-wave oscillator. With the proper choice of circuit constants, this closed-loop feedback produces an output voltage which is linear with the quantity of cryogen in the tank.

Components within each of the blocks shown in figure B-6 are arranged in a high-density, three-dimensional matrix which is potted for support and hermetic sealing. All connections are made by spot welding. Completed modules are assembled by spot welding connections to the baseboard. The entire assembly is then placed in a prefabricated metal housing for final potting. Design specifications are as follows.

Electrical requirements

Input voltage:	20 to 34 V
Power (26 V dc):	1 W maximum
Output impedance:	$<250\ \Omega$
Output ripple (at maximum signal output):	5 mV (peak to peak)
Nominal output load:	25 000 Ω

Maximum envelope dimensions

Length:	6.03 in.
Width:	2.28 in.
Height:	1.75 in.
Weight:	1.5 lb

Electrical Interface Connectors

Electrical interface connectors are located on the top of the EMI filter housing on the signal-conditioner plate. One connector is used for ground and vehicle power supplies, while the second is reserved for instrumentation signals. Signal connector J2 is described in table B-IV. Design specifications are given in table B-V.

TABLE B-I. - PHASE II STORAGE VESSEL DESIGN SPECIFICATIONS

Parameter	Value
Internal net volume	2.58 to 2.62 ft^3
Usable fluid capacity	95 percent of net volume
Annulus	1.065 to 1.175 in.
Insulation	Fiber glass and vacuum
Operating pressure	130 to 170 psig
Proof pressure	360 psig
Burst pressure	480 psig minimum
Outer shell	
Material	Titanium, EMS 499
Inside diameter	22.892 to 22.992 in.
Wall thickness	0.030 to 0.035 in.
Closeout procedure	TIG weld
Closeout inspection	X-ray
Heat treatment	None
Inner shell	
Material	Inconel 718
Inside diameter	20.51 to 20.61 in.
Wall thickness	0.065 to 0.075 in.
Closeout procedure	TIG weld
Closeout inspection	X-ray and proof pressure test at 360 psia with ambient dry nitrogen
Heat treatment	1800° F per AF Specification 245
Support pads	Six 10-in. diameter
Annulus lines	Stainless steel
Fill (1)	0.32-in. o.d. by 0.028-in. wall by 18-in. minimum length
Vent (1)	0.32-in. o.d. by 0.028-in. wall by 18-in. minimum length
Supply (1)	0.25-in. o.d. by 0.028-in. wall by 18-in. minimum length

TABLE B-II. - DESIGN SPECIFICATIONS FOR PRESSURE SENSORS

Operating pressure, P_1 and P_2:	20 to 250 psia
Operating pressure, P_3:	0 to 100 psia
Maximum pressure without damage:	150 percent of range
Output voltage:	0 to 5 V dc
External load:	15 000-Ω minimum
Output regulation:	0.05 percent of full-scale per volt change in input (over 22 to 32 V dc; ref. 28 V)
Power requirements	
Voltage:	28-V dc nominal, operable 22 to 32 V dc
Current:	9-mA maximum, over 22 to 32 V
Balance:	0 psia
Linearity:	±0.5 percent or less of total range
Hysteresis	
Ranges through 2500 psi:	0.1 percent or less of pressure span
Resolution:	Continuous
Output impedance:	200-Ω nominal, 300-Ω maximum from 15 000-Ω to open circuit load
Output ripple:	0.3-percent rms or less of full-scale output voltage
Rise time:	1.5 msec to 67 percent
Temperature effects:	Less than ±2.5 percent of range over the temperature range from -65° to +200° F
Acceleration sensitivity:	0.001 percent to 0.05 percent of full scale per g, depending on range
Vibration effects:	1-percent rms or less for 20g vibration, 40g without damage, 20 to 2000 cps

TABLE B-III. - DELIVERY TEMPERATURE CONTROLLER

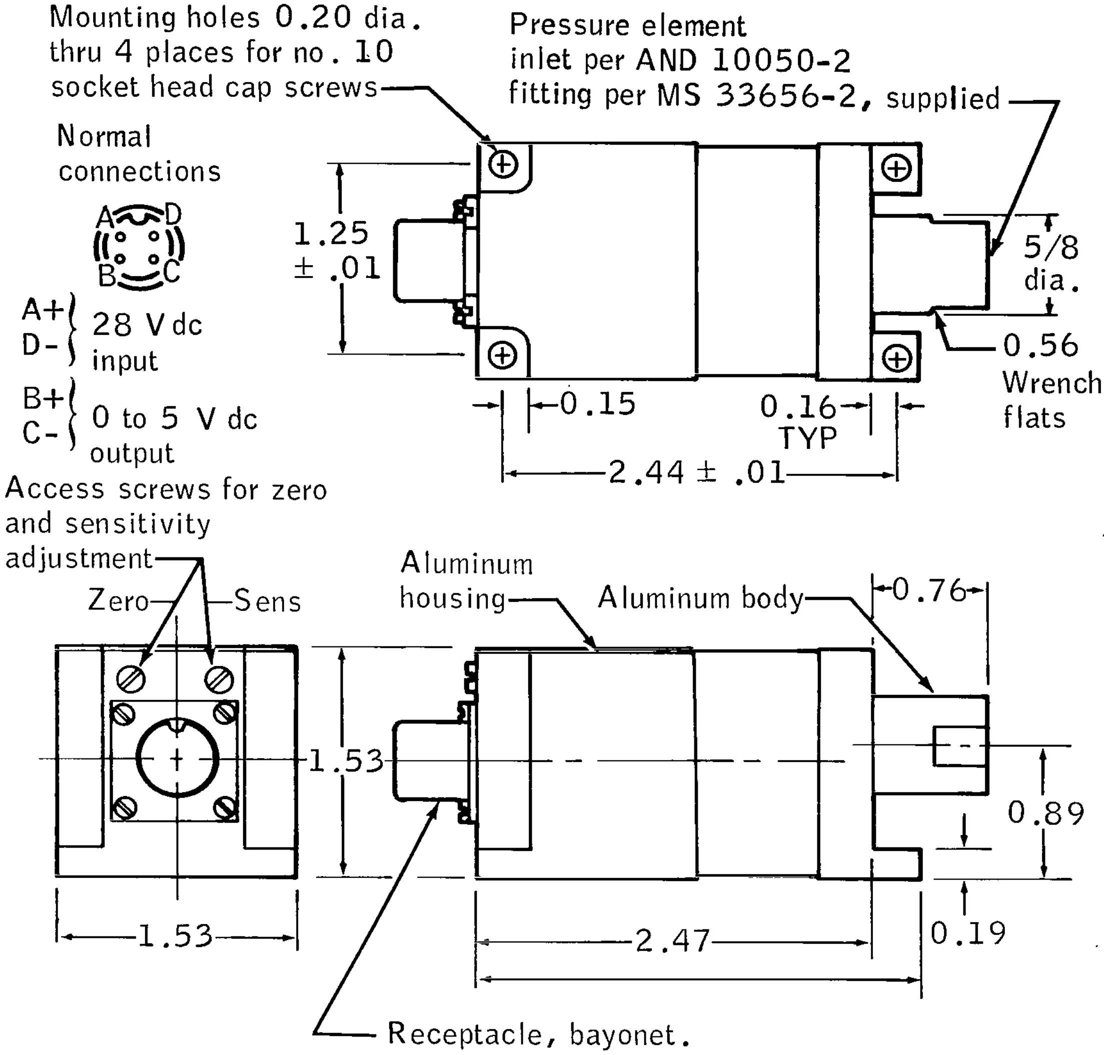
Electrical Heater	
Input voltage:	28 ± 0.3 V dc
Heating power:	70 ± 5 W
Flow medium:	Nitrogen
Heating element resistance at 70° F and at operating temperature:	11.24 ± 0.57 Ω
Flow rate:	1.25 ± 0.125 lb/hr
Maximum allowable weight:	0.5 lb
Minimum inlet temperature:	-320° F
Outlet temperature:	60° ± 10° F
Controller	
Input voltage:	28 ± 0.3 V dc
Maximum power consumption:	10 W

TABLE B-IV. - SIGNAL CONNECTOR J2

Pin	Designation	Use
A	T1	Stored fluid temperature
B	T2	Stored fluid temperature
C	T3	Phase-control heat-exchanger fluid inlet temperature
D	T4	Phase-control heat-exchanger fluid outlet temperature
E	T5	Regulated delivery fluid temperature
F	P1	Vessel storage pressure
G	P2	Delivery line heat-exchanger fluid outlet pressure
H	P3	Regulated delivery fluid pressure
J	F1	Delivery line flow
K	I1	Vessel heater power monitor
L	I2	Delivery line heat-exchanger heater power monitor
M		Spare
N	Q1	Vessel quantity
P		Spare
R		Spare
S		Spare
T		Spare
U		Spare
V		Common

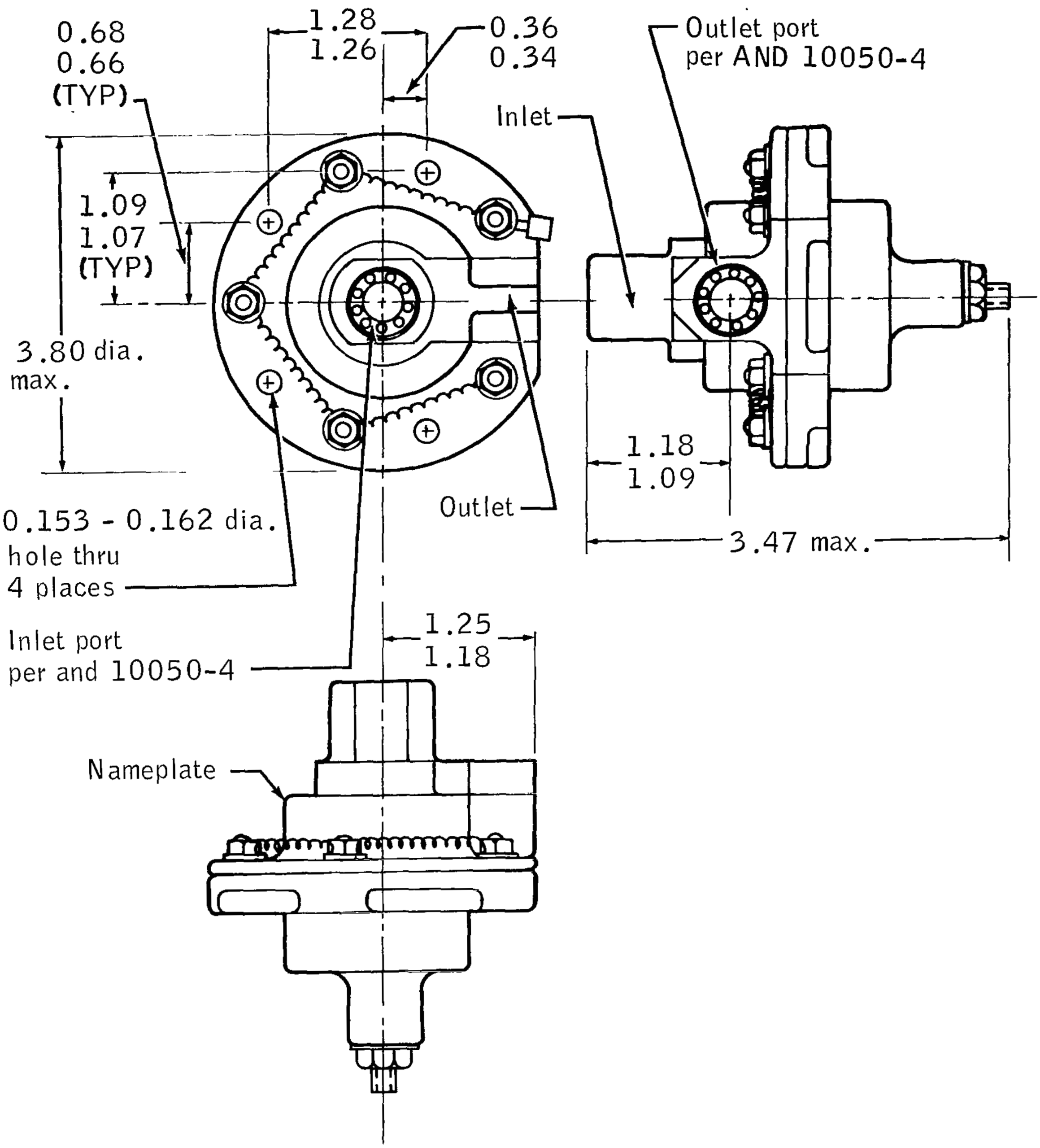
TABLE B-V. - ELECTRICAL INTERFACE CONNECTORS

Power connector			
Pin	Description	Use	Current required
A	28 V dc, return GSE	Solenoid valve	0.75 A
B	+28 V dc GSE		
C	28 V dc, return GSE	Buildup heater	7.5 A total
D	+28 V dc GSE		
E	28 V dc, return IU		
F	+28 V dc IU		
G	28 V dc, return IU		
H	+28 V dc IU		
J	28 V dc, return GSE	Buildup heater	
K	+28 V dc GSE		
L	28 V dc, return GSE	Buildup heater	
M	+28 V dc GSE		
N	28 V dc, return IU		
P	+28 V dc IU		
R	28 V dc, return IU		
S	+28 V dc IU		
T	Spare		
U	Spare		
Z	Spare		



(All dimensions are in inches.)

Figure B-1. - Pressure sensor.



(All dimensions are in inches.)

Figure B-2. - Absolute-pressure regulator.

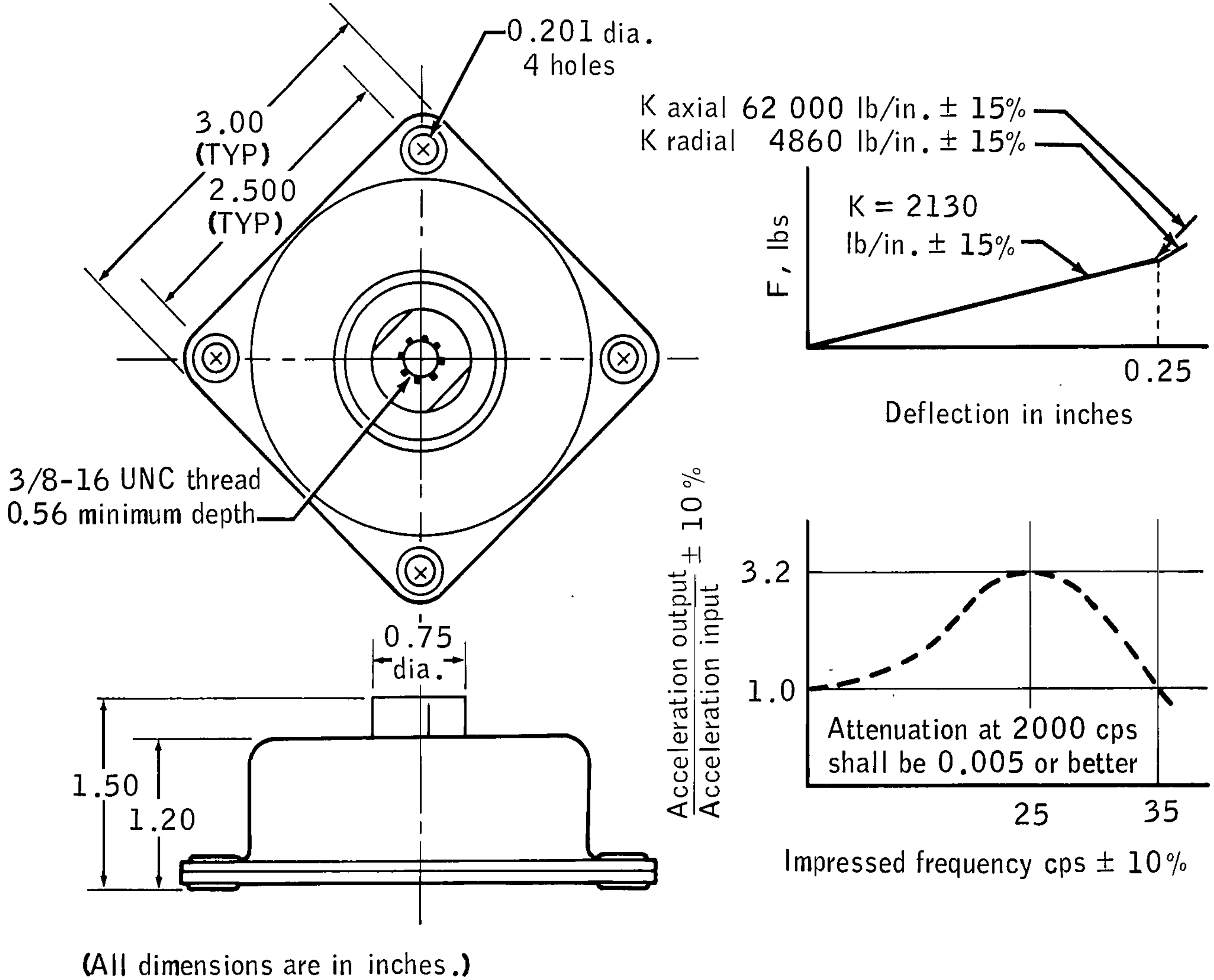


Figure B-3. - Vibration isolator.

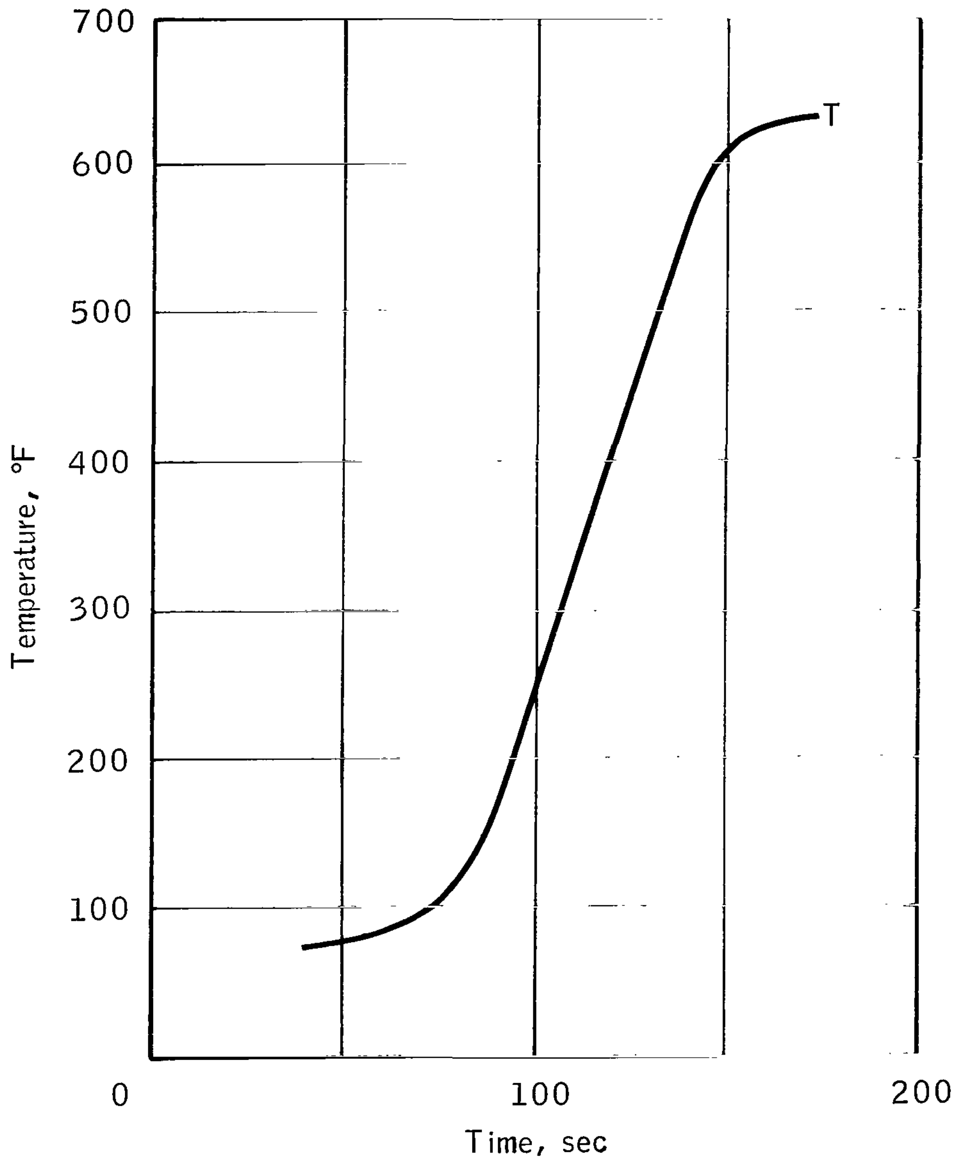
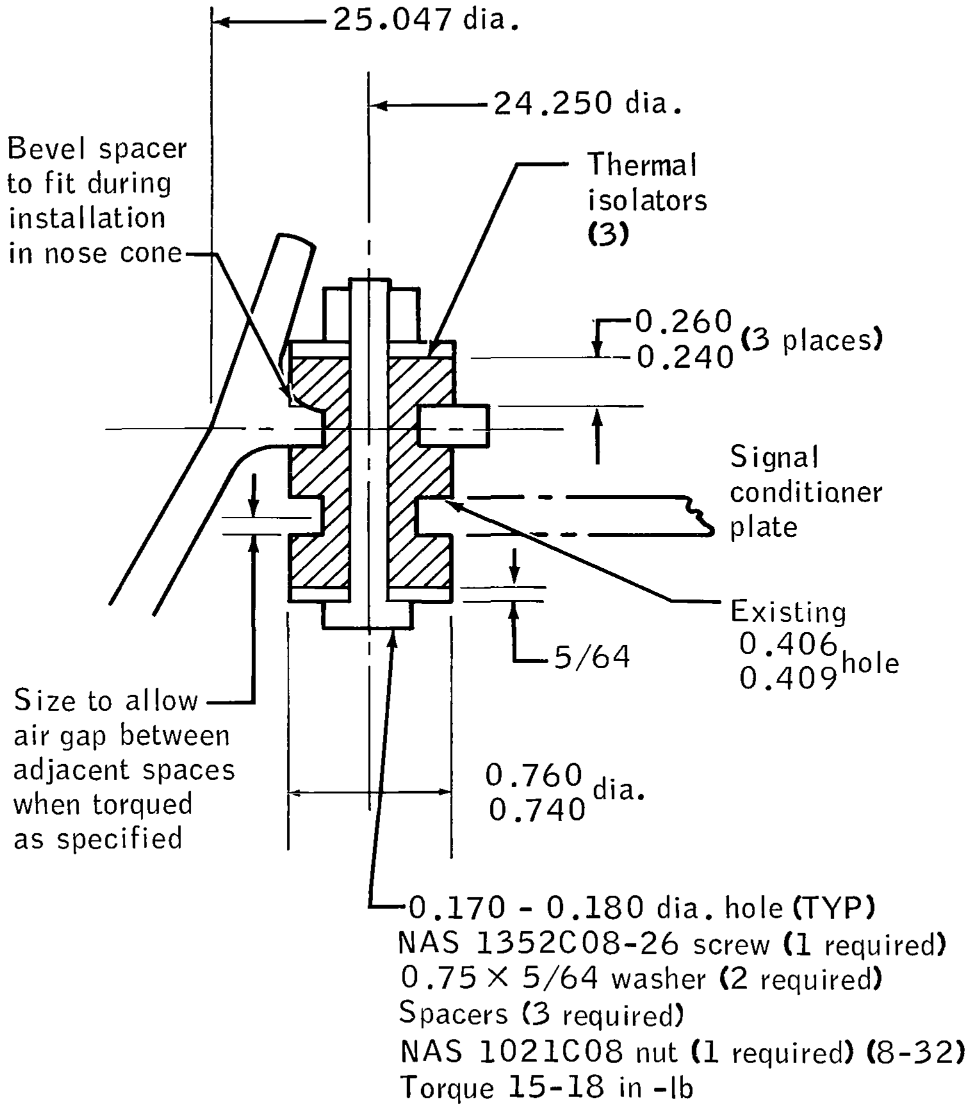


Figure B-4. - Temperature of 0.160-in. aluminum extension on 25° frustrum at station 2035.



(All dimensions are in inches.)

Figure B-5. - Revised plate-mounting details.

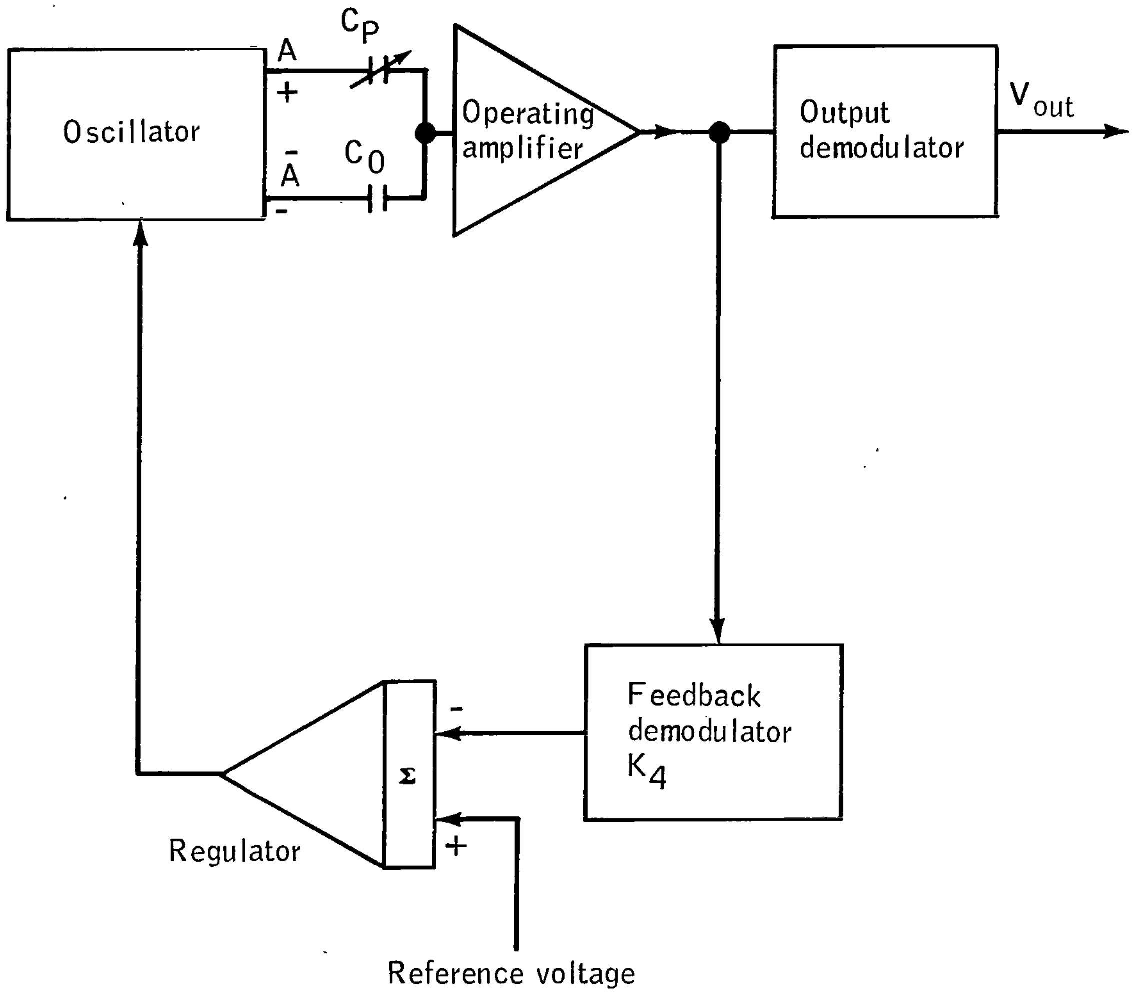


Figure B-6. - Quantity-gage signal conditioner.

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