MSC-01506

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

NASA GENERAL WORKING PAPER

SPACECRAFT CRYOGENIC GAS STORAGE SYSTEMS

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SPACECRAFT CRYOGENIC GAS STORAGE SYSTEMS

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SPACECRAFT CRYOGENIC GAS STORAGE SYSTEMS

By Gordon Rysavy

SUMMARY

Cryogenic gas storage systems have been developed for the liquid storage of oxygen, hydrogen, nitrogen, and helium. Cryogenic storage is attractive because of the high liquid density and low storage pressure of cryogens. This situation results in smaller container sizes, reduced container-strength levels, and lower tankage weights. The Gemini and Apollo spacecraft have used cryogenic gas storage systems as standard spacecraft equipment. In addition to the Gemini and Apollo cryogenic gas storage systems, other systems have been developed and tested in the course of advancing the state of the art. All of the cryogenic storage systems that have been used, developed, and tested to date for NASA manned-spacecraft applications are described in this paper.

INTRODUCTION

As used to date, the purpose of the cryogenic gas storage system (CGSS) is the storage and supply of certain fluids for the functions that are shown in the following list.

Oxygen: Environmental control system and electrical power system (fuel cells)

Nitrogen: Environmental control system

Hydrogen: Electrical power system (fuel cells)

Helium: Pressurization of propellants

To date, all spacecraft cryogens have been stored in double-wall containers called Dewars. A Dewar has two concentric walls and a vacuum between the walls for thermal protection against heat leak. However, a cryogenic gas storage system that does not involve the Dewar concept has been developed and tested; this system is known as a single-wall tank.

Unlike a Dewar system, the pressure vessel is insulated externally and does not have a vacuum annulus. Usually, cryogenic gas storage systems include the following components.

Pressure vessel	Valves
Insulation	Filters
Outer shell (Dewar concept only)	Switches
Temperature sensor	Transducers
Pressure sensor	Regulators
Quantity sensor	Heat exchangers (H-X)
Signal conditioners	Electrical wiring and connectors
Heaters	Vacuum ion pump
Mounting structure	

The words "liquid, gas, vapor, and fluid" as used herein refer to the stored cryogen. The word "liquid" is used to describe the cryogen when it is in a saturated liquid or near-liquid state. The words "gas and vapor" are used to describe the cryogen when it is in a gaseous or near-gaseous state. The word "fluid" is a general term used to describe the cryogen regardless of its thermodynamic state.

GENERAL DESCRIPTION AND CONSIDERATIONS OF SPACECRAFT CRYOGENIC GAS STORAGE SYSTEMS

Cryogenic gas storage systems have been used successfully in the Gemini and Apollo Programs. Both the Gemini and Apollo spacecraft involved cryogenic oxygen (LO_2) and cryogenic hydrogen (LH_2) which were expelled as required to the electrical power system (fuel cells) and environmental control system. Cryogenic storage is useful because a finite mass of fluid can be stored at high density and low pressure, significantly reducing storage weight relative to the weight involved in ambient gas storage.

To date, all the spacecraft cryogens have been stored in Dewar systems. The internal components of a Dewar system include temperature, pressure, and quantity sensors, and heaters that are used for fluid expulsion. External components include the mounting structure, plumbing, valves, filters, signal conditioners, switches, transducers, regulators, heat exchangers, and the associated wiring and connectors. Also, Dewar systems may include an ion pump that is used to maintain a vacuum within the annulus (between the concentric walls). A typical spacecraft Dewar CGSS is shown in figure 1.

The design of a cryogenic gas storage system for a spacecraft is different from the design of a terrestrial system. Primarily, this is because of the zero-gravity environment of space. Cryogen stratification and possible random orientation of the liquid and vapor phases requires appropriate design consideration for expulsion and quantity measurement of the stored fluid.

Storage Techniques

The three most common methods of storing gases for spacecraft application are (1) high-pressure gas storage at ambient temperature, (2) single-phase cryogenic-fluid storage at or above supercritical pressure, and (3) two-phase cryogenic-fluid storage at subcritical pressure.

High-pressure systems.- High-pressure gas-storage systems are simple, reliable, and have indefinite standby capability. However, the large volume and weight required for even a small payload are serious disadvantages, as can be seen in figures 2 and 3.

Supercritical storage.- The term supercritical storage means that the cryogenic fluid is stored at a pressure that is greater than the critical pressure of the fluid and that the fluid exists in a single-phase throughout the duration of the mission. Supercritical storage of cryogenic fluids is shown thermodynamically in figure 4. Point 1 indicates the initial fill condition, which is a mixture of saturated liquid and vapor at atmospheric pressure. After fill, heat input causes the pressure to increase at a constant density (density based on vessel volume). During the process from point 1 to point 2, the liquid expands and the ullage gas condenses until the entire volume is filled with liquid. From point 2 to point 3, thermal energy is absorbed by the stored fluid; hence, the pressure is increased above the critical pressure. Constant-pressure supercritical operation, path 3 to 4, is achieved by heating the stored fluid during fluid withdrawal. During supercritical operation, the stored mass remains a homogeneous single-phase fluid, and fluid expulsion is assured because of the high pressure.

The operation of a typical supercritical system, shown in figure 5, starts with the purging of the system internal vessel and fluid lines. Usually, purging is accomplished by vacuum pumping; thus, static and dead-ended parts are free from contamination. After the system has been purged, the vessel is filled with a saturated liquid cryogen at ambient pressure. Initially, most of the liquid is vaporized as it enters the pressure vessel and vapor is vented through the vent valve. As the temperature of the pressure vessel drops, the liquid level rises. The fill line enters the pressure vessel at the bottom of the vessel and the vent line leaves the pressure vessel close to the top at a point that corresponds to the design fill level.

Then, the system is chilled to an equilibrium temperature by allowing it to vent boiloff vapors through the fluid vent line. After chilldown, the vessel is topped off to full capacity with additional saturated liquid cryogen. Then, the fill and vent valves are closed and the fluid pressure begins to increase because of the liquid expansion that is caused by the energy absorbed from the heat entering the system. Eventually, the liquid phase completely fills the inner vessel; then, the fluid is in the compressed-liquid region. If a more rapid pressure increase is desired, an electrical heater inside the vessel may be energized. After reaching the required pressure, which is greater than the critical pressure, the system supply valve is opened and the fluid flows out of the vessel through an external temperature-control heat exchanger and pressure regulator. As the fluid flows out of the storage system, the fluid pressure decreases. However, an electrical pressure-regulation switch operates automatically to energize the internal heater whenever the pressure decreases below a predetermined level. Thus, the thermal energy that is absorbed by the stored fluid maintains supercritical pressure operation.

Subcritical storage.- The term subcritical storage means that the cryogenic fluid is stored at a pressure that is less than the critical pressure, and that the fluid exists as a liquid-vapor mixture. Subcritical cryogenic storage is thermodynamically illustrated in figure 6. Point 1 indicates the initial fill condition, which is a mixture of saturated liquid and vapor at atmospheric pressure. After the vessel is filled, heat is added to increase the fluid pressure to point 2, the operating pressure. The operation of a typical subcritical system is similar to the operation of a supercritical system for the purge, fill, chilldown, topoff, and heater operation for initial pressurization. However, delivery techniques must involve both the liquid and gas phases which are present in a subcritical system. A subcritical system can be designed to withdraw either a liquid or a vapor from the pressure vessel and to condition it to the required density, pressure, and temperature before the fluid leaves the system. A subcritical storage system that involves heat exchangers for the purpose of conditioning the expelled vapor is shown in figure 7. A typical subcritical system involves an internal regulator valve which throttles the fluid that is being withdrawn from the pressure vessel to a predetermined delivery pressure. The throttling process causes the fluid to expand and the fluid temperature to decrease to a value that is less than the stored liquid temperature. Then, the liquid leaves the internal regulator valve, passes through a heat exchanger, and vaporizes completely prior to exiting the Dewar. If required, the external temperature-control heat exchanger transmits additional heat to the vapor. As the vapor flows from the system, the fluid pressure decreases; however, a pressure bypass control valve operates automatically to cause the warm gas to flow into the internal heat exchanger where heat is transferred to cold liquid in the pressure vessel. The thermal energy that is absorbed by the liquid in the pressure vessel maintains constant temperature; the operating pressure is the corresponding fluid-saturation pressure. After leaving the internal heat exchanger, the vapor is reheated in the second external heat exchanger before it passes through the pressure regulator and out of the system. When the tank pressure is at or above the operating pressure, the flow is directed to the regulator and does not pass through the internal heat exchanger.

System Considerations

Considerations that influence the design of a cryogenic gas storage system include the following items.

1. Mission considerations

a. Reliability: The reliability for any system on manned spacecraft is of paramount inportance.

b. Operational pressure: The operational pressure either may be greater or less than the fluid critical pressure; hence, cryogens may be stored in the single-phase or in the two-phase condition.

c. Quantity measurement: The quantity-measurement accuracy that is required may determine the thermodynamic design. A supercritical (homogeneous fluid) system involves a simple and effective method of measuring the quantity, whereas subcritical (liquid and vapor mixture) systems involve a more complex and possibly a less accurate method.

d. Pressure control: The extent of pressure control that is required may influence the thermodynamic design. A subcritical system may undergo pressure instabilities that are caused by random liquid-vapor orientation. A supercritical system may undergo pressure drops that are caused by thermal stratification and subsequent fluid mixing.

2. Manufacturing considerations

a. Reproducibility: Predictable and consistent performance of a CGSS is critical to the success of any mission.

b. Shelf life: A CGSS must be designed and fabricated to withstand a shelf life of several years with no serious degradation.

c. Weight: Like most other systems on a spacecraft, the CGSS must be designed for minimum weight.

d. Materials: The materials selected must be compatible with the environment and cryogens and also must have high strength-to-weight ratios.

e. Envelope constraints: Spacecraft interfacing constraints may influence the physical and structural design parameters.

3. Performance considerations

a. Standby time: The dormant period between filling and launch may influence the fill quantity and method of storage.

b. Fluid quantity: The CGSS size, weight, and capacity are dictated by the usable fluid, residual, ullage, and contingency requirements.

c. Fluid-usage rate: The fluid flow rate will determine the heater size, design, and power requirements.

d. Power requirements: Power requirements for the CGSS controls, instrumentation, and heaters should be compatible with the availability and type of spacecraft power.

e. Ambient conditions: Ambient temperatures will influence significantly the thermal and thermodynamic design. A high ambient temperature would necessitate a CGSS that has good insulation and vapor cooling of the insulation during fluid withdrawl. Also, consideration must be given to the possibility of venting fluid overboard; such a situation would dictate a larger storage system.

GEMINI CRYOGENIC GAS STORAGE SYSTEM

On January 3, 1962, the Gemini Program was recognized offically. The Gemini two-man spacecraft served as an intermediate step between Project Mercury and the Apollo Program; it had the following prime objectives.

1. To expose the astronauts and supporting equipment to long-duration flights

2. To rendezvous and dock with another orbiting vehicle

3. To experiment with extravehicular activities while in orbit

The first space-flight cryogenic gas storage system was used on the Gemini spacecraft for the storage and expulsion of supercritical oxygen and hydrogen. Hydrogen and oxygen were used by the fuel cells (FC) which were the primary source of electrical power for the spacecraft. The fuel cell converted hydrogen and oxygen into electricity and yielded potable water as a byproduct. Oxygen was used by the cabin environmental control system (ECS); this system provided an oxygen environment and controlled pressurization, flow rate, suit cooling, humidity, and purification of the atmosphere.

The Gemini cryogenic gas storage system consisted of six different types of tanks that were designed to satisfy the requirements of both the 2-day and 14-day missions. The oxygen requirements for the ECS and the electrical power system (EPS) fuel cell reactant supply system (RSS) were supplied by separate tanks, as shown in table I. For thermal protection of the stored fluids, the Gemini Dewar system contained aluminized Mylar insulation within the vacuum annulus as the radiant-heat barrier. The pressure vessel was supported within the outer shell by fiber-glass pads. The fluid-equilibration-heater system consisted of perforated copper spheres and electric-heater elements that were coiled and fastened to the external surface of the copper sphere. A typical Gemini cryogenic storage tank, a tank system, and a spacecraft RSS are shown in figures 8 to 10. The cryogenic storage system design characteristics for the six different tanks are given in tables II to IV. The weight summaries of actual tanks and components are given in tables V and VI, and table VII contains actual thermal performance data of the storage tanks. The Gemini CGSS was furnished by a contractor under contract to the Gemini spacecraft manufacturer.

APOLLO COMMAND AND SERVICE MODULES

On July 2, 1960, The House Committee on Science and Astronautics recommended "a Manned lunar expedition within this decade." On May 25, 1961, the late President John F. Kennedy made the lunar landing and the safe return of the astronauts before the end of the decade a national goal. The primary objectives of the Apollo Program are given in the following list.

1. To land two men on the moon

2. To perform limited exploration in the landing area

3. To take photographs and gather samples of the lunar surface

4. To return safely to earth with the lunar samples and photographs

Like the Gemini spacecraft, the Apollo spacecraft uses supercritical cryogenic storage for the storage of oxygen and hydrogen. These gases are used for the electrical power system (EPS) fuel cells and the ECS in the same manner as discussed previously for the Gemini spacecraft.

The Apollo CGSS consists of two oxygen and two hydrogen tanks, which are designed according to the requirements for the ECS and the EPS fuel cells. The oxygen for the ECS and EPS is furnished from the same oxygen tanks. Both the oxygen- and hydrogen-storage tanks are of the typical Dewar design. The oxygen tanks have load-bearing insulation that consists of alternate layers of foil-Fiberglas and Dexiglas paper. The load-bearing insulation supports the pressure vessel and transmits the loads to the mount support structure. The hydrogen tanks have non-load-bearing laminar insulation that consists of gold-plated H-film and vapor-cooled shields (one per tank). The pressure vessel is supported by a strap mechanism that consists of three equally spaced beam assemblies that are composed of alternate layers of titanium, Fiberglas, and H-film. The fluid-equilibration heater system for both the oxygen and hydrogen tanks consists of a perforated cylindrical tube that has redundant electric-heater elements coiled and fastened to the external surface of the tube. An electric motor-fan unit, mounted on each end of the tube, provides the flow necessary for convective heating of the fluid and for the maintenance of a homogeneous fluid mixture.

A typical Apollo CGSS tank and spacecraft storage system are shown in figures 11 and 12. The hydrogen and oxygen tanks are shown as finished products in figure 13, and as installed in the spacecraft as shown in figure 14. The hydrogen and oxygen minimum and maximum flow rates are given in figures 15 and 16; and in figure 17, oxygen and hydrogen fluid temperatures are compared with tank quantity. The hydrogen minimum and maximum pressurization rates for different ullages are shown in figures 18 and 19. The oxygen minimum and maximum pressurization rates for different ullages are given in figures 20 and 21. The CGSS design characteristics for the oxygen and hydrogen tanks are given in tables VIII to X. The component and system weights of the oxygen and hydrogen tanks are shown in tables XI and XII. The Apollo CGSS was furnished by the contractor under contract to the Apollo spacecraft manufacturer.

SUPERCRITICAL HELIUM CRYOGENIC GAS STORAGE SYSTEM AND RELATED GROUND SUPPORT EQUIPMENT

The lunar module (LM) contains a supercritical helium cryogenic gas storage tank for the pressurization of the fuel and oxidizer for the LM descent propulsion system (DPS).

Because cryogenic helium has an extremely low heat of vaporization and a boiling temperature point that is lower than the other cryogens that are used for spacecraft applications, it is much more difficult to transfer and maintain as a liquid. Therefore, the LM helium-storage system involves unique and complex ground support equipment (GSE) for servicing and filling. Because the GSE is unique to the LM helium-storage tank, both the GSE and spacecraft systems will be described. Basically, the GSE and spacecraft requirements consist of the following three major systems.

1. Spacecraft LM helium-storage tank

2. GSE helium-storage/transfer Dewar

3. GSE helium-conditioning unit

Lunar Module Helium-Storage Tank

The LM cryogenic helium-storage tank is of the typical Dewar design. The annulus is filled with aluminized Mylar insulation and is evacuated to minimize ambient heat transfer into the tank. The pressure vessel is supported by fiber-glass pads which transmit the loads to a mount structure. The LM helium-storage tank (fig. 22) includes vacuum-jacketed fill and vent couplings, a pressure transducer, and a double burst-disk assembly. If required, system pressure relief is provided by two burst disks in series and a vent valve between the disks. The vent valve prevents low-pressure buildup between the burst disks in the event the upstream burst disk leaks slightly. The valve is open at pressures below 150 psia and it closes when the pressure exceeds 150 psia, so that for greater leaks, the subsequent pressure buildup eventually will rupture the downstream burst disk. If the burst disk(s) rupture, the helium supply is lost, curtailing operation of the LM descent engine. The nonflight quantity-gaging assembly is used during servicing only and is attached to the exterior of the storage system with quick-disconnect fasteners. The LM helium-storage system also includes an internal and an external heat exchanger. The internal helium-to-helium heat exchanger maintains the stored helium at the required expulsion pressure. The external fuel-to-helium heat exchanger is used to increase the temperature of the helium supply fluid.

Heat transfer from the outside to the inside of the cryogenic system causes a gradual increase in pressure (approximately 5 to 10 psi/hr). The initial loading pressure and temperature of the supercritical helium are planned so that the helium will not exceed a predetermined maximum pressure prior to use. The fluid-flow route of the LM helium-storage system is shown in figure 23. Initially, the helium supply fluid passes through the first loop of the external two-pass fuel-to-helium heat exchanger, where it absorbs heat from the fuel. The helium is warmed and routed back through the internal helium-to-helium heat exchanger inside the pressure vessel. The warm helium transfers heat to the remaining supercritical helium in the pressure vessel, causing an increase in fluid pressure; thus, continuous expulsion of helium is ensured throughout the period of operation. After the helium passes through the internal helium-to-helium heat exchanger where it is cooled, the helium is routed back through the second loop of the fuel-to-helium heat exchanger and is heated before delivery as the pressurizing agent to the propulsion fuel and oxidizer tanks. The LM helium-storage system design characteristics are given in table XIII.

Ground Support Equipment Helium-Conditioning Unit and Helium-Storage/Transfer Dewar Systems

The helium-conditioning unit and the storage/transfer Dewar systems are used in conjunction with each other to service the LM helium-storage tank. The GSE is capable of precooling, filling, and topping the LM helium-storage tank (fig. 24). The helium-storage/transfer Dewar is used for cooldown and initial fill of the LM helium-storage tank; also, the Dewar fills the liquid helium precooler tank in the helium-conditioning unit. The helium-conditioning unit refrigerates ambient helium gas to a near-liquid-helium temperature (8.2° R or less) prior to delivery to the LM helium-storage tank. Initially, the ambient helium gas flows through a coiled, finned tube heat exchanger that is submerged in liquid nitrogen, and is thus cooled to liquid-nitrogen temperature. Then, the helium gas passes through the external helium-to-helium regenerative heat exchanger where it is cooled to 16° ± 2° R by the boiloff helium vapors from the liquid-helium precooler. Final cooling is accomplished in the coiled tube heat exchanger that is submerged in the liquid-helium precooler vessel, from which the helium exits at a temperature of 8.2° R or less. The conditioned helium flows through a fluid-distribution assembly which facilitates servicing or bypassing the LM helium-storage tank. All operational modes that are associated with servicing the LM helium-storage tank are controlled and monitored remotely.

Helium-storage/transfer Dewar system.- The GSE helium-storage/transfer Dewar design is similar to the spacecraft Dewars. The pressure vessel is supported within an outer shell and the annular space is evacuated for thermal protection. A radiation shield is positioned within the vacuum annulus and has provisions for vapor cooling. Boiloff vapor is emitted from the stored helium and is circulated through the small tube that is coiled and fastened to the radiation shield. Radiation heat leak is reduced further by plating the surfaces within the vacuum annulus with gold. The GSE helium-storage/transfer Dewar system is shown in figure 25, and the design characteristics are specified in table XIV.

Helium-conditioning-unit system.- The helium-conditioning unit (fig. 26), is a compact and unique system of liquid-nitrogen and liquid-helium containers, heat exchangers, control equipment, and instrumentation. The liquid-nitrogen and liquid-helium containers and heat exchangers are enclosed within an outer shroud which facilitates evacuation for thermal protection. The liquid-helium precooler tank is supported by three equally spaced beam assemblies that are composed of alternate layers of titanium, Fiberglas, and aluminized Mylar. The beam assemblies are connected to the outer shroud through a series of steel cables and fiber-glass compression bumpers. A thin aluminim shield is positioned in the annulus between the pressure vessel and the outer shell. This shield, cooled by the cold helium gas that is being vented because of heat leak to the pressure vessel, provides a low-temperature barrier to heat transfer. Further thermal protection is obtained by the aluminized Mylar insulation that is installed between the vapor-cooled shield and the outer shroud. The GSE helium-conditioning-unit-system design characteristics are specified in table XV. The LM helium-storage tank was furnished by a contractor. The GSE helium-storage/transfer Dewar and GSE helium-conditioning unit were furnished by another contractor.

APOLLO APPLICATIONS PROGRAM CRYOGENIC GAS STORAGE SYSTEM

After the Apollo Program, the next phase of the manned space-flight effort is the Apollo Applications Program (AAP). The AAP is to make maximum use of hardware and techniques developed in the Apollo Program. The basic AAP objective is to provide an environment in which man can live and work under controlled conditions for extended periods (beyond that provided by the Gemini and Apollo Programs) of time in space. Besides the Apollo command and service module (CSM), the AAP will have a workshop which is basically a modified Saturn S-IVB launch stage and a manned solar observatory known as the Apollo telescope mount (ATM). The workshop and ATM will be launched together and both will arrive in orbit ready for immediate occupancy and use by the astronauts (who will be launched separately). The ATM will facilitate astronomical observations under conditions that are free from the optical interference of the earth atmosphere. Also, the ATM will provide a platform to demonstrate the ability of men to perform scientific experiments in space. The modified S-IVB stage workshop will be equipped on the ground prior to launch and will be the living and working quarters for the astronauts. Experiments that are being considered for the workshop involve the scientific, technological, applications operation, and medical categories. The experiments will involve a study of human physiological and psychological responses in the space environment and should result in more detailed information on human capabilities for extended manned flights.

Apollo Applications Program mission durations lasting up to 56 days necessitated the development of larger and thermally better cryogenic gas storage systems. Because cryogens cannot be stored indefinitely and a Dewar storage system is thermodynamically limited, the Gemini and Apollo tanks were not capable of fulfilling the AAP requirements. A new CGSS design was selected and development was in progress when the AAP was reconfigured. This resulted in the termination of the AAP CGSS and fuel-cell-system-development efforts. The reconfigured AAP is not required to furnish electrical power or environmental control when docked to the S-IVB workshop. However, the AAP CGSS design is different from the Gemini and Apollo systems and will be discussed even through this effort was terminated. Initially, the AAP spacecraft was designed to use cryogenic storage Dewars for the storage and expulsion of supercritical oxygen, nitrogen, and hydrogen. The oxygen and hydrogen were for the electrical power system fuel cells and the oxygen and nitrogen were for the environmental control system. Basically, the AAP CGSS oxygen, nitrogen, and hydrogen tanks were similar. The oxygen- and nitrogen-Dewar systems were identical in all respects except for the quantity signal conditioners, which were tailored for the density of the specific cryogen. The hydrogen-Dewar system was identical to the oxygen/nitrogen system except for the number of heaters and valves and the signal conditioner and mount structure.

A typical spacecraft system would have consisted of three oxygen tanks, three hydrogen tanks, and one nitrogen tank. The oxygen requirements for the environmental control system and the electrical power system fuel cells were to be furnished in a common mode from the three oxygen tanks. Each storage tank was of the Dewar design with two concentric discrete aluminum shells within the vacuum annulus. The innermost shield on all three types of tanks (oxygen, nitrogen, and hydrogen) had provisions for vapor cooling. Before exiting the Dewar system, the supply fluid passed through a tube that is brazed to the shield. Thus, the incoming heat is intercepted and is carried out with the fluid. The pressure vessel was supported by 16 radial bumpers: eight on the bottom hemisphere and eight on the top hemisphere. The pressure vessel loads were transmitted through the bumpers to the mount support structure. The fluid-equilibration heater system consisted of a perforated cylindrical tube with electric heater elements that are coiled and fastened to the external surface of the tube. An electric motor fan unit was mounted on each end of the tube; the unit provided convective heating of the fluid and maintained a homogeneous fluid mixture. The AAP fluid-equilibration heater system was packaged with the quantity-measuring sensor within one cylindrical tube; whereas, the Apollo tanks had two separate tube structures.

The initial CGSS design required that all three tank types operate at the nominal supercritical pressure of 900 psi; thus, common pressure vessels and relief valves were used. However, during the fabrication of the CGSS Inconel 718 pressure vessels, it became evident from test results (tests were independent of the CGSS effort) that Inconel 718 is susceptible to hydrogen embrittlement, which was subsequently verified by tests at the Manned Spacecraft Center (MSC). The MSC test results were indicative that the common Inconel 718 pressure vessel could be used for hydrogen if a maximum pressure of 440 psi is not exceeded. A typical AAP cryogenic storage tank and storage system are shown in figures 27 and 28. The typical AAP CGSS is shown as a finished product in figure 29. The CGSS design characteristics for the oxygen, nitrogen, and hydrogen tanks are specified in tables XVI to XVIII. The major component and system weights are given in table XIX. The AAP cryogenic gas storage system was furnished by a contractor as government furnished equipment under the management of the MSC.

DISCRETE-SHIELD CONCEPT CRYOGENIC GAS STORAGE SYSTEM

A unique approach to the Dewar design involves the use of discrete radiation shields suspended within the vacuum annular space in lieu of the multilayer types of insulation. This concept was incorporated into a Dewar design and three systems were developed and tested sucessfully. The discrete shields can be mounted within the vacuum annulus in many different ways; however, only the method that was developed and tested will be discussed. The discrete-shield suspension system involves the pressure-vessel supports and the fluid fill and vent lines. The pressure vessel is supported by radial bumpers equally positioned on the annular fill and vent lines; thus, the annular space is defined and maintained. The radial-bumper-support concept is illustrated in figure 30. The pressure-vessel loads are transmitted directly through the radial bumpers to the mount structure. A Dewar with the discrete shields mounted isothermally within the vacuum annulus is shown in figure 31. The discrete shields are attached to the annular fill and vent tubes. Shield attachment and spacing are achieved by the use of low-conductivity devices. Vacuum integrity within the annulus is improved because of minimum obstructions to molecular migration and a high bakeout temperature during vacuum pumping. Dewar thermal protection is improved further by plating all the surfaces within the vacuum annulus with low-emissivity materials such as silver, copper, or gold. A typical descrete-shield radial-bumper cryogenic storage tank is shown in figure 32. The discrete-shield radial-bumper cryogenic storage system is shown as a finished product in figure 33. The discrete-shield radial-bumper design characteristics for the three cryogenic storage systems that were developed and tested are given in table XX. The discrete-shield radial-bumper Dewar concept was developed and tested by a contractor under the management of the MSC.

EXPERIMENTAL SUBCRITICAL CRYOGENIC GAS STORAGE SYSTEM

On July 5, 1966, a subcritical nitrogen cryogenic storage system was flown as an experiment on the Apollo-Saturn 203 flight. This experiment was the culmination of a program to develop a cryogenic Dewar which would deliver warm vapor from two-phase (subcritical) storage in low gravity regardless of the liquid orientation. The subcritical storage mode has the following potential advantages over single-phase (supercritical) storage.

1. Relief of storage-Dewar thermal-design limits because of an increase in the total allowable specific heat input to the fluid

2. A substantial weight savings as a direct result of lower operating pressures which make possible the use of lighter components

3. Liquid delivery for refilling portable environmental systems

To ensure delivery of vapor only, the delivery circuit has a phase-control heat exchanger brazed to the pressure vessel. The function of the phase-control heat exchanger is to vaporize any liquid exiting the inner vessel. 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 in the phase-control exchanger is less than the storage pressure, the boiling point of the fluid in the phase-control exchanger is lower than the boiling point of the stored fluid. Because of this temperature difference, heat from the stored fluid is transferred to the fluid passing through the phase-control heat exchanger. Therefore, liquid exiting the internal regulator valve is evaporated in the phase-control heat exchanger and leaves the phase-control heat exchanger as a vapor. Not only is vapor delivery from the phase-control heat exchanger ensured, but heat is removed from the stored fluid. Essentially, the overall thermodynamic effect of the phase-control heat exchanger is 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 heat exchanger. Delivery is initiated by the opening of a solenoid valve in the delivery line. When the pressure in the delivery line decreases to less than normal, the internal regulator valve opens to allow flow into the phase-control heat exchanger; thus, the delivery-line pressure is increased. The absolute-pressure regulator in the delivery line controls the pressure of the fluid as it leaves the system. An electric heater is used to assist in the pressurization of the stored fluid. Instrumentation is used to measure the fluid temperature and pressure at different locations, fluid flow rate, heater current, and fluid quantity. The fluid quantity within the pressure vessel was measured with a matrix-capacitance gage. The subcritical cryogenic storage system is shown in figure 34 and the subcritical cryogenic storage system design parameters are given in table XXI. The subcritical nitrogen CGSS was furnished by a contractor under the management of the MSC.

LIQUID-SHROUDED CRYOGENIC GAS STORAGE SYSTEM

A liquid-shrouded cryogenic storage system has not been used on any spacecraft to date; however, this concept has been developed and tested. A liquid-shrouded tank is a Dewar, constructed so that the innermost vessel containing the primary cryogenic fluid is surrounded by a concentric vessel which contains a secondary cryogenic fluid. This basic liquid-shroud arrangement is contained in an evacuated annulus which may contain discrete radiation shields or the laminar-type insulation as additional thermal protection. A typical liquid-shrouded cryogenic storage tank is shown in figure 35.

The function of the liquid-shrouded tank is to reduce the leakage of radiant and conductive heat to the cryogen in the innermost tank. Heat that enters the system must pass through the vacuum annulus and the conventional insulation and the shroud fluid before it can reach the primary fluid. The shroud fluid is maintained at a saturation temperature that corresponds to a controlled pressure at which the liquid is allowed to evaporate (boil off); removing the incoming heat from the system before it reaches the primary fluid. The boiloff vapor may be used further by routing it through a vapor-cooled shield in the vacuum annulus, thus intercepting and removing heat before it reaches the shroud fluid. The liquid-shrouded-Dewar concept is a versatile and effective thermal-barrier system and is useful for applications that require exceedingly low loss rates. Different combinations of fluids can be used for various applications; for example, liquid hydrogen can be used as the shroud fluid when storing supercritical helium. Also, indefinite standby time can be achieved by controlling the shroud-fluid temperature or by replenishing the shroud fluid (if required).

The liquid-shrouded cryogenic gas storage system was developed and tested by a contractor under the management of the MSC.

SINGLE-WALL TANK CRYOGENIC GAS STORAGE SYSTEM

The single-wall tank has a pressure vessel which contains the cryogen, but does not have an outer shell. Unlike a Dewar system, the pressure vessel is insulated externally without a vacuum annulus. A single-wall tank was fabricated and tested as a research tool (fig. 36). This single-wall-tank concept consists of a pressure vessel enclosed in a two-component insulation scheme. The ground-hold insulation, designed for servicing and prelaunch environments, consists of a 2-inch layer of polyurethane foam bonded to the outer wall of the pressure vessel. The orbital insulation, designed for space environments, consists of 100 layers of aluminized Mylar wrapped on the outside of the foam insulation at a density of 50 layers per inch. The tank is supported by fiber-glass tension rods that are attached to an aluminum frame assembly. The single-wall-tank design included a regenerative cooling system that consisted of a Joule-Thompson expansion valve and an external cooling coil that was attached to the pressure-vessel external surface. Other components included a fluid-quantity sensor, a fluid-temperature sensor, and an electrical heater, all located within the pressure vessel.

Because the insulation is exposed to the atmosphere, condensation may accumulate within the aluminized Mylar when the tank is filled with a cryogen. Therefore, the insulation should be purged with a dry inert gas during filling and ground-hold because tests have shown that excessive moisture will tend to wash the aluminum off the Mylar, degrading the thermal performance. The dry inert gas replaces the terrestrial atmosphere that surrounds the tank, and the inert gas will not condense when the insulation temperature is lowered. During storage, an empty tank may under go some condensation in the insulation because of ambient-temperature variations and changes in atmospheric conditions. The single-wall-tank cryogenic storage system design characteristics are specified in table XXII. The single-wall-tank system was developed by a contractor and was tested by the MSC.

ASSOCIATED TECHNOLOGY

Pressure Vessels

The pressure vessel is the innermost vessel; it contains the cryogenic fluid at operating pressures as great as 3000 psi. Most pressure vessels are spherical; however, serious consideration is directed toward cylindrical vessels that have hemispherical or elliptical ends. Usually, fabrication of the pressure vessel is accomplished either by drawing, forging and machining, spinning, or hydraulic-forming techniques. The pressure-vessel membrane thickness is determined readily by theoretical analysis based on known material properties. However, discontinuities such as openings, bosses, and weld areas primarily are analyzed by emprical methods that are based on applicable test data. Depending on the system design, internal components (such as the quantity sensor, temperature sensor, electrical heater, and thermal conductor) may have to be installed prior to welding the pressure vessel. The electrical leads and fluid lines penetrate the pressure vessel through special fittings that are designed to withstand the temperature, pressure, and leakage requirements. The choice of materials for pressure vessels must involve consideration of the following characteristics, both at the cryogenic and maximum operating temperatures: fracture toughness, strength-to-weight ratio, fluid compatibility, corrosion resistance, formability, joinability, fatique properties, chemical properties, mechanical properties, configuration, permeation, creep properties, cycling properties, embrittlement properties (parent and weld materials), joint efficiency, galvanic corrosion on dissimilar metal joints, application, availability, developmental problems, and cost.

To date, titanium, Inconel, stainless steel, and aluminum are considered the most suitable materials for cryogenic pressure vessels. The mechanical properties of several materials are given in table XXIII. It should be noted that titanium A110-AT (Ti 5Al-2.5 Sn) is susceptible to creep at room temperature and that Inconel 718 is susceptible to stress cracking when exposed to gaseous hydrogen. Test results have shown that

Ti 5Al-2.5 Sn ELI has a room-temperature creep-strength level of approximately 71 200 psi. Therefore, appropriate design considerations and safety factors must be applied to the creep-strength level as well as to the ultimate-strength and yield-strength levels. Test results have shown that Inconel 718 is susceptible to environmental-stress cracking when exposed to gaseous hydrogen. Results of an MSC test program were indicative that stress cracking would not occur if the maximum operating pressure was limited to 22 percent of a proof-test pressure that involved liquid nitrogen. The liquid-nitrogen proof-pressure test was performed to screen a maximum flaw size in the material at a pressure slightly less than the liquid-nitrogen-temperature yield strength of 204 000 psi. Hence, the pressure-vessel design-stress level corresponds to a safety factor of 4.5, based on the room-temperature ultimate strength of the material.

Outer Shells

The outer shell encloses the pressure vessel, pressure-vessel supports, insulation, shields, fluid lines, and electrical leads and forms the outer surface for the vacuum annulus. Therefore, the outer shell must be sound structurally and must be compatible metallurgically with a vacuum environment. Because the inner surface of the outer shell is exposed to a high vacuum (10^{-6} torr), the shell must be designed to withstand collapsing pressures from the external atmospheric pressure. Primarily, the outer shells are designed to resist buckling types of failures. Because the outer-shell weight is proportional to the material density and is inversely proportional to the square root of the modulus, low density and high modulus are important factors in the selection of the outer-shell material; the material tensile strength is secondary.

There are many theoretical equations for the design of a sphere that is to be subjected to external pressure. The critical pressures which are calculated from these equations may vary considerably because of variations and imperfections in the shells. As a result, the outer shell equations must be developed from applicable test data for the specific shell configuration. As the overall size of the outer shells becomes larger, the shells become increasingly vulnerable to buckling. This fact must be compensated for by the use of a heavier gage material; thus, the weight is increased. To overcome the undesirable characteristics of large monolithic outer shells, a honeycomb-sandwich design has been developed and tested. Test results have been indicative that the buckling-pressure-to-weight ratios for honeycomb spheres are larger than for monolithic spheres. The three basic components in a honeycomb sandwich are the facings, the core, and the adhesives. The facing material consists of the skins which are attached to the honeycomb core to make up the composite honeycomb structure. The core is the honeycomb cell structure which makes up the heart of the honeycomb sandwich. The adhesives are the materials which bond the facings to the core. In the selection of facing materials, the material must have excellent bonding characteristics. The selected core material should be designed to fit over cylindrical and hemispherical shapes. Epoxy is considered to be the conventional adhesive for honeycomb-sandwich binding. These bindings must have minimum outgassing characteristics.

Cryogen Pressurization and Stratification

Electrical heaters and thermal conductors are used to control the cryogen pressure and stratification by adding and diffusing heat to the fluid stored within the pressure vessel. Heat is required for maintaining or increasing the fluid pressure for expulsion, and thermal conductors are required for the maintenance of a homogenous fluid. The two basic approaches that are used for transferring heat within the cryogenic fluid are classified as static or dynamic. The static system depends on thermal conduction from electric heaters and thermal conductor combinations, such as an electrofilm resistive coating on a large internal heat-transfer surface or by electric heaters which conduct heat through a large surface thermal conductor. The dynamic system depends on forced mixing that involves convective heat transfer; mixing is accomplished by an internal heater and fan that are powered by an electric motor or by an external pumping loop (which circulates the fluid over a heater). A static system consists of a thermal conductor, such as one or more copper spheres positioned internally and concentric within the pressure vessel, that distributes the heat and equalizes the fluid temperature. Usually, the thermal conductors have holes for weight reduction and fluid mixing. The electric heater unit consists of a nichrome-wire resistance-heater element that is insulated by powdered magnesium oxide contained within a metallic sheath. The heater is coiled and is attached to the surface of the thermal conductor. The major advantage of a static heater system is that there are no moving parts; thus, inherently higher reliability is achieved. However, thermal stratification considerations are significant and detailed attention must be directed toward the thermal conductor design.

A thermally stratified system is not in equilibrium, and an unstable pressure occurs; the unstable pressure is established by the vapor pressure of the highest temperature fluid zone. Equilibration, or mixing of a thermally stratified system, results in a new equilibrium storage pressure. Stratification is common to all fluids that are subjected to heat transfer. The density layers (strata) are caused by the temperature differences that must accompany heat transfer. In a one-g environment, these layers will segregate according to weight, but in a low- or zero-g environment the layers remain static unless disturbed by some internal or external force. If a supercritical fluid is stratified and then mixed, a pressure decrease will result. Initially, heat energy is distributed heterogeneously within the fluid, and, in turn, this heated portion pressurizes the total contents of the vessel. Therefore, the resulting pressure is not an equilibrium condition which is acheived theoretically by the homogeneous distribution of heat energy.

Stratification is undesirable for two reasons: possible pressure decay below the critical pressure (thus operating in a two-phase regime) and inaccurate quantity measurement. Because the accuracy of capacitance-type probes is dependent on a uniform fluid density, it is essential that stratification be minimized if such a device is to be used for the measurement of cryogen-fluid quantity. A homogeneous fluid mixture will facilitate sampling a uniform medium by use of the capacitance probe, which will indicate an accurate quantity measurement.

A dynamic system consists of two electric-motor-driven impellers in conjunction with a heater which provides antistratification and convective heating of the fluid simultaneously. The internal electric heater (fig. 37) consists of a heater coiled around and fastened to an internally finned column. For fluid intake, the finned column has holes through its lateral surface. Two electric-motor-driven centrifugal impellers, located at opposite ends of the heater column, draw fluid through the radial-tube holes and force it across the heat-transfer surface; then, the fluid is expelled radially through the impellers.

A dynamic system that involves an external loop does not require the heater or motor-fan/pump to be located within the pressure vessel. The fluid is withdrawn from the pressure vessel by the use of a pump, is routed over an electric heater, and is returned to the tank or is expelled to the supply line. An external-loop heater system is shown in figure 38. The advantages of a dynamic system are improved quantity gaging, homogeneous pressurization of the fluid, operation independent of the gravity environment, rapid pressurization and withdrawal rates, and the ease of assembly and maintenance. The disadvantage of a dynamic system is that it is dynamic, reducing the reliability. The possibility of introducing impurities and excess heat from motor operation must be considered also.

Vacuum Processing and Insulation

Vacuum processing.- A critical requirement of a cryogenic Dewar system is the vacuum integrity of the annulus. If the vacuum integrity is poor, the Dewar will undergo a high heat leak because of excessive gas conduction of heat transferred into the stored cryogen. Then, the system will be forced to vent fluid overboard if the demand is not sufficient to use the increased expulsion rate. All materials contain residual gases which may be released when the material is exposed to a vacuum. The volume of gas that is released by a material will vary depending on the material characteristics. To obtain and maintain a high static vacuum, the materials must be processed properly to remove the residual gases. Usually, during the evacuation process, the Dewar is heated; this process forces more gases to be emitted and removed from the annulus. To prevent additional outgassing from destroying the vacuum after processing, it is a normal practice to use an absorbent (getter) or vacuum ion pump to remove the gases that are released after the Dewar is sealed. Careful selection of materials and vacuum processing can result in a reduction of residual gases which may be outgassed, but complete elimination is virtually impossible. For effective thermal protection, a pressure level of 5×10^{-5} torr or lower is required.

Insulations.- Of the several insulation techniques that have been used, the powder and laminar insulations and the discrete shields and vapor-cooled shields have received the most attention. Usually, the insulation material is placed within the Dewar vacuum annulus; however, in some cases the laminar insulation is placed external to the annulus.

Powder insulation.- These insulations consist of finely divided solid materials that have low thermal conductivity. Generally, the average density of the powder is low so that there is a relatively small ratio of solid material to gas-filled spaces between the particles. Heat is transferred within the insulation by conduction through the solid particles, by conduction and convection through the interstitial gas, and by radiant transfer through the partially transparent powder and from particle to particle. A problem that may be encountered in the use of powder insulations is the settling or packing of the particles. Vibration and movement during use may break down the powder particles, causing them to come into closer contact with each other, resulting in an increase of solid thermal conductivity. Perlite, silica aerogels, charcoal, diatomaceous earth, and calcium silicate are examples of powders.

Laminar insulation.- This type of insulation consists of alternate layers of radiation-shielding material and low-conductivity spacing material. A common laminar radiation shield is made of aluminum foil, which serves as the reflective shield material. The shields are separated from each other by thin layers of low-conductivity materials such as fiber-glass paper or cloth. Another type of laminar insulation, aluminized Mylar, is made of single sheets which have the reflective material on one side and the low-conductivity material on the opposite side; thus, separate layers of shields and spacers are eliminated. The effectiveness of laminar insulation depends upon the emissivity of the shields and upon thermal isolation between the shields and the number of layers that can be applied in a given space. Usually, the layers are loosely spaced or purposely crinkled to minimize contact between layers. The application of laminar insulation to surfaces that are not flat or cylindrical is critical. It is difficult to achieve ideal performance because the spacing of layers generally is not uniform and allowances must be made for lines, leads, and other objects that interfere with the application. The normal method of applying laminar insulation consists of wrapping, overlapping, taping, sewing, and heat sealing. Evacuation of the annular space is difficult because of the many surfaces of material and the large quantities of residual gases which must be pumped out of the annulus.

Discrete shields.- These structures are low-emissivity radiation shields that are mounted within the Dewar vacuum annulus. Usually, the shields are positioned and mounted by a minimum number of supports that have low thermal conductance. The heat transfer between surfaces in discrete-shielded vessels is composed of solid conduction through the supports and interconnecting lines, conduction by the residual gas, and thermal radiation. Discrete radiation shields have advantages regarding fabrication, assembly, reproducibility, analytical prediction, vacuum acquisition, and long shelf life. The major disadvantage of discrete radiation shields is that the surface conditions of the shields affect the emissivity values considerably. Aluminum, copper, gold, and silver are the customary materials that are plated onto the shield substratum material for low-emissivity shield surfaces. Because some of the low-emissivity materials will degrade quickly because of oxidation when exposed to air, it is desirable that the tank be assembled in an inert atmosphere or be assembled quickly if exposed to the normal atmosphere.

Vapor-cooled shields.- These structures are discrete shields which have the capability of being cooled by the effluent fluid from the tank. Fluid issuing from the pressure vessel, either from venting or usage, is routed through tubing that is attached to the shield. The vapor-cooled shield acts as a heat exchanger between the fluid and the shield; the fluid picks up heat energy from the shield and carrys it out of the system along with the cryogen vapor.

Plating Processes

Plating involves the deposition of a film of metal onto the pressure vessel, outer shell, and discrete-shield surfaces that are exposed to the vacuum annulus. Plating results in a low-emissivity surface that limits radiation heat transfer and outgassing in a static vacuum environment.

Usually, surface plating of cryogenic-tank components is accomplished by electroplating and vapor plating. Electroplating involves the production and deposition of metallic coatings on the tank parts by the use of an electrochemical process. The metal coating is produced by the passage of an electric current through an ionic solution, causing the production of metal ions at one of the electrodes. Two conducting electrodes are connected to the poles of a suitable electromotive force (emf) source and are placed in an electrolytic solution which is capable of conducting an electric current. When the emf is applied to the electrodes, a current flows through the electrolyte and, because of the potential difference between the two electrodes, the ions are displaced in the solution. The ions migrate to the electrodes where they are discharged in the form of a metal coating. Vapor-phase deposition includes several different processes; however, usually the evaporation and condensation of metals under vacuum conditions is used. A major criterion for the successful use of the vacuum-evaporation process is that the part to be plated must have a smooth surface. A smooth surface can be achieved by the application of a coat of either an epoxy or polyamide varnish; the varnish is allowed to level out to a high-gloss surface. Prior to plating, the coatings must be processed to remove any volatile materials.

Quantity Measurement

A supercritical storage (single phase) system involves a coaxial cylindrical capacitor as the sensing element for the measurement of fluid quantity. This device operates on the Clausius-Mosotti relationship between the density and the dielectric constant of the cryogen by sensing the dielectric properties of the fluid between two capacitor plates. Because theoretically the supercritical fluid is homogeneous, the density sample within the capacitor is considered to be uniform; thus, a corresponding quantity read-out is achieved.

Because subcritical storage consists of storing both the liquid and the gas phases, a simple capacitance probe is not suitable for quantity measurement. A device which has been used for quantity measuring in a subcritical system consists of a cubical matrix arrangement of two electrically isolated lattice wire grids. The matrix grids facilitate the measurement of the fluid capacitance throughout the container volume. When an electric potential is applied to each grid, the two grids act as plates of a capacitor. A matrix can be designed for a desired resolution and configuration. Voids can be left in the matrix to fit around baffles or structural members. Because the capacitance of the stored fluid varies as a function of the bulk density of the stored fluid, the capacitance between the grids is measured and translated into an integrated quantity read-out.

A quantity-measuring system that is in the developmental stage, the radio-frequency (rf) gaging system, involves the use of radio-frequency energy. The rf technique employs electromagnetic energy at microwave frequencies to "illuminate" the tank with rf energy, and thereby measure the entire quantity of fluid in a tank, regardless of fluid density or its location within the tank. Basically, the rf system responds to variations in the average dielectric constant of the stored medium. The dielectric constant is related to fluid density by the use of the Clausius-Mosotti relationship. The tanks are operated as rf-resonant cavities, and variations in reasonant frequencies in a cavity that are caused by dielectric-constant changes, coupled with different requirements in rf power absorption by the fluid, are used as measurement parameters. The rf system involves a sensing antenna in the tank. The antenna transmits the rf energy throughout the tank and receives the reflected portion of the incident power. Then, the reflected signal is converted to a signal which is pulse modulated by the measurement-detection circuitry. The resultant signal is integrated to form an analog signal that represents the quantity of fluid that is present in the tank.

Pressure and Temperature Measurement

Usually, fluid pressure measurements are obtained by the use of pressure transducers that involve strain gages that are bonded to a diaphragm. The diaphragm deflects in proportion to the applied pressure and causes a millivolt signal to be transmitted to a signal conditioner. Temperature measurements within cryogenic storage tanks usually are obtained though the use of copper-constantan thermocouples and platinum resistance-sensing elements.

Signal Conditioners

Signal conditioners are used in conjunction with the temperature, pressure, and quantity-sensing elements and provide the read-out signal. Usually, the signal conditioner amplifies the voltage that is developed from the sensing elements and provides a 0- to 5-volt dc output signal which is linearly proportional to the measured parameters. Parameters which are not linear are compensated for in the signal conditioner.

Pressure Switches

Pressure switches are used to energize and deenergize the electrical heater system at predetermined pressures. The pressure switch senses the tank pressure and actuates a toggle mechanism which is used for the control and actuation of the heater circuit.

Valves

Usually, the cryogenic gas storage system includes the following valves for the control of the fluid flow: fill, vent, pressure relief, supply, and check. The fill valve is used during the filling of the system and is operated either remotely or manually. If it is operated remotely, a solenoid valve is used. Solenoid valves use electrical energy for opening and closing and usually have an override which allows the valve to be opened or closed manually. If the valve is operated manually, a quick-disconnect valve with an integral check valve to prevent backflow or a simple hand-operated cryogenic valve is used. After filling, a seal cap is screwed on the fill coupling as a secondary leak seal and cover.

The vent valve is used during the filling of the system to facilitate vapor venting and is operated remotely or manually as the fill valve. The pressure-relief valve prevents the system pressure from rising above a maximum level by allowing the fluid to escape until the pressure is decreased to a safe level, at which time the valve will close. Usually, this valve is a mechanical-type valve, and the spring tension is correlated with the pressure-relief requirements. The supply valve serves as the control for fluid flow during operation of the system. This valve is usually of the solenoid type. The check valve, installed in a fluid line, is used to prevent backflow of the fluid; it consists of a spring-loaded poppet which seals against a seat.

Filters

One type of filter that is used consists of multiple stainless-steel disks that are stacked to achieve a long flow path. The disk elements are capable of retaining fibers and other contaminants that exceed specific dimensions which are correlated to the disk pore size.

Ion Pumps

The ion pumps are used to monitor the vacuum-annulus pressure and also are capable of removing small amounts of gases that occur as a result of material outgassing. The ion pumps that are used vary from 0.2 to 1.0 liter/sec capacity. The electrical current that is required by the ion pump during operation is indicative of the pressure within the vacuum annulus by correlation with a calibration curve of current compared with pressure.

Electrical Connectors

Usually, the electrical connectors are sealed hermetically and are capable of withstanding system pressures and temperatures. The connector pins are sealed in a ceramic material which has the same coefficient of thermal expansion as the connector shell and pin material.

Electrical Leads

The electrical leads that are used for power input and sensor-signal output usually consist of conductors that are surrounded by magnesium oxide insulation and that are encased in a metallic sheath.

Fluid Lines

Usually, fluid-line sizes are dictated by manufacturing considerations and flow requirements. Fluid-line material is governed by cryogen compatibility, joinability, and heat-conduction characteristics.

Tank Mounting

After the tank is fabricated and assembled, it must be supported suitably and must be mounted in the spacecraft. Specific mounting arrangements are dependent on the design by the manufacturer and the spacecraft interfaces. Some tanks are supported by their girth ring only, and others may have a mount which encompasses and supports the vessel at various areas or points. High strength-to-weight-ratio materials such as titanium, aluminum, and magnesium are favored as the structural mount material. In the event the system will be exposed to stringent vibration requirements, vibration dampeners may be placed between the tank and spacecraft.

Nonmetallic Materials

Considerations for the selection of nonmetallic materials include such parameters as temperature effectivity, cryogen compatibility, cleanliness maintainability, and fungus resistivity. Teflon, Kel-F, Rulon, and glass are considered suitable for use in cryogenic storage systems.

Heat Transfer

The heat input into a storage vessel consists of conductive and radiant heat energy. Convective heat transfer is negligible; therefore, usually it is not considered in the thermal analyses. The heat inputs will vary with the thermal environment, design, and the cryogen that is stored. A thermal analysis of a cryogenic Dewar is complex and usually does not lend itself to the consideration of one mode of heat transfer without consideration of the other mode. Heat transfer into the Dewar occurs by means of conduction through the tubes, leads, and inner vessel supports and by radiation through the vacuum annulus. Heat input can be minimized by long conduction paths of low-conductivity material and by thermal barriers within the vacuum annulus. Heat transfer by conduction through the inner-vessel supports is dependent on the specific support design, contact area, and load.

Fluid Thermodynamics

Usually, after filling and capping a spacecraft cryogenic storage system, it is required to standby for several hours. During the standby time, the stored cryogen is receiving heat energy which pressurizes the stored fluid.

The system can be considered either nonvented or vented during standby. Nonvented standby time is the time from capping a vessel until venting from the relief valve occurs. During nonvented standby, it is assumed that no venting will take place prior to using the fluid. For vented standby, it is assumed that the system will vent overboard at some predetermined pressure prior to using the fluid. A vented compared with nonvented system depends on the mission characteristics, standby time, weight, effect of vapor cooling, ambient temperature, vessel volume, and system design. For a vented system, the heat required to pressurize the vessel can be expressed by the following energy-balance equation.

$$Q = M_f'H_f' + M_fH_f - M_iH_i - M_fP_fV_f + M_iP_iV_i \tag{1}$$

For a nonvented system, the flow term $M_f'H_f'$ in equation (1) is zero because the system is only building up pressure. Therefore, for a nonvented system the heat that is required to pressurize the vessel is described in equation (2).

$$Q = M_fH_f - M_iH_i - M_fP_fV_f + M_iP_iV_i \tag{2}$$

After filling and capping, initially the fluid is in two distinct phases (liquid and gas), and the total stored mass can be expressed as shown in equation (3).

$$M_f = M_l + M_g \tag{3}$$

Where Q = heat energy, Btu/lb

M = stored mass, lb

H = enthalpy, Btu/lb

P = pressure, lb/ft^2

V = specific volume, ft^3/lb

f = final fluid condition

i = initial fluid condition

g = gas

l = liquid

If the volume fraction of the liquid or gas in the system is F, then equation (4) can be subsituted for the intial conditions.

$$F_l = \frac{M_l V_l}{M_f V_f} \qquad F_g = \frac{M_g V_g}{M_f V_f} \tag{4}$$

For example, substituting equations (3) and (4) into equation (2) yields equation (5).

$$Q = M_f H_f - \left(\frac{F_l M_f V_f}{V_l} H_l + \frac{F_g M_f V_f}{V_g} H_g \right) - M_f P_f V_f + \left(\frac{F_l M_f V_f}{V_l} P_l V_l + \frac{F_g M_f V_f}{V_g} P_g V_g \right) \tag{5}$$

The heat input that is required to pressurize a supercritical vessel is shown in figures 39 and 40 as a function of pressure and percent fill for oxygen and parahydrogen, respectively. After a storage system has been pressurized, the pressure must be maintained during operational fluid delivery. The heat that is required to maintain the operating pressure in a cryogenic storage system can be determined from the energy balance equation (1). The energy that is required to maintain pressure in a supercritical system also can be expressed as shown in equation (6).

$$Q = -D\left(\frac{dH}{dD}\right)_p \tag{6}$$

where Q = heat energy, Btu/lb

D = density, lb/ft^3

H = enthalpy, Btu/lb

p = constant pressure

The solution of equation (6) represents the heat energy that is required to maintain pressure (per pound of fluid withdrawn) as a function of fluid density.

The total heat input is from internal-heater operation, environmental heat input, electrical sensors, lead resistance, motors, and any other heat sources that are associated with the storage system. Then, the required heat energy must maintain the fluid in equilibrium at the desired pressure during operation. The heat that is required to maintain constant pressure during operation for various storage pressures as a function of fluid density for oxygen and parahydrogen is shown in figures 41 and 42, respectively. Several of the cryogenic properties of gases have been summarized in table XXIV.

Because specific missions involve certain cryogen flow rates, it is desirable to design the vessel heat-input rates for the required mission flow rates. That is, a vessel should be designed thermally so that its expelled fluid is utilized, not wasted by venting overboard because of excessive pressurization. The various fluid-expulsion rates are shown (figs. 43 to 46) as a function of heat input and fluid density for oxygen- and parahydrogen-storage systems.

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TABLE I.- THE LIFETIME RATINGS OF THE SIX GEMINI

CRYOGENIC GAS STORAGE SYSTEM TANKS

Cryogen	ECS tank lifetimes, days	EPS/RSS tank lifetimes, days
Oxygen[a]	2 14	2 14
Hydrogen	None	2 14

[a]Although the lifetime ratings for the ECS and EPS/RSS O_2 tanks are identical, the tank capacities are different.

TABLE II.- THE GEMINI CRYOGENIC GAS STORAGE SYSTEM DESIGN CHARACTERISTICS

(ENVIRONMENTAL CONTROL SYSTEM)

Gemini ECS supercritical oxygen-storage system	2-day ECS oxygen	14-day ECS oxygen
Subsystem part no.		
McDonnell	83700-163	83700-127
AiResearch	630094-1	630050-1
Container part no.		
McDonnell	83700-159	83700-129
AiResearch	630096-1	630048-1
Mission time, days	2	14
Dry system weight, ±5 percent, lb	16.30	41.79
Usable fluid per vessel, lb	15.3	104.0
Fluid at fill, minimum, lb	15.75	106.0
Ullage, percent	15.4	9.7
Normal operating pressure, psig	850^{+60}_{-50}	850^{+60}_{-50}
Maximum operating pressure		
At 70° F, psig	930	930
At -160° F, psig	1000	1000
Relief-valve pressure range, psia	1000^{+0}_{-55}	1000^{+0}_{-55}
Proof pressure		
At 70° F, psig	1550	1550
At -160° F, psig	1670	1670
Burst pressure		
At 70° F, psig	2000	2000
At -160° F, psig	2220	2220

TABLE II.- THE GEMINI CRYOGENIC GAS STORAGE SYSTEM DESIGN CHARACTERISTICS

(ENVIRONMENTAL CONTROL SYSTEM) - Continued

Gemini ECS supercritical oxygen-storage system	2-day ECS oxygen	14-day ECS oxygen
Minimum flow rate at 100° F ambient, lb/hr . . .	0.286	0.286
Maximum flow rate, lb/min	0.35	0.35
Design standby time, hr	72	72
Revised standby time,[a] hr	50	96
Vented fluid during standby, lb	None	None
Design heat leak,[a] Btu/hr	5.5	10.55
At internal temperature, °F	-280	-162
At ambient temperature, °F	+160	+100
Off-design heat leak,[a] Btu/hr	--	17.8
At internal temperature, °F	--	-280
At ambient temperature, °F	--	+160
Internal heater operation, V dc	28	28
Normal: Automatic pressure control, W	12 ± 2	12 ± 2
Emergency: Manual control, W	550^{+25}_{-0}	325^{+25}_{-0}
Cryogenic antistratification device	Static thermal copper conductor	Static thermal copper conductor
Pressure vessels		
Volume, minimum, ft^3	0.262	1.65
Inside diameter, in.	9.562	17.60
Material	Inconel 718	Inconel 718
Wall thickness, nominal, in.	0.032	0.058

[a]Per McDonnell Aircraft Corporation.

TABLE II.- THE GEMINI CRYOGENIC GAS STORAGE SYSTEM DESIGN CHARACTERISTICS

(ENVIRONMENTAL CONTROL SYSTEM) - Concluded

Gemini ECS supercritical oxygen-storage system	2-day ECS oxygen	14-day ECS oxygen
Outer shells		
Inside diameter, in.	12.08	19.95
Wall thickness, nominal	0.0225	0.027
Material	Ti 5Al-2.5Sn	Ti 5Al-2.5Sn
Collapse pressure, psia	20	20
Insulation, aluminized Mylar		
Layers per vessel	65	65
Thermal conductivity, $\frac{\text{Btu}}{\text{ft-hr }^{\circ}\text{R}}$	1 to 3 × 10^{-4}	1 to 3 × 10^{-4}
Pressure-vessel support pads, Fiberglas		
Number per vessel	4	12
Thermal conductivity, $\frac{\text{Btu}}{\text{ft-hr }^{\circ}\text{R}}$	6 to 7 × 10^{-4}	6 to 7 × 10^{-4}
Density, lb/ft^3	20	20
Total area, ft^2	0.436	2.03
Diameter per pad, in.	2.0	2.0

TABLE III.- THE GEMINI CRYOGENIC GAS STORAGE SYSTEM DESIGN CHARACTERISTICS

(REACTANT SUPPLY SYSTEM, OXYGEN)

Gemini RSS supercritical oxygen-storage system	2-day RSS, oxygen	14-day RSS, oxygen
Subsystem part no.		
McDonnell	83701-73	83701-71
AiResearch	639046-1	639002-1
Container part no.		
McDonnell	83701-15	83701-13
AirResearch	639006-1	639004-1
Mission time, days	2	14
Dry system weight, ±5 percent, lb	23.61	59.06
Usable fluid per vessel, lb	45.0	177.4
Fluid at fill, minimum, lb	46.0	180.0
Ullage, percent	10.4	4.0
Normal operating pressure, psig	850^{+60}_{-50}	850^{+60}_{-50}
Maximum operating pressure		
At 70° F, psig	930	930
At -160° F, psig	1000	1000
Relief valve pressure range, psig	1000^{+0}_{-55}	1000^{+0}_{-55}
Proof pressure		
At 70° F, psig	1550	1550
At -160° F, psig	1670	1670

TABLE III.- THE GEMINI CRYOGENIC GAS STORAGE SYSTEM DESIGN CHARACTERICS

(REACTANT SUPPLY SYSTEM, OXYGEN) - Continued

Gemini RSS supercritical oxygen-storage system	2-day RSS, oxygen	14-day RSS, oxygen
Burst pressure		
At 70° F, psig	2000	2000
At -160° F, psig	2220	2220
Minimum flow rate		
At 160° F, lb/hr	--	0.490
At -160° F, lb/hr	0.540	--
Maximum flow rate at -60° F, lb/hr	2.22	2.22
Design standby time, hr	72	72
Revised standby time,[a] hr	65	55
Vented fluid during standby, lb	None	None
Design heat leak,[a] Btu/hr	10.8	20.9
At internal temperature, °F	-280	-280
At ambient temperature, °F	+160	+160
Off-design heat leak,[a] Btu/hr	--	12.5
At internal temperature, °F	--	-162
At ambient temperature, °F	--	+100
Internal heater operation, V dc	28	28
Normal: automatic pressure control, W	78^{+0}_{-16}	78^{+0}_{-16}
Emergency: manual control, W	None	None
Oxygen antistratification device	Static thermal copper conductor	Static thermal copper conductor

[a]Per McDonnell Aircraft Corporation.

TABLE III.- THE GEMINI CRYOGENIC GAS STORAGE SYSTEM DESIGN CHARACTERISTICS

(REACTANT SUPPLY SYSTEM, OXYGEN) - Concluded

Gemini RSS cupercritical oxygen-storage system	2-day RSS, oxygen	14-day RSS, oxygen
Pressure vessels		
Volume, minimum, ft^3	0.721	2.64
Inside diameter, in.	13.35	20.56
Material	Inconel 718	Inconel 718
Wall thickness, nominal, in.	0.0455	0.070
Outer shells		
Inside diameter, in.	15.56	22.942
Wall thickness, nominal, in.	0.0225	0.0325
Material	Ti 5Al-2.5Sn	Ti 5Al-2.5Sn
Collapse pressure, psia	20	20
Insulation, aluminized Mylar		
Layers per vessel	65	65
Thermal conductivity, $\frac{\text{Btu}}{\text{ft-hr }^{\circ}\text{R}}$	$1 \text{ to } 3 \times 10^{-4}$	$1 \text{ to } 3 \times 10^{-4}$
Pressure vessel support pads, Fiberglas		
Number per vessel	6	12
Thermal conductivity, $\frac{\text{Btu}}{\text{ft-hr }^{\circ}\text{R}}$	$6 \text{ to } 7 \times 10^{-4}$	$6 \text{ to } 7 \times 10^{-4}$
Density, lb/ft^3	20	20
Total area, ft^2	0.904	3.37
Diameter per pad, in.	2.0	2.0

TABLE IV.- THE GEMINI CRYOGENIC GAS STORAGE SYSTEM DESIGN CHARACTERISTICS

(REACTANT SUPPLY SYSTEM, HYDROGEN)

Gemini RSS supercritical hydrogen-storage system	2-day RSS, hydrogen	14-day RSS, hydrogen
Subsystem part no.		
McDonnell	83701-77	83701-81
AiResearch	639048-1	639018-1
Container part no.		
McDonnell	83701-11	83701-9
AiResearch	639022-1	639020-1
Mission time, days	2	14
Dry system weight, ±5 percent, lb	27.52	50.41
Usable fluid per vessel, lb	5.6	21.9
Fluid at fill, minimum, lb	5.80	22.25
Ullage, percent	33.1	8.0
Normal operating pressure, psig	250^{+0}_{-40}	250^{+0}_{-40}
Maximum operating pressure		
At 70° F, psig	200	200
At -320° F, psig	350	350
Relief-valve pressure range, psig	350^{+0}_{-35}	350^{+0}_{-35}
Proof pressure		
At 70° F, psig	335	335
At -320° F, psig	585	585
Burst pressure		
At 70° F, psig	440	440
At -320° F, psig	777	777

TABLE IV.- THE GEMINI CRYOGENIC GAS STORAGE SYSTEM DESIGN CHARACTERISTICS

(REACTANT SUPPLY SYSTEM, HYDROGEN) - Continued

Gemini RSS supercritical hydrogen-storage system	2-day RSS, hydrogen	14-day RSS, hydrogen
Minimum flow rate at 160° F ambient, lb/hr	0.070	0.064
Maximum flow rate at -60° F ambient, lb/hr	0.276	0.276
Design standby time, hr	72	72
Revised standby time,[a] hr	50	67
Vented fluid during standby, lb	None	None
Design heat leak,[a] Btu/hr	7.26	7.25
At internal temperature, °F	-415	-392
At ambient temperature, °F	+160	+100
Internal heater operation, V dc	28	28
Normal: automatic pressure control, W	18 ± 2	18 ± 2
Emergency: manual control, W	None	None
Cryogen antistratification device	Static thermal copper conductor	Static thermal copper conductor
Pressure vessels		
Volume, minimum, ft^3	1.97	5.49
Inside diameter, in.	18.65	26.25
Material	Ti 5Al-2.5Sn	Ti 5Al-2.5Sn
Wall thickness, nominal, in.	0.030	0.056

[a]Per McDonnell Aircraft Corporation.

TABLE IV.- THE GEMINI CRYOGENIC GAS STORAGE SYSTEM DESIGN CHARACTERISTICS

(REACTANT SUPPLY SYSTEM, HYDROGEN) - Concluded

Gemini RSS supercritical hydrogen-storage system	2-day RSS, hydrogen	14-day RSS, hydrogen
Outer shells		
Inside diameter, in.	21.466	28.928
Wall thickness, nominal, in.	0.0305	0.040
Material	Ti 5Al-2.5Sn	Ti 5Al-2.5Sn
Collapse pressure, psia	20	20
Insulation, aluminized Mylar		
Layers per vessel	65	65
Thermal conductivity, $\frac{\text{Btu}}{\text{ft-hr }^{\circ}\text{R}}$	1 to 3 × 10^{-4}	1 to 3 × 10^{-4}
Pressure vessel support pads, Fiberglas		
Number per vessel	6	10
Thermal conductivity, $\frac{\text{Btu}}{\text{ft-hr }^{\circ}\text{R}}$	6 to 7 × 10^{-4}	6 to 7 × 10^{-4}
Density, lb/ft^3	20	20
Total area, ft^2	0.294	0.775
Diameter per pad, in.	2.0	2.0

TABLE V.- THE GEMINI CRYOGENIC GAS SUBSYSTEM ACTUAL-WEIGHT SUMMARY

Part no.	Subsystem	Specific weight, lb	Actual weights, lb
630050-1	ECS O_2, L/M[a]	41.79 ± 5 percent	40.65, 42.50, 41.40, 41.45, 41.50, 41.25
630094-1	ECS O_2, S/M[b]	16.30 ± 5 percent	14.22, 14.50, 14.65, 14.40, 14.45, 14.35
639002-1	RSS O_2, L/M	59.06 ± 5 percent	60.65, 60.40, 61.50, 60.50, 59.95, 62.00
639046-1	RSS O_2, S/M	23.61 ± 5 percent	21.55, 21.15, 22.25, 21.10, 21.10, 21.80
639018-1	RSS H_2, L/M	50.41 ± 5 percent	54.6, 54.5, 54.3, 53.3, 53.12, 53.35
639048-1	RSS H_2, S/M	27.52 ± 5 percent	25.61, 24.35, 25.40, 25.15, 24.25, 24.70

[a]L/M = long mission, 14 days.
[b]S/M = short mission, 2 days.

TABLE VI.- AN ACTUAL-WEIGHT SUMMARY OF THE GEMINI CRYOGENIC GAS STORAGE SYSTEM COMPONENTS

Part no.	Component	Specified weight, lb	Actual weights, lb
630156-1	ECS, S/M indicator	1.05	0.997, 0.816, 1.0, 1.007, 0.990
630158-1	L/M, quantity and pressure indicator	1.05	1.007, 0.990, 0.995, 0.983, 1.005
639112-1	L/M, quantity and pressure indicator	1.05	1.005, 0.9834, 1.00, 0.996, 0.812
639116-1	L/M, quantity and pressure indicator	1.05	1.007, 0.990, 0.994, 0.8118, 0.9988
639114-1	S/M, quantity and pressure indicator	1.05	1.005, 0.8074, 0.990, 0.9878, 0.8106
639118-1	L/M, quantity and pressure indicator	1.05	1.014, 0.9944, 0.990, 0.994, 0.996
631000-2	ECS, S/M, quantity sensor	.60	0.4906, 0.482, 0.480
631000-1	ECS, L/M, quantity sensor	.95	0.810, 0.820, 0.814, 0.823, 0.825
631000-5	RSS, S/M, O_2 quantity sensor	.80	0.6446, 0.653, 0.647, 0.656, 0.651
631000-3	RSS, L/M, O_2 quantity sensor	1.10	0.9206, 0.9208, 0.915, 1.198
631000-6	RSS, S/M, H_2 quantity sensor	1.00	0.832, 0.8162, 0.8189, 0.827, 0.8228
631000-4	RSS, L/M, H_2 quantity sensor	1.35	1.133, 1.144, 1.286, 1.1308
[a]639066	Control	1.00	0.996, 0.831, 0.818, 0.811, 0.860, 0.836
639064-1	Inverter	.60	0.477, 0.464, 0.482, 0.475, 0.4774
630212-2	O_2 pressure switch	.71	0.5742, 0.5830, 0.5676, 0.5654
639132-1	H_2 pressure switch	.56	0.572
630056-1	Transducer, oxygen	.40	0.374, 0.378, 0.385, 0.370, 0.385
639034-1	Transducer, hydrogen	.40	0.349, 0.352, 0.343, 0.337

[a]639066-1 to 639066-6.

TABLE VII.- GEMINI CRYOGENIC GAS STORAGE SYSTEM THERMAL-PERFORMANCE DATA

(a) Two-day ECS oxygen vessel

Manufacturer serial no.[a]	Vent heat loss, lb/hr at 75° F ambient	Fluid	Vented heat leak, Btu/hr	Nonvented heat leak, Btu/hr	Standby time, hr at 75° F ambient	
					Predicted	Actual
2	0.0635	O_2	5.82	6.05	65.0	>72
3	.0484	O_2	4.44	4.50	88.2	>72
5	.0834	O_2	7.63	8.05	49.1	48.8
6	.077	N_2	6.57	6.85	57.4	>72
12	.110	N_2	9.40	10.00	39.0	--
14	.084	N_2	7.20	7.55	52.0	--

[a]All serial numbers are for part number 630094.

(b) Fourteen-day ECS oxygen vessel

Manufacturer serial no.[a]	Vent heat loss, lb/hr at 75° F ambient	Fluid	Vented heat leak, Btu/hr	Nonvented heat leak, Btu/hr	Standby time, hr at 75° F ambient	
					Predicted	Actual
2	0.154	N_2	13.1	13.6	128.8	>72
9	.1502	O_2	13.8	14.65	119.0	>72
10	.194	N_2	16.5	18.65	96.0	>72
16	.195	N_2	16.6	18.80	96.5	--

[a]All serial numbers are for part number 630050.

TABLE VII.- GEMINI CRYOGENIC GAS STORAGE SYSTEM THERMAL-PERFORMANCE DATA - Continued

(c) Two-day RSS oxygen vessel

Manufacturer serial no.[a]	Vent heat loss, lb/hr at 75° F ambient	Fluid	Vented heat leak, Btu/hr	Nonvented heat leak, Btu/hr	Standby time, hr at 75° F ambient	
					Predicted	Actual
2	0.11	N_2	9.39	10.25	80.3	--
3	.1466	O_2	13.44	14.6	55.5	51
6	.1175	N_2	10.0	10.9	75.0	>72
8	.113	N_2	9.63	10.5	78.0	69
9	.105	N_2	8.97	9.75	84.5	68.9
10	.1345	N_2	11.5	12.5	65.3	66
11	.118	N_2	10.05	10.95	75.0	--
12	.1191	N_2	10.12	11.05	74.0	>72
13	.1245	N_2	10.65	11.55	70.5	--
15	.1275	N_2	10.84	11.80	69.0	67
17	.114	N_2	9.71	10.60	77.3	--

[a]All serial numbers are for part number 639046.

(d) Fourteen-day RSS oxygen vessel

Manufacturer serial no.[a]	Vent heat loss, lb/hr at 75° F ambient	Fluid	Vented heat leak, Btu/hr	Nonvented heat leak, Btu/hr	Standby time, hr at 75° F ambient	
					Predicted	Actual
2	0.199	N_2	17.0	19.4	78.6	>72
7	.2678	N_2	22.8	27.1	56.5	42.75
9	.2155	N_2	18.4	21.5	69.8	
11	.245	N_2	20.9	25.25	58.3	57.75 at 950 psi

[a]All serial numbers are for part number 639002.

TABLE VII.- GEMINI CRYOGENIC GAS STORAGE SYSTEM THERMAL-PERFORMANCE DATA - Continued

(e) Two-day RSS hydrogen vessel

Manufacturer serial no.[a]	Vent heat loss, lb/hr at 75° F ambient	Fluid	Vented heat leak, Btu/hr	Nonvented heat leak, Btu/hr	Standby time, hr at 75° F ambient		Date of test
					Predicted	Actual	
6	0.0358	H_2	6.91	8.78	55.03	53.0	12-22-63
7	.0262	H_2	5.06	6.45	73.5	--	11-29-63
8	.0236	H_2	4.55	5.85	--	>72.0	1-7-64
9	.0350	H_2	6.75	8.60	56.4	56.5	1-2-64
10	.0216	H_2	4.17	5.35	88.5	--	12-5-63
11	.0260	H_2	5.01	6.38	74.0	>72.0	1-15-64
12	.0191	H_2	3.68	4.65	107.0	--	1-12-64
13	.0429	H_2	8.26	10.44	46.0	50.5	12-29-63
14	.0408	H_2	7.88	9.99	48.5	--	1-3-64
15	.0320	H_2	6.16	7.86	--	--	2-8-64
16	.0270	H_2	5.20	6.64	--	--	2-17-64
17	.0283	H_2	5.45	6.95	--	--	4-1-64
19	.0350	H_2	6.74	8.60	--	--	--

[a]All serial numbers are part of number 639048.

TABLE VII.- GEMINI CRYOGENIC GAS STORAGE SYSTEM THERMAL-PERFORMANCE DATA - Concluded

(f) Fourteen-day RSS hydrogen vessel

Manufacturer serial no.[a]	Vent heat loss, lb/hr at 75° F ambient	Fluid	Vented heat leak, Btu/hr	Nonvented heat leak, Btu/hr	Standby time, hr at 75° F ambient		Date of test
					Predicted	Actual	
6	0.0325	H_2	6.28	9.50	64.1	--	1-31-64
7	.0275	H_2	5.31	8.08	76.3	>72.0	12-4-63
8	.0458	H_2	8.85	13.45	45.6	40.5	12-26-63
9	.0316	H_2	6.1	9.25	66.1	52.5 at 300 psi	12-13-63
10	.0487	H_2	9.4	14.3	43.0	38.0 at 300 psi	1-20-64
11	.0354	H_2	6.82	10.38	58.8	61.5	1-6-64
12	.0412	H_2	7.96	12.08	50.8	--	1-12-64
13	.0441	H_2	8.51	12.90	47.7	64.0	1-16-64
14	.0404	H_2	7.80	11.87	51.7	--	2-20-64

[a]All serial numbers are for part number 639018.

TABLE VIII.- APOLLO CRYOGENIC GAS STORAGE SYSTEM OPERATIONAL CHARACTERISTICS

Condition	Hydrogen	Oxygen
Weight, per tank		
Empty (approximate), lb	80.0	91.0
Usable fluid, lb	28.14	323.45
Stored fluid (100-percent indication), lb	29.32	330.1
Ullage (100-percent indication), percent	4	2
Maximum fill quantity, lb	30.2	336.7
Volume, per tank, ft^3	6.83	4.73
Flow rate, per tank		
Spec minimum dQ/dM,[a] lb/hr	0.0725	0.79
Spec maximum,[b] lb/hr	0.135	1.28
Relief valve maximum flow at 130° F, lb/hr	6	26
Pressure		
Normal operating, psia	245^{+15}_{-15}	900 ± 35
Spec minimum dead band of pressure switches, psi	10	30
Minimum operating, psia	100	150
Vent valve[c]		
Crack, psig	273	983
Full flow, psig	285	1010
Reseat, psig	268	965
Temperature		
Operating, °F	-425 to 80	-300 to 80
Delivery, °F	35 to 130	35 to 130
Heater thermostat		
Open, °F	80 ± 10	80 ± 10
Close, °F	60 ± 7	60 ± 7

[a]Figure 15.
[b]Figure 16.
[c]Relief valves are referenced to environmental pressure.

TABLE VIII.- APOLLO CRYOGENIC GAS STORAGE SYSTEM OPERATIONAL CHARACTERISTICS - Concluded

Condition	Hydrogen	Oxygen
Minimum open limit, °F	200	75
Servicing		
Fill time, hr	1	1
Conditioning time, hr	4	4
Standby time, hr	30	30
Heat leak (specification)		
Operating, dQ/dM at 140° F, Btu/hr	7.25	27.7
Standby, Btu/hr	21.00	39.5
Valve module leakage rate		
External, scc gas/hr/valve	400 (0.736×10^{-6} lb/ H_2/hr/valve)	400 (9.2×10^{-6} lb/ O_2/hr/valve)
Interface line sizes		
Fill connections, in.	1/4 (0.015 wall)	3/8 (0.022 wall)
Vent connections, in.	1/4 (0.015 wall)	3/4 (0.028 wall)
Relief connections, in.	3/16 (0.022 wall)	3/16 (0.022 wall)
Feed connections, in.	1/4 (0.015 wall)	1/4 (0.022 wall)
Outer-shell burst disk		
Nominal burst pressure, psid	$90 ^{+10}_{-20}$	75 ± 7.5
Cryogenic valve module		
Feed connections, in.	1/4 (0.015 wall)	1/4 (0.022 wall)
Fuel cell supply connections, in.	1/4 (0.022 wall)	1/4 (0.022 wall)
Relief-valve outlet, in.	1/4 (0.022 wall)	1/4 (0.022 wall)
Fuel-cell module		
Feed connections, 2, in.	1/4 (0.022 wall)	1/4 (0.022 wall)
Fuel cell supply connections, 3, in.	1/4 (0.022 wall)	1/4 (0.022 wall)

TABLE IX.- APOLLO CRYOGENIC GAS STORAGE SYSTEM ELECTRICAL AND INSTRUMENTATION CHARACTERISTICS

Item	Hydrogen	Oxygen
Beech/NR interface	Pigtails	Pigtails
Tank connectors	Hermetically sealed pin receptacle	Hermetically sealed pin receptacle
Heaters, 2 elements/tank		
Flight		
Resistance, ohms/element	78.4 (39.2 ohms/tank)	10.12 (5.06 ohms/tank)
Maximum voltage, V dc	28	28
Nominal power, W/tank	[a]20	[a]155
Current at 28 V, A/tank	0.72	5.5
Operating time, percent	10	10
Ground power		
Maximum voltage, V dc	65	65
Power, W/element	[b]54	[b]418
Operating time, hr	1	1
Pressure switch		
Maximum open pressure, psia	260	935
Minimum close pressure, psia	230	865
Minimum dead band, psid	10	30
Destratification fan motors, 2 each		
Voltage, 3 phase at 400 Hz, V	115/200	115/200
Power, W/motor	[c]3.6	[c]26.4
Operating time, percent	10	10
Speed[d]		
Flight operation, wet-cold, rpm	4000	1300
Ground checkout, dry-hot, rpm	6000	4000

[a]Equivalent to 68.2 and 530 Btu/hr, respectively.
[b]Equivalent to 108 and 836 W/tank, respectively.
[c]Equivalent to 24.6 and 180 Btu/hr, respectively.
[d]Two-phase operation reduces speed by one-third.

TABLE IX.- APOLLO CRYOGENIC GAS STORAGE SYSTEM ELECTRICAL AND INSTRUMENTATION CHARACTERISTICS - Continued

Item	Hydrogen	Oxygen
Pressure transducer		
Range, psia	0 to 350	50 to 1050
Accuracy, percent of full range	±2.5	±2.5
Readability, psi	1.4	3.9
Output voltage, V dc	0 to 5	0 to 5
Output impedance, ohms	500	500
Power, W	1.5	1.5
Voltage, V dc	28	28
Quantity-gaging system		
Range, lb	[e]0 to 28	[e]0 to 320
Accuracy, percent of full range	±2.5	±2.5
Readability, lb	±0.1	±1.26
Output voltage, V dc	0 to 5	0 to 5
Output impedance, ohms	500	500
Power at 115 V and 400 Hz, W	2.5	2.5
Vac Ion pump		
Weight, lb/tank	4.2	4.2
Capacity, liters/sec	1	1
Temperature-gaging system		
Range, °F	-425 to -200	-300 to +80
Accuracy, percent of full range	±2.5	±2.5
Readability, °F	0.9	1.6
Output voltage, V dc	0 to 5	0 to 5
Output impedance, ohms	5000	5000
Power at 115 V and 400 Hz, W	1.25	1.25

[e]Equivalent to 0 to 4.31 and 0 to 69.5 lb/ft^3, respectively.

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TABLE IX.- APOLLO CRYOGENIC GAS STORAGE SYSTEM ELECTRICAL AND INSTRUMENTATION CHARACTERISTICS - Concluded

Item	Hydrogen	Oxygen
Solenoid valves (3)		
Voltage, V dc	28	28
Current, A	2	2
Total flight power		
28 V dc		
Solenoid, W for 10 sec	168	168
Instrumentation, W for 336 hr	3.0	3.0
Heaters, W for 33.6 hr	40	310
115 V and 400 Hz		
Instrumentation, W for 336 hr	7.50	7.50
Motors, W for 33.6 hr	14.2	102
Total electrical load for Apollo CGSS		
28 V dc, 12.77 kW-hr		
115 V and 400 Hz, 8.61 kW-hr		
Combined ac and dc load = 21.38 kW-hr		

TABLE X.- APOLLO CRYOGENIC GAS STORAGE SYSTEM STRUCTURAL CHARACTERISTICS

Characteristic	Hydrogen	Oxygen
Material	5 Al-2.5 Sn ELI Ti	Inconel 718
Ultimate strength, psi	105 000	180 000
Yield strength, psi	95 000	145 000
Young's modulus, psi	17×10^6	30×10^6
Creep stress, psi	71,200	No creep at 145 000
Safety factors		
Ultimate	1.5	1.5
Yield	1.33	1.33
Creep	1.33	NA
Design stress level, psi	53 000	110 000
Pressure-vessel diameter, in.	28.24	25.06
Pressure-vessel thickness, in.	0.044 nom $^{+0.004}_{-0.000}$	0.059 nom $^{+0.004}_{-0.000}$
Outer-shell diameter, in.	31.74	26.48
Outer-shell thickness, in.	0.033 nom ± 0.002	0.020 ± 0.002
Support brackets	Aluminum	Inconel
Proof pressure, psi	400	1357
Burst pressure, psi	450	1530

TABLE XI.- APOLLO CRYOGENIC GAS STORAGE SYSTEM OXYGEN-TANK COMPONENT WEIGHTS (TWO TANKS)

System component	No. required	Total weight, lb
Inner tank assembly	2	80.6
Hemisphere, lower	2	39.7
Hemisphere, upper	2	40.3
Fan-heater mounts	2	.6
Fan-heater assembly	2	7.4
Tube assembly	2	3.2
Motor-fan assembly	4	3.5
Heater element	4	.6
Thermostat	4	.1
Upper-shell assembly	2	14.6
Upper shell	2	13.8
Housing ring	2	.8
Lower-shell assembly	2	20.2
Lower shell	2	13.2
Support ring	2	6.4
Seal assembly	2	.6
Insulation	2	22.9
Fiberglas and Dexiglas paper	2	14.9
Aluminum shields, tubing, and couplings	2	6.6
Miscellaneous	2	1.4

TABLE XI.- APOLLO CRYOGENIC GAS STORAGE SYSTEM OXYGEN-TANK COMPONENT WEIGHTS (TWO TANKS) - Continued

System component	No. required	Total weight, lb
Coil-housing assembly	2	14.4
Housing cylinder	2	1.5
Housing	2	1.6
Diaphragm	2	.1
Seal assembly	2	.6
Vac Ion pump and converter	2	10.0
Insulation	2	.6
Probe assembly	2	5.14
Tube assembly	2	2.7
Electrical lead adapter	2	.4
Tube	2	.01
Adapter	2	.01
Adapter	2	.02
Density sensor	2	1.9
Filter	2	.1
Placard	2	.008
Adapter electrical connector	2	.4
Heat shield	2	1.5
Electrical connector	2	.5
Electrical lead installation	2	.6

TABLE XI.- APOLLO CRYOGENIC GAS STORAGE SYSTEM OXYGEN-TANK COMPONENT WEIGHTS (TWO TANKS) - Concluded

System component	No. required	Total weight, lb
Tank assembly	2	168.2
Disconnect valves		4.1
Fill valve	3	1.7
Vent valve	2	2.4
Harness assembly — signal conditioner and electrical plug	2	9.34
Signal conditioner	2	3.0
Electrical connector plug	2	.4
Wire bundle and potting		5.94
Total		181.64

TABLE XII.- APOLLO CRYOGENIC GAS STORAGE SYSTEM HYDROGEN-TANK COMPONENT WEIGHTS (TWO TANKS)

System component	No. required	Total weight, lb
Pressure-vessel assembly	2	40.35
Tank hemisphere, lower	2	20.00
Tank hemisphere, upper	2	20.00
Heater supports and hardware		.35
Outer shells	4	29.36
Ring installation	2	27.64
Girth ring	2	19.00
Disconnect, fill	2	1.30
Disconnect, vent	2	1.60
Diaphragm, burst	2	.20
Electrical connector receptacle	2	.50
Heat shield	2	1.80
Bracketry, hardware, and tubes		3.24
Vac Ion pump, magnet, and bracket	2	8.8
Converter	2	1.6
Probe and heater installation	2	12.70
Probe assembly	2	5.30
Probe density	2	3.08
Filter	2	.20

TABLE XII.- APOLLO CRYOGENIC GAS STORAGE SYSTEM HYDROGEN-TANK

COMPONENT WEIGHTS (TWO TANKS) - Continued

System component	No. required	Total weight, lb
Wire bundle	2	.70
Tubes and couplings	--	1.32
Heater assembly	2	7.40
Tube and nozzle assembly	2	3.00
Fan-motor assembly	4	3.88
Heater element	4	.10
Thermostat	4	.10
Wire bundle		.32
Harness assembly	2	6.68
Electrical plug	2	.58
Signal conditioner	2	3.30
Wire bundle		2.80
Insulation	2	22.41
Beam assembly	2	5.40
Shield assembly	2	11.48
Spider assembly	4	5.21
Fiberglas, insulation, and clamps		.32
Hardware, weld wire, and clamps		.70

TABLE XII.- APOLLO CRYOGENIC GAS STORAGE SYSTEM HYDROGEN-TANK

COMPONENT WEIGHTS (TWO TANKS) - Concluded

System component	No. required	Total weight, lb
Tank assembly	2	150.24
Purge disconnect valve	1	.60
Support skirt	2	9.15
Total		159.99

TABLE XIII.- LUNAR MODULE HELIUM-STORAGE SYSTEM DESIGN CHARACTERISTICS

Characteristic	Value
Maximum fluid fill, lb	48.5
Usable fluid, lb	41.9
Tank-assembly dry weight, maximum, lb	114.0
External fuel to helium heat exchanger, maximum, lb	10.6
Tank volume, ft^3	5.95
Tank inside diameter, in.	26.9
Tank outside diameter, in.	33.0
Design operating pressure at 140° R, psia	1710
Proof pressure at 140° R, psia	2274
Burst pressure at 140° R, psia	3420
Burst-disk range, psid	1881 to 1967
Maximum flow rate, lb/min	5.3
Standby time, hr	131
Pressure-vessel material	Ti-5Al-2.5Sn
Outer-shell material	Ti-5Al-2.5Sn

TABLE XIV.- GROUND SUPPORT EQUIPMENT HELIUM-STORAGE/

TRANSFER DEWAR-SYSTEM-DESIGN CHARACTERISTICS

Characteristic	Value
Helium capacity, ft^3	23.6
Vented heat leak at NTP, Btu/hr	1.1
Insulation	Aluminized Mylar Vapor-cooled shield Gold-plated surfaces
System empty weight, lb	355
Envelope size	
Width, in.	36
Depth, in.	50
Height, in.	75
Dewar material	6061 aluminum
Tubing material	Stainless steel

TABLE XV.- GROUND SUPPORT EQUIPMENT HELIUM-CONDITIONING UNIT

SYSTEM-DESIGN CHARACTERISTICS

Characteristic	Value
Delivery flow rate, lb/hr	1.25 to 3.25
Delivery-pressure range, psig	35 to 500
Delivery temperature, maximum, °R	8.2
LHe precooler tank size and configuration, sphere diameter, in.	40
Vented heat leak during standby, Btu/hr	3.0
Insulation	Vapor-cooled shield Aluminized Mylar Gold-plated surfaces
Temperature sensors	
For 50° to 180° R	Platinum
For 7° to 60° R	Germanium
Basic material	6061 aluminum
Tubing material	Stainless steel

TABLE XVI.- OPERATIONAL CHARACTERISTICS OF THE AAP CRYOGENIC GAS STORAGE SYSTEM

Characteristic	Oxygen, per tank	Hydrogen, per tank	Nitrogen, per tank
Fluid			
Maximum fill, percent	98	98	98
Maximum fill quantity, lb	1221	76.6	868
Usable quantity, lb	1200	75.0	850
Residual, lb	21	1.0	18
Flow rates at NTP			
Minimum normal, lb/hr	0.80	0.06	0.57
Maximum normal lb/hr	8.0	0.60	8.0
Maximum heat leak at minimum dQ/dM for a 1500-hr mission, Btu/hr	28	5	25
Minimum dQ/dM, Btu/lb	35 at 900 psi	100 at 250 psi	44 at 900 psi
Maximum dQ/dM, Btu/lb	160 at 900 psi	275 at 250 psi	180 at 900 psi
Fluid pressure			
Normal operating range, psia	820 to 910	200 to 260	820 to 910
Minimum delivery, psia	150	100	150
Relief valves[a]			
High-pressure			
Crack, min., psi	980	430	980
Full flow, max., psi	1020	440	1020
Reseat, min., psi	950	390	950
Low-pressure			
Crack, min., psi	950	420	950
Normal flow, max., psi	975	430	975
Full flow, max., psi	1020	440	1020
Reseat, max., psi	920	400	920

[a]psi is defined as pressure above ambient pressure.

TABLE XVI.- OPERATIONAL CHARACTERISTICS OF THE AAP CRYOGENIC GAS STORAGE SYSTEM - Concluded

Characteristic	Oxygen, per tank	Hydrogen, per tank	Nitrogen, per tank
Heater circuit			
High-pressure			
Open, psia	$910 \begin{smallmatrix}+0\\-25\end{smallmatrix}$	$260 \begin{smallmatrix}+0\\-15\end{smallmatrix}$	$910 \begin{smallmatrix}+0\\-25\end{smallmatrix}$
Close, psia	$845 \begin{smallmatrix}+25\\-0\end{smallmatrix}$	$220 \begin{smallmatrix}+15\\-0\end{smallmatrix}$	$845 \begin{smallmatrix}+25\\-0\end{smallmatrix}$
Low-pressure			
Open, psia	$845 \begin{smallmatrix}+0\\-25\end{smallmatrix}$	$240 \begin{smallmatrix}+0\\-15\end{smallmatrix}$	$845 \begin{smallmatrix}+0\\-25\end{smallmatrix}$
Close, psia	$820 \begin{smallmatrix}+25\\-0\end{smallmatrix}$	$200 \begin{smallmatrix}+15\\-0\end{smallmatrix}$	$820 \begin{smallmatrix}+25\\-0\end{smallmatrix}$
Operating fluid temperature, °F . . .	-300 to 80	-425 to 80	-325 to 80
Servicing characteristics			
Fill time, hr	3.0	3.0	3.0
Chilldown time, hr	36.0	36.0	36.0
Top-off time, hr	3.0	3.0	3.0
Pressure buildup at NTP			
Standby time, min., hr	50	50	50
Heater time, max., hr	10	10	10

TABLE XVII.- ELECTRICAL AND INSTRUMENTATION CHARACTERISTICS OF THE AAP CRYOGENIC GAS STORAGE SYSTEM

Characteristic	Oxygen per tank	Hydrogen, per tank	Nitrogen, per tank
Connectors	Hermetically sealed pin receptacle	Hermetically sealed pin receptacle	Hermetically sealed pin receptacle
Heaters			
Voltage, V dc	28	28	28
Power, each, W	45	45	45
Number	8	1	8
Resistance per heater, nominal, ohms	15	15	15
Power, total, W	360	45	360
Fan motors			
Voltage at 400 Hz, V ac	115	115	115
Power, each, W	25	25	25
Number	2	2	2
Power, total, W	50	50	50
Pressure-gaging system			
Range, psia	0 to 1200	0 to 550	0 to 1200
Accuracy, percent full range	±2.5	±2.5	±2.5
Output voltage, V dc	0 to 5	0 to 5	0 to 5
Output impedance, ohms	500	500	500
Power, W	0.35	0.35	0.35
Voltage, V dc	28	28	28
Quantity-gaging system			
Range, percent full	0 to 100	0 to 100	0 to 100
Accuracy, percent of full range	±2.5	±2.5	±2.5
Output voltage, V dc	0 to 5	0 to 5	0 to 5
Output impedance, ohms	500	500	500
Power, W	4.5	4.5	4.5
Voltage at 400 Hz, V ac	115	115	115

TABLE XVII.- ELECTRICAL AND INSTRUMENTATION CHARACTERISTICS OF THE AAP CRYOGENIC GAS STORAGE SYSTEM - Concluded

Characteristic	Oxygen per tank	Hydrogen, per tank	Nitrogen, per tank
Temperature-gaging system			
Range, °F	-425 to 80	-425 to 80	-425 to 80
Accuracy, percent full range . . .	±2.5	±2.5	±2.5
Output voltage, V dc	0 to 5	0 to 5	0 to 5
Output impedance, ohms	500	500	500
Power, W	1.1	1.1	1.1
Voltage, V dc	28	28	28
Ion-pump power supply			
Power, W	10	10	10
Voltage, V dc	28	28	28

TABLE XVIII.- STRUCTURAL CHARACTERISTICS OF THE AAP CRYOGENIC GAS STORAGE SYSTEM

Characteristic	Oxygen, per tank	Hydrogen, per tank	Nitrogen, per tank
Pressure vessel			
Material	Inconel 718	Inconel 718	Inconel 718
Ultimate strength, psi	180 000	180 000	180 000
Yield strength, psi	145 000	145 000	145 000
Safety factors			
Ultimate strength	2	4.5	2
Yield strength	1.5	3	1.5
Configuration	Spherical	Spherical	Spherical
Volume, ft^3	17.5	17.5	17.5
Outside diameter, in.	39.0	39.0	39.0
Wall thickness[a], in.	$0.130\,^{+0.011}_{-0.017}$	$0.130\,^{+0.011}_{-0.017}$	$0.130\,^{+0.011}_{-0.017}$
Girth thickness, in.	0.141 ± 0.003	0.141 ± 0.003	0.141 ± 0.003
Weight, lb	182 to 185	182 to 185	182 to 185
Outer shell			
Material	6061 Al	6061 Al	6061 Al
Buckling pressure differential at 140° F, minimum, psid	20	20	20
Configuration	Spherical	Spherical	Spherical
Outside diameter, in.	41.5	41.5	41.5
Wall thickness, in.	0.064	0.064	0.064
Weight, lb	34.5	34.5	34.5

[a]Tolerance varies along the meridian.

TABLE XIX.- APOLLO APPLICATION PROGRAM CRYOGENIC GAS STORAGE SYSTEM WEIGHTS

Item	Oxygen, per tank	Hydrogen, per tank	Nitrogen, per tank
System weight			
CGSS assembly, lb	380	338	380
Dewar assembly, lb	283	283	283
Mount/interface structure, lb	74	32	74
External components	10	10	10
Interface connections	13	13	13
Major parts weight			
Pressure vessel, lb	182 to 185	182 to 185	182 to 185
Outer shell, lb	34.5	34.5	34.5

TABLE XX.- DISCRETE-SHIELD RADIAL-BUMPER CRYOGENIC GAS STORAGE SYSTEM

DESIGN CHARACTERISTICS

Characteristic	Oxygen, phase A	Oxygen, phase B	Hydrogen, phase B
Fluid			
Maximum fill quantity, lb	174.5	327	28.5
Percent fill	98.8	97	97
Heat leak at NTP, vented			
Oxygen test fluid			
Non-vapor-cooling, Btu/hr	7.3	11.7	--
Nitrogen test fluid			
Non-vapor-cooling, Btu/hr	6.8	10.3	9.1
Hydrogen test fluid			
Non-vapor-cooling, Btu/hr	5.1	7.9	8.0
Vapor cooling, Btu/hr	--	--	2.9
Helium test fluid			
Non-vapor-cooling, Btu/hr	--	--	5.3
Vapor cooling, Btu/hr	--	--	1.7
Operating pressure range, psi	900	800 to 815	235 to 250
Pressure-relief valve			
Cracking pressure, psi	950	900 ± 10	285 ± 5
Reseat pressure, psi	--	810 ± 10	270 ± 5
Heater circuit			
Open, psi	--	815 ± 10	250 ± 5
Close, psi	--	800 ± 10	235 ± 5
Heater	None		
Type	--	Electrical resistance	Electrical resistance
Element	--	Nichrome	Nichrome
Insulation	--	Magnesium oxide	Magnesium oxide

TABLE XX.- DISCRETE-SHIELD RADIAL-BUMPER CRYOGENIC GAS STORAGE SYSTEM

DESIGN CHARACTERISTICS - Continued

Characteristic	Oxygen, phase A	Oxygen, phase B	Hydrogen, phase B
Sheath	--	Stainless steel	Stainless steel
Element size, in.	--	65 long by 0.062 o.d.	24 long by 0.062 o.d.
Voltage (a.c. at 60 Hz), V	--	115	28 d.c.
Power, each, W	--	171.5	30
Number	--	2	2
Quantity sensor	--	Interleaf plate capacitor	Interleaf plate capacitor
Temperature sensor	Thermocouple, copper-constantan	Thermocouple, copper-constantan	Thermocouple, copper-constantan
Fan-motor			
Voltage at 900 Hz, V ac	--	200	200
Power, each, W	--	5.0	5.0
Number	--	2	2
Ion pump			
Capacity, liter/sec	0.2	0.2	0.2
Voltage, kV dc	2.9	2.9	2.9
Internal thermal conductor	Spiral 5052 aluminum	--	--
Pressure vessel			
Volume, ft^3	2.50	4.8	6.7
Inside diameter, in.	20.3	25.1	28.1
Material	Inconel 718	301 stainless steel cryoformed	Inconel 718
Wall thickness, in.	0.084	0.036	0.028
Proof pressure, psi	1600	1275	430
Burst pressure, psi	2100	1500	500
Outside surface	Silver plated	Silver plated	Silver plated

TABLE XX.- DISCRETE-SHIELD RADIAL-BUMPER CRYOGENIC GAS STORAGE SYSTEM

DESIGN CHARACTERISTICS - Concluded

Characteristic	Oxygen, phase A	Oxygen, phase B	Hydrogen, phase B
Radial bumpers			
Number	6	8	8
Material	Glass-filled Teflon	Kel-F	Kel-F
Fill and vent tubing			
Material	304L stainless steel	304L stainless steel	304L stainless steel
Outer diameter, in.	0.3125	0.3125	0.3125
Wall thickness, in.	0.016	0.010	0.010
Radiation shields			
Number	2	2	4
Material	5052 aluminum	6061 aluminum	6061 aluminum
Thickness, in.	0.017	0.020	0.020
Surfaces	Silver plated	Silver plated	Silver plated
Outer shell			
Outside diameter, in.	22.0	28.96	32.36
Material	304L stainless steel	304L stainless steel	304L stainless steel
Wall thickness, in.	0.035	0.033	0.037

TABLE XXI.- CRYOGENIC GAS STORAGE SYSTEM DESIGN

PARAMETERS FOR SUBCRITICAL NITROGEN

Operating pressure range, psia	130 to 170
Delivery pressure, psia	60 ± 5
Relief pressure, psia	220 ± 20
Proof pressure, min., psia	360
Burst pressure, min., psia	480
Maximum filled weight, lb	275
Liquid nitrogen capacity, lb	128
Standby time, nonvented at 160° F, hr	30
Ambient temperature range, °F	-65 to +160
Delivery rate, lb/hr	1.25 ± 0.13
Total 28 V dc electrical power available, prelaunch, W	400
Total 28 V dc electrical power available, postlaunch, W	174
Shelf life, yr	1
Radio noise specification	MIL-1-26600 (USAF)

TABLE XXII.- DESIGN CHARACTERISTICS OF THE SINGLE-WALL-TANK CRYOGENIC GAS STORAGE SYSTEM

Pressure vessel	
Material	Inconel 718
Outside diameter, in.	39.0
Volume, ft^3	17.36
Liquid nitrogen capacity, lb	875
Thermodynamic performance (with nitrogen)	
Environmental pressure, torr	1.2×10^{-6}
Environmental temperature, °F	86
Fluid pressure, psia	16.6
Heat leak, Btu/hr	8.52
Flow rate, lb/hr	0.1001
Insulation	
Ground-hold	2 in. of nopcofoam (polyurethane foam)
Orbital	2 in. of 0.25 mil NRC-2 (aluminized Mylar)

TABLE XXIII.- PRESSURE-VESSEL-MATERIAL PROPERTIES AT 70° F[a]

	Tensile strength, ultimate, F_{TU}, ksi	Tensile strength, yield, F_{TY}, ksi	Elongation, percent	Young's modulus $E \times 10^{-6}$, psi	Density, ρ, lb/in^3	$\frac{F_{TU}}{\rho}$
Titanium alloy C 120-AV (annealed)	136	127	12	15.8	0.160	850
Titanium alloy A 110-AT (annealed)	115	105	16	15.6	0.161	715
Rene 41 (solution treated)	200	160	14	31.6	0.298	672
304 ELC stainless steel (SS)	82	30	62	29	0.29	282
304 SS (40 percent cold reduction)	155	130	8	25	0.20	535
AM 350 SS (SCT 1050)	166	138	15	28	0.29	572
301 SS cryogenic formed	260	220	5	28	0.29	897
Aluminum alloy 6061-T6	45	38	18	10	0.098	459
Inconel 718 (double aged)	192	156	18	31	0.298	645
Aluminum alloy 2219-T62	54	39	11	10	0.098	551
Aluminum alloy-Kaiser 7039-T6	63	55	13	10	0.098	643
Aluminum alloy Alcoa X 7006-T6	63	57	15	10	0.098	643
Beryllium	69	59	5	43	0.066	1045

[a]Titanium A110-AT (Ti 5Al-2.5 Sn) is susceptible to room temperature creep and Inconel 718 is susceptible to stress cracking when exposed to gaseous hydrogen.

TABLE XXIV.- CRYOGENIC PROPERTIES OF GASES

Property	Gas					
	He	Ne	H_2	N_2	O_2	F_2
Density, 32° F, 1 atm, lb/ft^3	0.01114	0.0562	0.00561	0.0781	0.0892	0.106
Boiling point, 1 atm, °F	-452.0	-410.6	-423.0	-320.4	-297.4	-306.5
Melting point, 1 atm, °F	-458.0 (at 26 atm)	-415.7	-434.6	-345.8	-361.1	-363.3
Vapor density at boiling point, lb/ft^3	0.999	0.593	0.0830	0.288	0.296	--
Liquid density at boiling point, vapor pressure, lb/ft^3	7.803	74.91	4.37	50.19	71.29	94.4
Vapor pressure solid at melting point, mm Hg	<0.02	323	54	96.4	2.0	0.12
Heat of vaporization at boiling point, Btu/lb	10.3	37.4	194.4	85.7	91.6	73.7
Heat of fusion at melting point, Btu/lb	<1.8	7.2	25.2	11.0	5.9	5.8
[a]C_p, 59° F and 1 atm, Btu/lb-°F	1.25 (at -292° F)	~0.25	3.39	0.248	0.218	0.180
C_p/C_v, 59° to 68° F and 1 atm	1.66 (at -292° F)	1.64	1.41	1.40	1.40	--
Critical temperature, °F	-450.2	-379.7	-399.8	-232.8	-181.1	-200.2
Critical pressure, psia	33.2	394.6	188.1	492.3	730.3	808.3

[a]C = specific heat, Btu/lb-°F.
v = constant volume.
p - constant pressure.

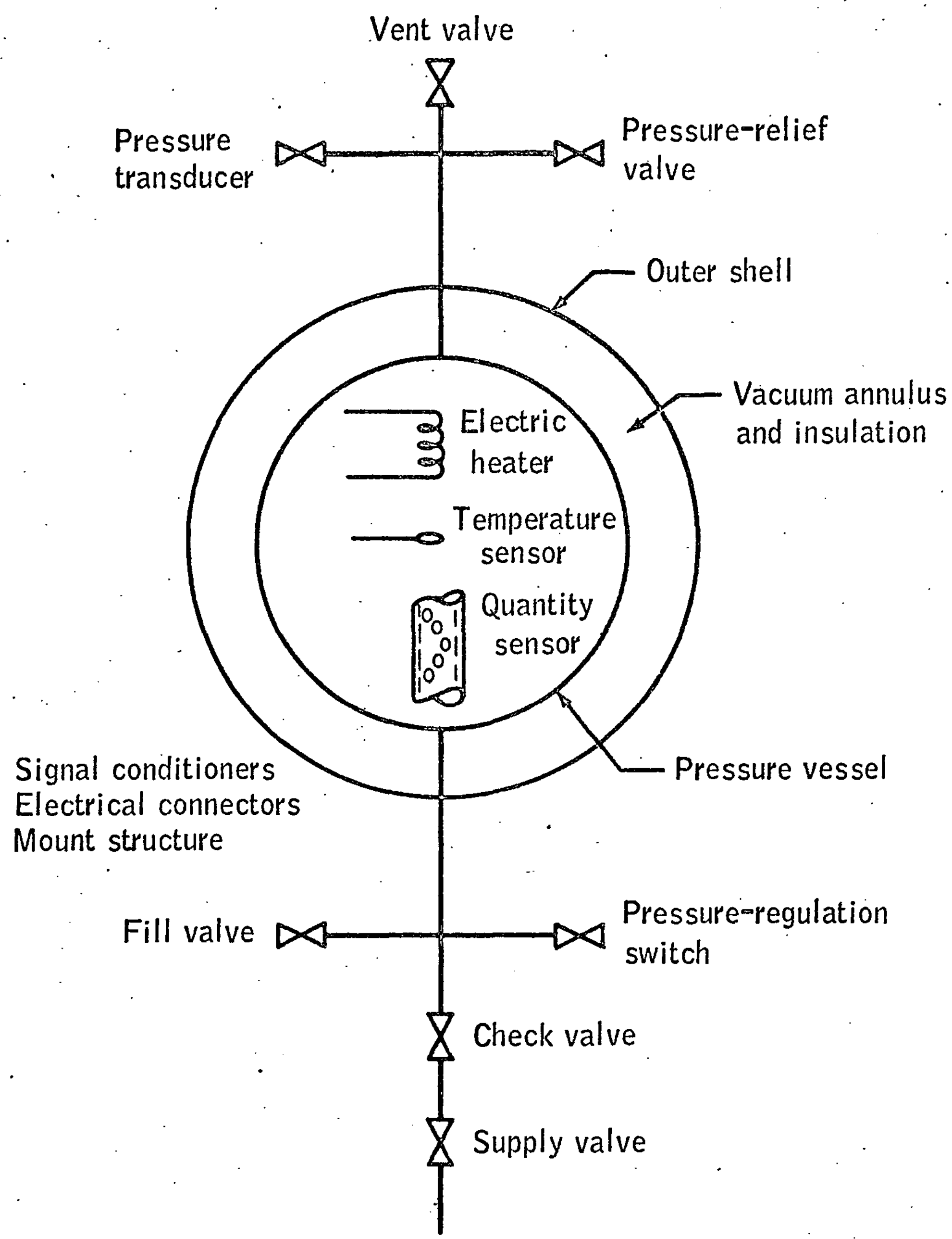


Figure 1.- A typical Dewar cryogenic gas storage system for a spacecraft.

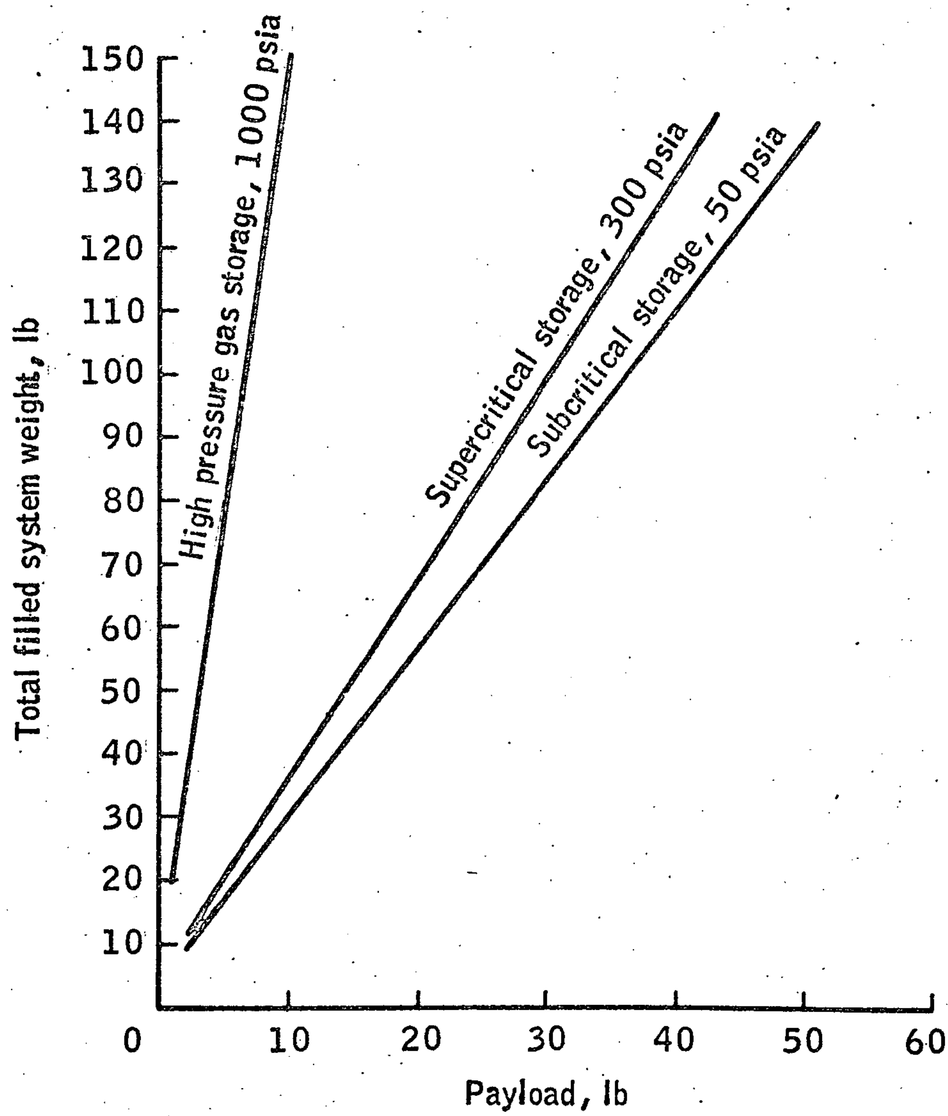


Figure 2.- Total hydrogen tankage weight plotted as a function of payload.

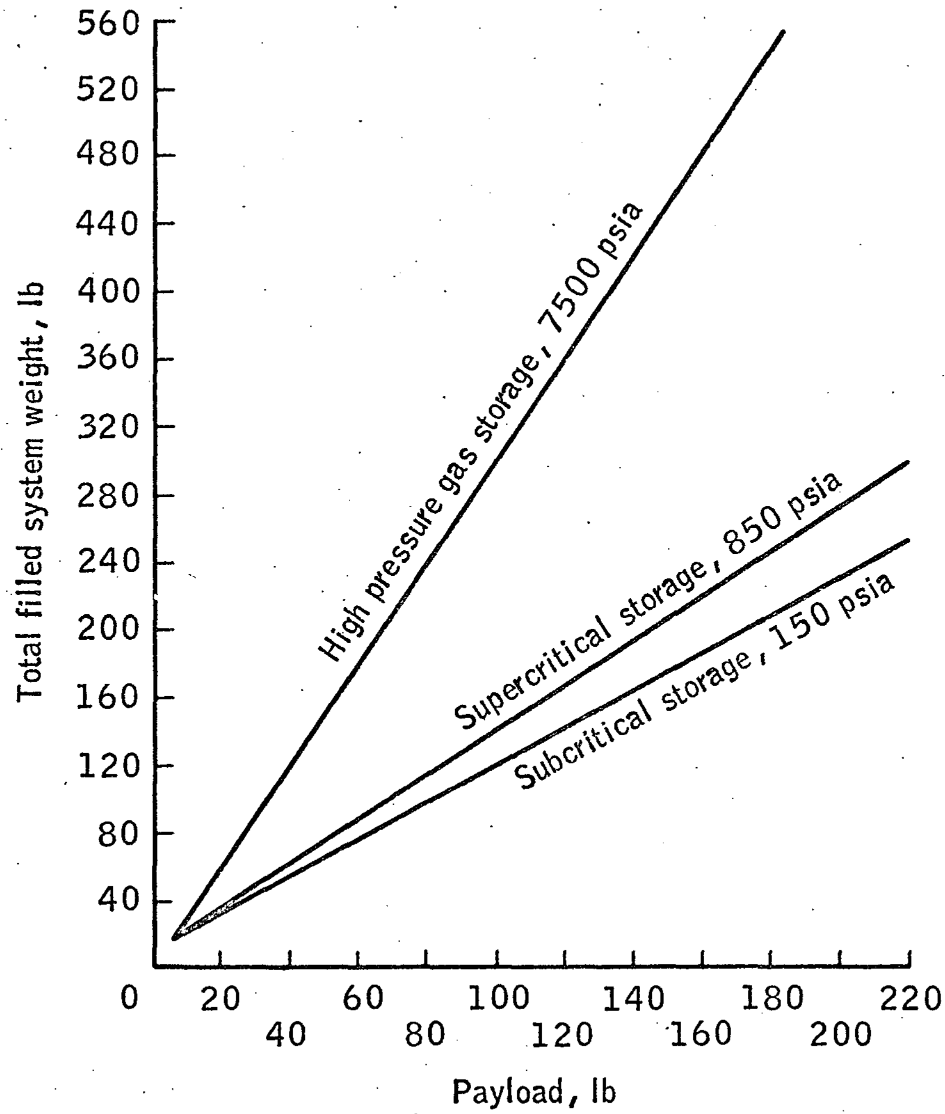


Figure 3.- Total oxygen tankage weight plotted as a function of payload.

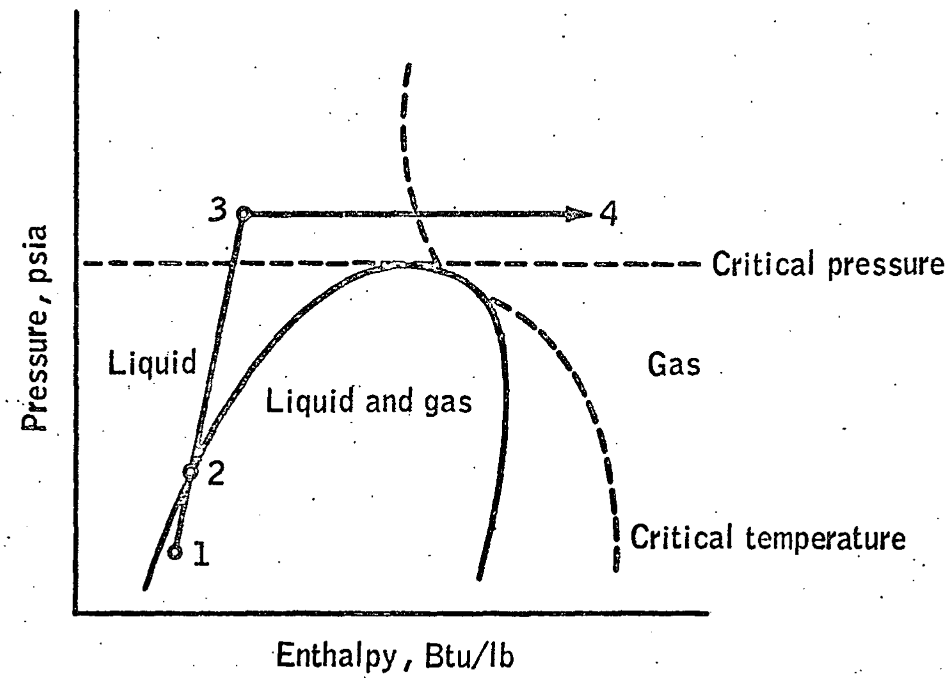


Figure 4.- A pressure-enthalpy diagram of supercritical storage.

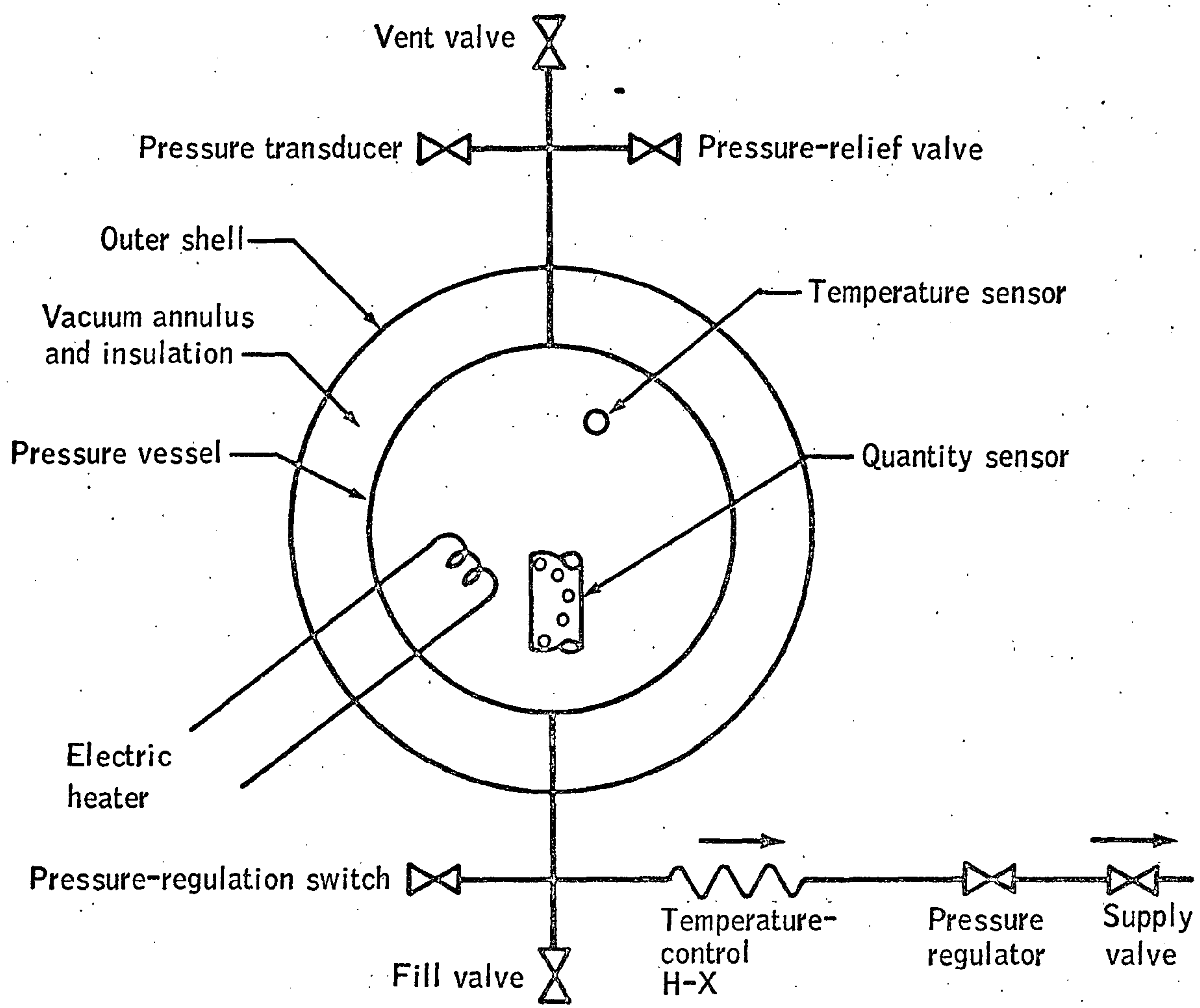


Figure 5.- A supercritical storage system.

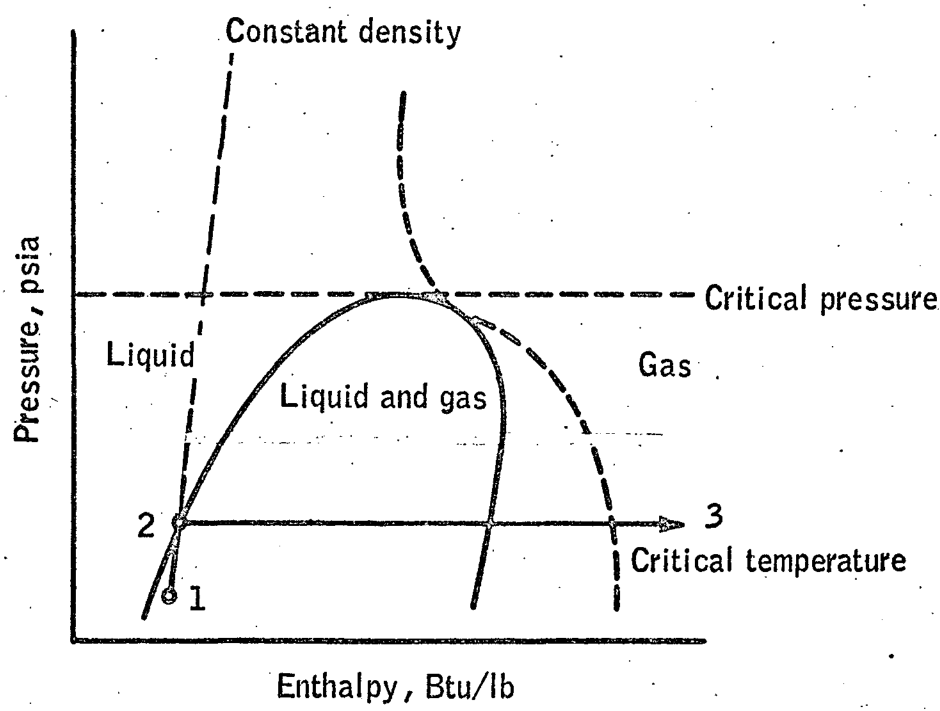


Figure 6.- A pressure-enthalpy diagram of subcritical storage.

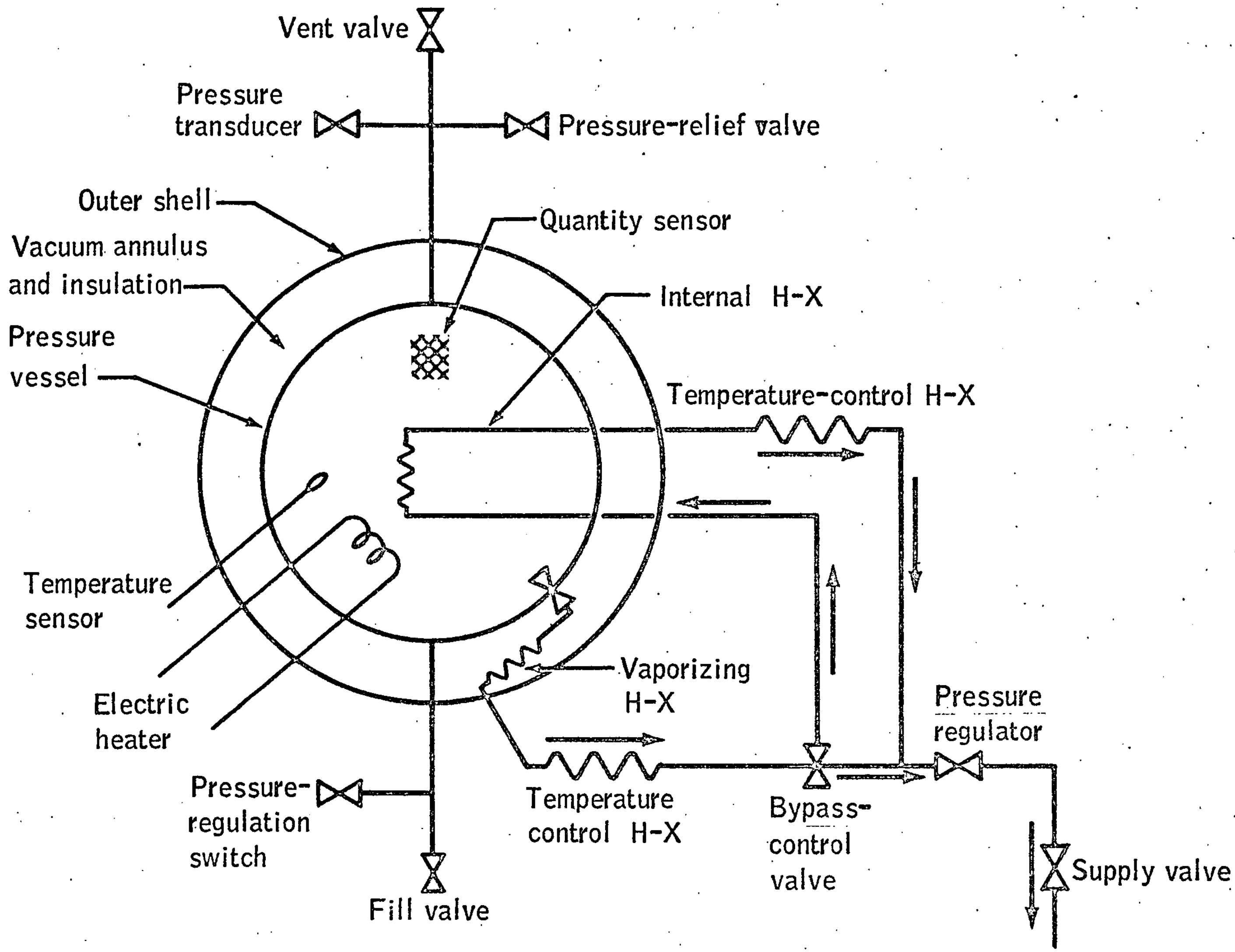


Figure 7.- A subcritical storage system.

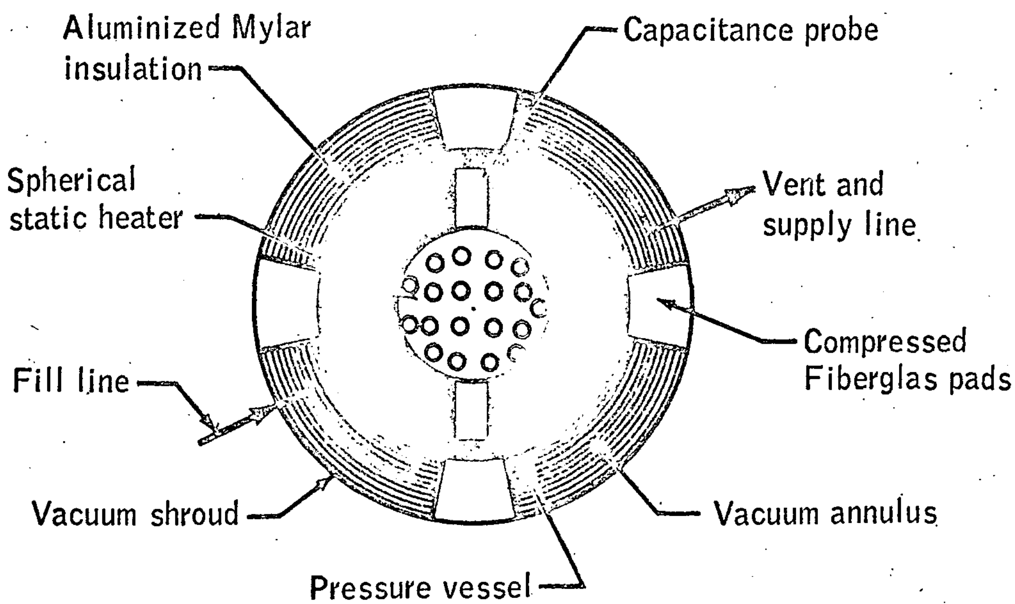


Figure 8.- A typical Gemini cryogenic storage tank.

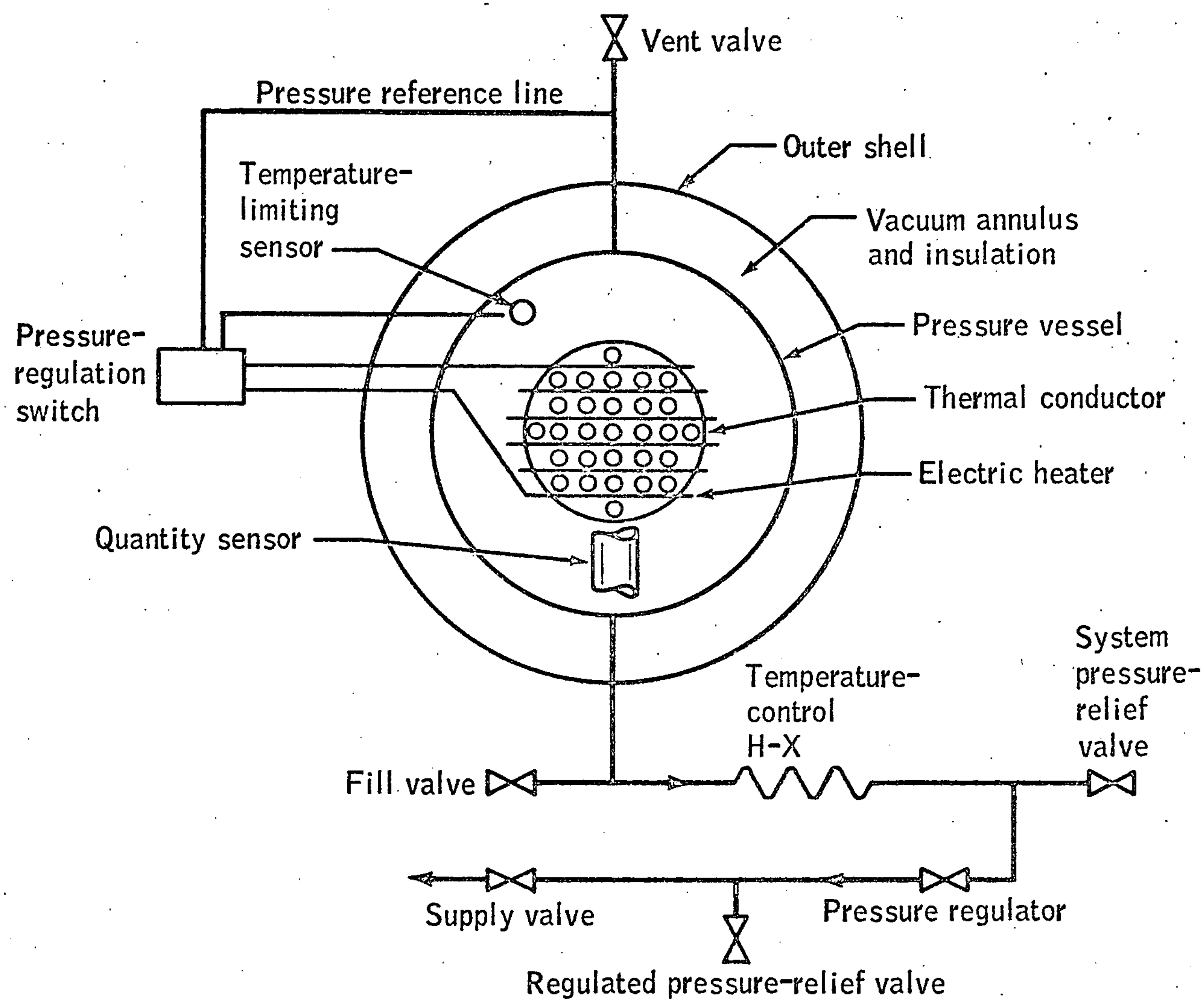


Figure 9.- A typical Gemini cryogenic storage system.

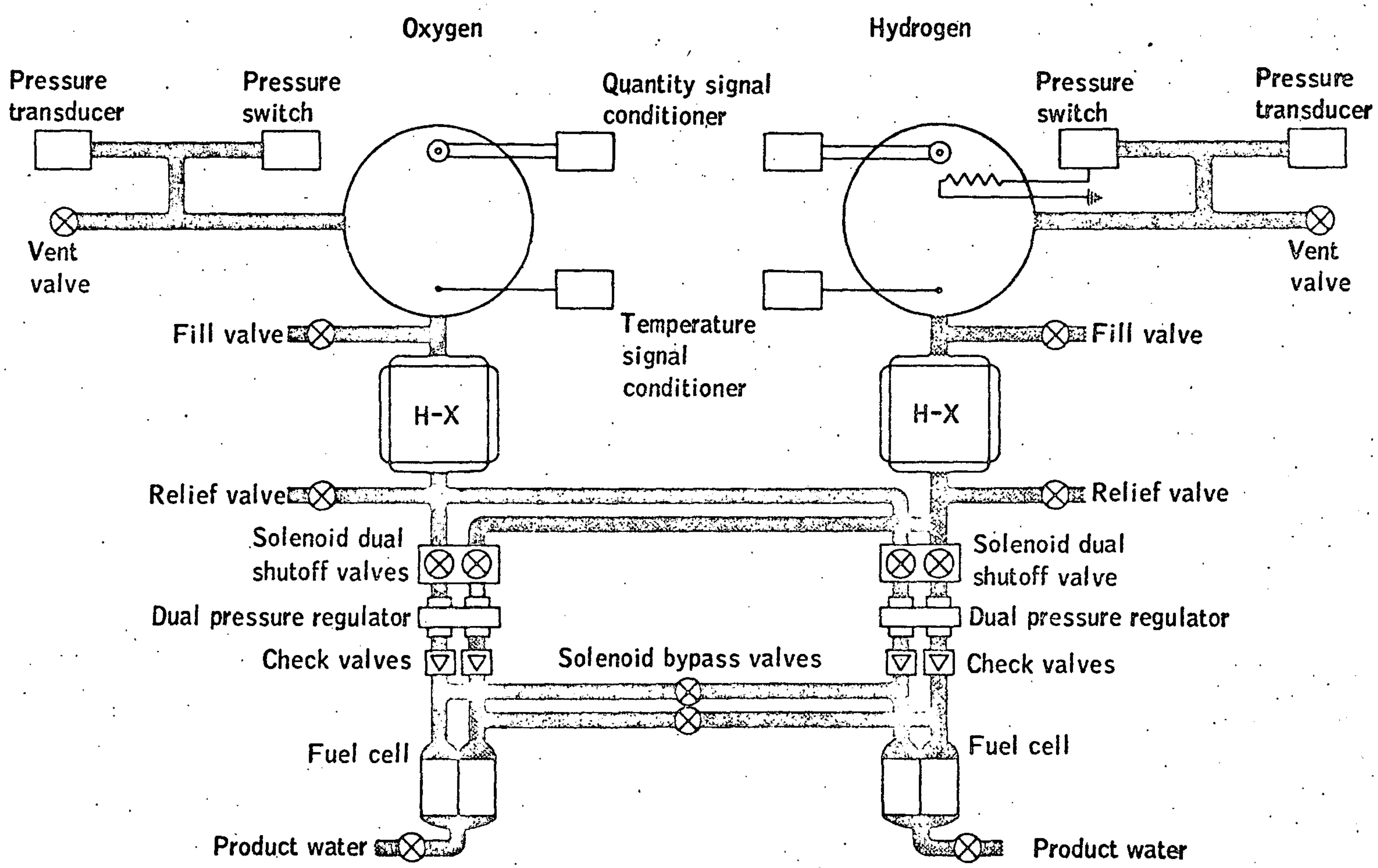


Figure 10.- The Gemini reactant supply system.

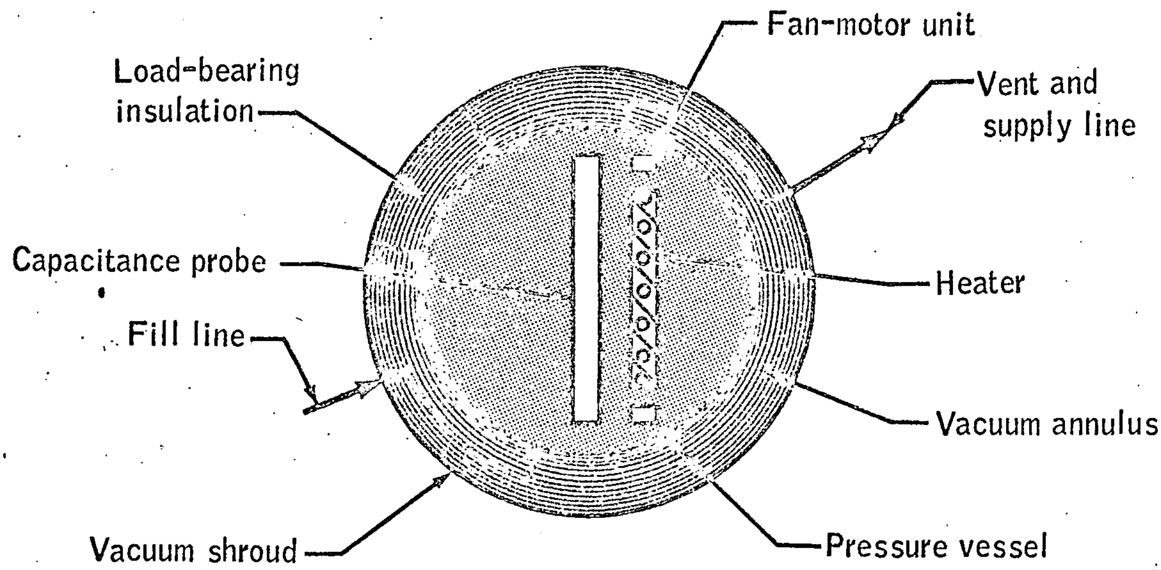


Figure 11.- A typical Apollo oxygen cryogenic storage tank.

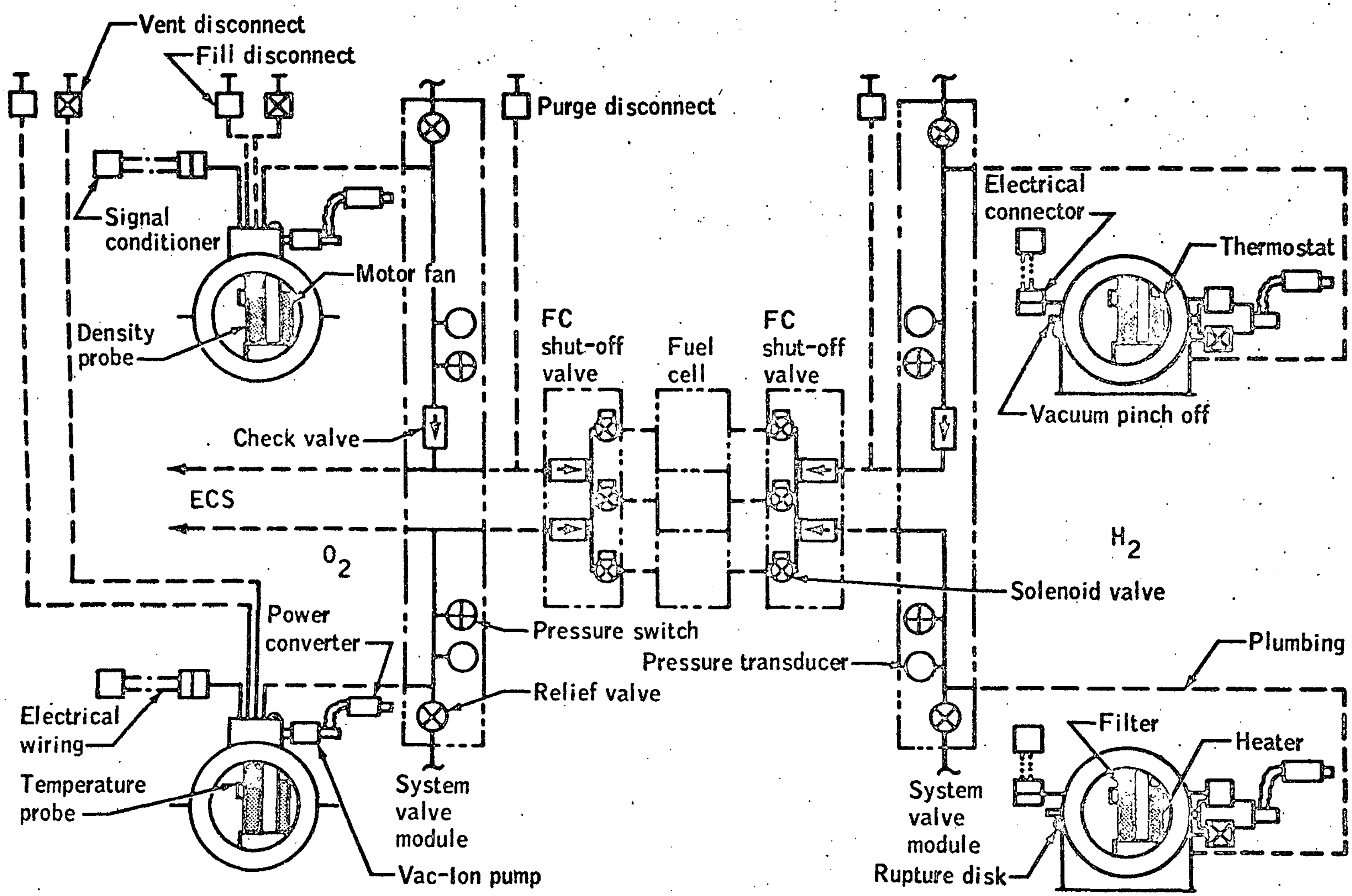


Figure 12.- The Apollo spacecraft cryogenic gas storage system.

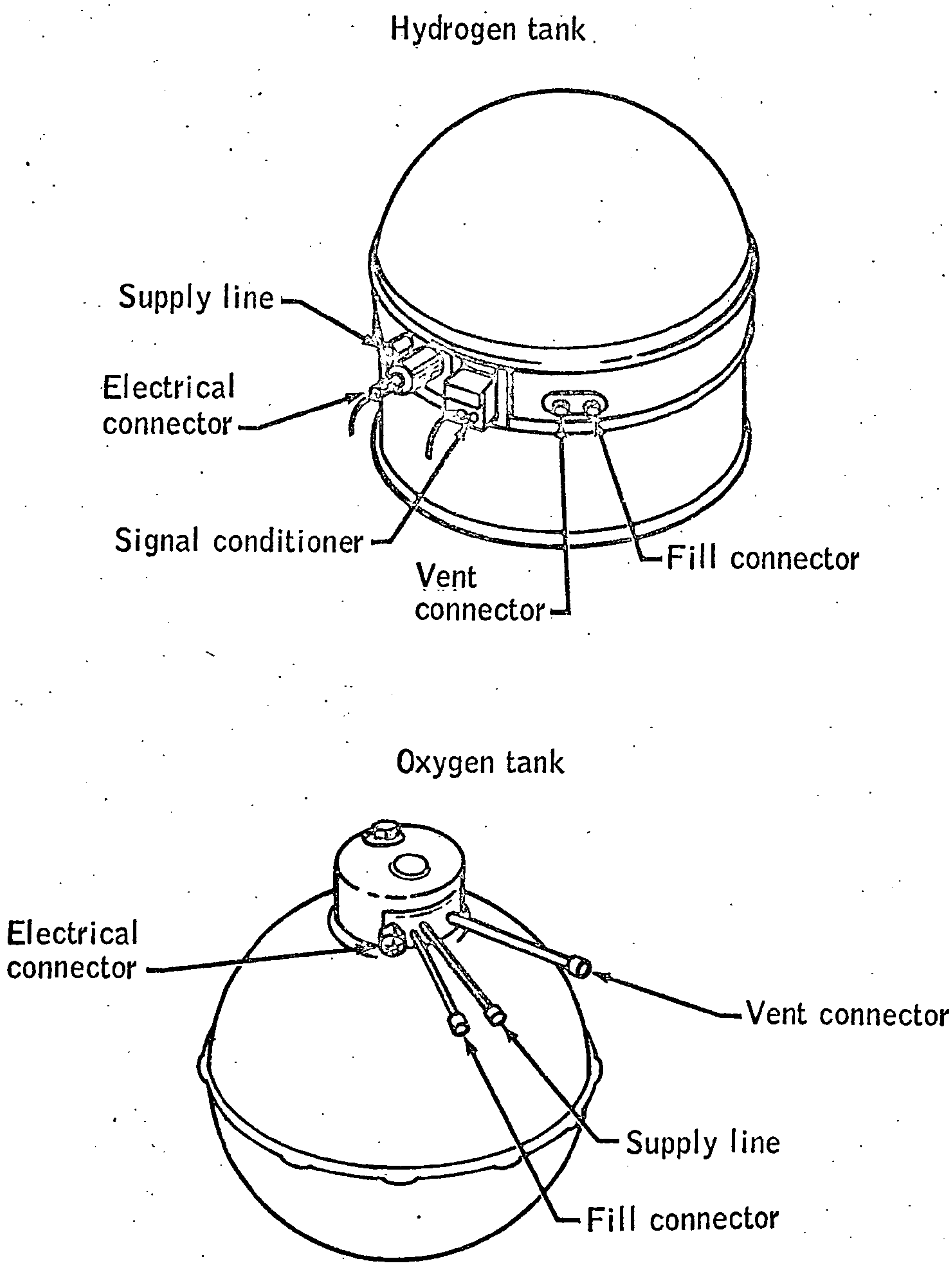


Figure 13.- The Apollo cryogenic storage tanks.

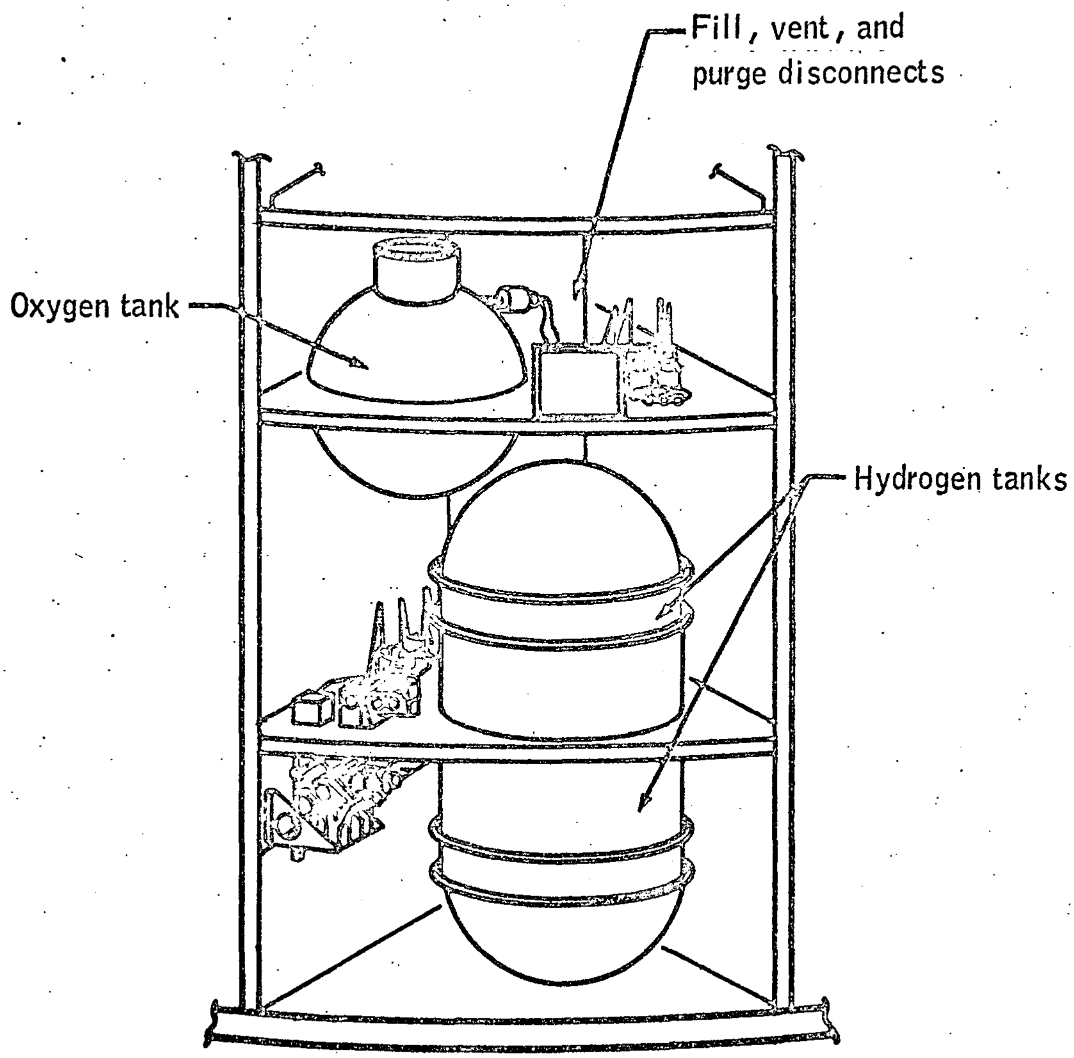


Figure 14.- The Apollo cryogenic storage tanks installed in the spacecraft.

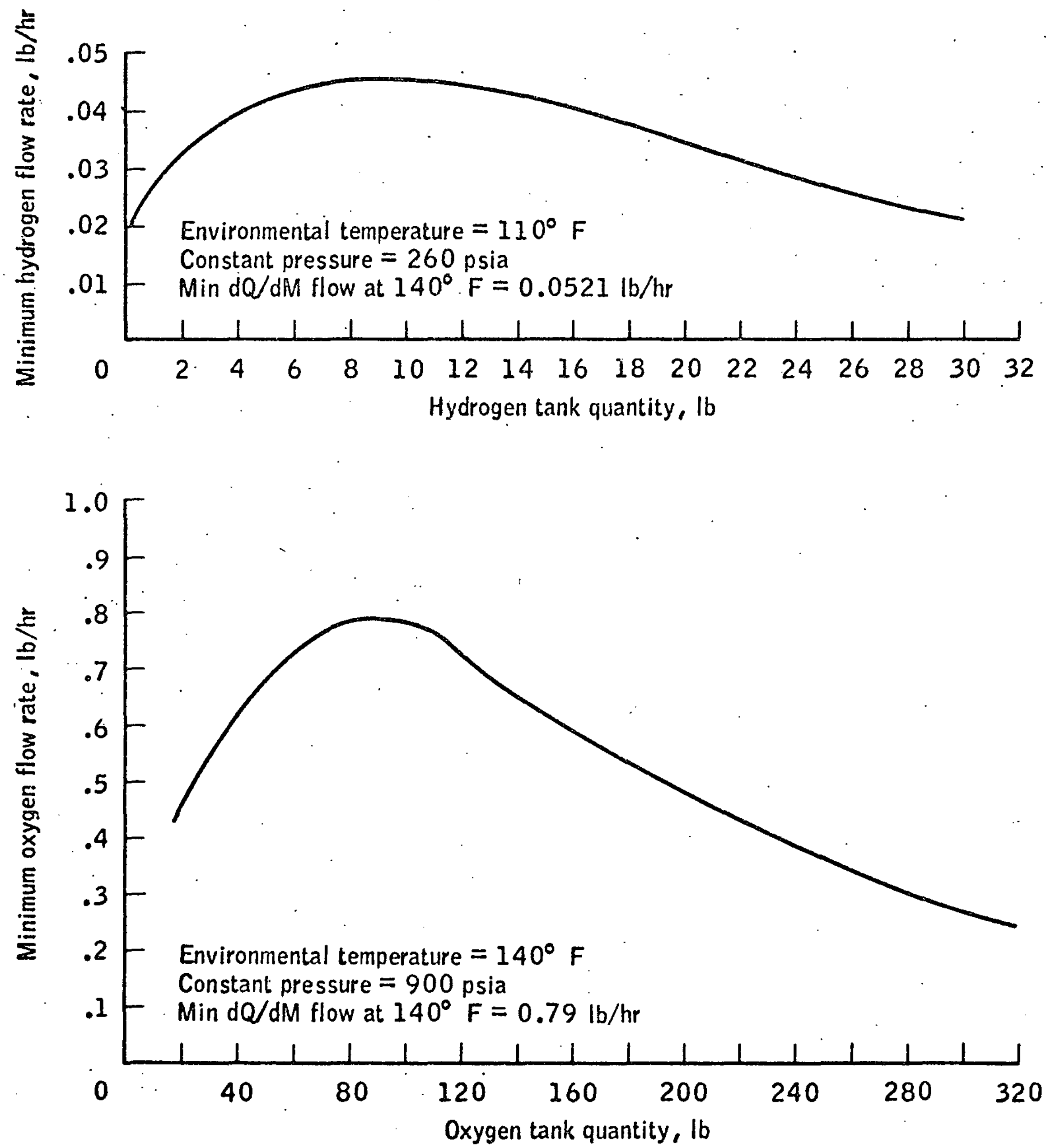
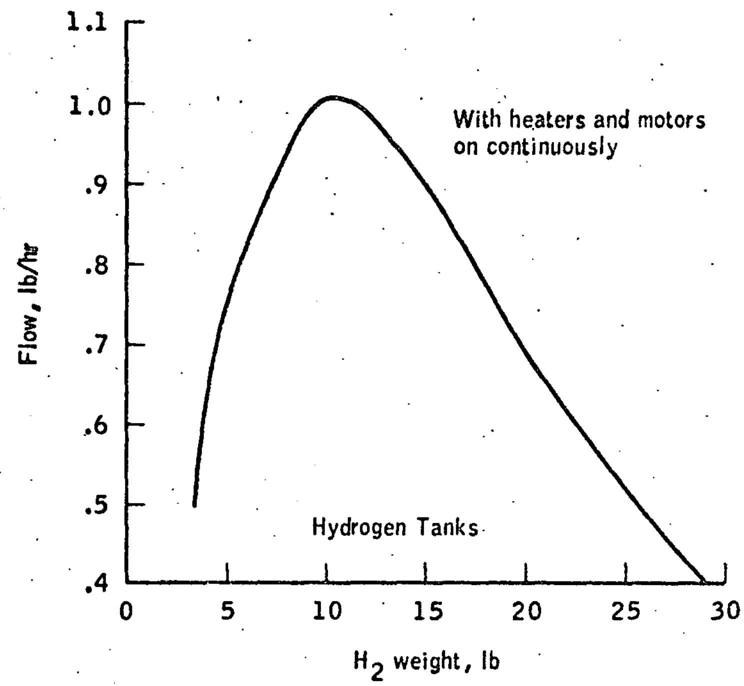


Figure 15.- The minimum continuous flow rate at a constant pressure compared with tank quantity for the Apollo CGSS.



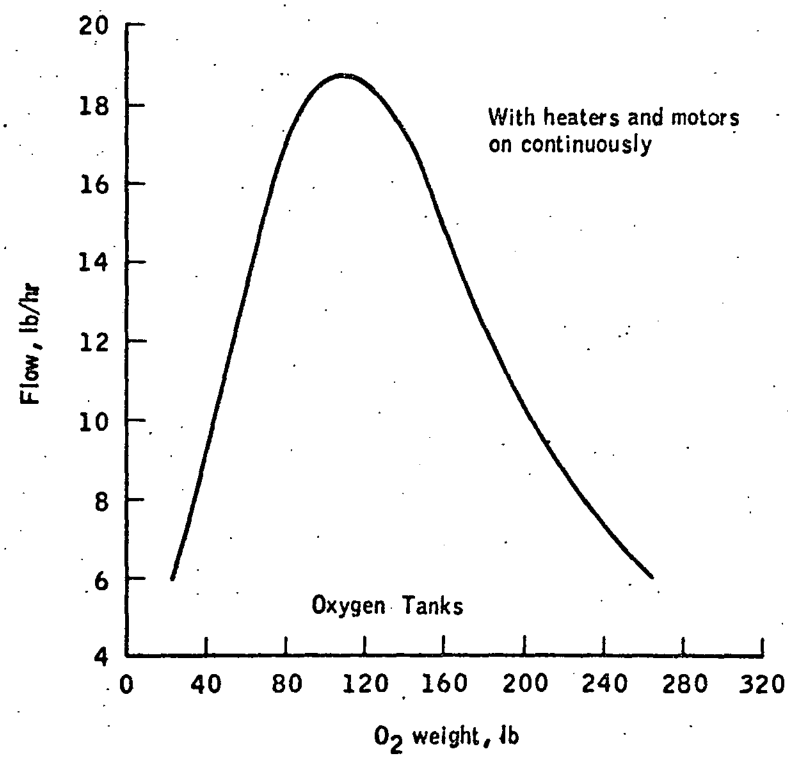


Figure 16.- The maximum continuous flow rates for the Apollo CGSS.

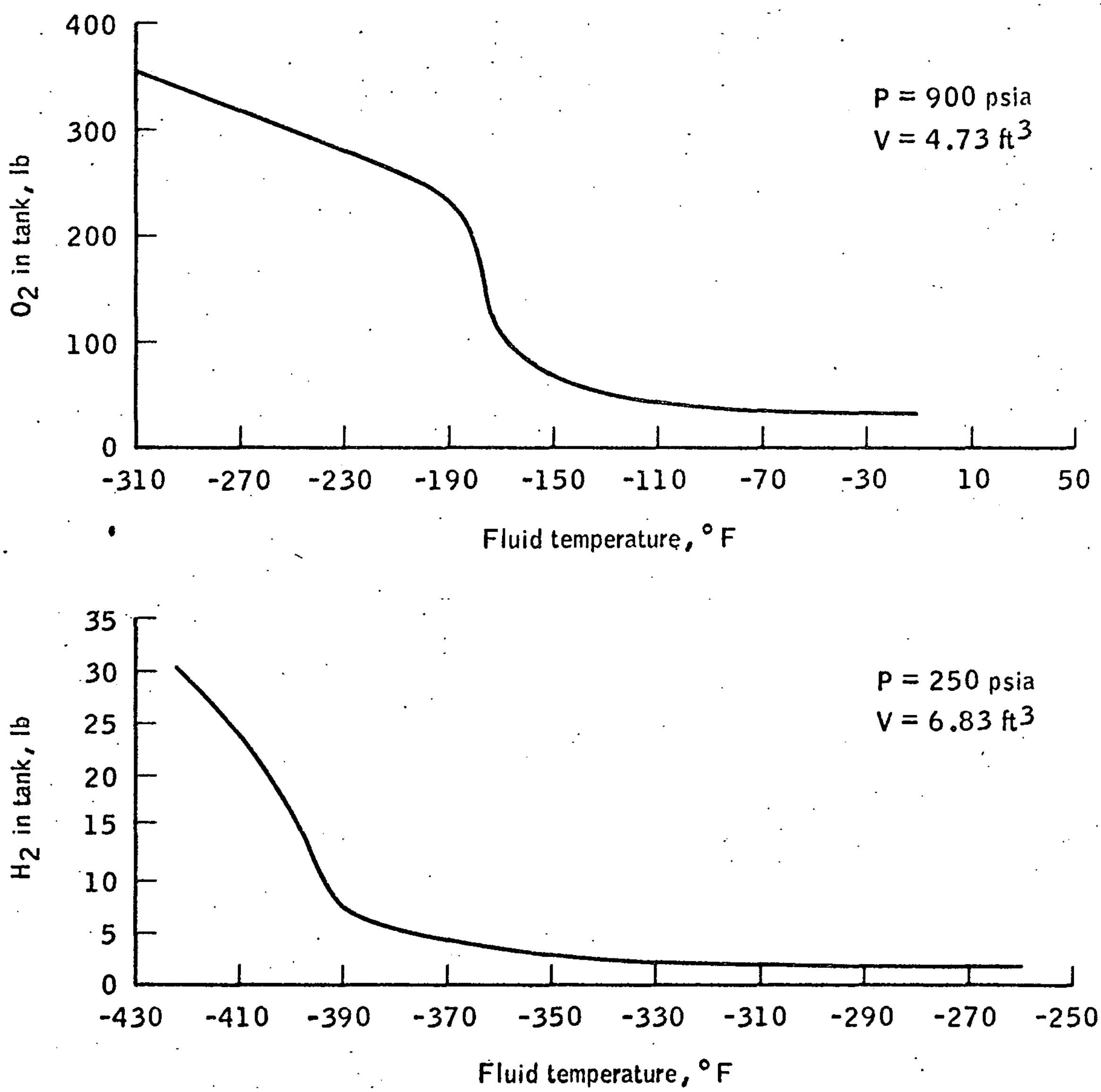


Figure 17.- Tank quantity compared with fluid temperature for the Apollo CGSS.

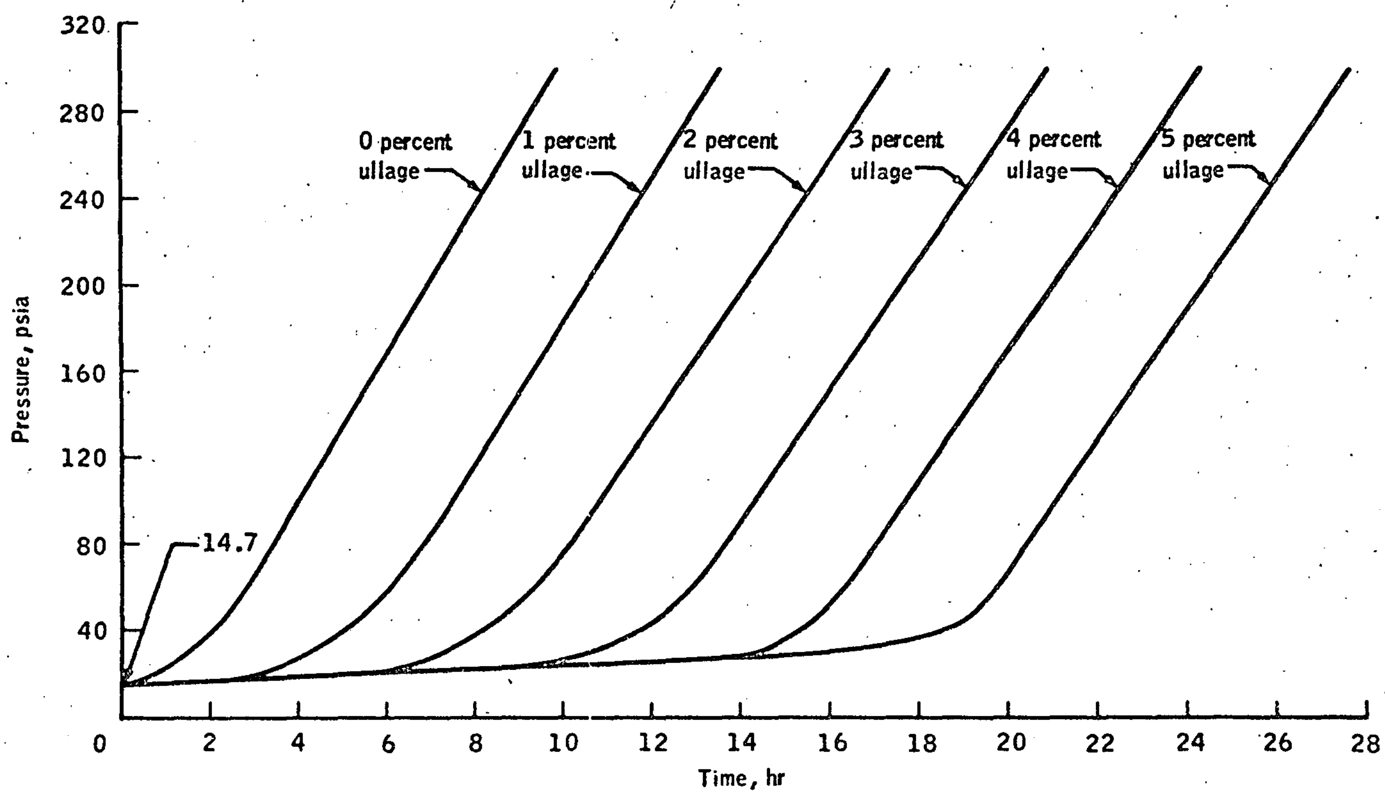


Figure 18.- The hydrogen-tank pressurization rate for the Apollo CGSS; no flow, standby, and heaters off.

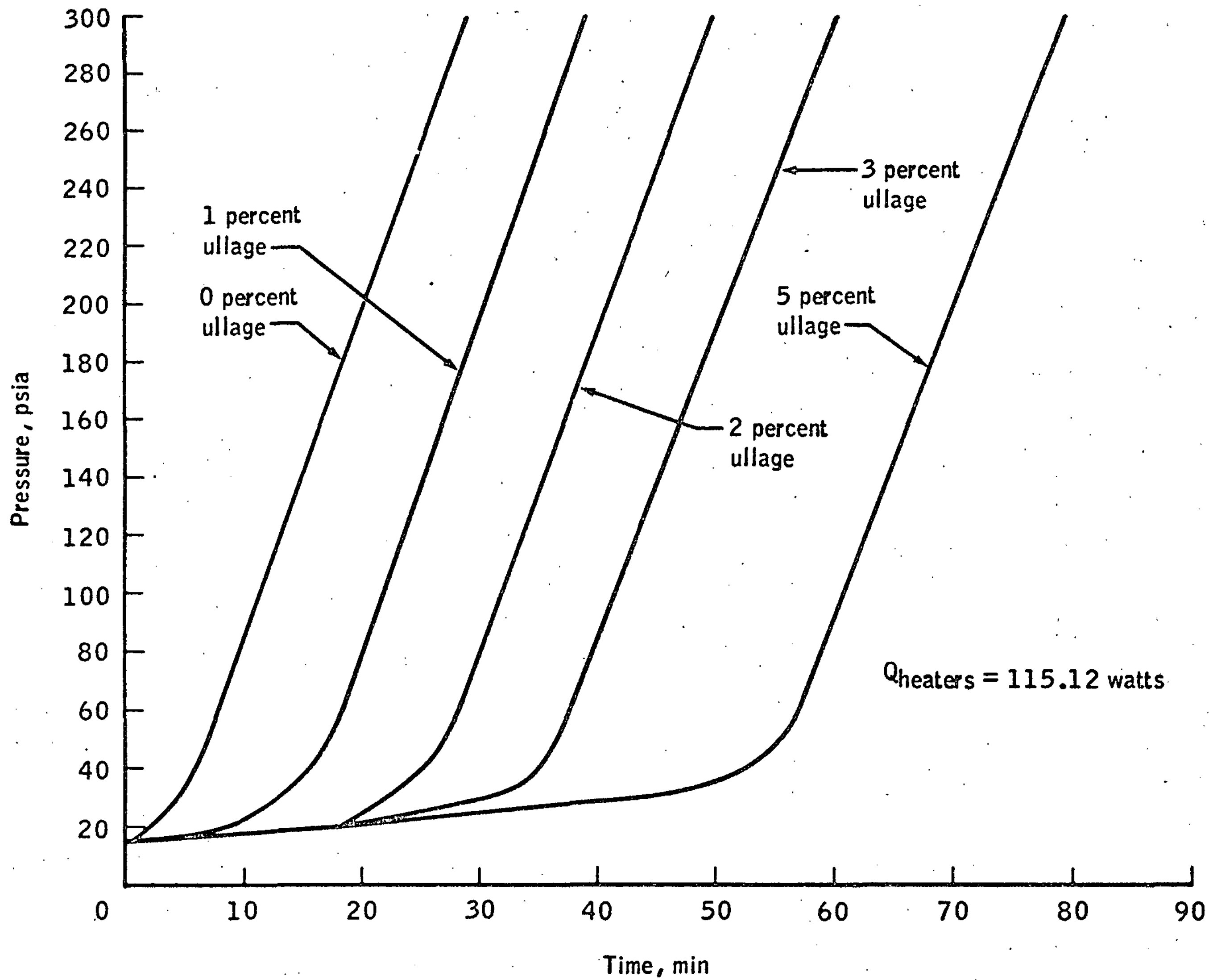


Figure 19.- The hydrogen-tank pressurization rate for the Apollo CGSS; no flow and with heaters and motors operating on GSE power.

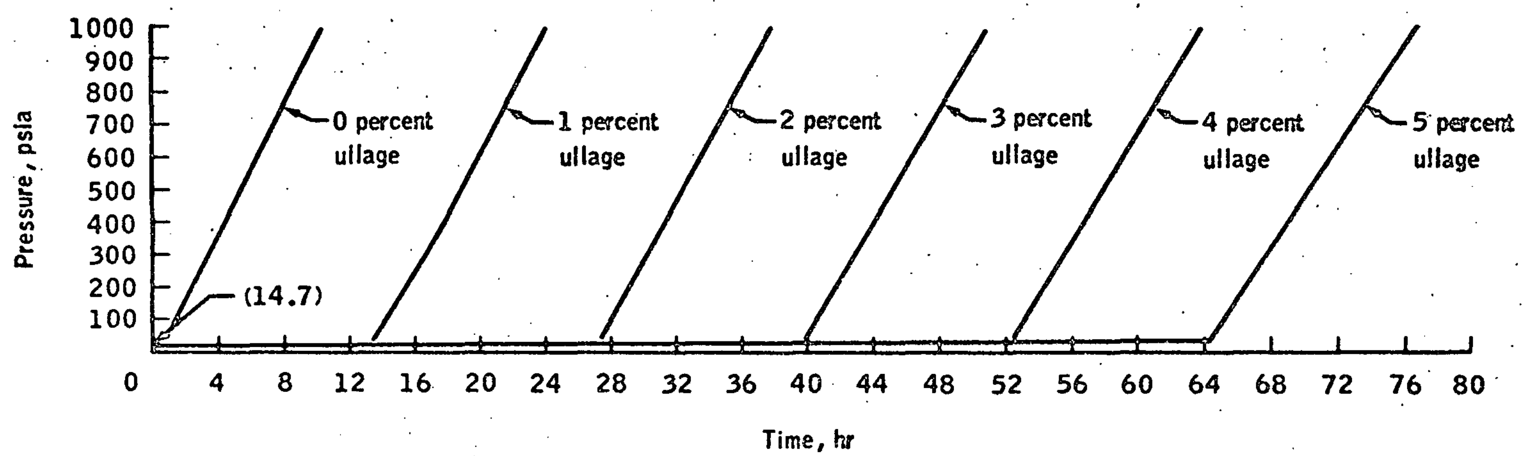


Figure 20.- The Apollo CGSS oxygen-tank pressurization rate; no flow, standby, and heaters off.

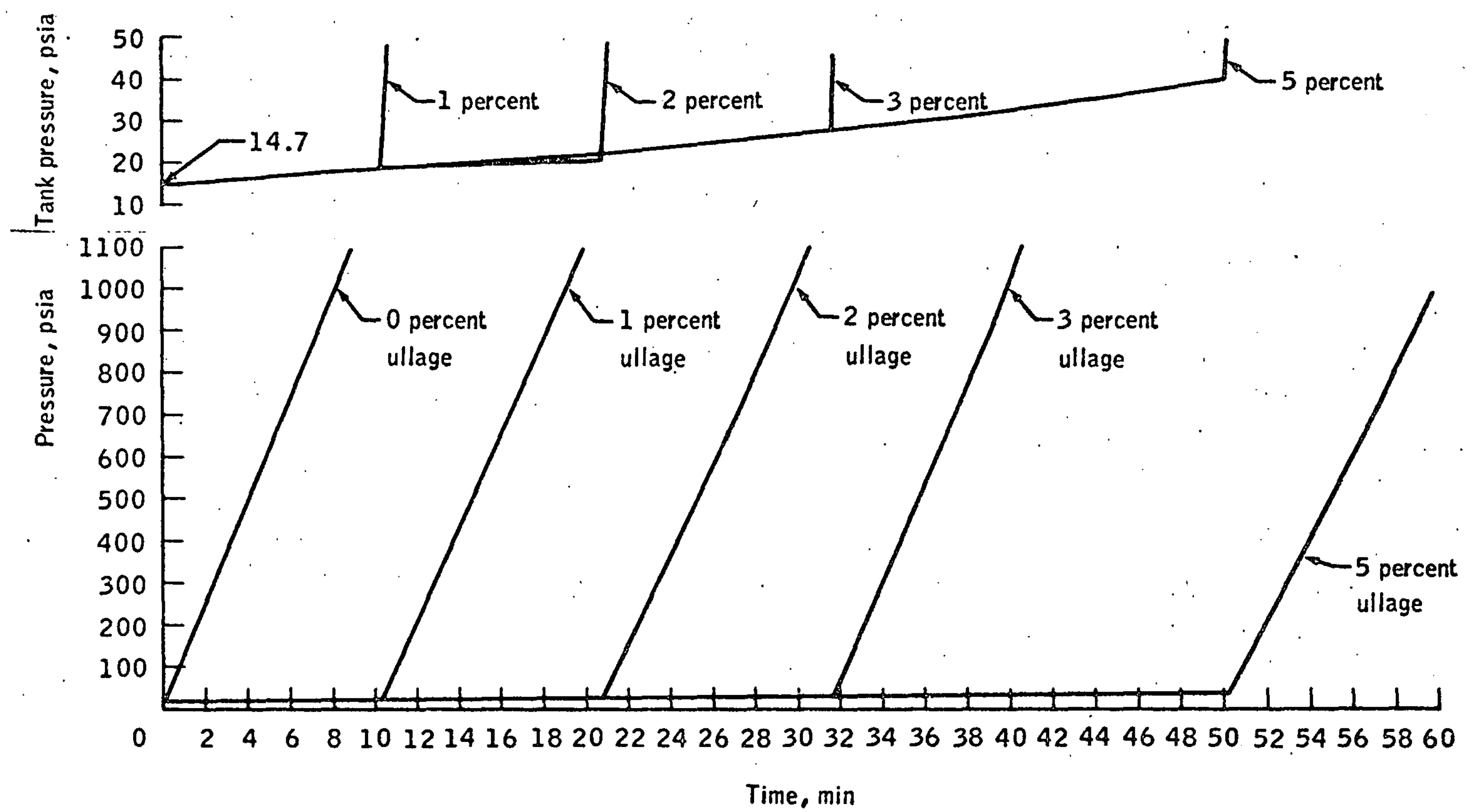


Figure 21.- The Apollo CGSS oxygen-tank pressurization rate; no flow and heaters and motors operating on GSE power.

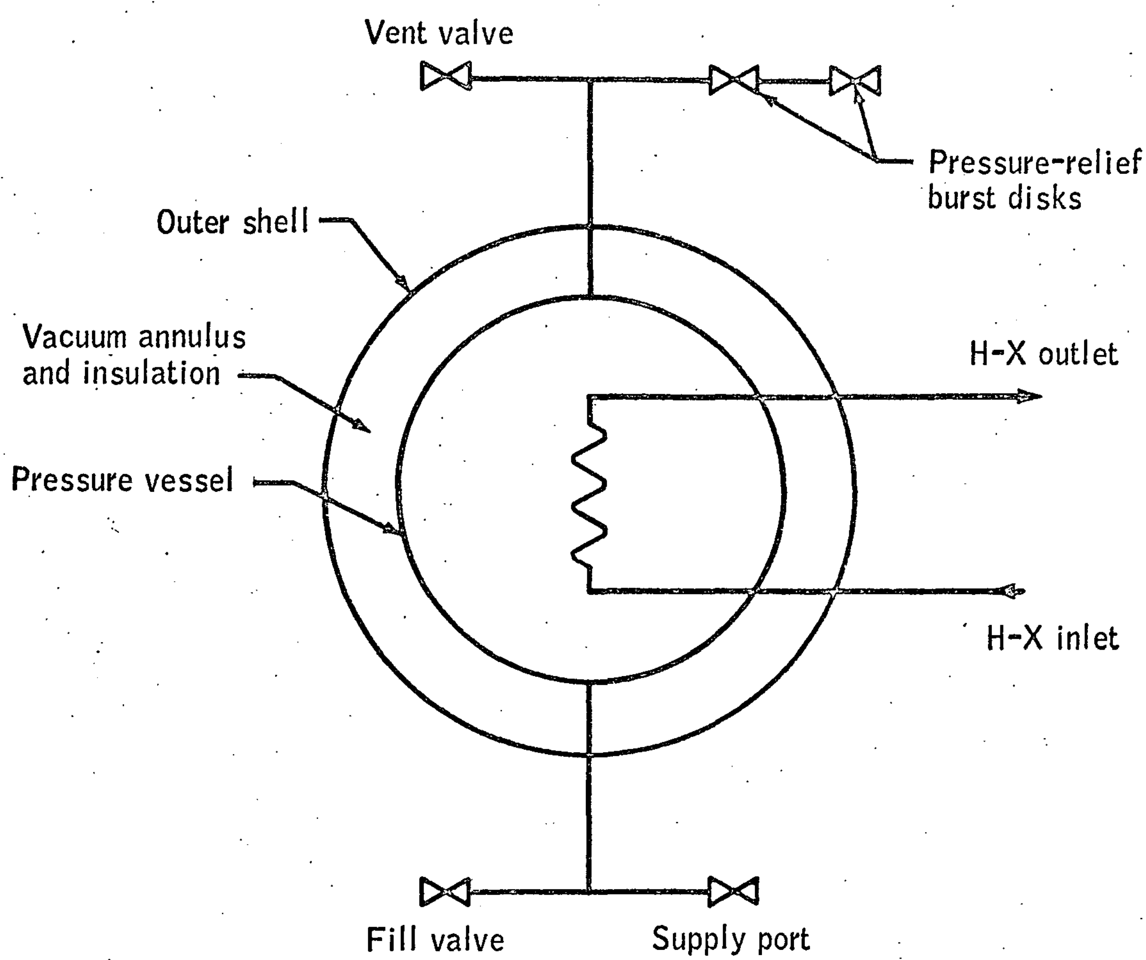


Figure 22.- The LM helium-storage tank.

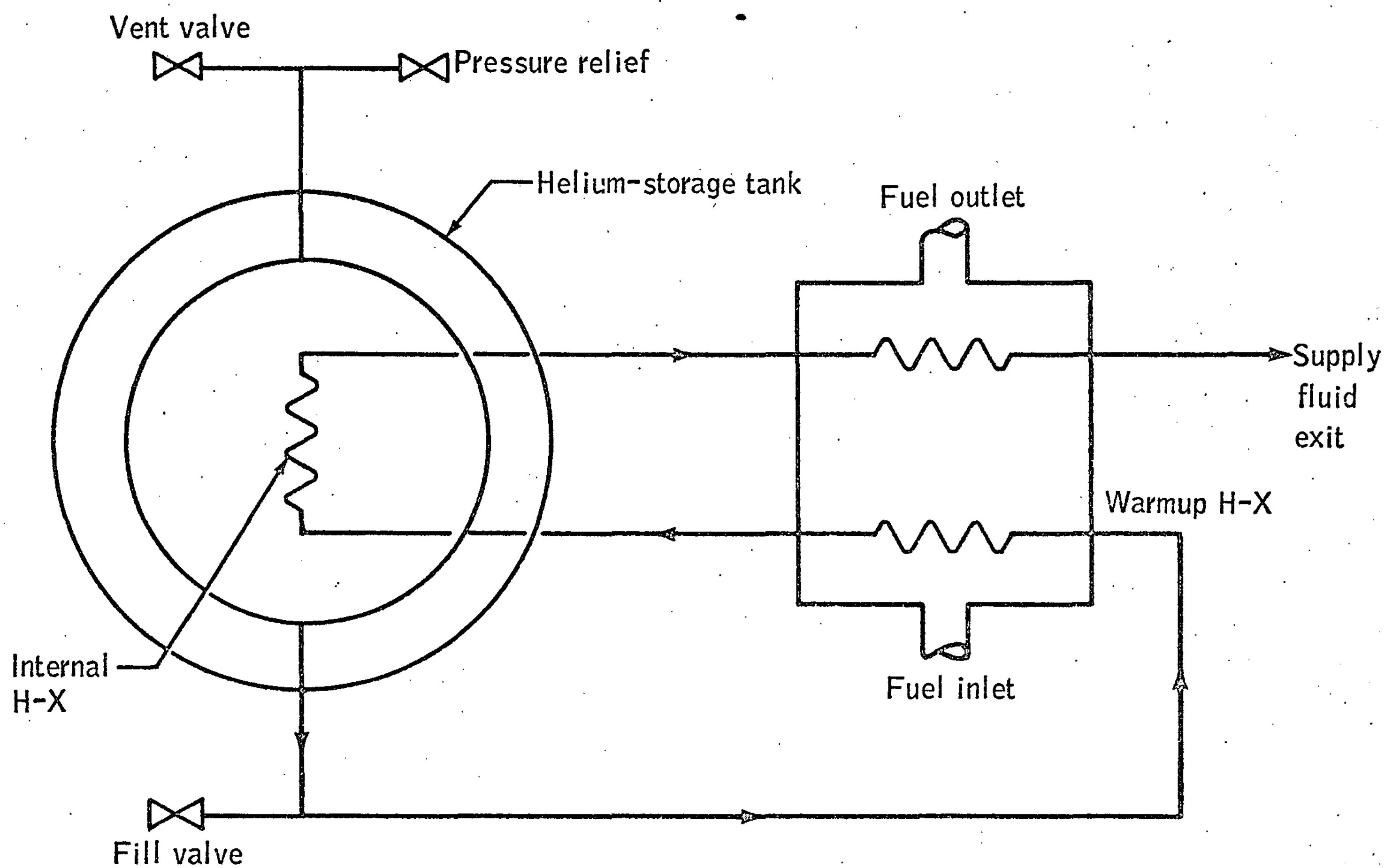


Figure 23.- The LM helium-storage system.

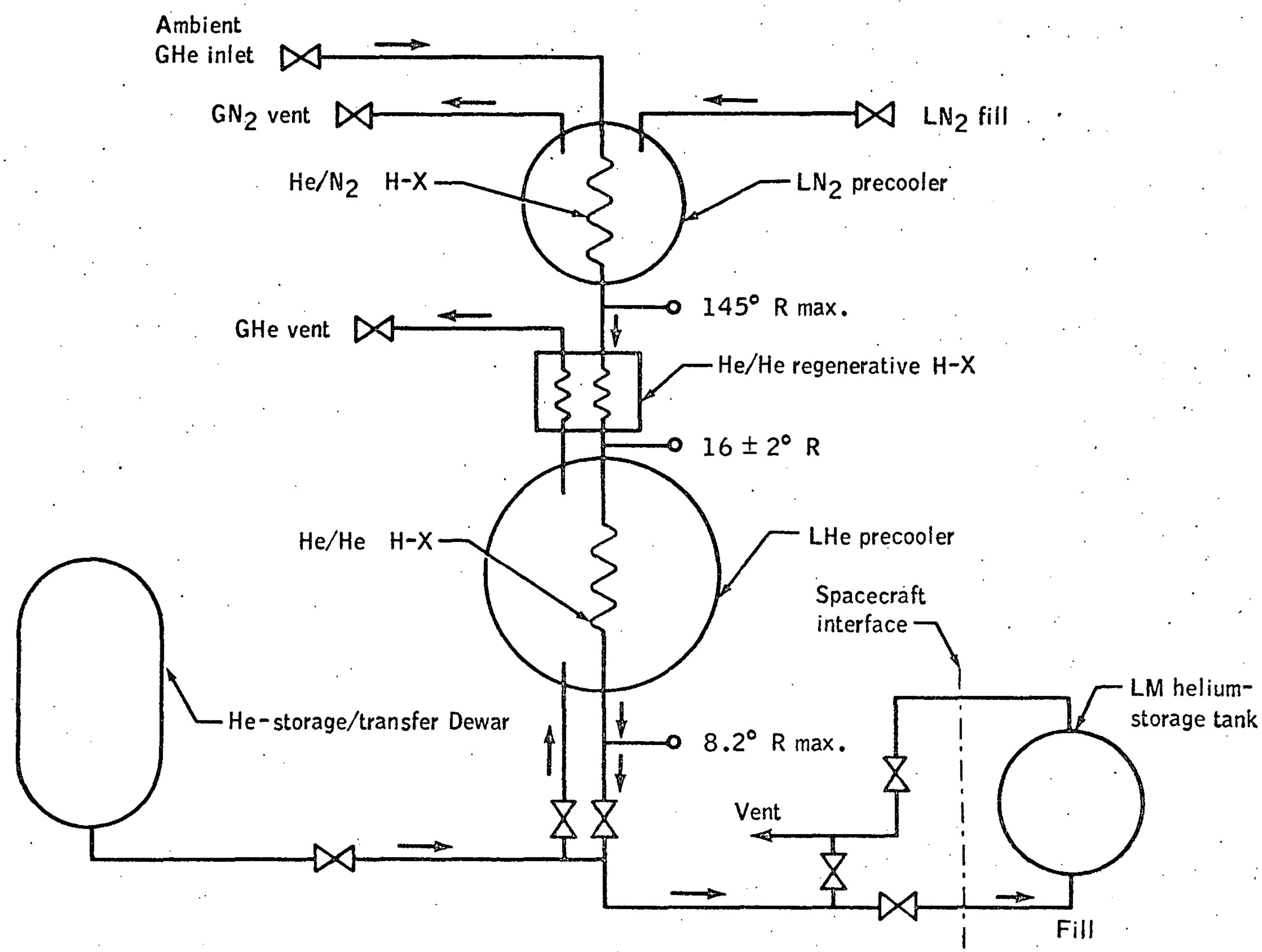


Figure 24.- The GSE helium-conditioning and servicing system.

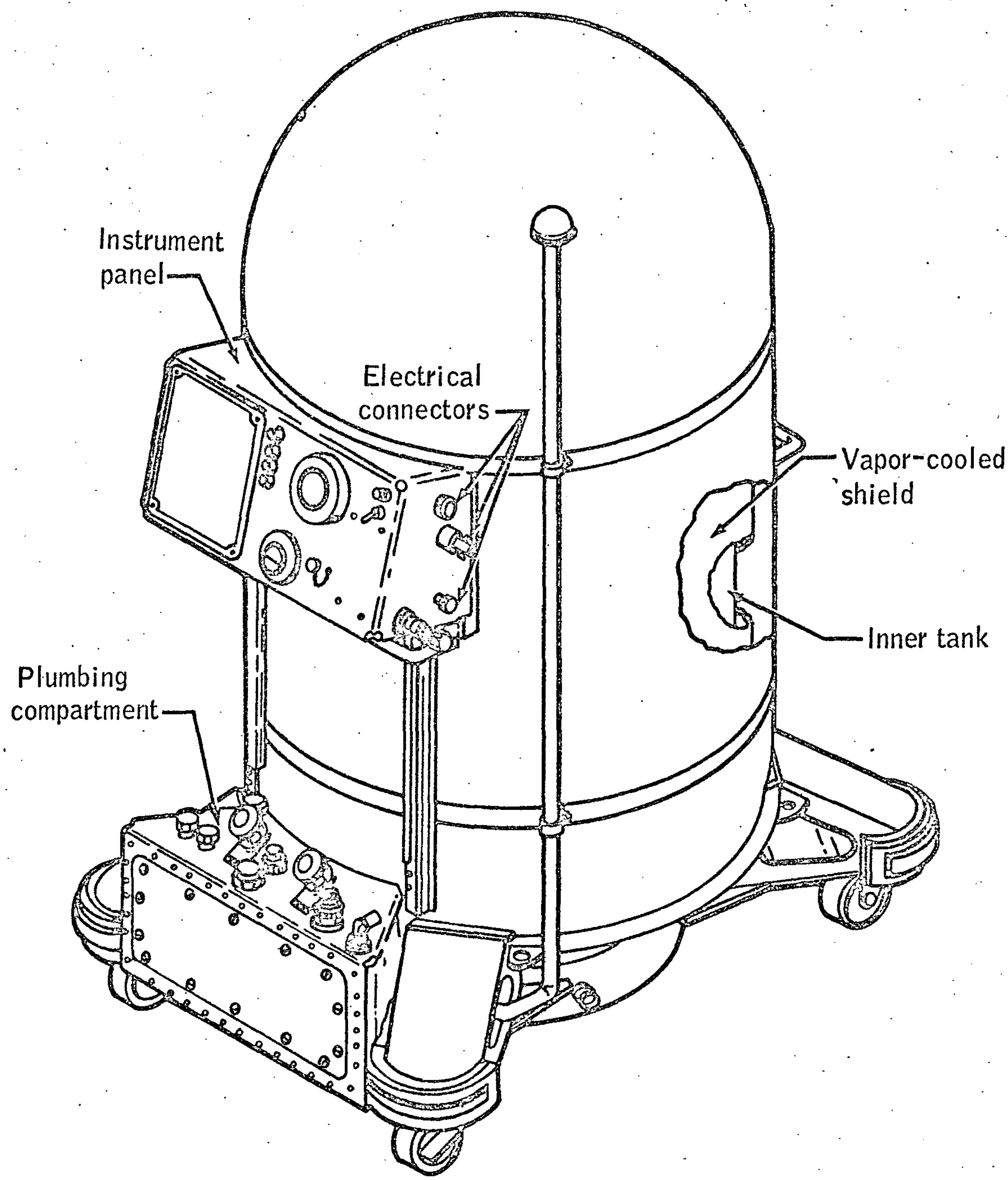


Figure 25.- The GSE helium-storage/transfer Dewar system.

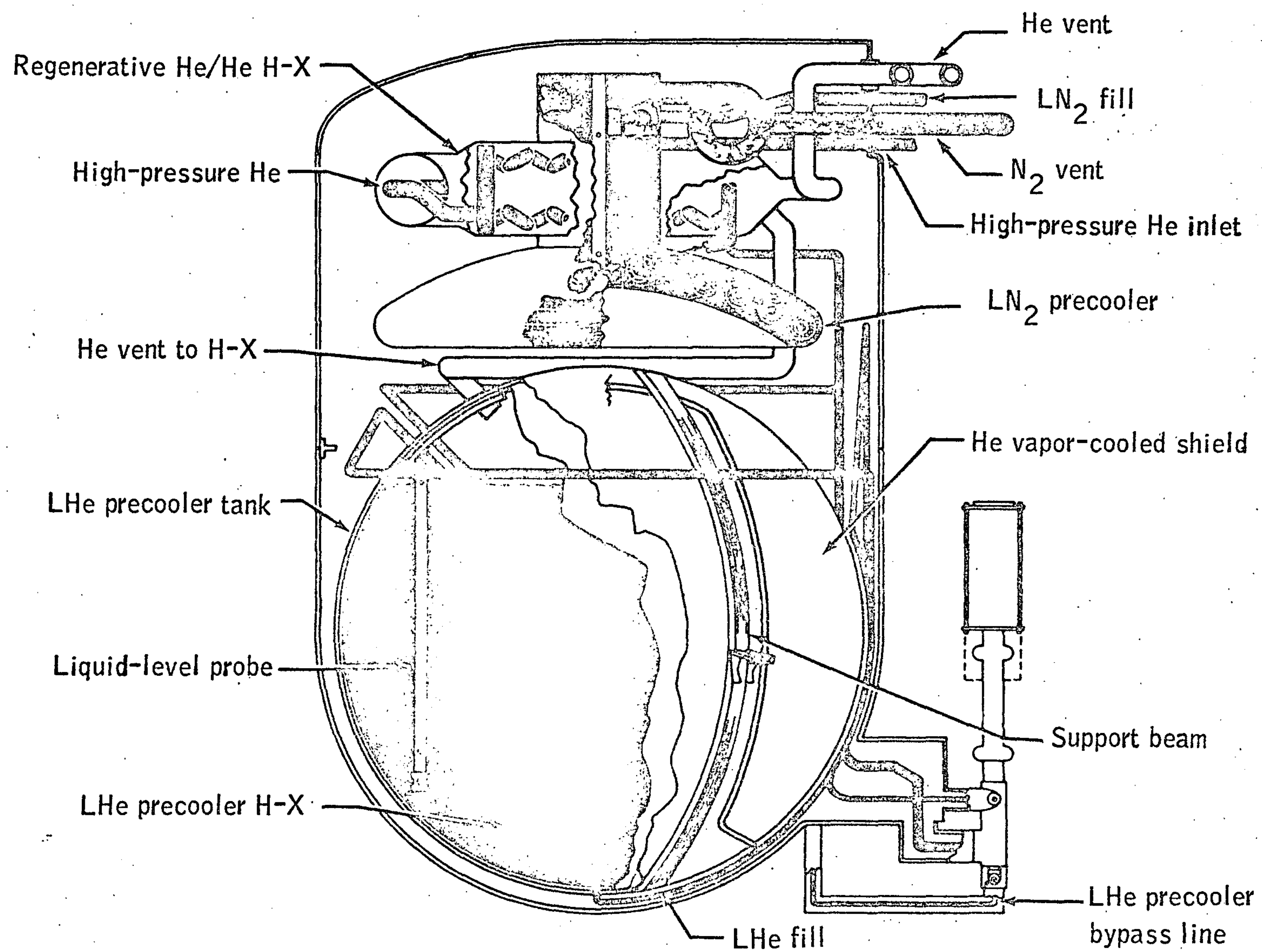


Figure 26.- The GSE helium-conditioning unit.

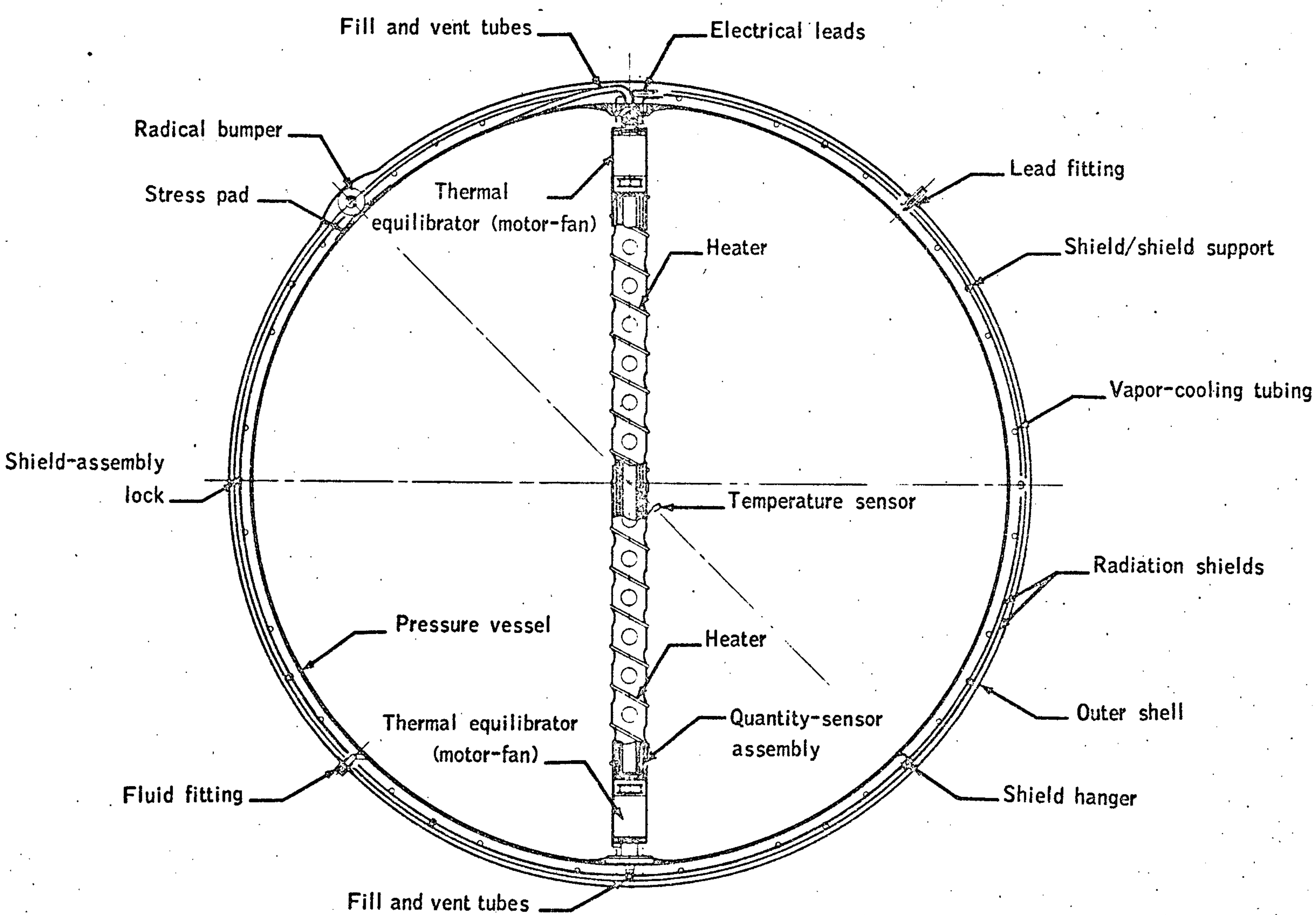


Figure 27.- The AAP cryogenic storage tank.

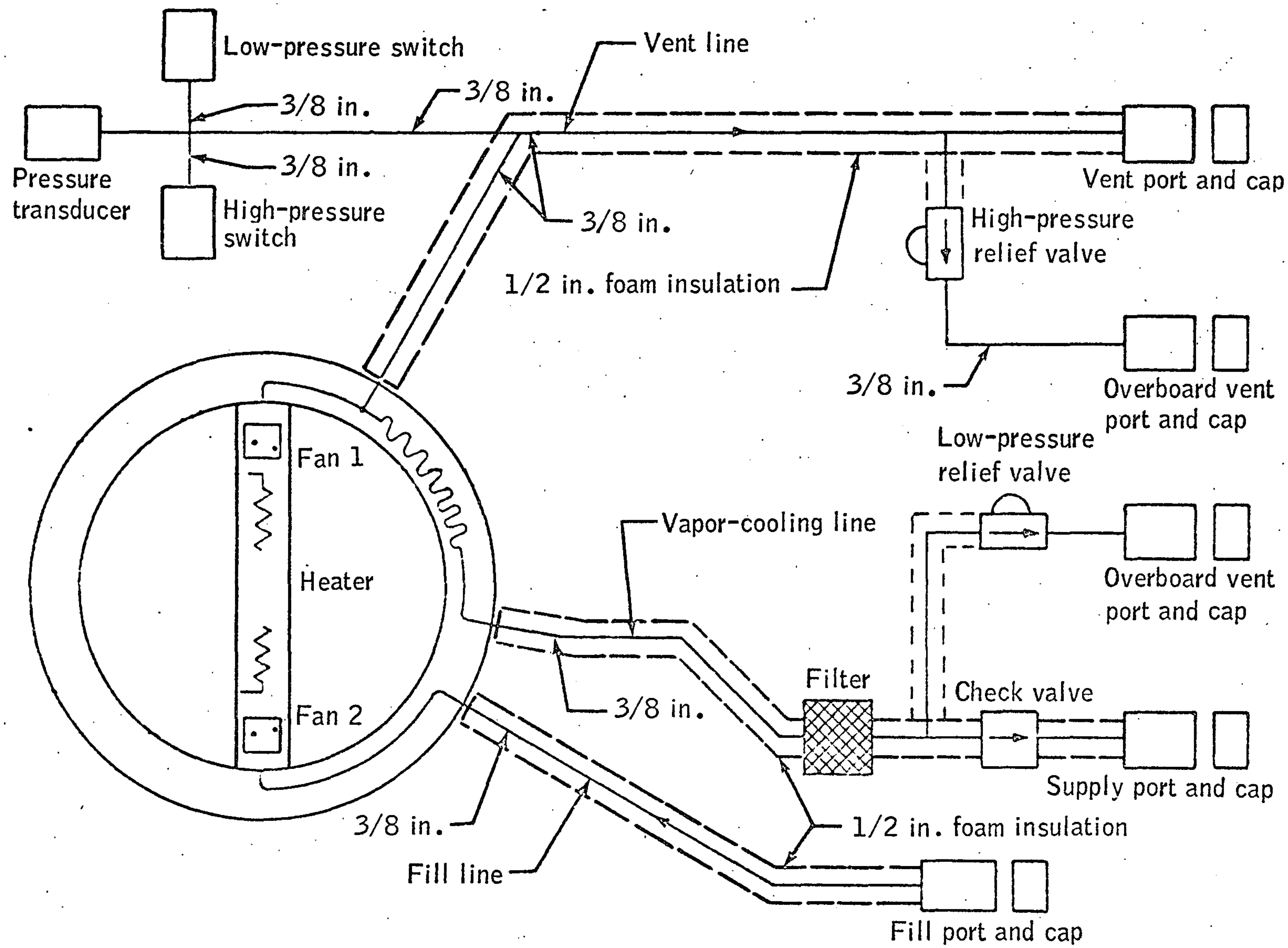


Figure 28.- The AAP cryogenic gas storage system.

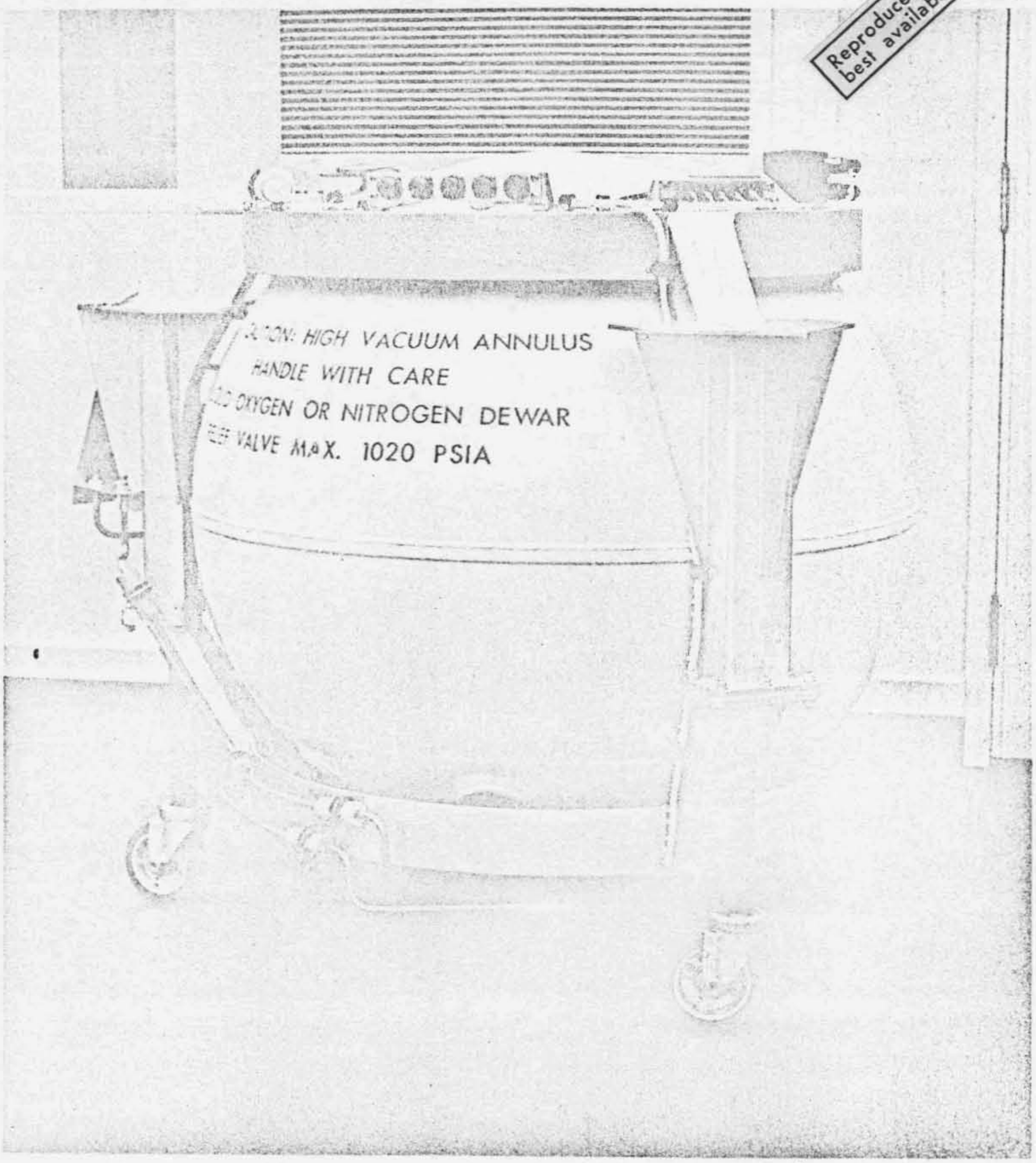


Figure 29.- An external view of the AAP CGSS.

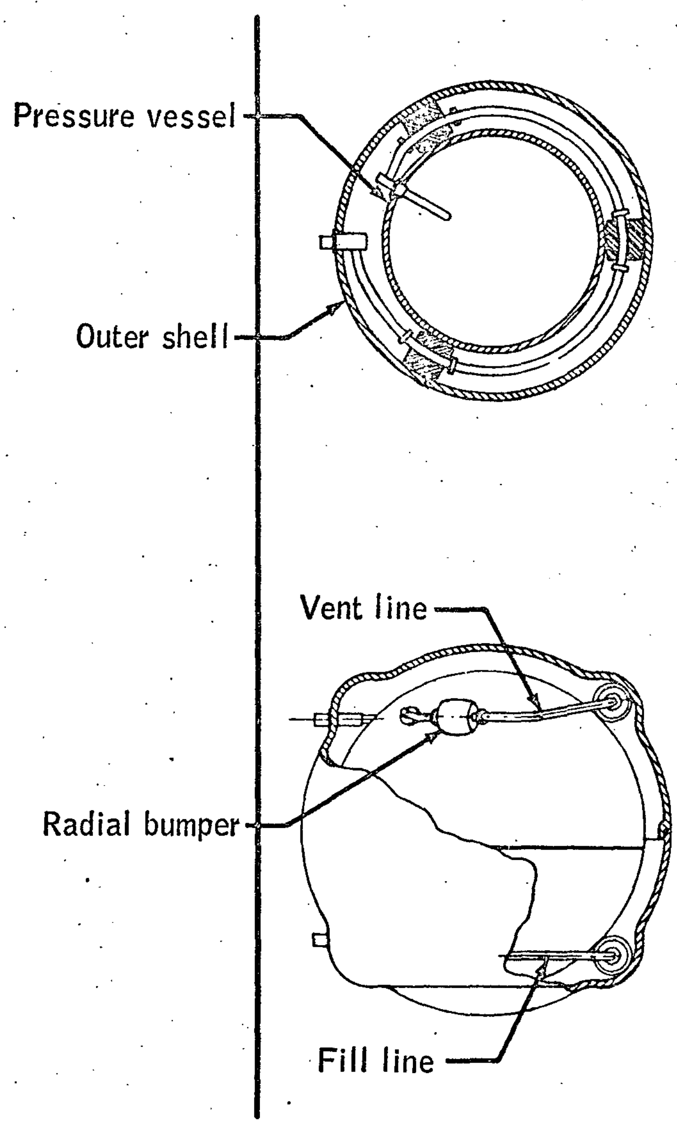


Figure 30.- The radial-bumper design schematic.

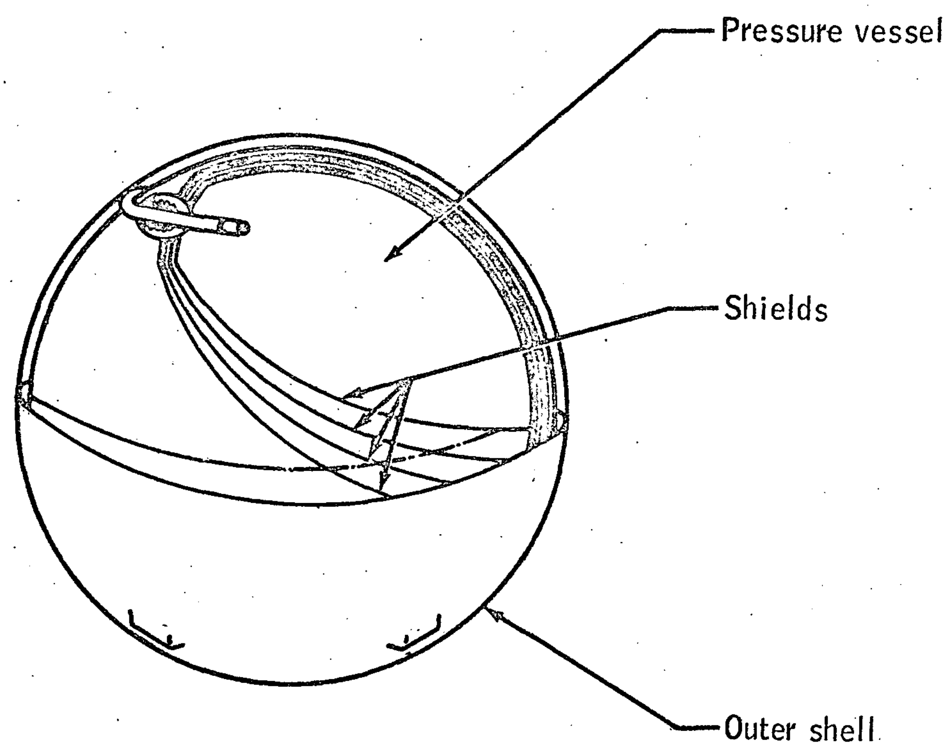


Figure 31.- The discrete-shield radial-bumper design schematic

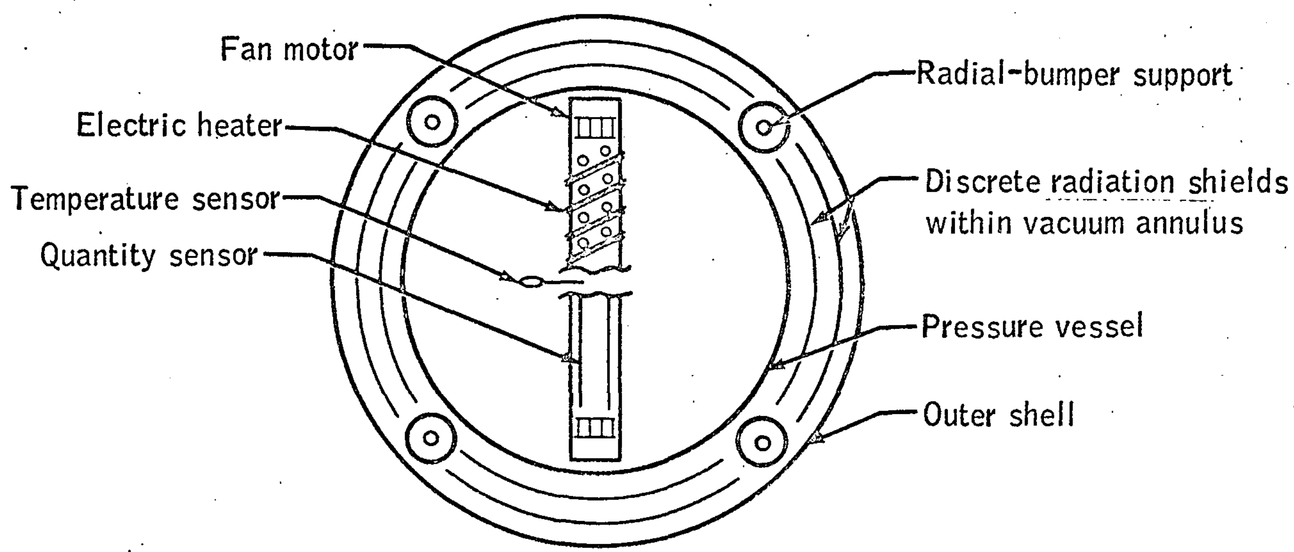


Figure 32.- The discrete-shield radial-bumper cryogenic-storage-tank schematic.

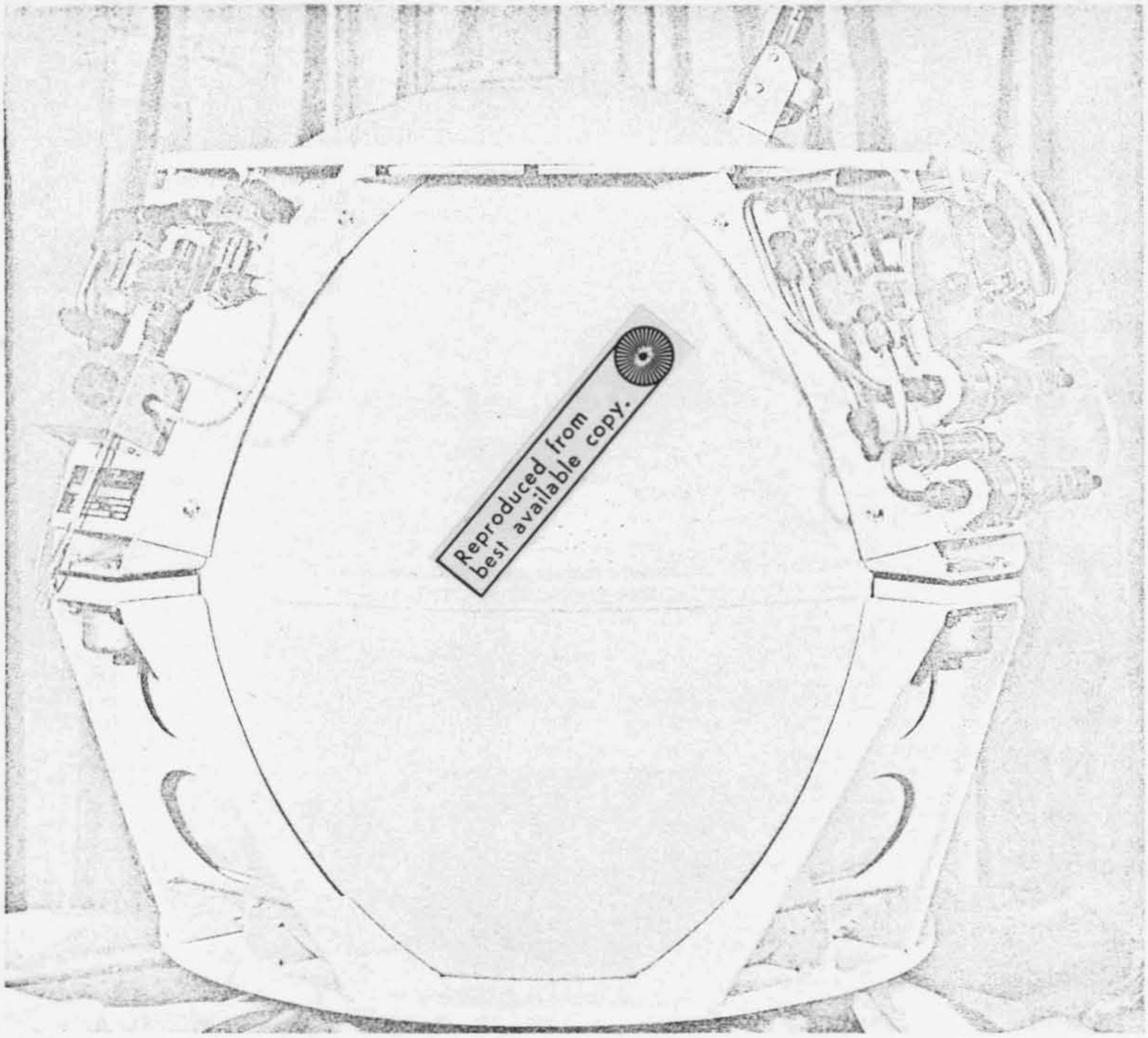


Figure 33.- A photograph of the discrete-shield radial-bumper CGSS.

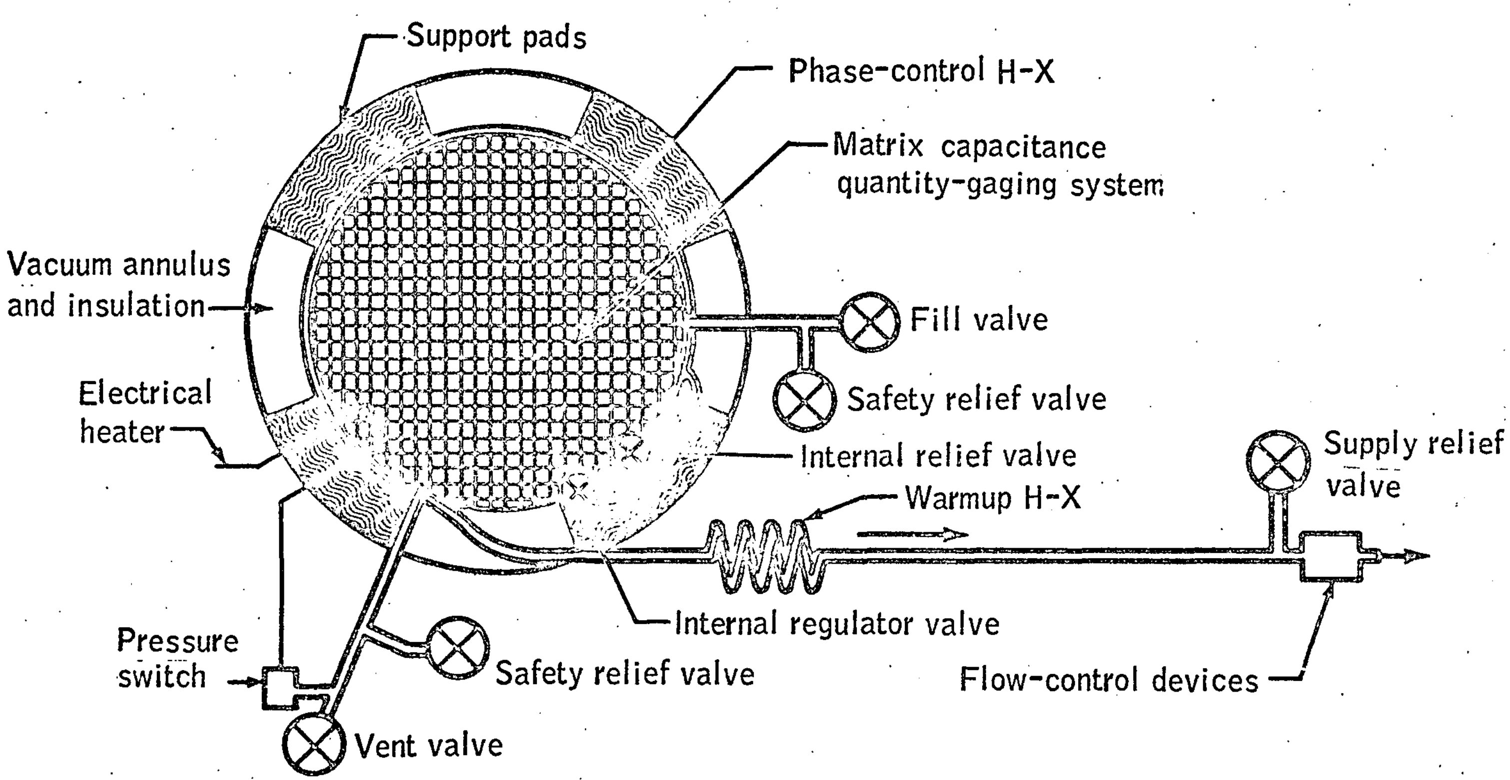


Figure 34.- A schematic of the subcritical nitrogen CGSS.

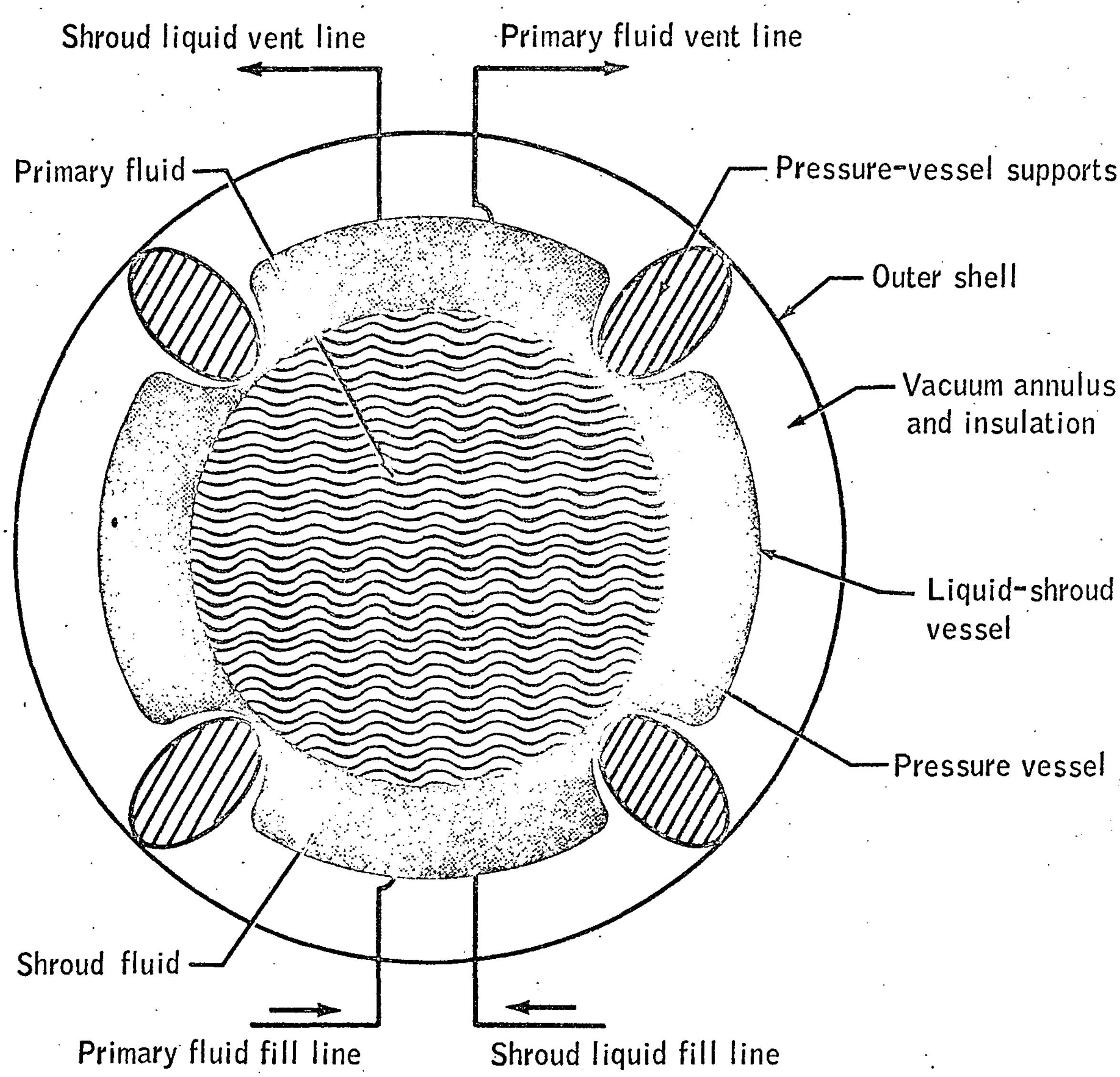


Figure 35.- A typical liquid-shrouded cryogenic storage tank.

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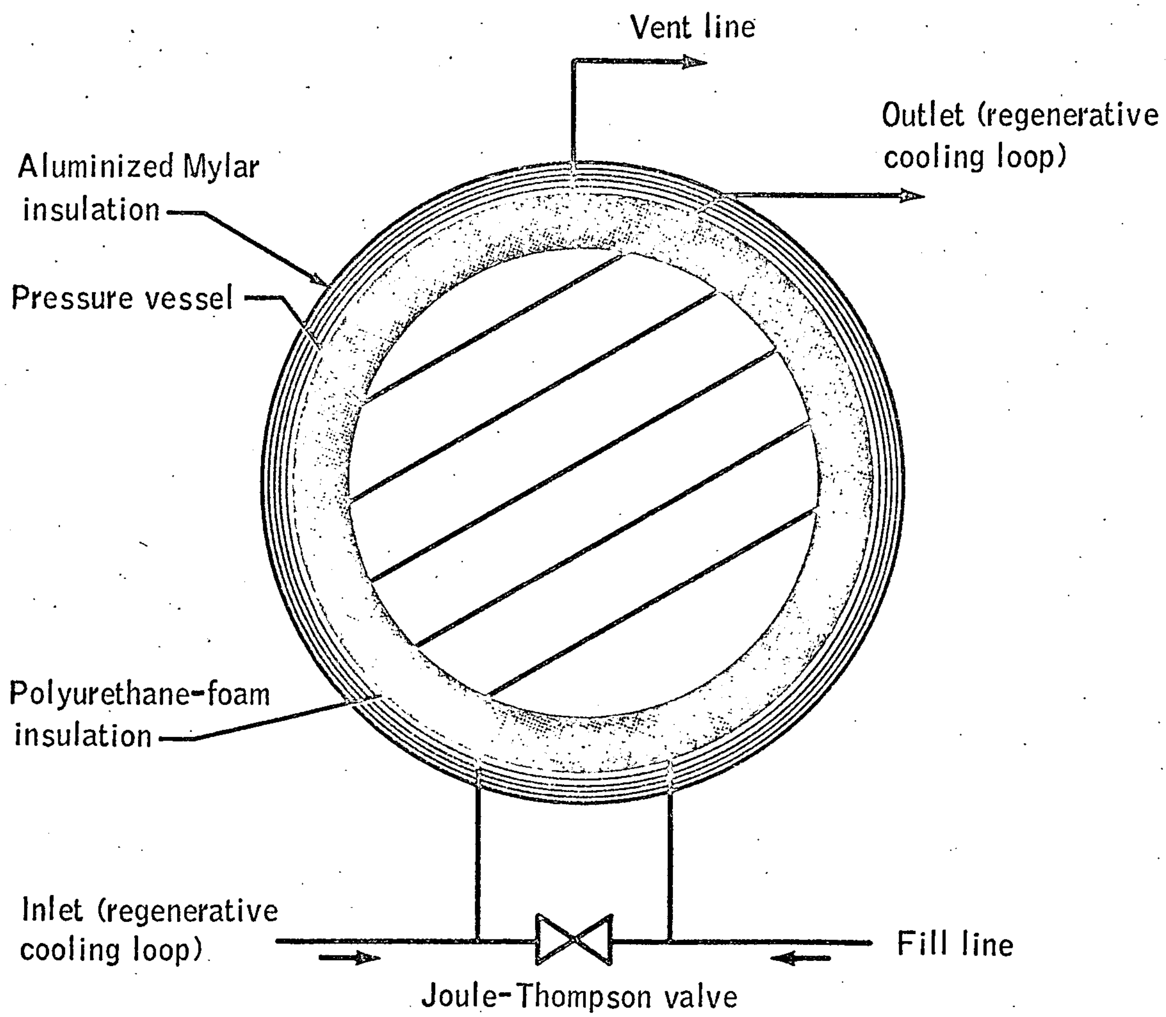

Figure 36.- The single-wall tank CGSS.

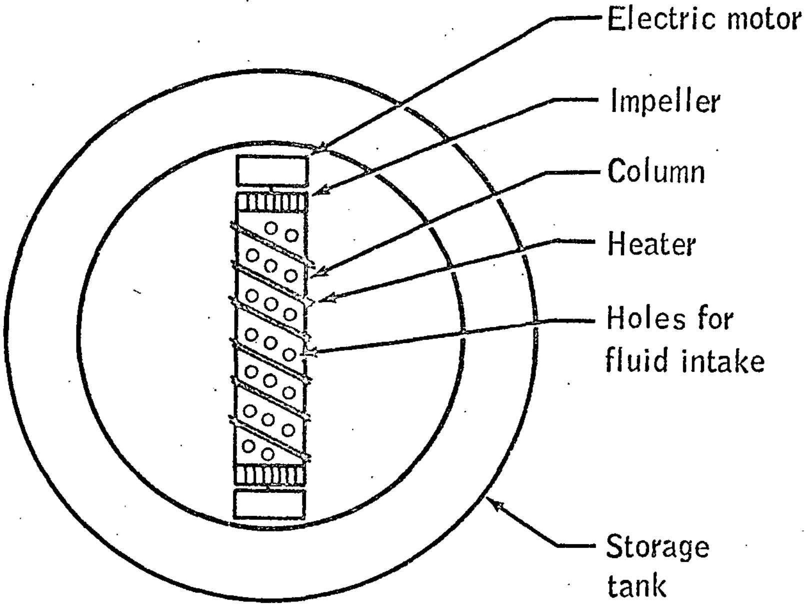

Figure 37.- The internal dynamic heater system.

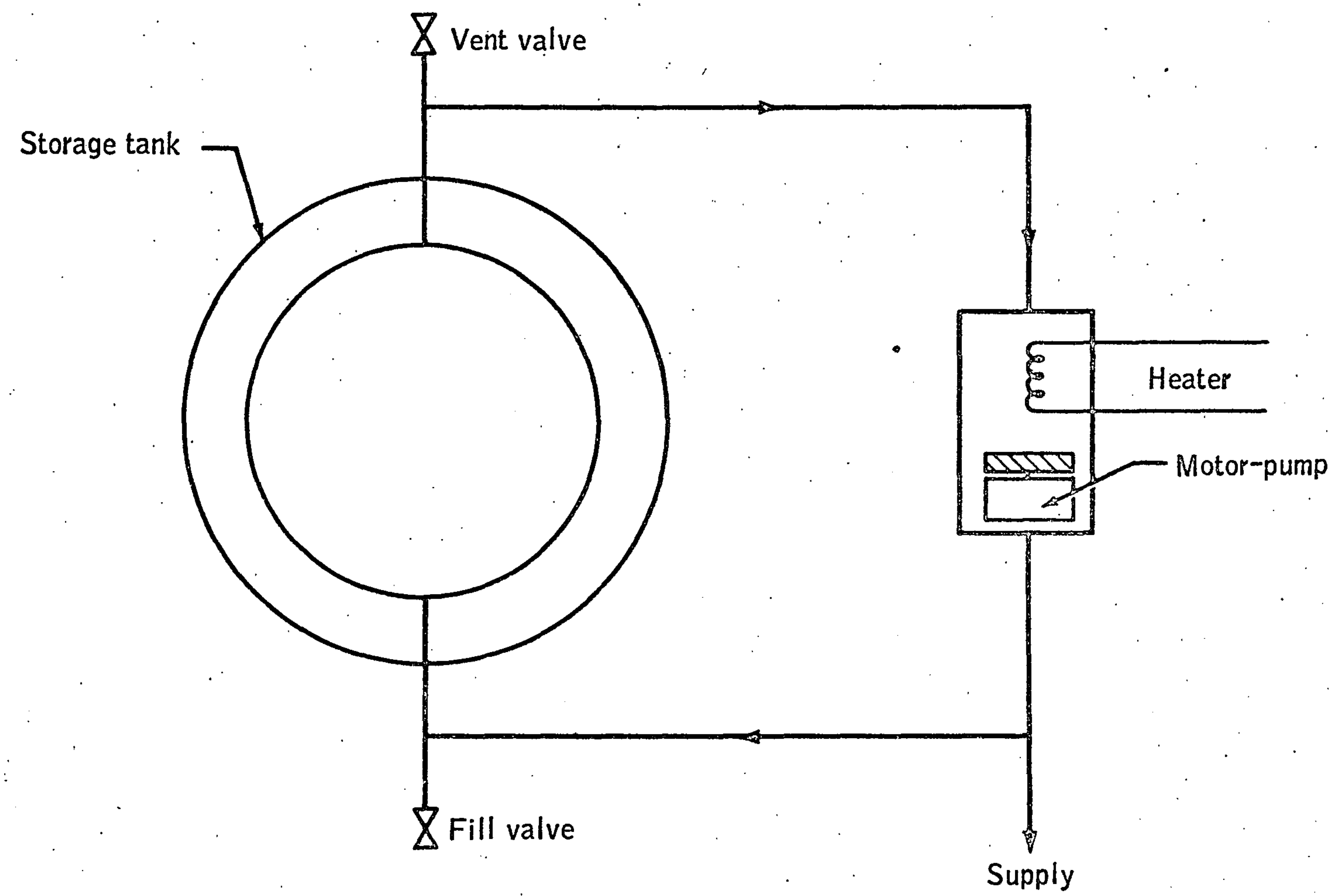

Figure 38.- The external-loop heater system.

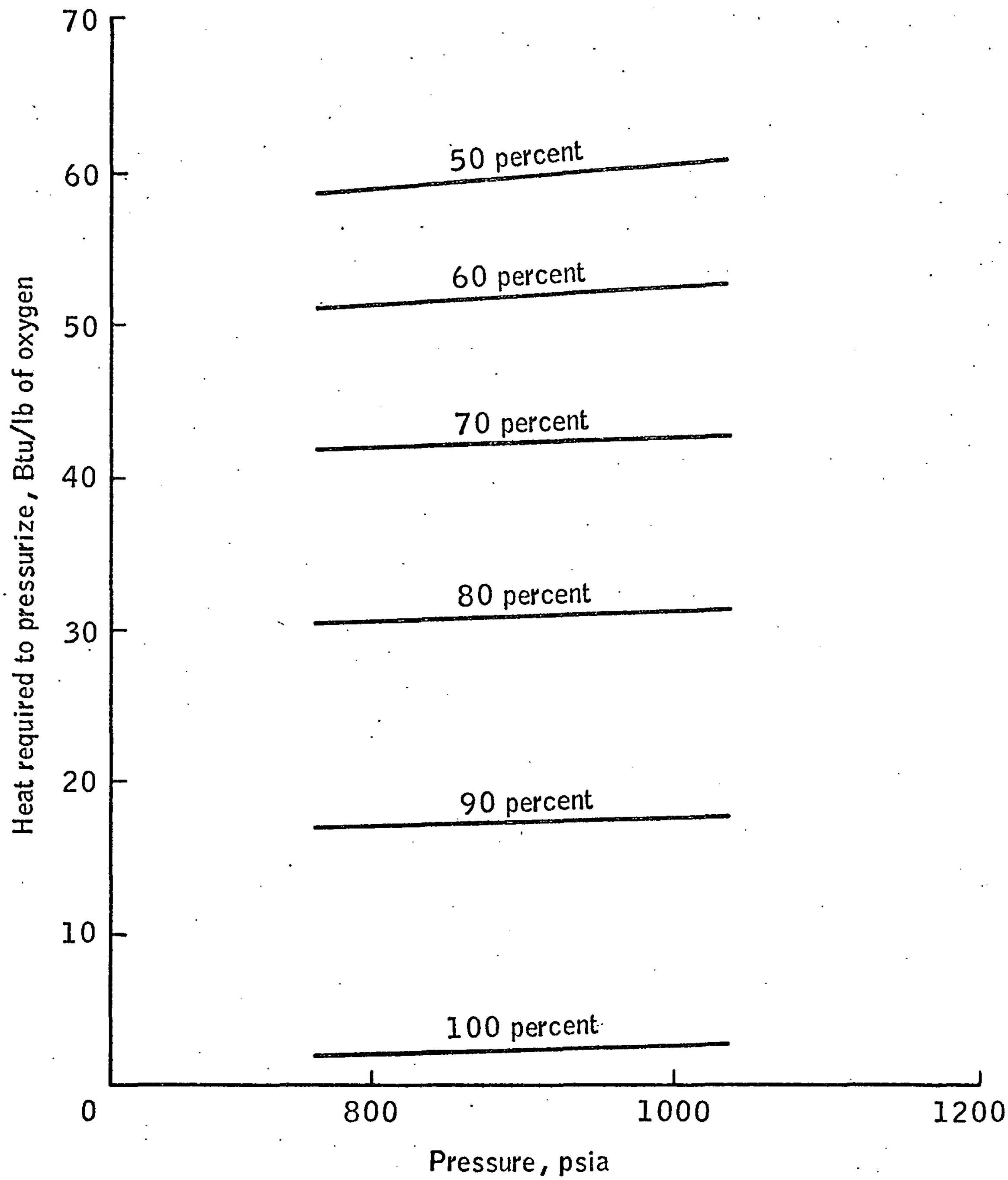

Figure 39.- The heat required to pressurize a supercritical vessel; heat is plotted as a function of pressure at various percentage fills with oxygen.

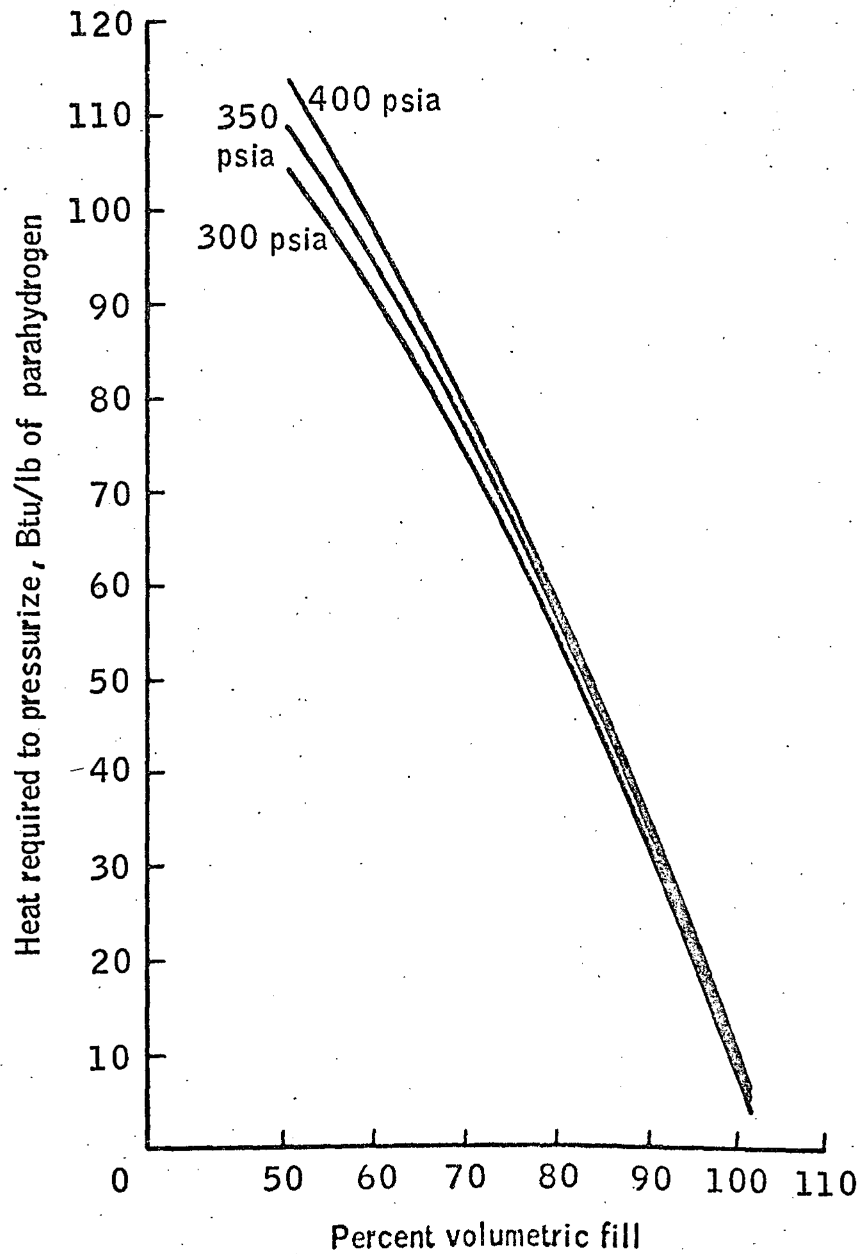

Figure 40.- The heat required to pressurize a supercritical vessel; heat is plotted as a function of percentage fill with parahydrogen.

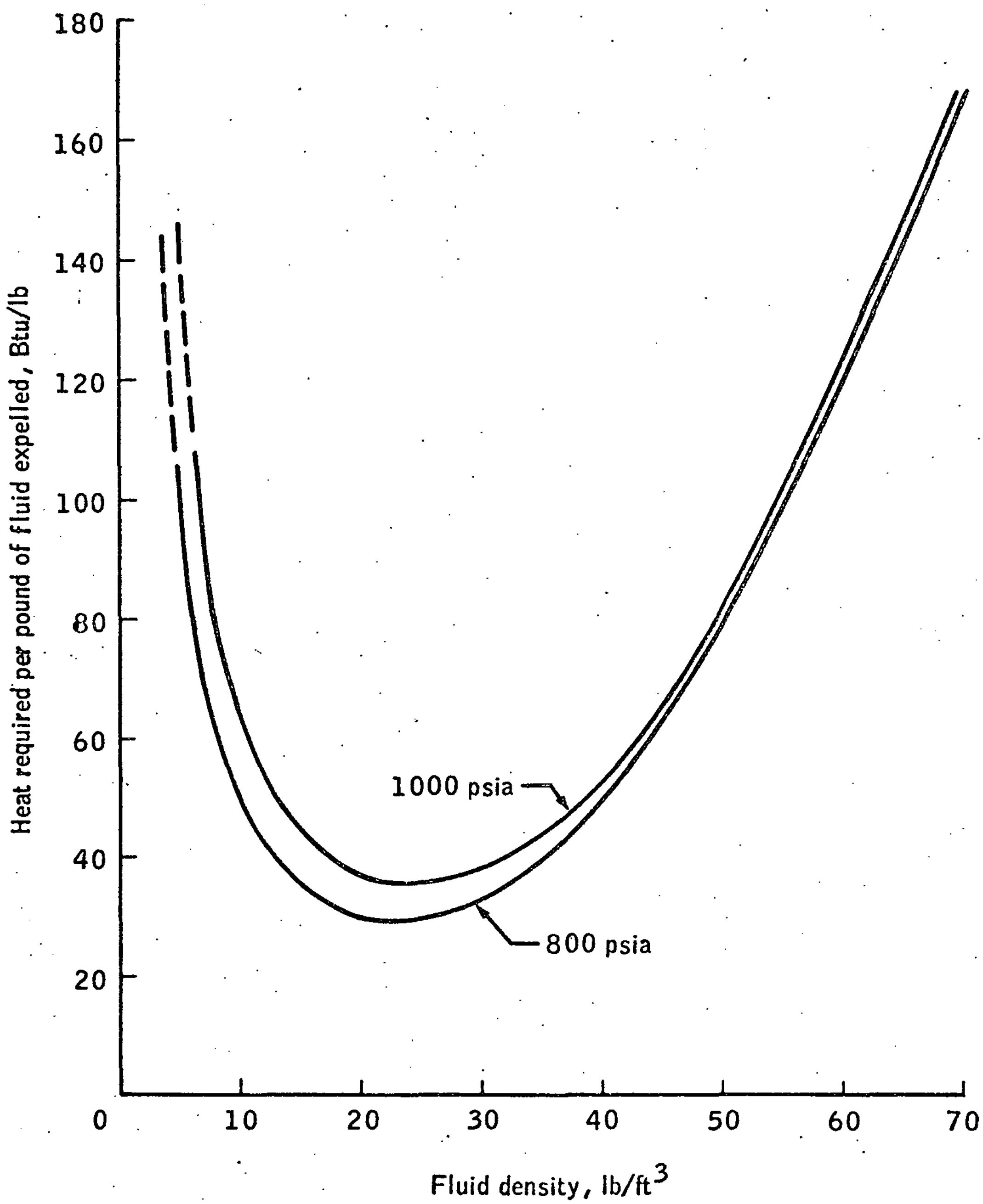

Figure 41.- A plot of the heat required to maintain pressure per pound of oxygen withdrawn (supercritical oxygen).

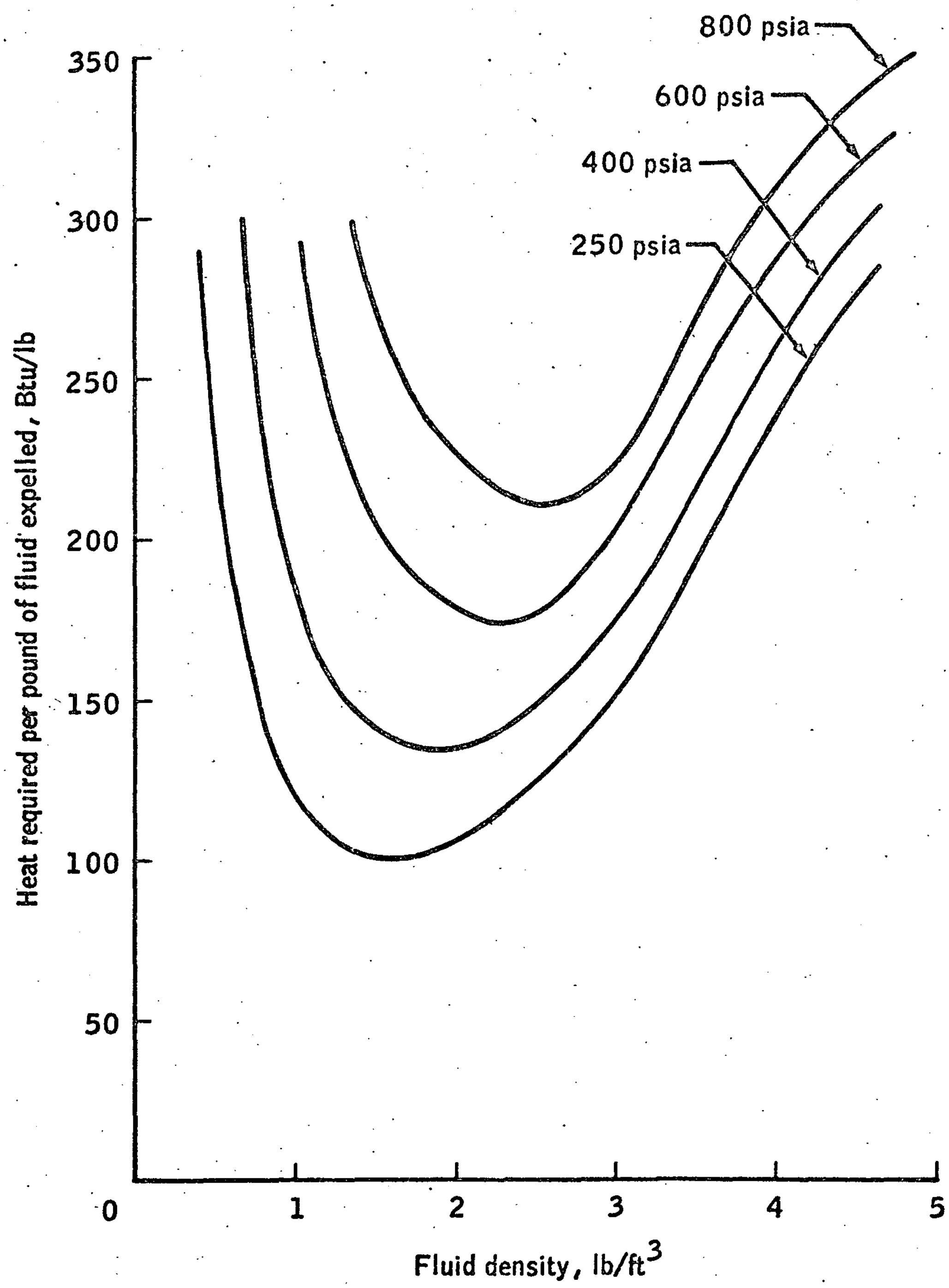

Figure 42.- A plot of the heat required to maintain pressure per pound of hydrogen withdrawn (supercritical parahydrogen).

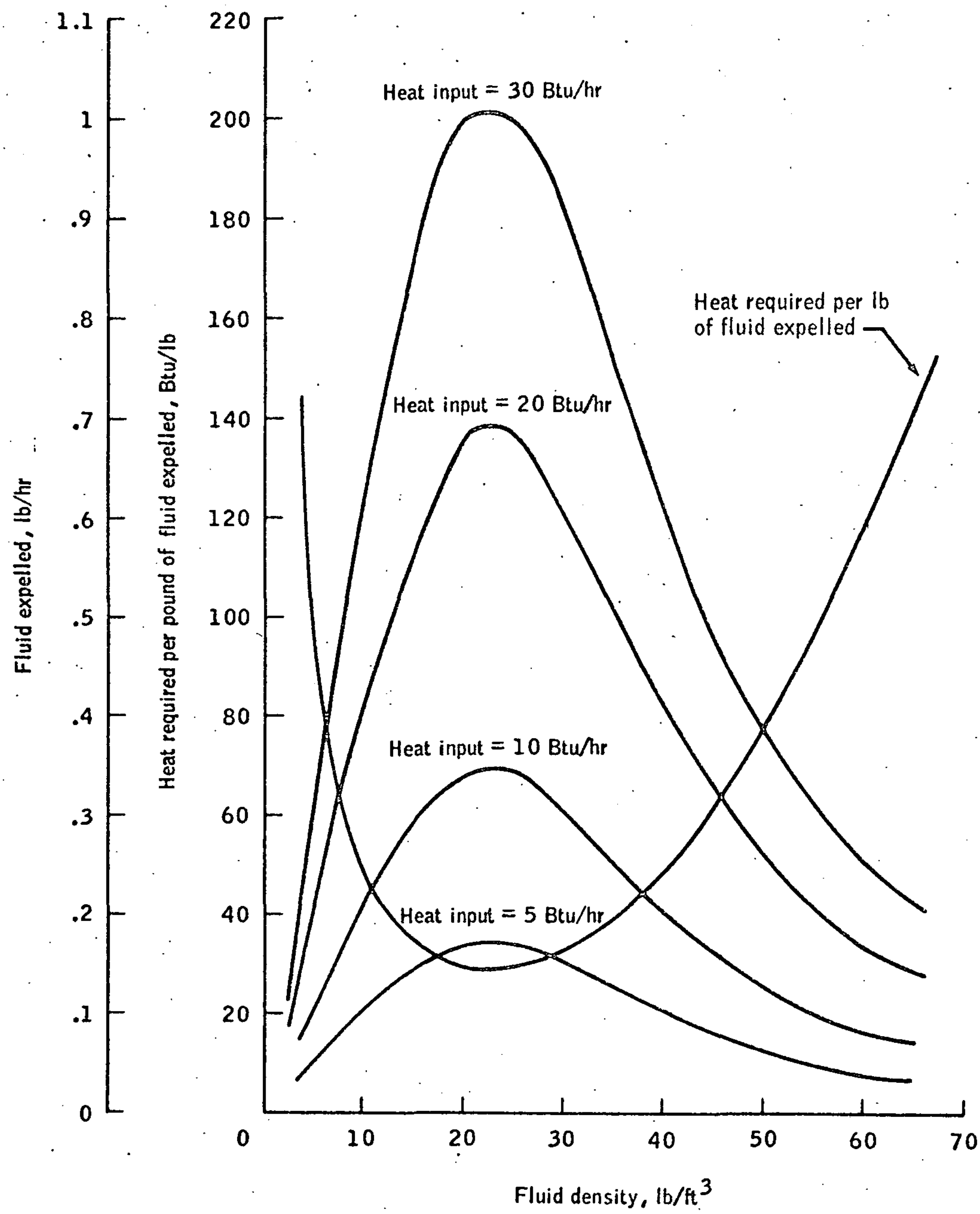

Figure 43.- A plot of the heat required to maintain pressure per pound of oxygen withdrawn and the fluid expelled at four heat-input rates (supercritical oxygen, 800 psia).

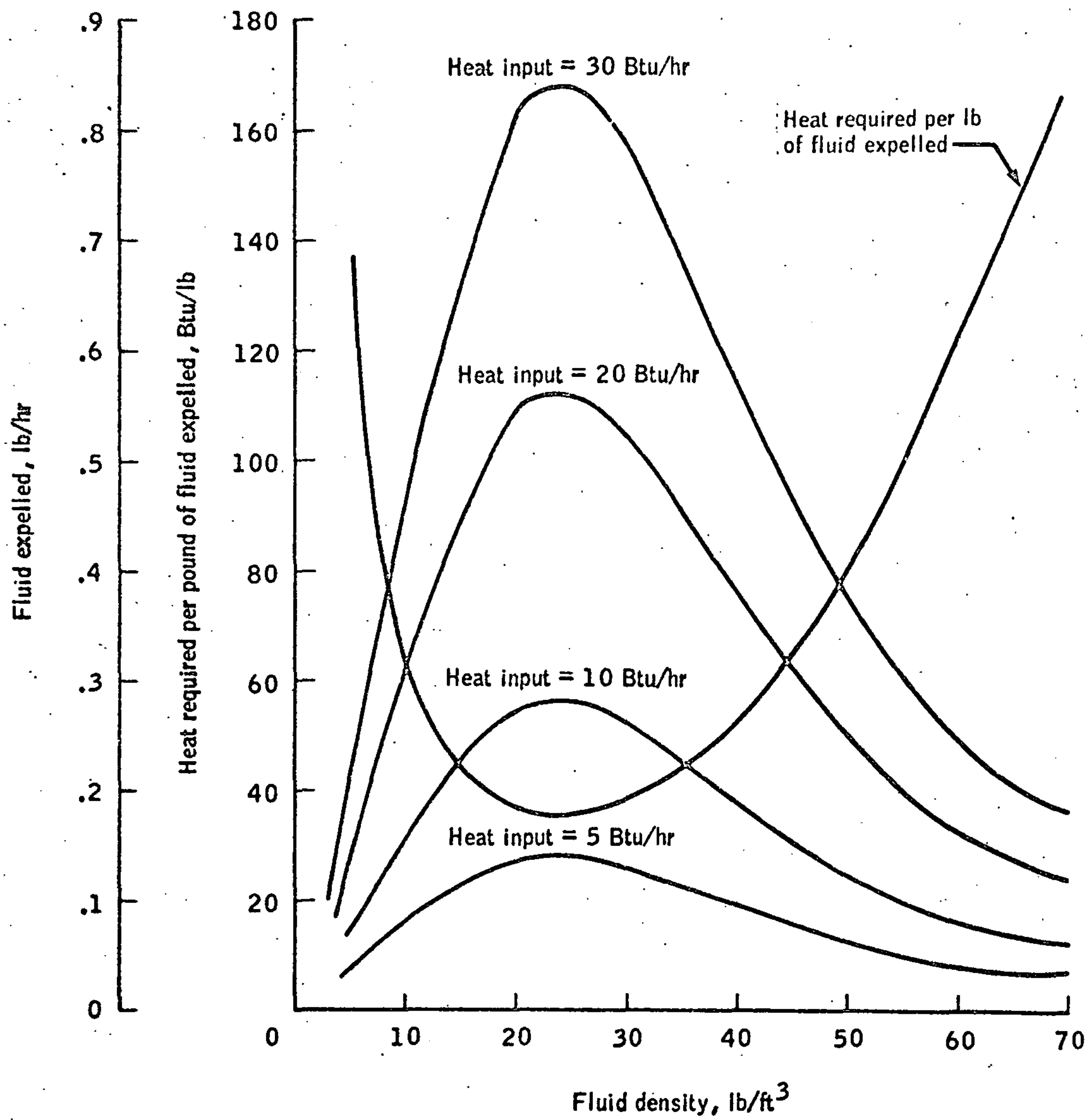

Figure 44.- A plot of the heat required to maintain pressure per pound of oxygen withdrawn and the fluid expelled at four heat-input rates (supercritical oxygen, 1000 psia).

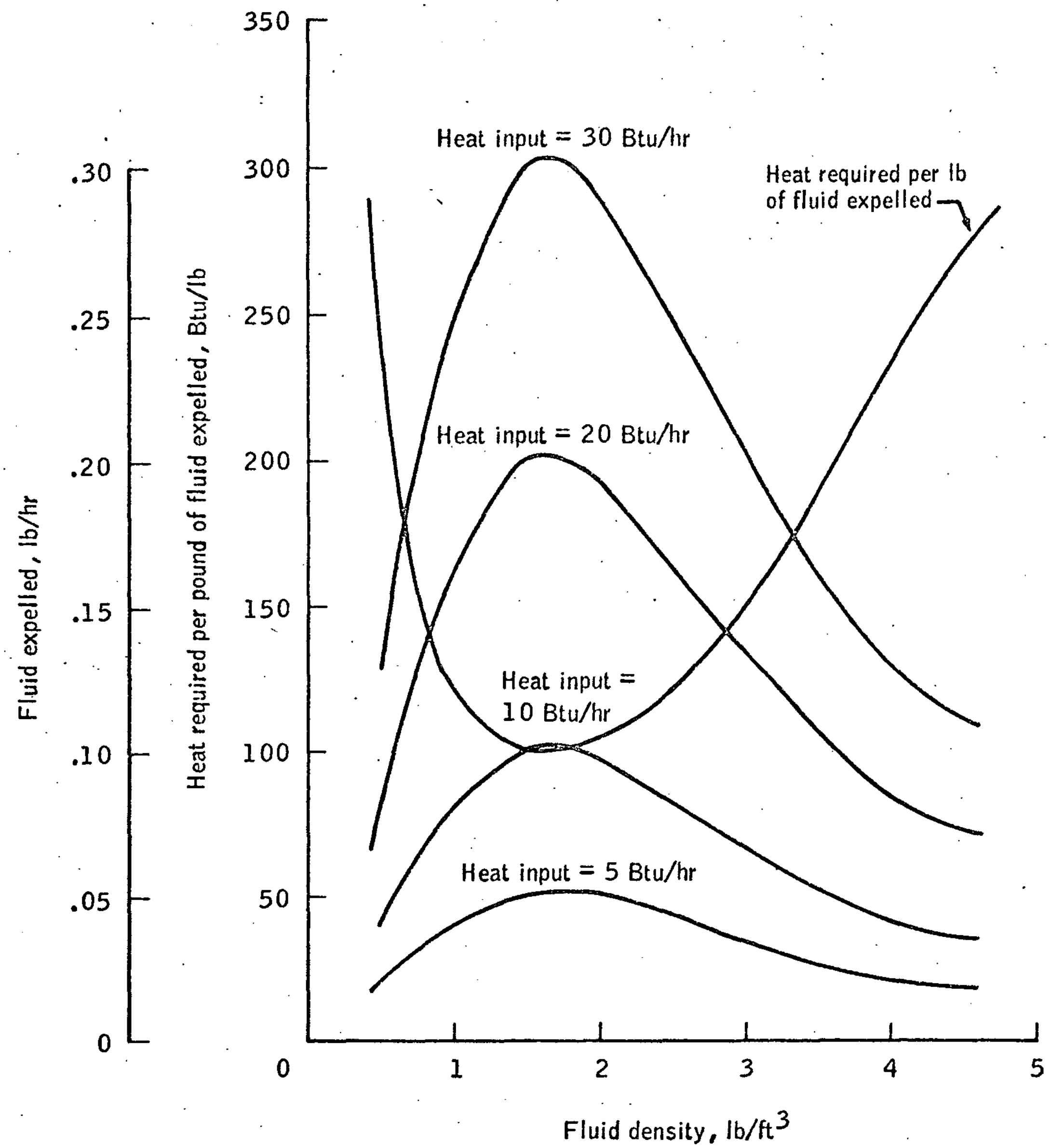

Figure 45.- A plot of the heat required to maintain pressure per pound of hydrogen withdrawn and the fluid expelled at four heat-input rates (supercritical parahydrogen, 250 psia).

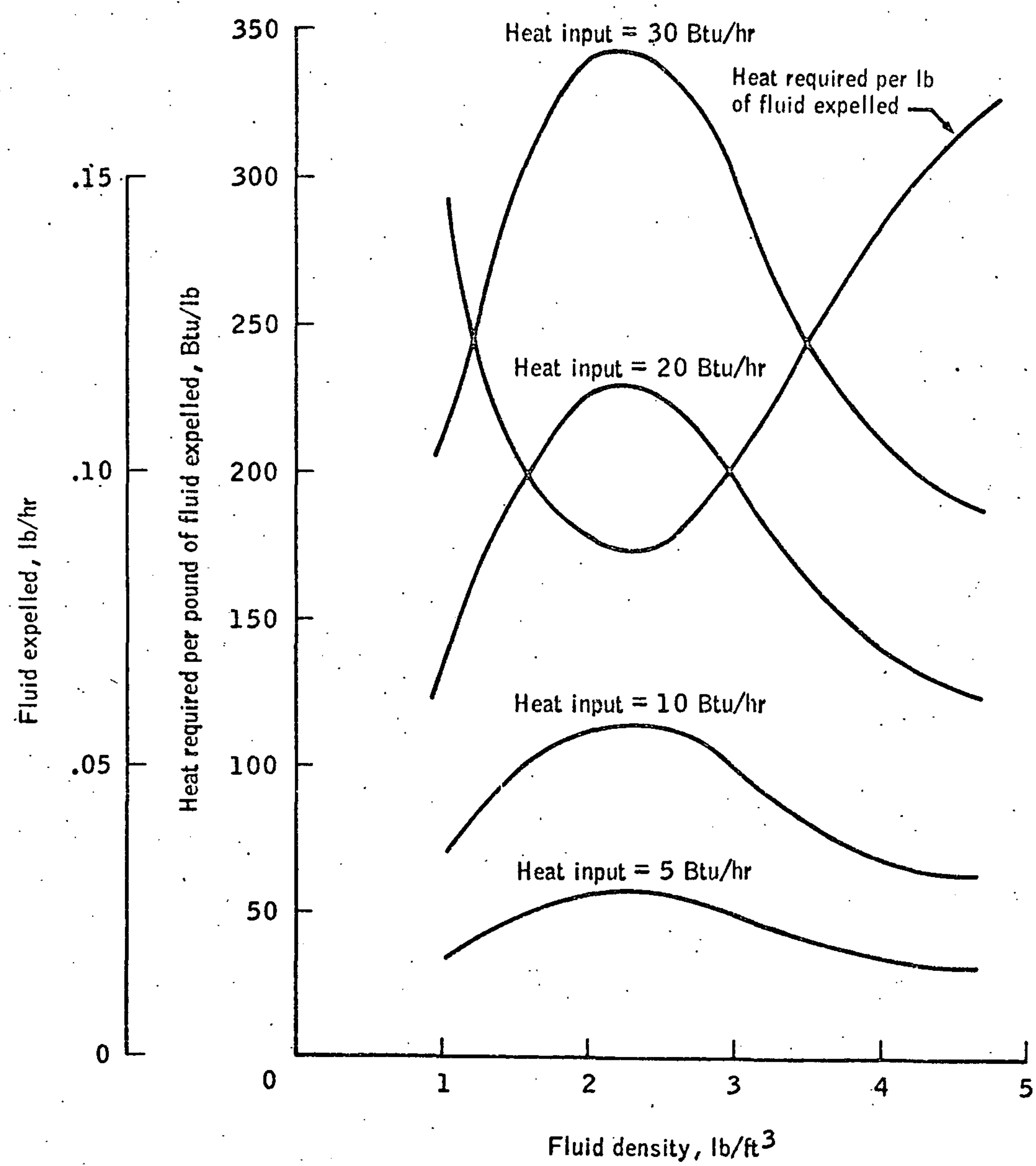

Figure 46.- A plot of the heat required to maintain pressure per pound of hydrogen withdrawn and the fluid expelled at four heat-input rates (supercritical parahydrogen, 600 psia).