NBSIR 76-850

LIQUID HELIUM STORAGE AT HIGH DENSITY AND DISCHARGE AT HIGH FLOW RATES

David E. Daney

Cryogenics Division
Institute for Basic Standards
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Prepared for:
Air Force Weapons Laboratory
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ABSTRACT

Equipment to store supercritical helium at high density and to demonstrate pulsed discharge at high flow rates has been designed, fabricated and successfully tested. A storage density of 0.193×10^3 kg/m^3 (12.03 lb/ft^3) at 8.3 MPa (81 atm) was achieved in a 135 liter (35 gal) dewar. Pulsed discharges of 2 seconds and 4 seconds duration were demonstrated at a flow rate of 1.0 kg/s (2.2 lb/s), and flow fluctuations of less than ± 1 percent were achieved without feedback control. In general, the system operated in a very stable and well behaved manner.

Key words: Cryogenic helium supply system; cryogenic storage; helium; helium supply system; high density helium storage; liquid helium storage; supercritical helium.

1. INTRODUCTION

The Air Force Weapons Laboratory has developed a requirement for bulk storage and discharge of cryogenic helium at densities and flow rates significantly in excess of previous applications. They require densities approaching 0.2×10^3 kg/m^3 (12.5 lb/ft^3) and pulsed flow rates of several kg/s. By comparison, the Apollo Lunar Module Helium Storage System has a fill density of 0.13×10^3 kg/m^3 (8.1 lb/ft^3) and a discharge rate of 0.04 kg/s (0.09 lb/s)[1]. In order to demonstrate the practical feasibility of a system meeting these requirements, the NBS Cryogenics Division was asked to design, build, and test a system to:

1. Store helium in a dewar at a density approaching 0.2×10^3 kg/m^3 (12.5 lb/ft^3) with a pressure less than 10.3 MPa (102 atm), and
2. discharge helium in pulses of 2 seconds or more and at a flow rate of at least 1.0 kg/s (2.2 lb/s) at greater than 3.5 MPa (35 atm) pressure.

In addition to these specific objectives, more general goals were to demonstrate a relatively large field-type system, measure the operating parameters of this system, and identify possible problems the system might have. Thus the task was to go from concept to practice, providing design information such as dewar fill time, agreement with equilibrium thermodynamic calculations, temperature stratification, mixing of the pressurant entrance jet, practical fluid supply temperatures, and blower requirements and performance. The laying to rest of potential problems that fail to occur is also an important result of the study.

The principal constraint on the project was that the results were required within seven months. Consequently, existing equipment was employed whenever possible, necessitating some design compromises. For example, the use of an Appolo oxygen dewar for the test vessel restricted the maximum fill pressure to 8 MPa (81 atm) and resulted in some crowding in the dewar neck.

The method of filling the test dewar is shown schematically in figure 1. The dewar is first filled with boiling-point liquid helium, after which it is pressurized with cold helium to the final fill pressure. Starting at ambient temperature, this helium is cooled to 80 K (144° R) in the precooler and then to about 4.5 K (8.1° R) in the subcooler before it enters the test dewar. The heat of compression of the helium in the dewar is removed by the test dewar cooler. Because of the relatively high compressibility of liquid helium, fill densities 60% greater than normal-boiling-point-liquid density can be obtained at 10 MPa (100 atm) pressure by this method.

The discharge system, figure 2, achieves a constant mass flow rate by maintaining constant pressure and temperature at the discharge nozzle during flow. Self pressurization of the dewar is accomplished by the blower-heat-exchanger loop in the upper portion of the figure. Cold fluid is drawn from the bottom of the dewar, warmed to ambient temperature, and returned to the top of the dewar. Temperature stratification results, and as fluid is drawn from the dewar, a warm zone propagates towards the bottom.

Demonstrations of the completed system were highly successful and indicated that the desired storage densities and discharge rates are indeed practical and require no technical

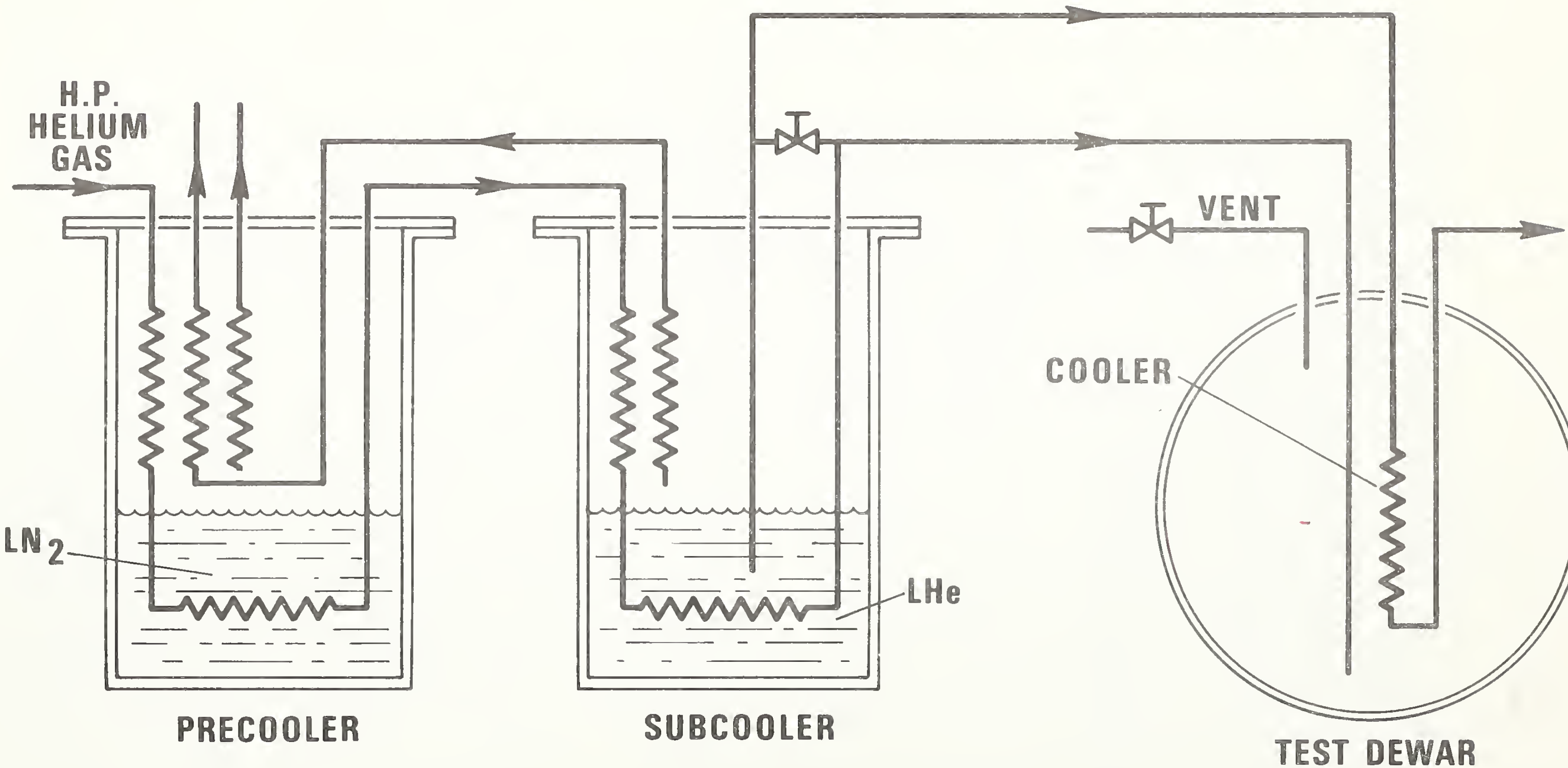


Figure 1. Fill system schematic.

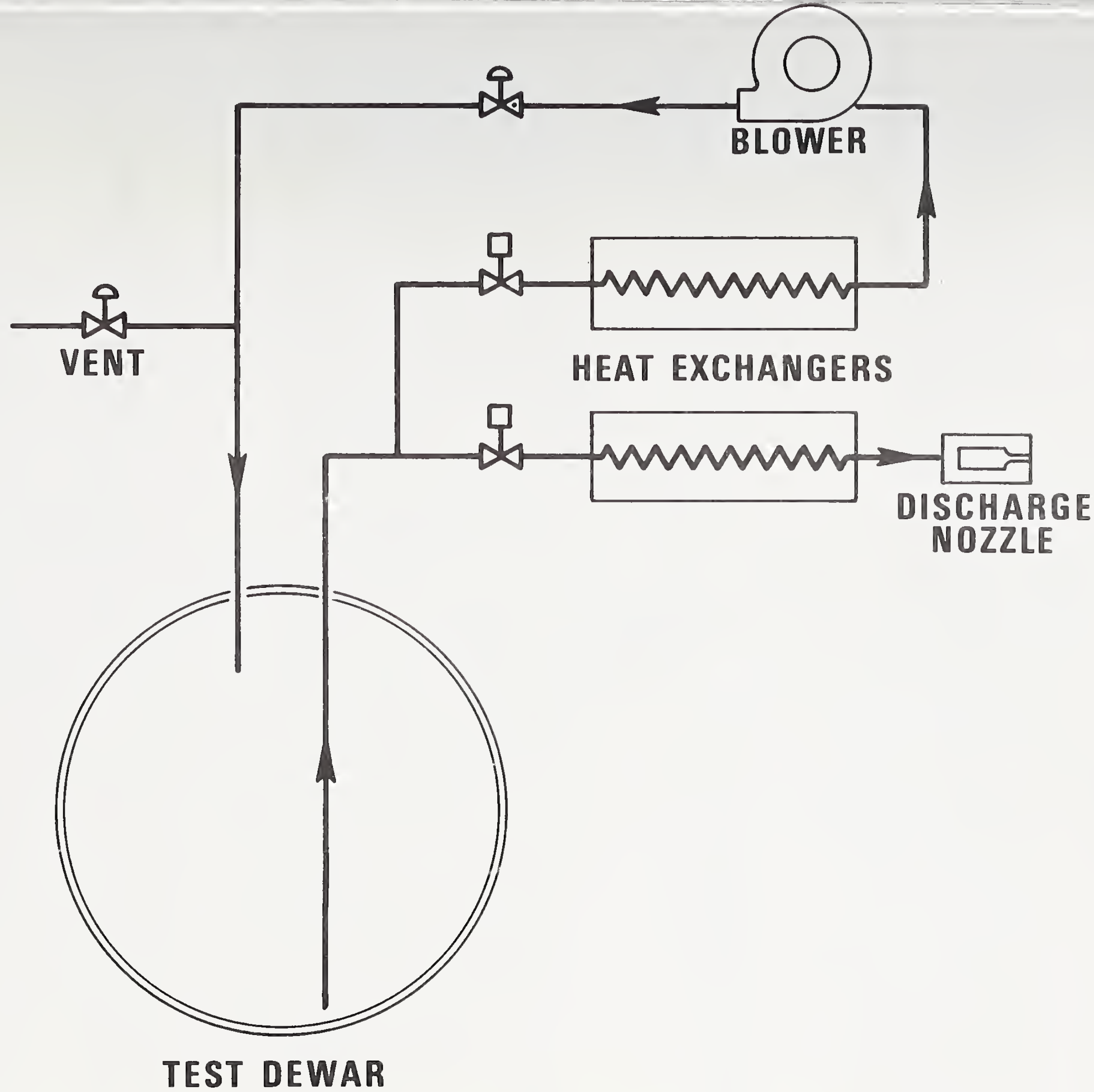


Figure 2. Discharge system schematic.

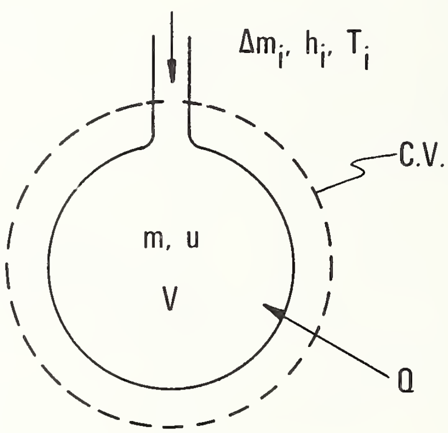
advances - only careful application of the existing state of the art. In the 135 liter (35 gal.) test dewar a density of 0.193 x 10^3 kg/m^3 (12.03 lb/ft^3) was achieved at 8.2 MPa (81 atm), the maximum dewar operating pressure. Although lower than the 0.2 x 10^3 kg/m^3 (12.5 lb/ft^3) goal, extrapolation of the density-pressure fill curve gives the goal density at the 10 MPa (102 atm) pressure limit. Discharge rates of 1 kg/s with a variability of less than $\pm$ 1% were achieved without feedback control; and in general, the system operated in a very stable and well-behaved manner.

2. ANALYSIS

Several system processes merit careful analysis, viz., the fill process, the pressurization-discharge process, and mixing of the temperature stratified contents of the dewar. Whereas analysis of the first two processes is necessary for the design of the fill and discharge systems, the last process is important in considering field applications in which sudden changes in dewar orientation might occur.

2.1 Fill Process

Consider the open system shown below.



The First Law of Thermodynamics for this system is

$$\Delta E = Q - W + h_i \Delta m_i . \tag{1}$$

Noting that the shaft work, W, is zero, and expanding the internal energy term gives

$$m_2 u_2 - m_1 u_1 = Q + h_i \Delta m_i , \tag{2}$$

where subscripts 1 and 2 refer to the initial and final states, respectively. Now

$$\Delta m_i = m_2 - m_1 ,$$

so that eq. (2) becomes

$$u_2 = \frac{m_1}{m_2} u_1 + \frac{Q}{m_2} + h_i \left(1 - \frac{m_1}{m_2}\right). \tag{3}$$

Using the definition of density

$$\rho = \frac{m}{V}$$

gives

$$\frac{m_1}{m_2} = \frac{\rho_1}{\rho_2}$$

and eq. (3) becomes

$$u_2 = \frac{\rho_1}{\rho_2} u_1 + \frac{\rho_1}{\rho_2} \frac{\rho_0}{\rho_1} \frac{Q}{m_0} + h_i\left(1 - \frac{\rho_1}{\rho_2}\right). \tag{4}$$

Absence of a simple equation of state requires that eq. (4) be solved by iteration since ρ_2 appears on the right hand side and is unknown. The helium thermodynamic property programs of McCarty [2] and Arp [3] were used in the numerical solution of eq. (4).

2.2 Pressurization - Discharge Process

During the discharge from the dewar we achieved constant discharge mass flow rate by maintaining the dewar pressure constant. This condition requires that the volume flow rate of the pressurant gas be equal to the volume flow rate of the fluid leaving the dewar. This intuitively obvious statement is easily demonstrated by considering a control volume of fixed dimensions moving along a column of temperature stratified fluid. The motion of the control volume does not affect the pressure in the column (neglecting the hydrostatic effect), and the fixed dimensions require equal volumes entering and leaving. When we consider that a portion of the discharged stream is recirculated as pressurant, we obtain

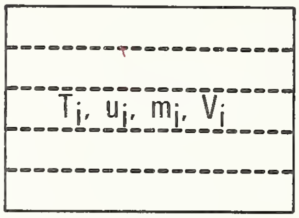
$$\overset{\circ}{m}_i = \frac{\rho_i/\rho_0}{1 - (\rho_i/\rho_0)} \cdot \overset{\circ}{m}_o \tag{5}$$

for the pressurant mass flow rate, where the subscript i refers to the warm pressurant, and the subscript 0 refers to the cold discharge fluid.

2.3 Mixing

In some field applications sudden changes in dewar orientation might occur, and it is important to know what changes in dewar pressure could result from the consequent mixing of the temperature-stratified contents. If a sudden pressure rise were to occur, rupture of the dewar might result. A large pressure decline could temporarily reduce the discharge capacity of the system.

Let us consider a system initially divided into n subsystems, each one of which is internally in a state of stable equilibrium, and which is in thermal isolation from its neighbors and the surroundings. Pressure equilibrium is assumed.



Let mixing or thermal equilibrium of the total system occur. During this process there is no external work, heat transfer with the surroundings, or mass flow; so the first law of thermodynamics becomes

$$\Delta U = 0.$$

The mean specific internal energy is given by

$$\bar{u} = \frac{\Sigma u_i m_i}{m} = \frac{\Sigma_i u_i \rho_i X_i}{\Sigma_i \rho_i X_i} \tag{6}$$

where X_i is a volume fraction.

The mean density of the fluid in the dewar is given by

$$\bar{\rho} = \Sigma_i \rho_i X_i . \tag{7}$$

Equations (6) and (7) define the initial and, for this process, the final state of the fluid in the dewar. The final pressure is then obtained by iteration for the state $\bar{\rho}$, $\bar{u}$.

3. EXPERIMENTAL SYSTEM

The experimental system, figure 3, is comprised of three subsystems: the fill system, the test dewar, and the discharge system.

In the fill system, a single fill line serves the dewar. Liquid transfer occurs with valve V-23 open, and supercritical fluid transfer with V-23 closed. The test dewar is initially filled with liquid helium, via V-23, the vent valve V-34 is closed (along with V-23), and the dewar is then pressurized and filled with supercritical helium (T ≃ 4.5 K) from the subcooler. Continuous transfer from the helium supply dewar to the subcooler occurs during this fill operation. High pressure (16 MPa, 160 atm) helium gas, supplied from a 1100 std. m^3 (40,000 scf) tube trailer, passes through a molecular sieve purifier and then to a dome-loaded pressure regulating valve which controls the pressure and flow rate. Passing to the precooler, the helium is then cooled to near 80 K (144°R) by helium and nitrogen boil-off gas in the three-pass counter flow heat exchange of the precooler. Cooling to 80 K (144° R)

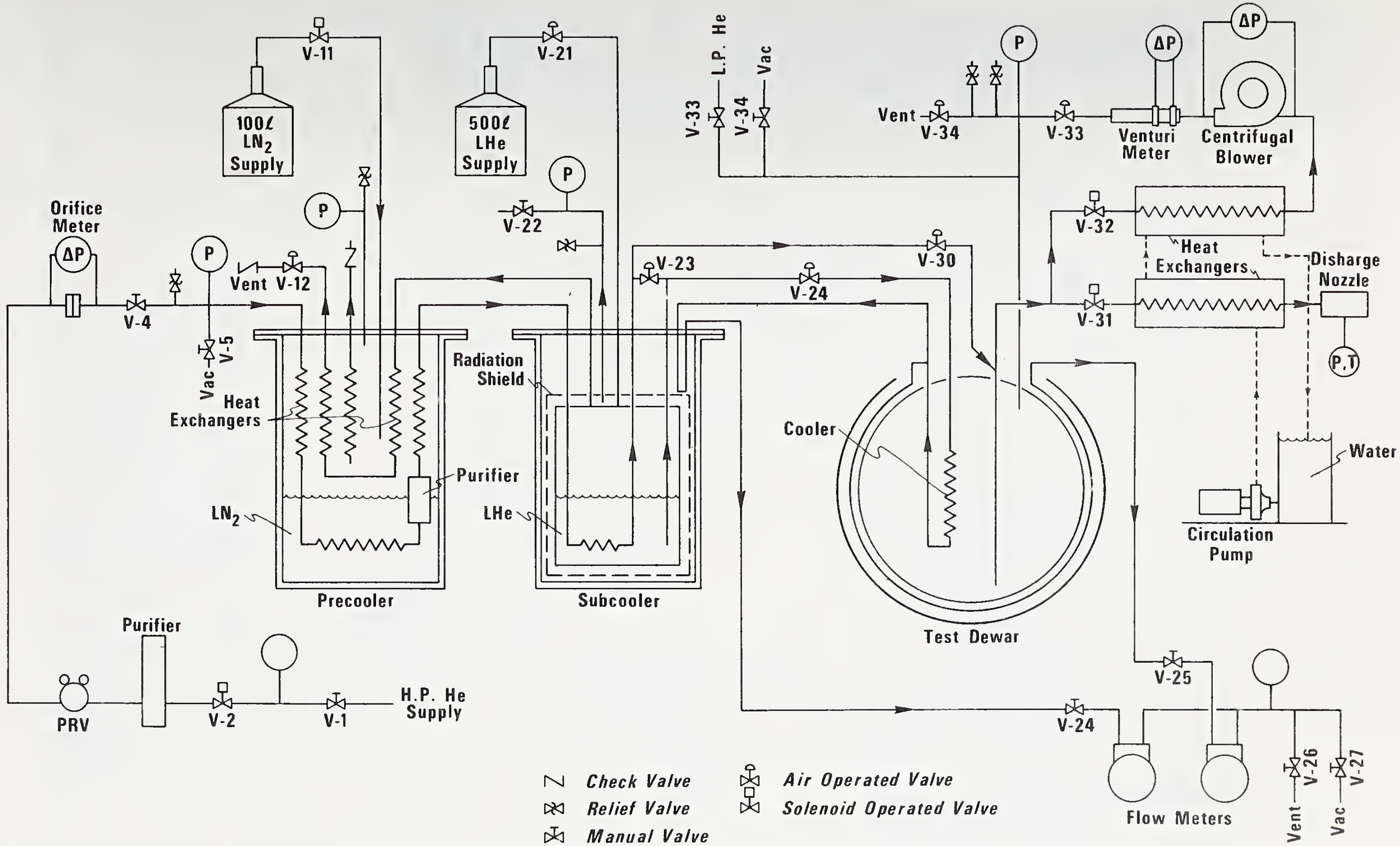


Figure 3. Experimental system.

occurs in the coil immersed in liquid nitrogen (LN_2), and trace impurities are removed in the charcoal purifier. Further cooling to near 5 K (9°R) by the helium boil-off gas then occurs in the two-pass counter flow heat exchanger, which is vacuum and multilayer insulated. After passing through a vacuum-insulated transfer line to the subcooler, the final temperature of 4.5 K is achieved in the liquid helium cooled coil. Finally, the stream passes through a second transfer line (vacuum insulated and vapor shielded) to the test dewar.

The test dewar cooler is supplied with liquid helium drawn from the subcooler and throttled through valve V-24. The cooler boil-off stream is split as it emerges from the dewar with one stream cooling shields on the transfer line and subcooler. The other stream cools an antipercolation line in the Apollo dewar, which was originally thought to be a shield line.

The discharge system is composed of the main heat exchanger, the blower heat exchanger and the blower. Pulsed, constant flow rate discharges of 1 kg/s are achieved by simultaneously starting the blower and opening valves V-31 and V-32 (V-33 is open except during filling). The blower and its associated heat exchanger provide the high flow rate of pressurant gas required to maintain constant pressure in the test dewar during the discharge. Regulation of the discharge rate is achieved by the fixed diameter discharge nozzle. By supplying this nozzle with gas of a relatively constant temperature and pressure, the desired fixed flow rate is achieved. Discharge flow measurement is achieved by simply measuring the temperature and pressure at the inlet to this sonic nozzle.

General views of the apparatus are given in figures 4 and 5, and figure 6 shows details near the test dewar. Operation of the test dewar at high pressures required installation of the equipment behind a protective concrete wall and operation by remote control when pressurized. The main control panel, located in an adjacent trailer, is shown in figure 7.

3.1 Fill System

The heat exchanger type fill system was chosen because it appeared to pose the fewest problems for development of a working system in the short time allowed. A system employing a high pressure reciprocating liquid helium pump would offer superior helium supply logistics because only a liquid helium supply would be required, but this system would require development of a pump.

Figure 8 gives a view of the fill system with the precooler dewar, subcooler vacuum can, and subcooler radiation shield removed. Both counter-flow heat exchangers are located in the subcooler for convenience. The high temperature heat exchanger sits in the nitrogen vapor space uninsulated, whereas the low temperature heat exchanger has multilayer insulation in a vacuum jacket.

Both heat exchangers are fabricated from ribbon packed heat exchanger tubing with an active surface area (all channels) of 0.13 m^2/m (4.2 ft^2/ft) and a hydraulic diameter of 2.4×10^{-3} m (0.008 ft). Two parallel 1.0 meter lengths of tubing form the high temperature heat exchanger, and a single 1.0 meter length forms the low temperature heat exchanger. At the design flow rate of 11 g/s, the calculated number of transfer units (NTU) of the low temperature heat exchanger is 11. In practice, flow rates were limited to 5 g/s by the rate

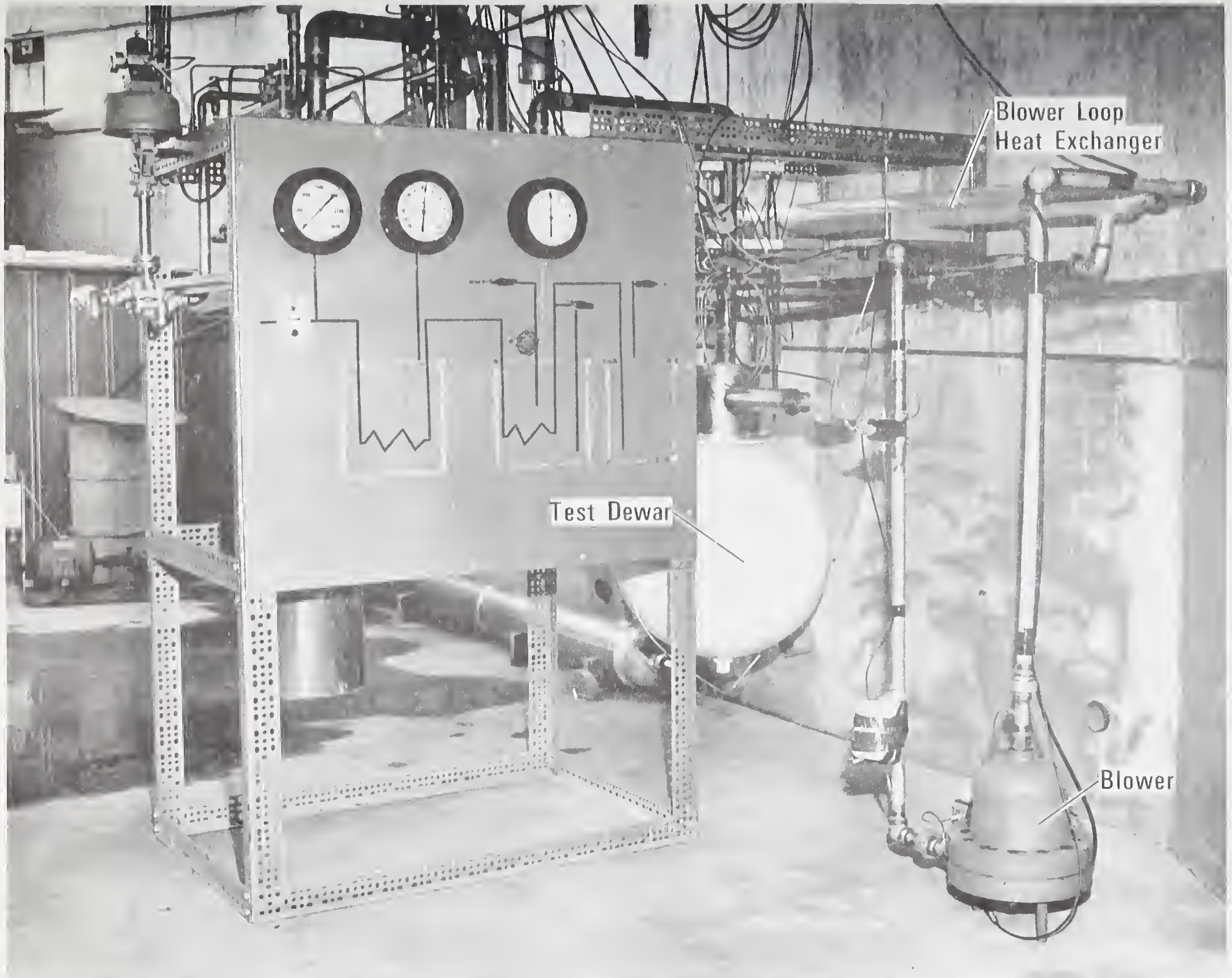


Figure 4. General view of apparatus.

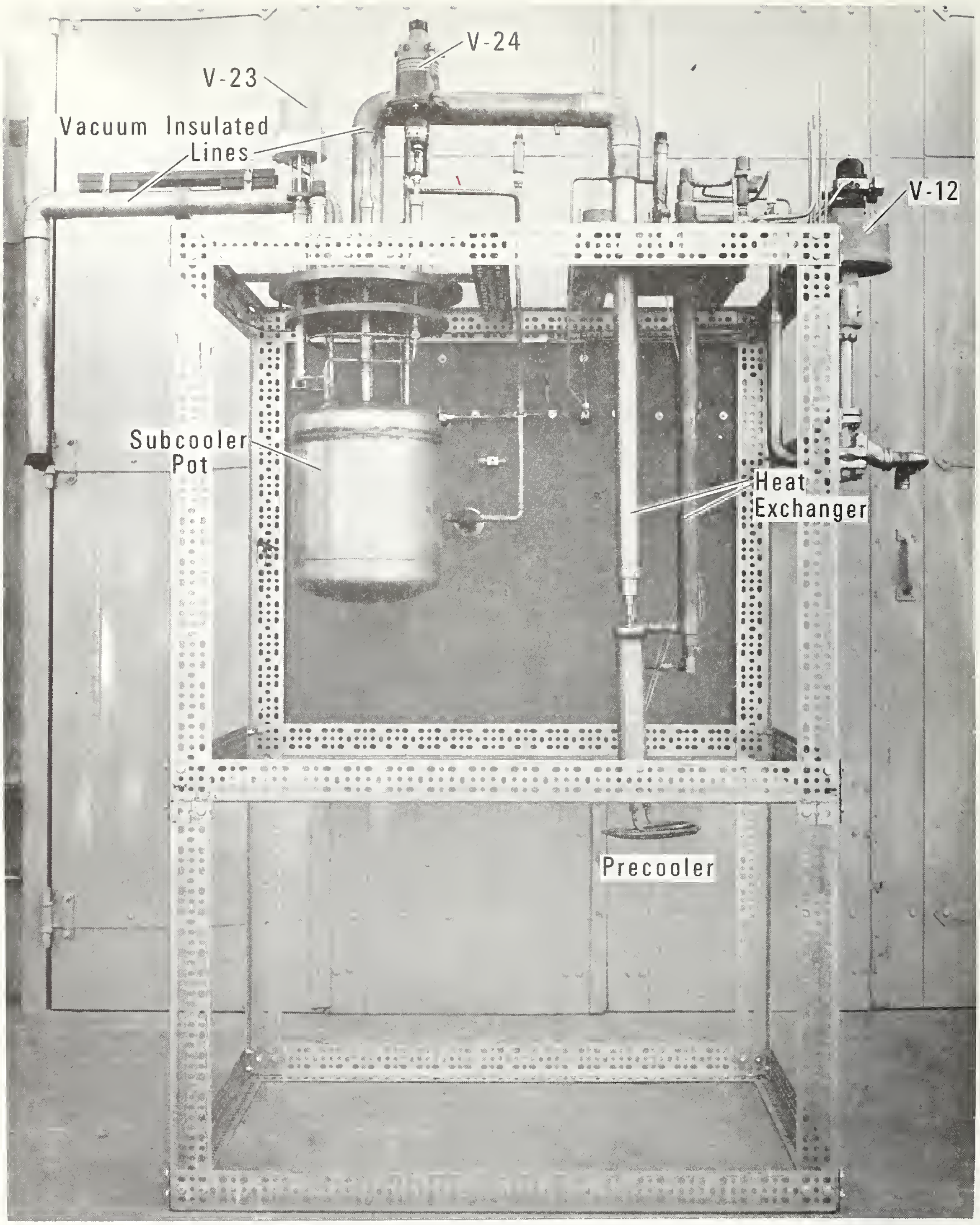


Figure 8. Partially assembled fill system.

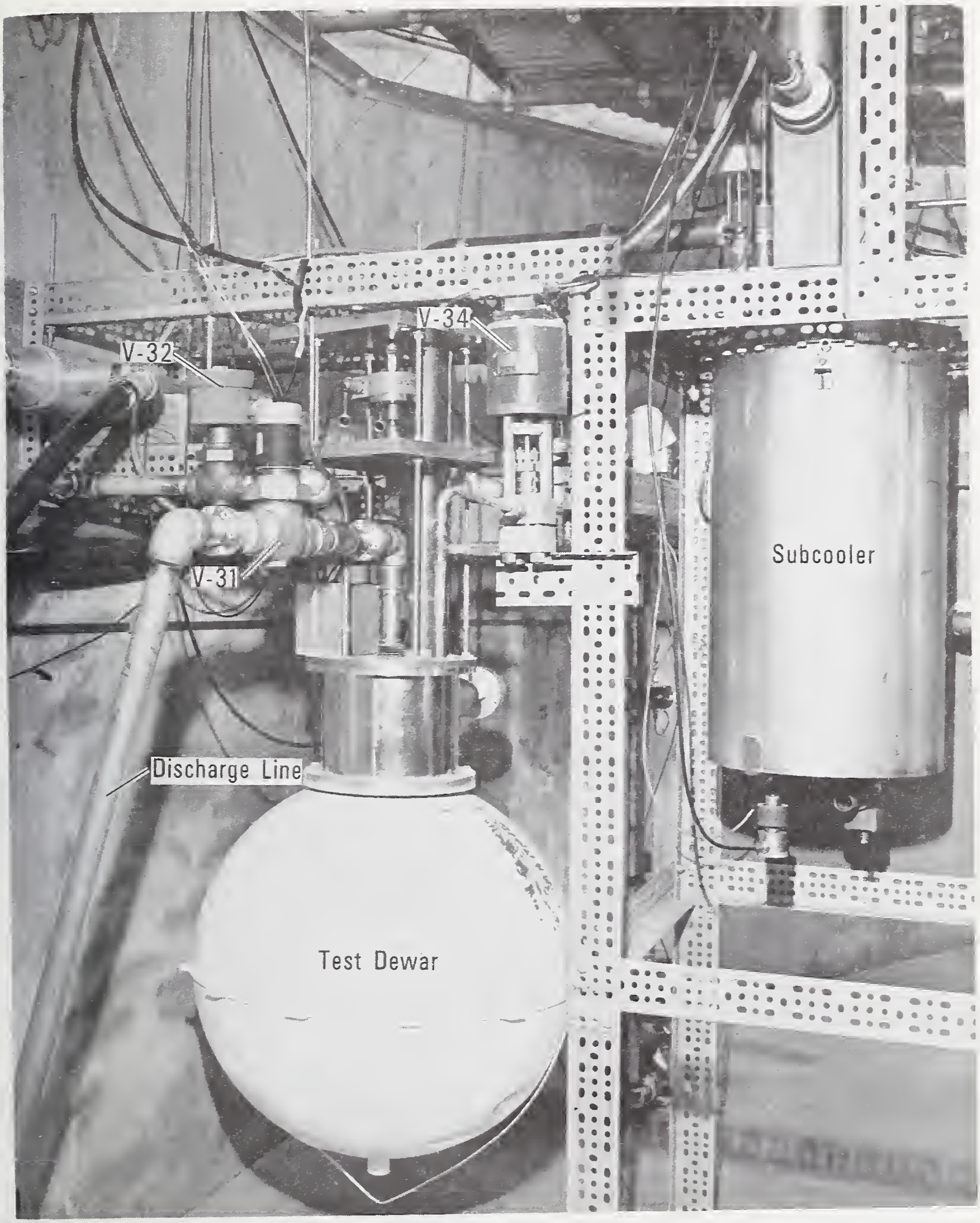


Figure 6. Test dewar and discharge piping.

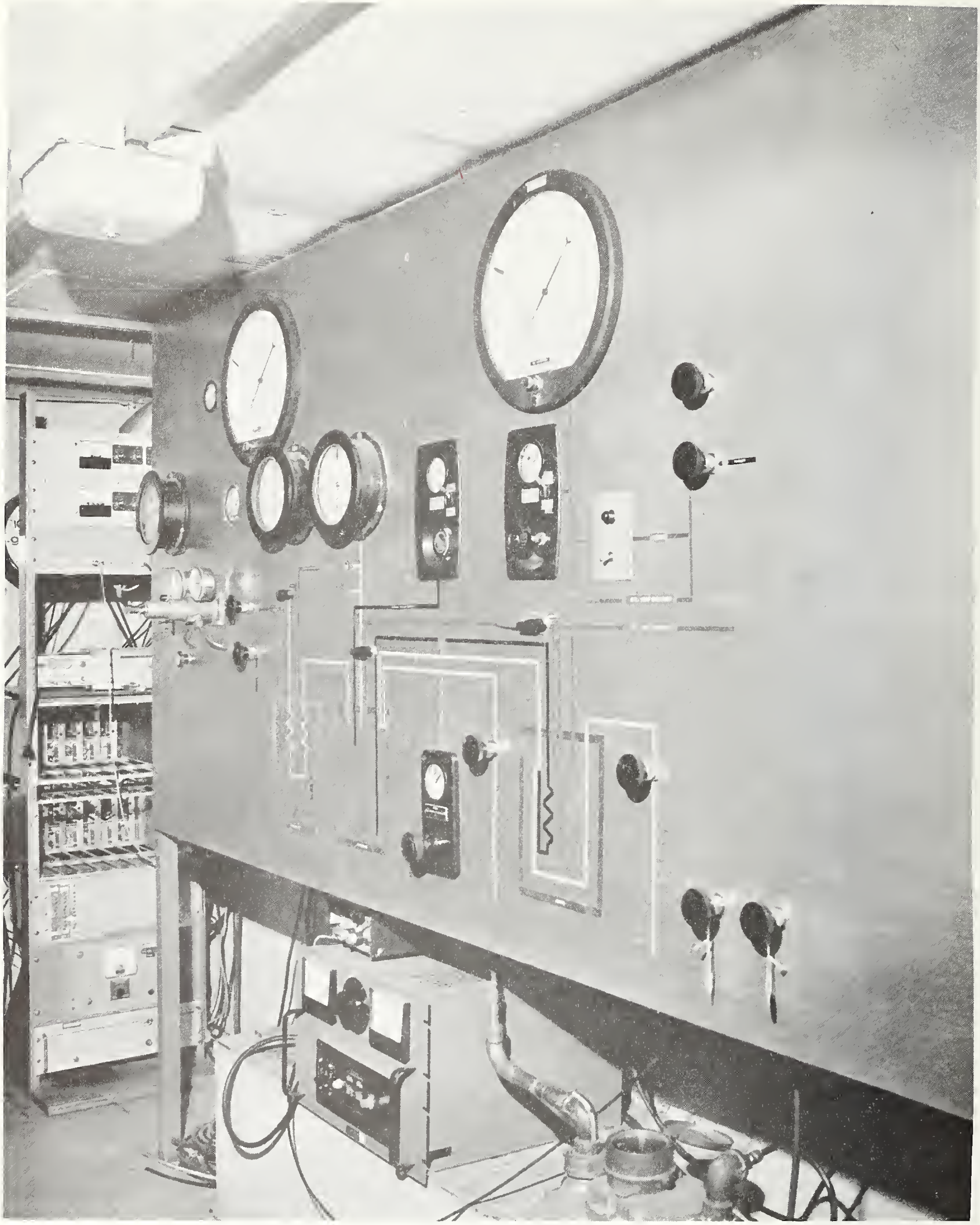


Figure 7. Main control panel.

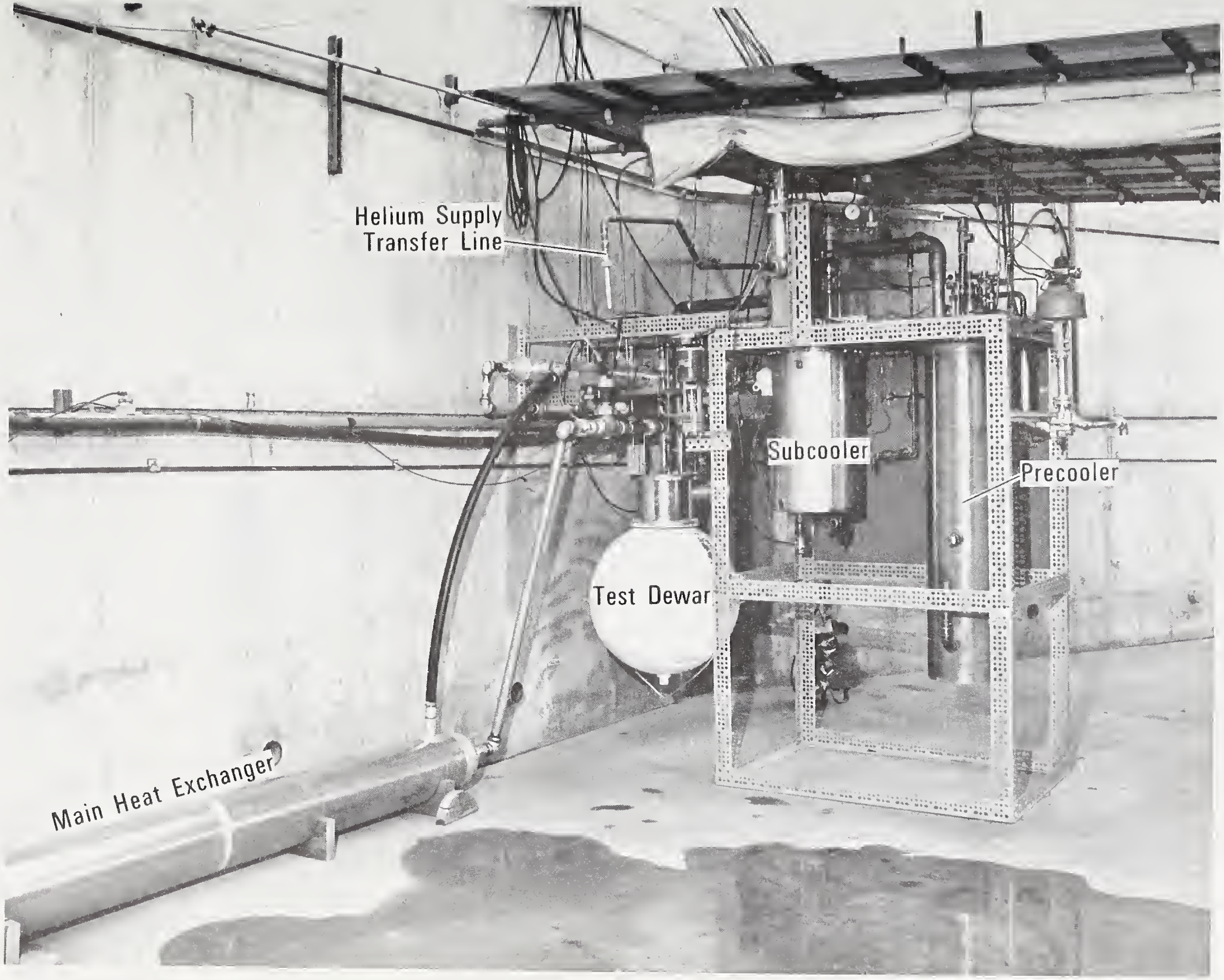


Figure 5. General view of apparatus.

of transfer from the liquid helium supply dewar to the subcooler pot, giving an estimated NTU of 24.

In the precooler, the liquid nitrogen-cooled coil consists of 3 meters (10 ft) of 9.5 mm (3/8-inch) O.D. copper tubing. The subcooler coil is 10 meters (33 ft) of 9.5 mm (3/8-inch) O.D. copper tubing, giving an estimated temperature difference between the bath and exit fluid of 0.1 K (0.2 R).

Gas-cooled radiation shields around the subcooler pot and fill line assure a low heat leak to the cold helium as it flows to the test dewar.

3.2 Test Dewar

The schedule did not allow time for fabrication of a dewar designed specifically for these tests. Instead, we modified an existing Apollo oxygen dewar by cutting off the bonnet and removing the neck plug and the dewar contents. Figure 9 shows the modified dewar, and Table 1 lists the characteristics of the dewar. The design pressure for this dewar is 7.2 MPa (1040 psi), but the operating pressure was extended for these tests to 8.3 MPa (1205 psi) by placing the equipment behind a protective barrier and operating it remotely.

Relatively large discharge (23.9 mm I.D.) and vent (16.6 mm I.D.) lines are required in order to achieve a low pressure drop in the blower circuit; otherwise, the blower head requirements would become excessive. The pressurant gas enters the dewar through the 31.8 mm (1-1/2 inch) I.D. x 44.5 mm (1-3/4 inch) O.D. annular space between the discharge and the dewar neck. No significant disturbance of the thermal stratification by the pressurant entrance jet was observed with this arrangement.

The cooler, which is wrapped around the discharge tube, is formed from 6.35 mm (1/4 inch) O.D. x 4 m (13 ft) long copper tubing. In these tests its cooling capacity was limited by the cooler flow rate rather than heat transfer capacity. The cooling rate based on the cooler flow rate is 10 watts, compared to a capacity of 88 watts calculated for a 0.5 K (0.9°R) ΔT.

3.3 Discharge System

The discharge heat exchanger represented the greatest problem in the design of the system because it must transfer 1.5×10^6 watts in order to warm the 1 kg/s discharge flow to ambient temperature. Ambient temperature discharge was not a specific requirement of the tests, but this seemed the best way to overcome the problems of flow control and flow measurement, since cold discharge would be accompanied by problems of large temperature transients and non-ideal gas properties.

The pulsed nature of the discharges, with the opportunity for recovery in between, suggested that a hybrid thermal-regenerator-heat-exchanger might satisfy the requirements. During the discharge, heat is withdrawn from the heat exchanger wall at a rate limited primarily by the thermal diffusivity of the wall. Between discharges, the wall temperature recovers through heat exchange with water circulated through the jacket of the heat exchanger.

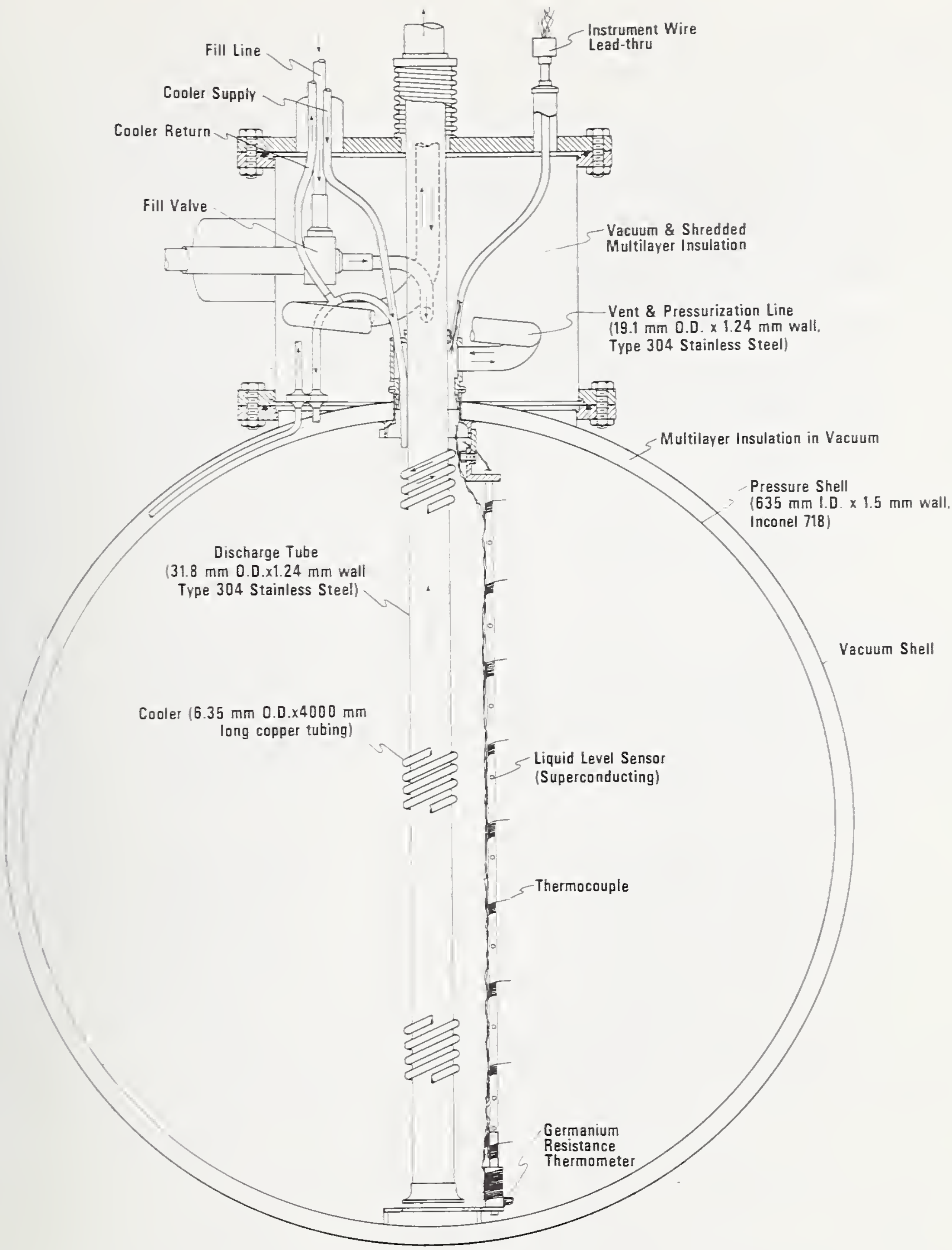


Figure 9. Test dewar assembly.

Table 1. Apollo oxygen tank characteristics [4].

Material	Inconel 718
Ultimate strength, MPa (psi)	1240 (180,000)
Yield strength, MPa (psi)	1000 (145,000)
Youngs' modulus, MPa (psi)	21×10^4 (30×10^6)
Safety factors (Apollo use)	
Ultimate	1.5
Yield	1.33
Safety factors (these tests)	
Ultimate	1.29
Yield	1.15
Pressure-vessel diameter, mm (in)	636.5 (25.06)
Pressure-vessel thickness, mm (in)	1.50 (.059)
Outer-shell diameter, mm (in)	0.51 (0.020)
Operating pressure (these tests), MPA (psi)	8.31 (1205)
Proof pressure, MPa (psi)	9.36 (1357)
Burst pressure, MPa (psi)	10.55 (1530)
Tank volume (measured) m^3 (ft^3)	0.1349 (4.76)
Tank weight before modification, kg (lb)	41 (91)

Figure 10 is a view of a short version of the partially assembled heat exchanger, before assembly of the water jacket and header cap. The heat exchanger used in the tests consisted of 19 tubes 12.7 mm (0.50 inches) I.D. x 25.4 mm (1.00 inches) O.D. x 3.7 m (12 ft) long of type 6061 aluminum welded into a header, and surrounded by a water jacket. The weight of the tubes is 72 kg (158 lbs) giving an ambient temperature heat capacity of 6.5 $(10)^4$ j/K. Typical decay rates of the exit temperature were 20 K/s. The construction of the blower heat exchanger is similar to that of the main heat exchanger, except it is smaller because it handles only 5 percent of the flow. It uses 3 aluminum tubes 12.7 mm (0.50 inches) I.D. x 25.4 mm O.D. x 1.8 m (6 ft) long.

The blower, which was subcontracted, was designed for the following conditions:

Gas	Helium
Inlet pressure	5.2 MPa (750 psi)
Inlet temperature	294 K (70°F)
Mass flow rate	0.05 kg/s (0.11 lb/s)
Volume flow rate	6.2 ℓ/s (13.2 CFM)
Pressure rise	69 kPa (10 psi)
Housing design pressure	8.6 MPa (1250 psi)

It is a partial admission blower with a 180 mm (4.25 inch) diameter impeller (5 straight vanes) attached directly to the motor shaft. The motor and impeller are enclosed in a single high-pressure housing, eliminating the need for a high-pressure rotating shaft seal, and part of the inlet flow cools the motor windings. Use of a universal motor in combination with a variable voltage dc power supply allows control of the blower over a wide range of operating conditions.* Typical test operating conditions were:

Inlet pressure	4.1 MPa (610 psi)
Developed pressure	38 kPa (5.6 psi)
Mass flow rate	0.048 kg/s (0.106 lb/s)
Volume flow rate	7.55 ℓ/s (16 CFM)
Speed	19,800 rpm
Input power	1.56 kW

The blower was operated at much lower speed if it was desired to build pressure in the dewar between discharges, because the normal operating speed gave the rather high pressure rise rate of 0.2 MPa/s (30 psi/s).

The discharge system piping is uninsulated and uses type 304 stainless steel pipe of the following sizes:

dewar to main heat exchanger - 1-1/4 inch nominal (schedule 10)

main heat exchanger to discharge nozzle - 1-1/2 inch nominal (schedule 10)

blower circuit - 1 inch nominal (schedule 10).

3.4 Instrumentation

Data acquisition and reduction were accomplished with a minicomputer system using the following instrumentation:

*The brush life is probably short in the dry helium atmosphere.

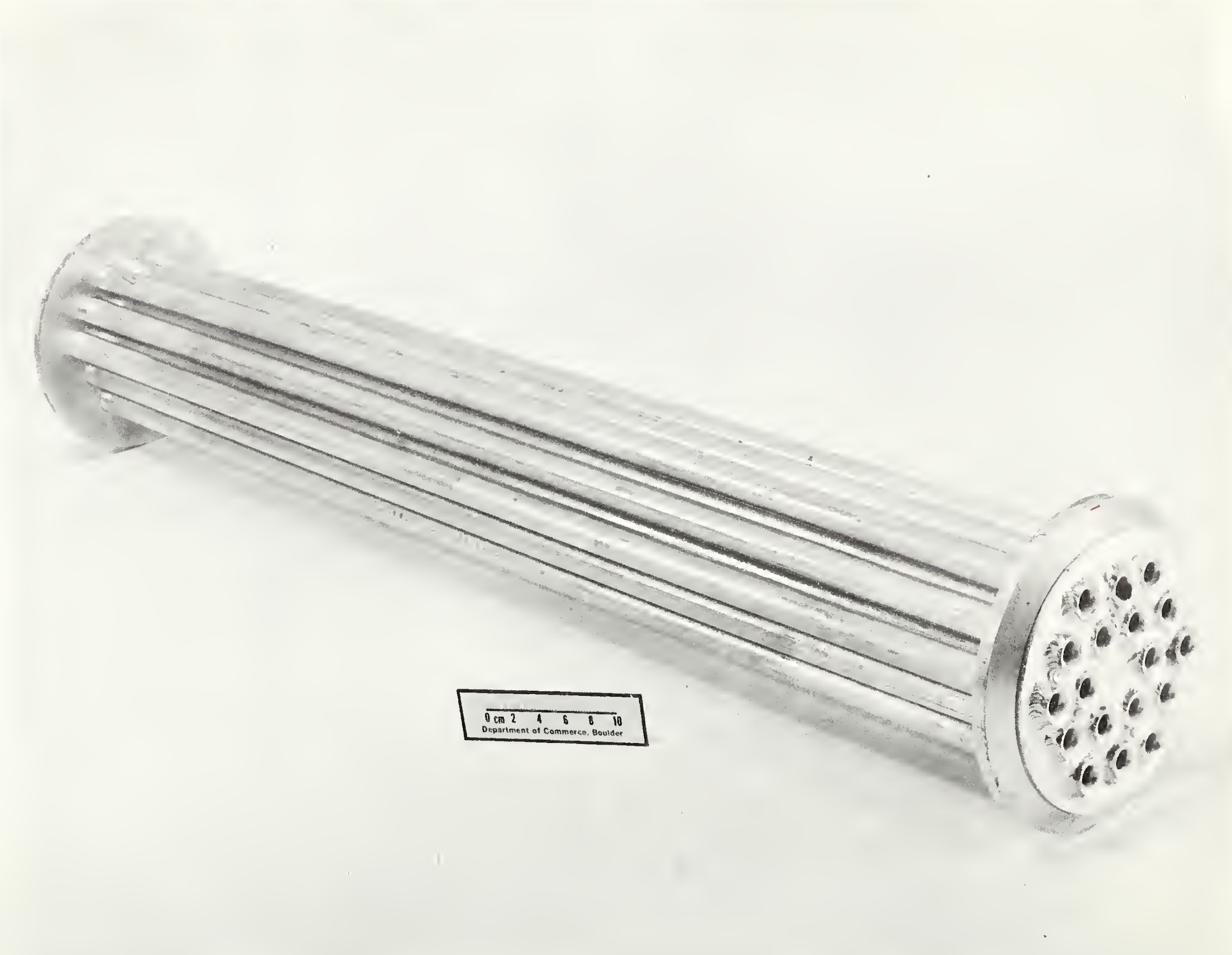


Figure 10. Short version of main heat exchanger without jacket or header cap.

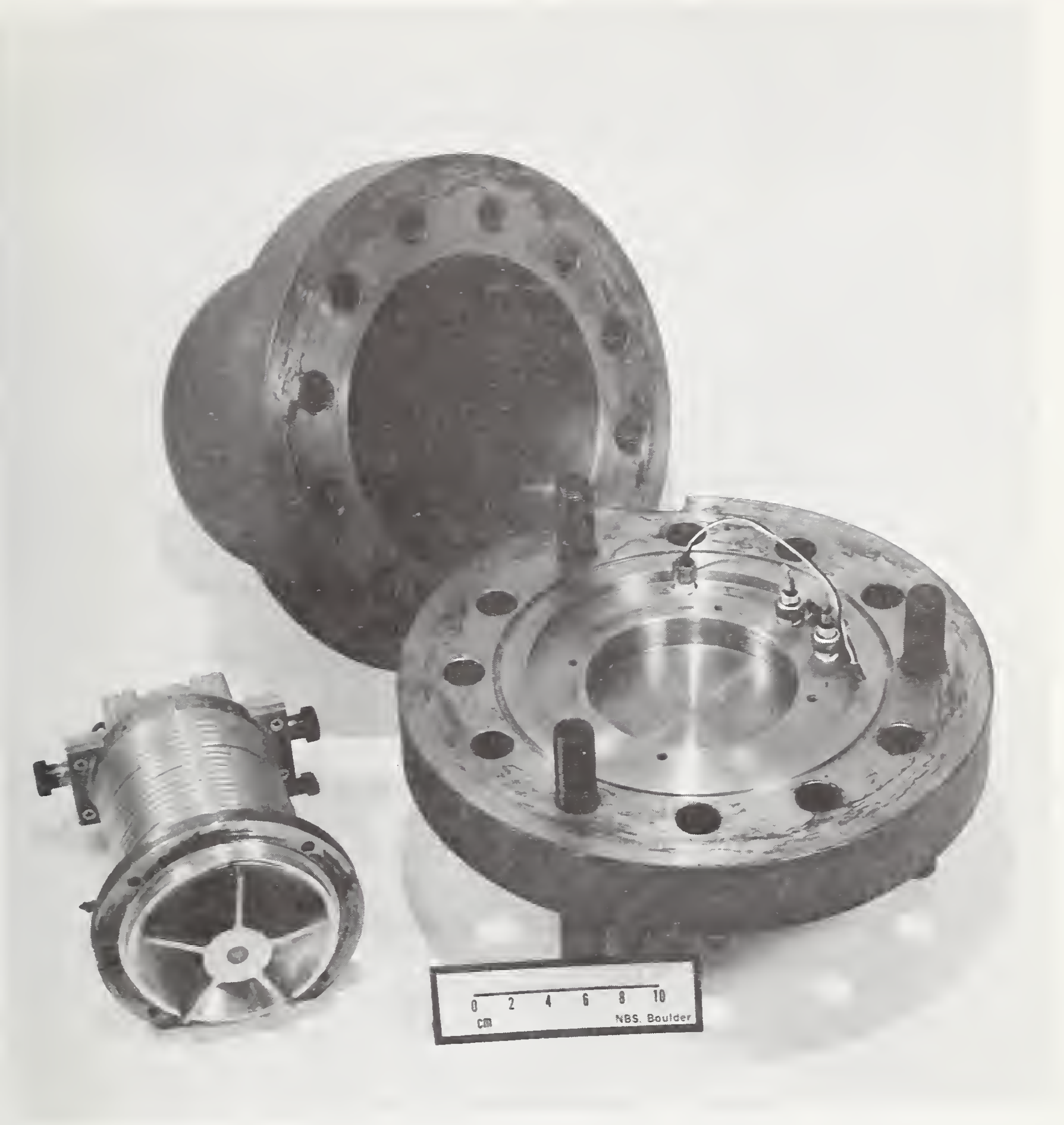


Figure 11. View of disassembled blower.

Temperature at bottom of test dewar (T_o) - germanium resistance thermometer,
Estimated total error $\pm$ 0.02 K (0.04°R).

Temperature at nine dewar locations - gold (0.07 at. percent iron) vs. chromel (type KP) differential thermocouples referenced to T_o. Estimated total error $\pm$ 0.05 K (0.09°R) or $\pm$ 1 percent of measured ΔT.

Temperature at dewar inlet - germanium resistance thermometer (shorted out and did not function)

Dewar pressure - variable reluctance pressure transducer. Estimated total error $\pm$ 0.1 MPa (1 atm)

Discharge nozzle temperature - copper-constantan thermocouple referenced to ice bath. Estimated total error $\pm$ 1 K (1.8 °R).

Discharge nozzle pressure - variable reluctance pressure transducer. Estimated total error $\pm$ 0.1 MPa (1 atm).

Blower developed pressure - variable reluctance pressure transducer. Estimated total error $\pm$ 2 percent.

Blower venturi ΔP - variable reluctance pressure transducer. Estimated total error $\pm$ 2 percent.

Blower venturi temperature - copper-constantan thermocouple referenced to ice bath. Estimated total error $\pm$ 1 K (1.8°R).

Blower speed - magnetic shaft pick up. Estimated total error $\pm$ 3 percent.

The total error in the discharge and blower flows is estimated to be about $\pm$3 percent. In addition to the pressure transducer, a bourdon tube pressure gauge with an accuracy of $\pm$ 50 kPa (0.5 atm) was used to measure the test dewar pressure.

Liquid level in the test dewar and subcooler were indicated with superconducting liquid level sensors since knowledge of these levels is necessary for operation of the apparatus.

The primary method of density determination was by measurement of the dewar pressure and temperature. The average bulk density was calculated using equation (7) and using volume weighting factors based on horizontal segments. In the first experiment (before the discharge piping was attached), mass determination was also attempted with a load cell, but the suspension system was inadequate for the thermal and pressure stresses of the fill piping. A mass balance of the gas supplied from the tube trailer gave agreement to within 1/2 percent of the density calculated from the pressure and the volume average temperature -- well within the accuracy of the calculation.

4. RESULTS AND DISCUSSION

Six tests, which are summarized in table 2, were made with the system. Except for fill system oscillation problems, which were eliminated, the system operated in a well behaved manner, and no other problems were encountered.

After attachment of the discharge system to the test dewar between tests 1 and 2 (with V-31 adjacent to the discharge nozzle and V-32 and V-33 absent), pressure oscillations with a frequency near 1/2 Hz occurred when liquid fill was attempted. The severity of these oscillations

Table 2. Summary of experiments.

Test No.	Comment	Pressurization Time	Final Pressure	Final Density	Total Discharge Time	Duration of Discharge Tests
		Minutes	MPa (atm)	kg/m^3 (lb/ft^3)	s	Minutes
1	Discharge system not attached.	28	6.8 (67)	0.185×10^3 (11.54)	--	--
2	Discharge system attached. Severe flow oscillations prevented filling of dewar with liquid helium.					
3	Discharge valve moved to upstream side of heat exchanger, oscillation amplitude greatly reduced, but not eliminated.	26	5.0 (49)	0.170×10^3 (10.61)	12	--
4	Addition of valve V-33 completely eliminated vent oscillation during fillings.	22	6.7 (66)	0.184×10^3 (11.48)	16	80
5		24	6.7 (66)	0.184×10^3 (11.45)	18	114
6	Lower fill rate used to achieve maximum density.	46	8.2 (81)	0.193×10^3 (12.03)	18	78

was such that no liquid could be accumulated in the dewar because of the concomitant heat input.

Pressure oscillations within helium systems are relatively common, but they are generally the thermal-acoustic (thistle tube) variety which occur in gauge lines, etc., and which have frequencies measured in ten's of hertz [5,6]. In contrast, these oscillations are believed to result from the addition to the vent and discharge lines of a large volume (about 30 liters), which acted as a soft pneumatic spring. With this configuration, a negative vent pressure perturbation moves cold fluid to a warmer region where heating and expansion occur, resulting in a pressure rise and motion of warm fluid towards the cold region.

One solution to the problem consists of increasing the spring constant of the attached volume (decreasing its volume). Thus, the first corrective action taken was to eliminate the heat exchanger volumes from the discharge side of the dewar by moving discharge valve V-31 to the position shown in figure 3, and to add V-32 to the system. These changes greatly reduced the oscillation problem, permitting filling during test number 3, but mild oscillations still occurred. Complete elimination of the oscillations was accomplished with the installation of V-33, which isolates the blower and blower heat exchanger from the vent line.

4.1 Fill Process

Densities attained during the tests are shown in figure 12. Extrapolation of the results for experiment number 6 indicates that the goal of 0.20×10^3 kg/m^3 (12.5 lbs/ft^3) is closely approached at the upper pressure limit of 10.3 MPa (102 atm). Restriction of the test dewar working pressure, however, limited the maximum density to 0.193×10^3 kg/m^3 (12.04 lb/ft^3) at a pressure of 8.2 MPa (81 atm). The densities were determined from the measured temperature profile and pressure and have an estimated total uncertainty of $\pm$ 1 percent -- about half of which is due to the uncertainty in the thermodynamic properties.

Fill experiments 1, 4, and 5 were run with an initial liquid-fill temperature of 4.1 K (7.4°R), an estimated helium supply temperature of 4.5 K (8.1°R), and a net cooling rate of 5 watts (17 BTu/hr) (equivalent to 7.5 J/kg·atm for a 30 minute fill at 67 atm). The inlet line thermometer was shorted out, but the measured subcooler pot pressure indicates a temperature of about 4.4 K (7.9°R) for the subcooler liquid. Allowance for a 0.1 K (0.2°R) ΔT between the liquid bath and the exit fluid results in the 4.5 K (8.1°R) supply temperature given above. The net cooling rate of 5 watts (17 BTu/hr) is based on measured cooler flow rate of 0.5 g/s (0.011 lb/s) (giving a cooling rate of 10 watts assuming use of the latent heat only) and a heat leak of 5 watts (determined from the boil-off rate). The estimated uncertainty in the cooling rate is about 3 watts (10 BTu/hr).

Experiment 6 was run with a reduced fill temperature, 4.3 K (7.7 °R) and increased cooling, 12.5 J/kg·atm. The resulting one percent increase in density, at the same pressure, is apparent in figure 12. These conditions were achieved by filling at a reduced rate and precooling the dewar a day before the experiments. The reduced fill rate resulted in a lower subcooler pressure and temperature, and it increased the cooling time per unit mass. Precooling the dewar reduced the heat leak to the steady state value rather than the higher initial values exhibited by dewars with warm insulation.

The analytical curve in figure 12 was obtained using the method described in section 2.1. The excellent agreement with the experimental data is partly fortuitous because of the estimated 5 percent uncertainty in the specific heat of helium in the region of concern. The agreement does indicate, however, that the actual fill process can be modeled rather well by a thermodynamic analysis that assumes continuous mixing (thermal equilibrium) of the tank contents.

The calculated effect of the amount of dewar cooling is illustrated in figure 13. Higher liquid-fill and supply temperatures are satisfactory for high density storage, given sufficient dewar cooling.

Figure 14 shows the dewar temperature profile during the fill process. The temperatures are measured along a vertical line displaced 49 mm (1.9 inches) from the vertical axis. Because previous studies [7,8] have demonstrated the virtual absence of horizontal temperature gradients (except in a thin wall boundary layer) during natural convection within vessels, a single vertical temperature profile is sufficient to characterize the dewar contents.

Approximately 400 liters (100 gal) of liquid helium were required for cooldown of the fill system and test dewar, fill of the dewar to final density, and supply of the cooler. This compares to an equivalent of 200 liters (50 gal) of helium stored in the 135 liter (35 gal) test dewar. Fill times varied somewhat, but times as short as the following were observed:

dewar cool down (dewar precooled to near 100 K)		6 minutes
Liquid fill		20 minutes
Supercritical fill		22 minutes
	total	48 minutes

4.2 Discharge Process

Figures 15 through 18 are typical traces of the discharge nozzle pressure and flow rate. Mass flow variations of less than $\pm$ 1 percent were attained with fixed nozzle size and blower supply voltage, i.e., without feedback control. A slow decay of the nozzle pressure compensates for the 20 K/s (36°F/s) decay in the nozzle temperature. A 0.1 second pressure rise time and the large flow decay tail are characteristics of this particular heat exchanger-valve arrangement and should not be considered unalterable. Placement of the discharge valve next to the discharge nozzle could reduce transient times to near valve response times. Valves in the positions of V-31, V-32 and V-33 would still be required to prevent fill oscillations.

The blower performance, figure 19, exhibits some modulation. Part of this may be instrument noise, but the congruence of part of the wave forms suggests that some of the modulation may be real. The small pressure dips in figures 15 and 17 suggest that pressure waves may be present in the system which effect the blower behavior and pressure and flow instrumentation.

The vertical temperature distribution in the dewar is shown in figure 20 as a function of the fraction of the initial mass which is left in the dewar. Although there is no liquid level, the region of steep temperature gradient (40 to 80 K) is somewhat analogous to one. When warm fluid reaches the discharge line inlet, the dewar may be considered empty since the

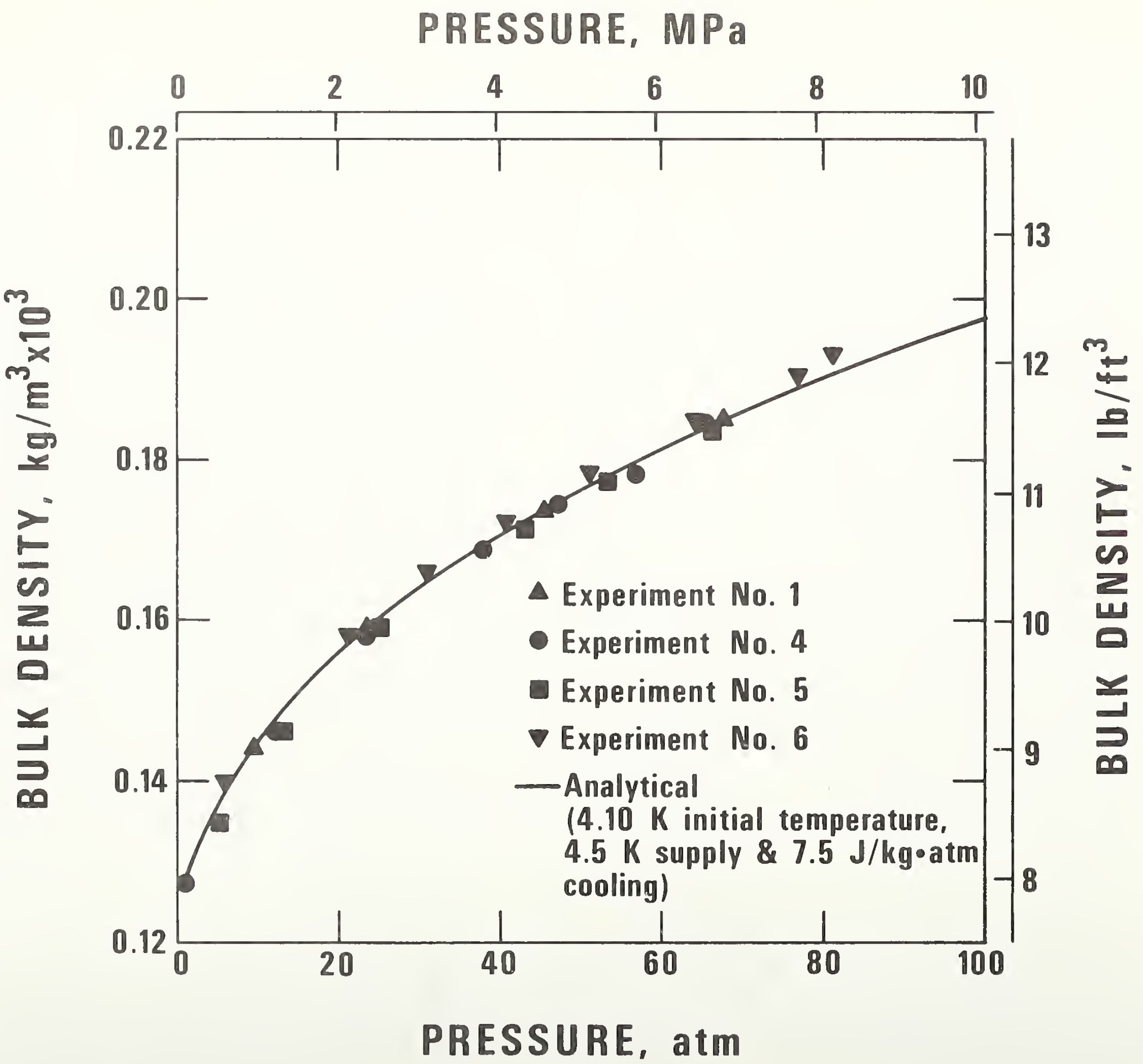


Figure 12. Experimental fill densities.

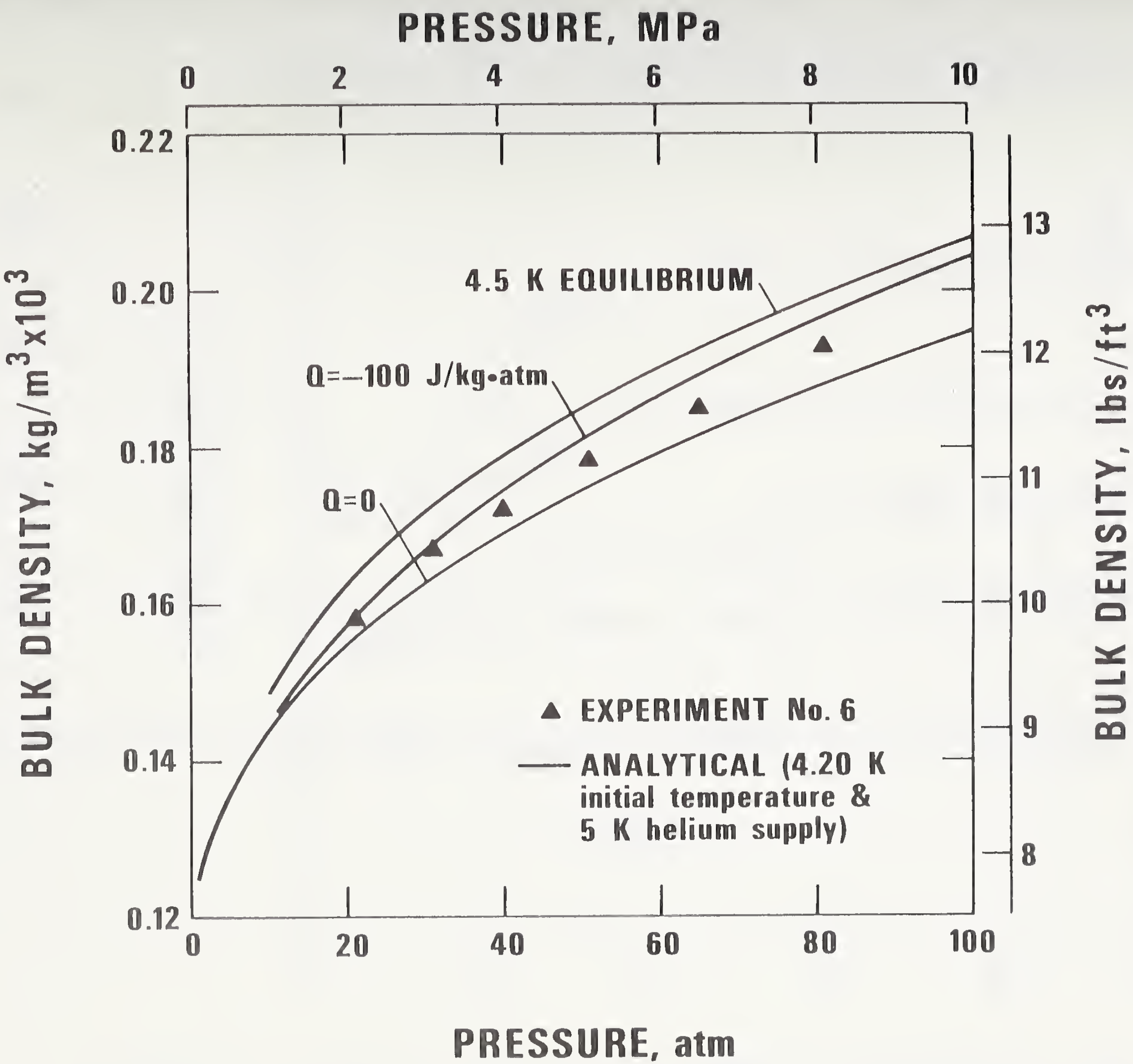


Figure 13. Effect of fill conditions on density.

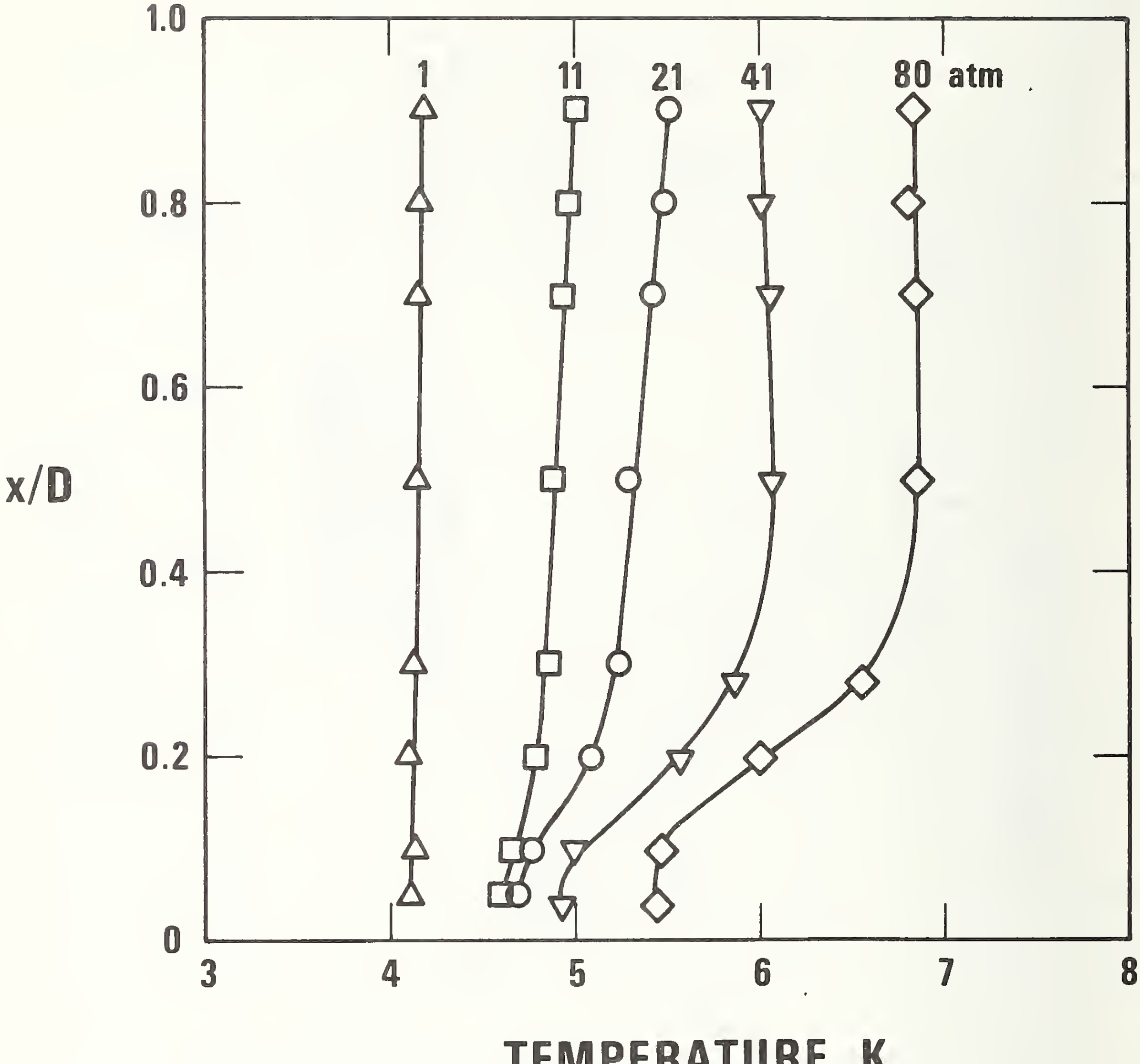


Figure 14. Dewar temperature profile during filling.

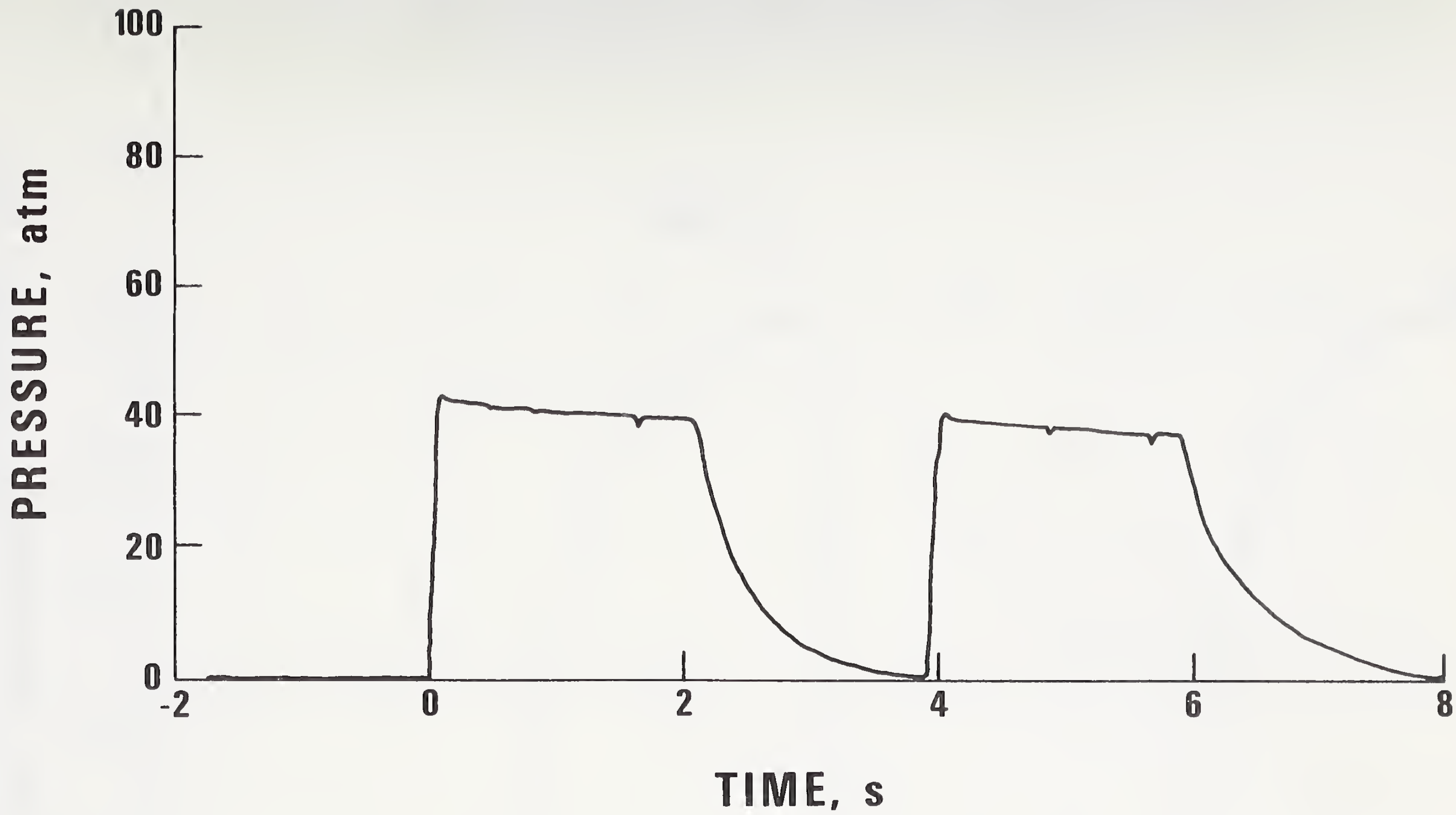


Figure 15. Discharge nozzle pressure during two successive two second discharges.

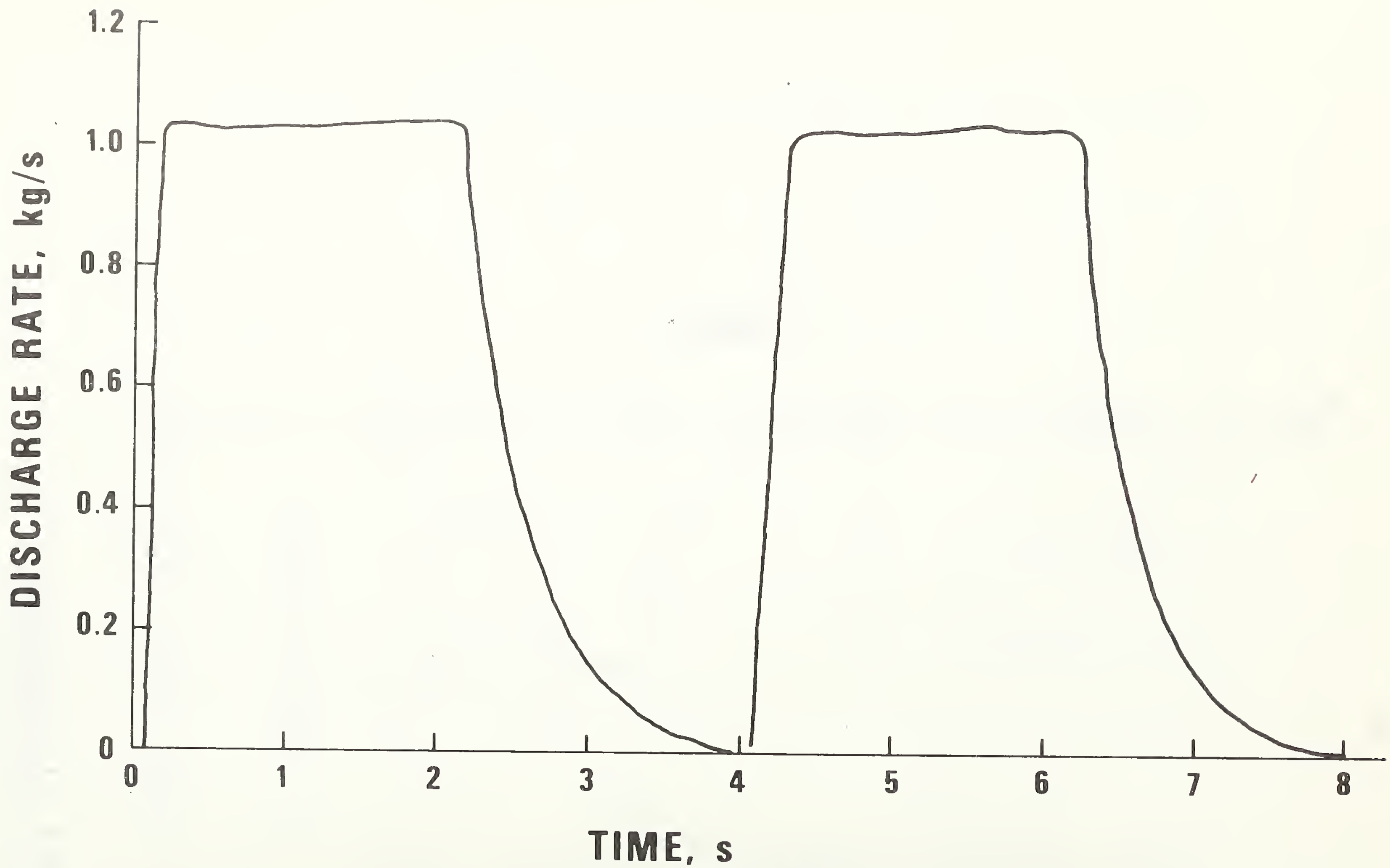


Figure 16. Mass flow during two successive two second discharges.

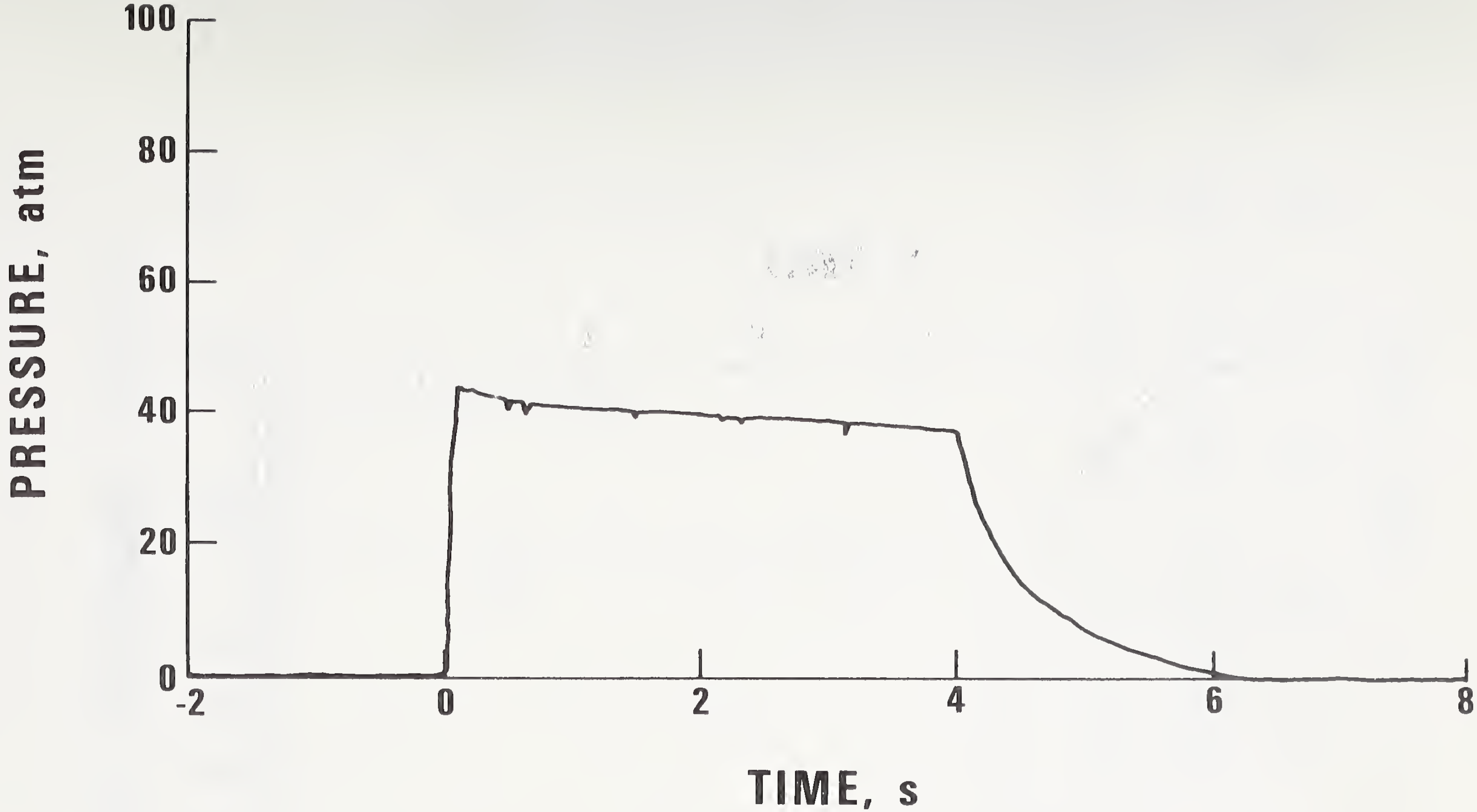


Figure 17. Discharge nozzle pressure during a single four second discharge.

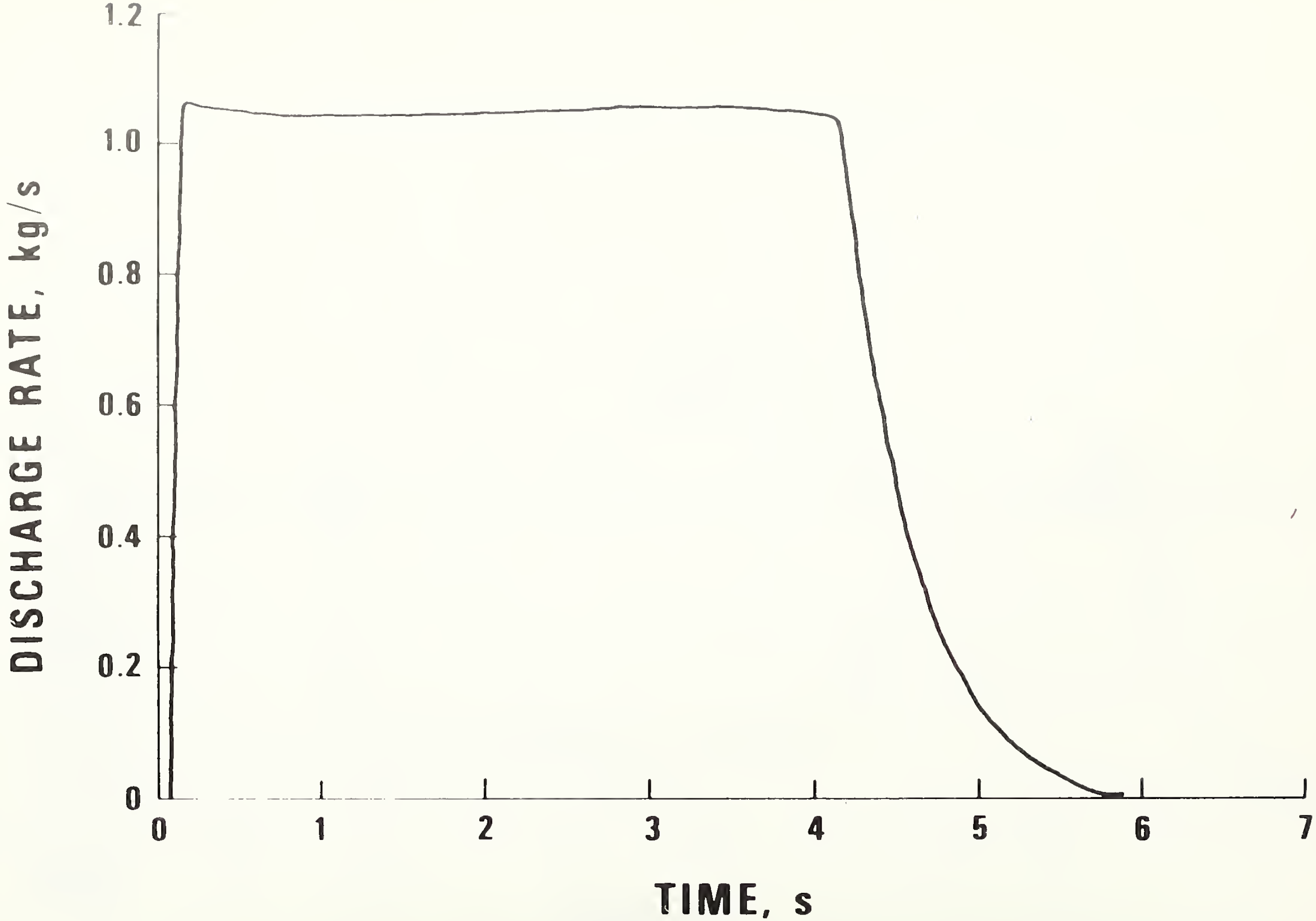


Figure 18. Mass flow during a single four second discharge.

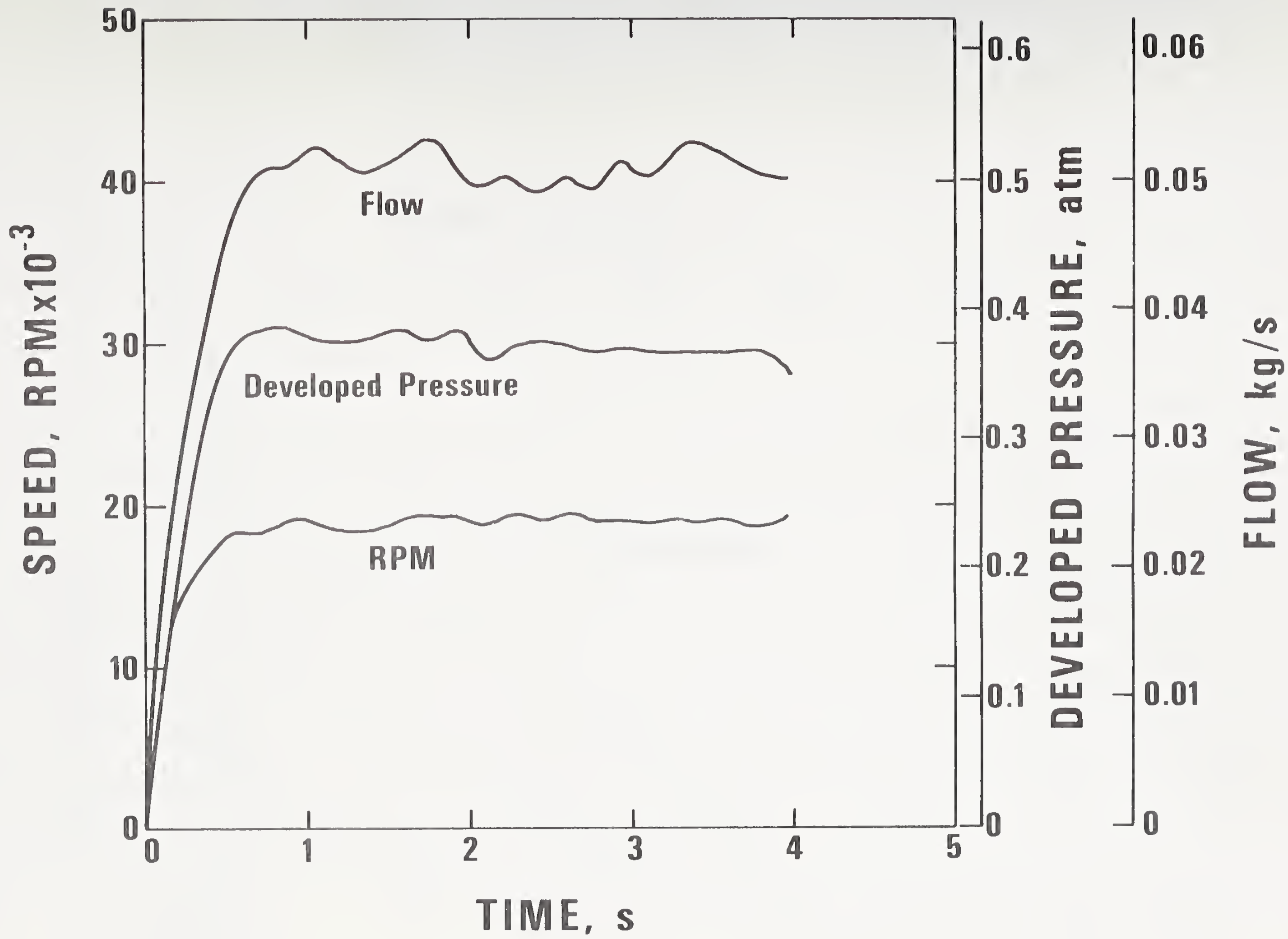


Figure 19. Blower performance during a four second discharge.

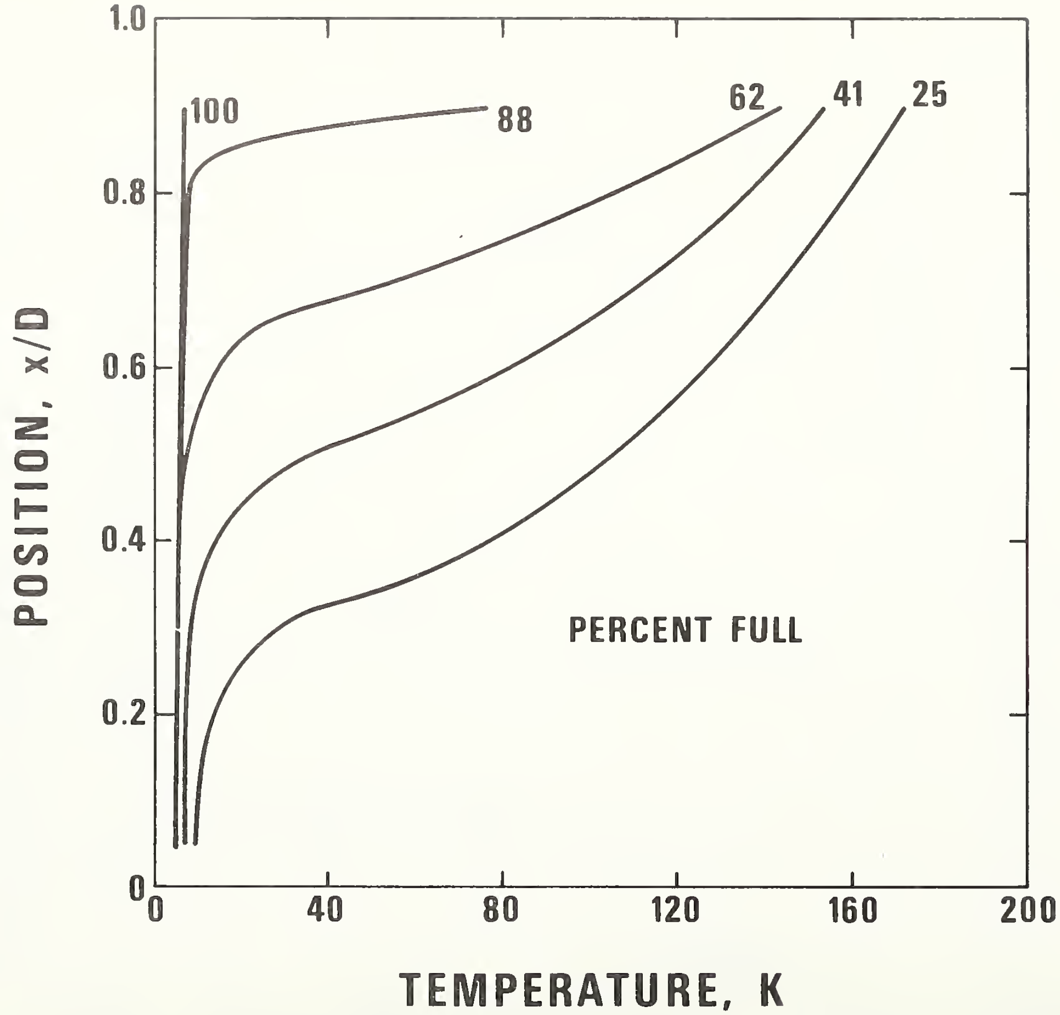


Figure 20. Dewar temperature profile as a function of mass remaining in the dewar.

blower can no longer maintain the dewar pressure during discharge. The downward progression of the warm zone, which should not be confused with thermal diffusion, is simply the result of withdrawal of cold fluid from the bottom and its replacement by warm fluid at the top. Heat transfer with the discharge tube and mixing in the ullage reduce the temperature of the pressurant from ambient (285 K) to the values indicated in figure 20.

The temperature of the fluid entering the discharge tube, figure 21, varies with the amount of fluid discharged. Although the density of the discharge fluid decreased by over 30 percent during the course of the discharges, the blower flow required to maintain constant mass discharge was invarient until the discharge temperature exceeded 16 K. This apparent contradiction with the requirement established in section 2.2 is reconciled by noting that the temperature at the top of the dewar gradually increased as the dewar was emptied. Thus the system is self-compensating.

When the dewar is considered empty (unable to supply flow at specified conditions) is a somewhat arbitrary judgement, of course, which depends on the tolerances specified for discharge flow, discharge pressure, and blower flow. For fixed blower supply voltage, an initial fill density of 0.193×10^3 kg/m^3 (12.03 lb/ft^3), and a minimum acceptable discharge flow of 0.9 kg/s (2.0 lb/s), the dewar was empty with 11.8 percent of the initial mass remaining. If conditions of 0.2×10^3 kg/m^3 (12.5 lb/ft^3) initial density and 0.75 kg/s (1.65 lb/s) minimum flow are accepted, then only 8.6 percent of the initial mass remains. Increasing the blower flow could increase the remaining usable mass even further.

The problem of the pressure change that accompanies mixing of the dewar contents is studied by applying the analysis of section 2.3, using experimentally determined dewar temperature profiles. The results of these calculations, table 3, are for complete mixing, so in practice the pressure decay would always be less. Because the pressure falls upon mixing, there is no danger of dewar rupture due to sudden accidental mixing. The calculated pressure decays are modest enough that there would be little problem in maintaining pressure with the blower during the mixing process.

The original discharge process data for experiment 6 are given in the Appendix.

5. SUMMARY AND CONCLUSIONS

Equipment to store supercritical helium at high density and to demonstrate pulsed discharge at high flow rates has been designed, fabricated, and successfully demonstrated.

A storage density of 0.193×10^3 kg/m^3 (12.03 lb/ft^3) at 8.3 MPa (81 atm) was achieved in a 135 liter (35 gal) dewar with an initial liquid fill temperature of 4.1 K (7.4°R) an estimated helium supply temperature of 4.3 K (7.8°R), and cooling of 12.5 J/kg·atm. The dewar used in these tests was limited to a maximum working pressure of 8.3 MPa (82 atm) but extrapolation of the experimental pressure-density curve indicates that the target density of 0.20×10^3 kg/m^3 (12.50 lb/ft^3) could have been achieved at 10.3 MPa (102 atm).

Pulsed discharges of 2 s and 4 s duration, with 2 s pauses between discharges, were demonstrated at a flow rate of 1.0 kg/s (2.2 lb/s), and flow fluctuations of less than $\pm$ 1 percent were achieved without feedback control.

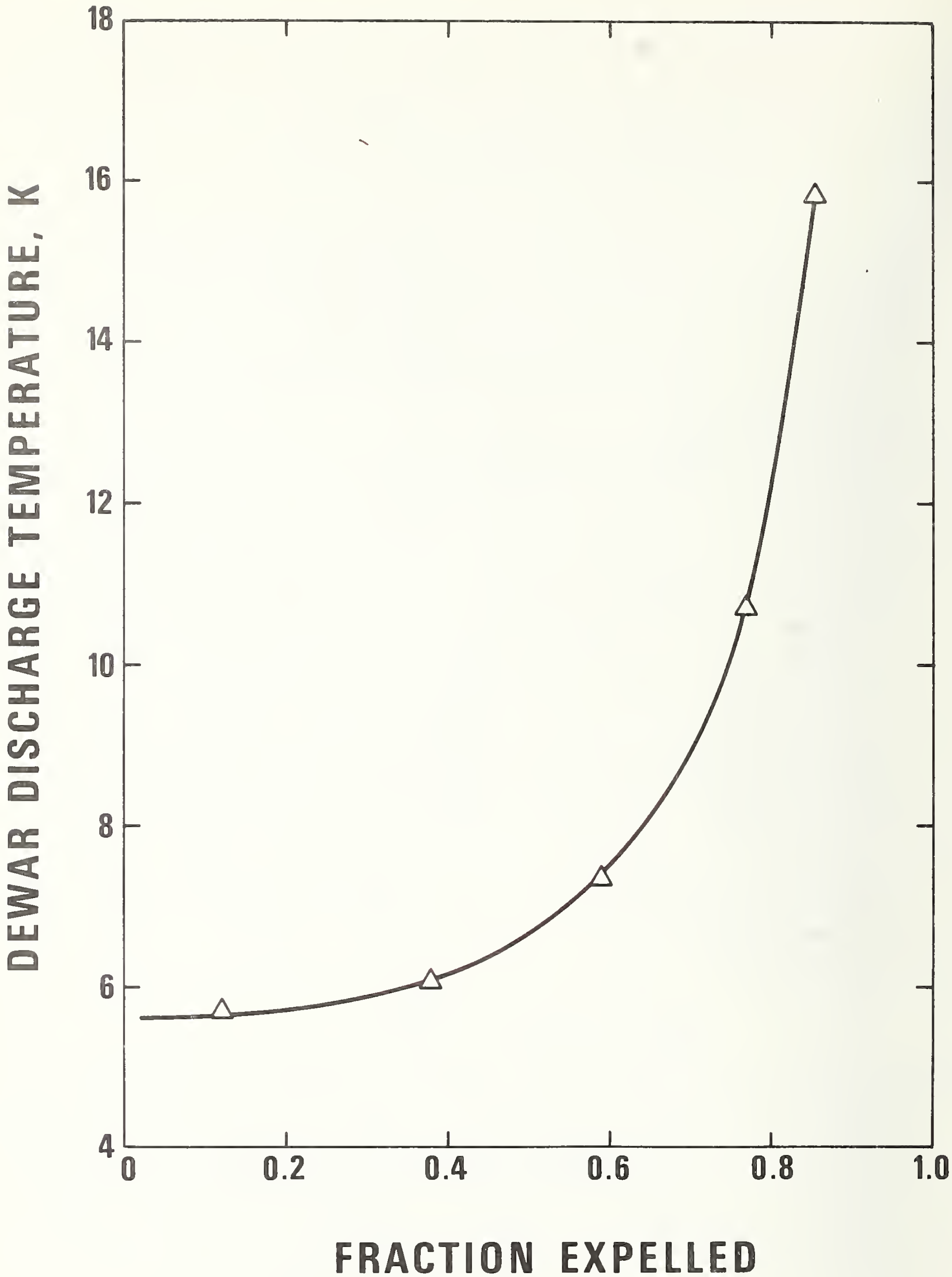


Figure 21. Dewar discharge temperature.

Table 3. Calculated effect of mixing on dewar pressure.

Position, X/D	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
initial temperature, K	5.68	5.66	5.64	5.70	5.79	6.08	6.37	8.22	75.26
initial pressure	=	5.13 MPa	(50.7 atm)						
pressure after mixing	=	4.60 MPa	(45.4 atm)						
initial temperature, K	6.02	6.23	6.55	7.25	7.92	14.0	57.5	104.5	142.9
initial pressure	=	5.39 MPa	(53.2 atm)						
pressure after mixing	=	4.13 MPa	(40.8 atm)						
initial temperature, K	8.57	9.51	23.30	50.0	94.6	126.0	142.6	152.2	155.3
initial pressure	=	4.34 MPa	(42.8 atm)						
pressure after mixing	=	4.05 MPa	(40.0 atm)						

The pressurant flow (blower flow) required to maintain dewar pressure during discharge was found to be 0.050 of the discharge flow rate for most of the range of discharge conditions. A reasonable estimate of the unusable fraction of the initial fill mass is taken to be about 10 percent.

In general, the system operated in a very stable and well behaved manner.

6. ACKNOWLEDGEMENTS

The author gratefully acknowledges the efforts of C. F. Sindt who contributed in several areas, particularly with the mini computer data acquisition system; and the efforts of L. M. Anderson whose exceptional craftsmanship and productivity were essential to the success of the project.

7. NOMENCLATURE

E	total energy of a system
h	specific internal enthalpy
m	mass
NTU	number of heat exchanger transfer units [9]
P	pressure
Q	heat transferred
T	absolute temperature
U	total internal energy
u	specific internal energy
V	volume
W	work
x	volume fraction of a horizontal dewar segment

Greek

ρ	density

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APPENDIX

Discharge Data for Experiment 6.

The position of the dewar thermometers is as follows:

Thermometer	Dimensionless distance from bottom of the dewar (X/D)
0	0.05
1	0.10
2	0.20
3	0.30
5	0.50
7	0.70
8	0.80
9	0.90

The computer printed times start at the beginning of each discharge cycle.

1 atm = $1.01325\ (10)^5$ Pa.

Discharge No. 1

Time: 0 min.

0	=	5.44336
1	=	5.42035
2	=	5.90531
3	=	6.08582
5	=	6.25588
7	=	6.21686
8	=	6.17046
9	=	6.31096

DEWAR PRESS = 72.3058 ATM

TIME MIN SEC	DEWAR PR. ATM	NOZ PR. ATM	NOZ T. K	NOZ FL. KG/SEC
0 : .008	72.2539	1.33667	298.438	4.7049E-2
0 : .193	64.0211	58.8287	263.089	1.39845
0 : .376	61.1833	55.7951	256.315	1.34472
0 : .559	57.8465	52.5245	255.185	1.26981
0 : .732	55.1231	49.9459	252.538	1.21473
0 : .906	52.5035	47.8697	249.743	1.17153
0 : 1.08	50.6636	45.86	247.293	1.1287
0 : 1.254	48.9173	44.5517	244.626	1.10302
0 : 1.438	47.4932	43.1486	242.173	1.0743
0 : 1.622	46.1626	41.9447	239.943	1.04971
0 : 1.806	44.9776	40.7502	237.89	1.02477
0 : 1.99	43.855	39.6979	235.899	1.00302

BLOW DP ATM	RPM	BLOW FLOW KG/SEC	BLOW TEMP K
-6.46118E-3	184.996	0	274.755
7.02976E-2	8389.97	0	273.325
.139984	10634.2	0	272.068
.171145	12257	7.03484E-3	267.515
.20259	12441.1	0	263.055
.207303	12832.4	2.53537E-2	260.837
.193032	12210.9	2.4931E-2	268.537
.191024	12694.3	2.69559E-2	273.576
.192072	13419.4	2.75171E-2	274.713
.178761	13350.3	2.67609E-2	275.147
.176404	12774.9	2.89917E-2	275.5
.175728	13097.1	2.44309E-2	275.647

TIME 0 : 2.187

DEWAR TEMP.

0	=	4.93691
1	=	5.14946
2	=	5.37213
3	=	5.3599
5	=	5.36762
7	=	5.4268
8	=	5.65072
9	=	64.8302

DEWAR PRESS = 42.9558 ATM

TIME 0 : .002

DEWAR TEMP.

0	=	5.32311
1	=	5.68217
2	=	5.66142
3	=	5.64082
5	=	5.78941
7	=	6.37113
8	=	8.22243
9	=	75.2672

Discharge No. 2

Time: 7 min.

DEWAR PRESS = 50.674 ATM

TIME MIN SEC	DEWAR PR. ATM	NOZ PR. ATM	NOZ T. K	NOZ FL. KG/SEC
0 : .008	50.7884	1.1244	293.359	.0427402
0 : .199	46.2458	42.8737	261.484	1.0274
0 : .382	45.6741	41.0441	253.874	.999003
0 : .555	45.1023	40.2193	253.09	.980826
0 : .726	44.7801	40.1529	249.87	.98553
0 : .898	44.4371	39.9349	247.079	.985802
0 : 1.069	44.1356	39.641	244.467	.983904
0 : 1.241	44.094	39.5083	241.936	.985791
0 : 1.413	43.8861	39.423	239.448	.988803
0 : 1.585	43.6471	39.1101	236.733	.986722
0 : 1.757	43.6159	39.058	234.231	.990684
0 : 1.929	43.4184	38.949	231.606	.993558
0 : 2.101	43.1221	38.7641	229.149	.994224
0 : 2.273	43.1793	38.5935	226.674	.995325
0 : 2.447	42.8311	38.6172	224.121	1.00158
0 : 2.621	42.7687	38.347	221.526	1.00052
0 : 2.793	42.7011	38.3754	219.383	1.00613
0 : 2.965	42.5036	38.2711	217.18	1.00853
0 : 3.137	42.3945	38.1147	215.147	1.00922
0 : 3.309	42.3841	38.1526	212.834	1.01568
0 : 3.483	42.1866	37.963	211.02	1.01507
0 : 3.655	42.2438	37.8161	209.284	1.01541
0 : 3.829	42.1762	37.8967	207.454	1.02201

BLOW DP ATM	RPM	BLO FLOW KG/SEC	BLOW TEMP K
-1.12939E-2	1056.66	0	276.379
-7.70513E-2	13361.9	0	276.083
.299346	16964.1	3.9805E-2	277.934
.361711	17493.5	4.73679E-2	278.737
.358918	17781.2	4.85548E-2	279.357
.365941	18494.8	4.83561E-2	279.352
.384057	19438.5	5.00575E-2	279.789
.367298	19035.7	4.93505E-2	279.746
.374281	18701.9	.0581482	279.717
.365941	19473	4.92336E-2	279.677
.364505	18713.4	5.04177E-2	279.62
.357522	18552.3	4.96747E-2	279.595
.374281	19593.4	4.97905E-2	279.513
.328547	18207	4.93139E-2	279.451
.328423	19116.2	4.96779E-2	279.392
.372224	19655.9	.049198	279.341
.361711	18701.9	4.99741E-2	279.284
.357522	18817	5.12924E-2	279.222
.363315	18655.9	4.97239E-2	279.141
.339759	18449.7	4.86197E-2	279.06
.358918	18299.1	.049748	278.984
.32671	19093.2	4.99428E-2	278.903
.365901	18979.1	5.13417E-2	278.8

TIME 3 : 4.014

DEWAR TEMP.

0 = 5.28814
1 = 5.4116
2 = 5.52836
3 = 5.43478

5 = 5.94854

7 = 65.3814
8 = 91.9946
9 = 114.674

DEWAR PRESS = 42.1138 ATM

TIME 9 : .002

DEWAR TEMP.

	=	5.95459
1	=	6.02044
2	=	6.23559
3	=	6.54722
5	=	7.92549
7	=	57.4704
8	=	104.3
9	=	142.98
10	=	3.78269E-28

Discharge No. 3

Time: 33 min.

Two discharges in succession.

DEWAR PRESS = 53.2104 ATM

TIME IN SEC	DEWAR PR. ATM	NOZ PR. ATM	NOZ T. K	NOZ FL. KG/SEC
0 : .007	53.3351	1.10619	289.95	.042583
0 : .193	49.4266	45.0352	263.399	1.07434
0 : .379	48.6158	43.471	254.093	1.05551
0 : .549	47.9298	42.9116	251.103	1.04933
0 : .72	47.6283	42.5704	247.833	1.04798
0 : .891	47.5555	42.3962	244.645	1.05041
0 : 1.063	47.3165	42.286	241.893	1.05382
0 : 1.235	46.9734	42.049	238.981	1.05439
0 : 1.407	46.9842	41.9825	236.461	1.05399
0 : 1.579	46.7344	41.7551	233.696	1.05893
0 : 1.751	46.4121	41.537	231.89	1.05989
0 : 1.923	46.3809	41.2526	229.299	1.05875

BLOW DP ATM	RPM	BLOW FLOW KG/SEC	BLOW TEMP K
-.012801	-1.06772	0	278.156
8.97958E-2	13730.1	.023707	276.047
.347746	16699.4	.033925	277.706
.381263	18184	4.78306E-2	279.203
.389643	18483.3	5.11979E-2	279.749
.389643	18699.9	5.2308E-2	280.043
.389643	18356.7	.0504692	280.003
.388246	18506.3	5.31263E-2	279.936
.395229	18506.3	5.15737E-2	279.824
.388246	17866.3	5.05956E-2	279.741
.388246	18092	5.20991E-2	279.661
.38265	18425.7	5.12811E-2	279.58

TIME 0 : 2.108

DEWAR TEMP.

0	=	5.76022
1	=	5.99144
2	=	6.51997
3	=	6.66226
5	=	8.93322
7	=	110.203
8	=	123.646
9	=	131.265

DEWAR PRESS = 45.2042 ATM

TIME MIN SEC	DEWAR PR. ATM	NOZ PR. ATM	NOZ T. K	NOZ FL. KG/SEC
0 : 4.019	50.4973	1.1007	248.741	4.58438E-2
0 : 4.193	47.0566	25.2692	264.072	.610249
0 : 4.373	45.5182	40.4184	223.308	1.04925
0 : 4.557	44.9049	39.9823	217.404	1.05215
0 : 4.729	44.5618	39.9823	213.72	1.06118
0 : 4.901	44.2604	39.6315	210.977	1.05887
0 : 5.073	44.3539	39.3566	208.58	1.0577
0 : 5.245	44.2188	39.2286	206.538	1.05953
0 : 5.417	43.9277	38.9964	204.46	1.05872
0 : 5.589	44.0109	38.7783	202.407	1.05824
0 : 5.761	43.9173	38.7025	200.6	1.06096
0 : 5.933	43.5847	38.5271	198.364	1.06085

BLOW DP ATM	RPM	BLOW FLOW KG/SEC	BLOW TEMP K
1.42003E-2	4315.83	0	280.558
1.33093	13269.7	4.64925E-2	269.4
.295942	15744.1	2.95339E-2	274.834
.371487	17240.3	4.13965E-2	278.047
.370091	17896.3	5.08907E-2	278.906
.357522	18529.3	4.98848E-2	279.16
.37847	18471.7	5.18936E-2	279.032
.384057	18575.3	.0522382	278.868
.372834	18333.6	5.09584E-2	278.637
.374281	18863.1	5.11827E-2	278.452
.372884	19035.7	5.15336E-2	278.348
.377074	18161	5.33397E-2	278.154

TIME 0 : 6.118

DEWAR TEMP.

0 = 6.06584
1 = 6.19913
2 = 6.82733
3 = 7.14755

5 = 30.3794

7 = 141.838
8 = 136.834
9 = 140.88

DEWAR PRESS = 43.7302 ATM

TIME Ø : .ØØ2

DEWAR TEMP.

Ø	=	7.45Ø87
1	=	7.3611
2	=	8.Ø878
3	=	8.92136
5	=	37.Ø511
7	=	113.824
8	=	137.Ø6
9	=	153.162

Discharge No. 4

Time: 60 min.

Three discharges in succession; the discharge valve failed to open for the third discharge.

DEWAR PRESS = 51.5784 ATM

TIME MIN SEC	DEWAR PR. ATM	NOZ PR. ATM	NOZ T. K	NOZ FL. KG/SEC
Ø : .ØØ7	51.4952	.7449	289.463	3.45418E-2
Ø : .193	48.7925	43.2719	265.231	1.Ø2941
Ø : .37	48.Ø961	42.7126	255.287	1.Ø3596
Ø : .543	47.6699	42.1438	252.457	1.Ø2813
Ø : .715	47.5244	41.9352	249.463	1.Ø2926
Ø : .886	47.17Ø9	41.812	246.447	1.Ø3255
Ø : 1.Ø57	46.7551	41.537	243.585	1.Ø319
Ø : 1.229	46.7967	41.3569	24Ø.788	1.Ø3346
Ø : 1.4Ø1	46.5265	41.2526	238.246	1.Ø3539
Ø : 1.573	46.225	41.Ø535	235.548	1.Ø3737
Ø : 1.745	46.2146	4Ø.8165	232.977	1.Ø3717
Ø : 1.917	46.Ø379	4Ø.6933	23Ø.791	1.Ø3899

BLOW DP ATM	RPM	BLOW FLOW KG/SEC	BLOW TEMP K
-3.45596E-3	736.523	Ø	278.876
.189322	137Ø7.1	1.68Ø49E-2	277.236
.325793	16Ø56.4	3.6Ø837E-2	278.Ø14
.371487	172Ø5.8	4.4797E-2	279.327
.391Ø39	17712.2	4.94394E-2	279.752
.389643	17723.7	5.Ø8413E-2	279.965
.399419	19162.3	5.1ØØØ8E-2	279.976
.384Ø57	17815.7	5.1Ø564E-2	279.864
.4Ø9195	181Ø3.5	5.14975E-2	279.784
.392436	19116.2	.Ø5Ø8ØØ2	279.714
.396626	19415.5	5.17533E-2	279.626
.4Ø2212	18863.1	5.12581E-2	279.491

TIME 0 : 2.102

DEWAR TEMP.

0	=	7.42205
1	=	7.71662
2	=	8.52024
3	=	9.35559
5	=	67.778
7	=	125.782
8	=	140.271
9	=	151.811

DEWAR PRESS = 45.7676 ATM

TIME MIN SEC	DEWAR PR. ATM	NOZ PR. ATM	NOZ T. K	NOZ FL. KG/SEC
0 : 4.02	48.6054	-1.45522	248.167	-1.58219E-2
0 : 4.194	46.3497	18.2302	277.226	.434779
0 : 4.37	44.8217	39.6078	226.167	1.0221
0 : 4.554	44.3643	39.3898	219.94	1.03087
0 : 4.726	44.1356	39.0058	216.812	1.02336
0 : 4.893	44.1356	38.8779	213.952	1.03189
0 : 5.07	43.803	38.7925	211.446	1.03575
0 : 5.242	43.5847	38.5413	209.299	1.03444
0 : 5.414	43.6159	38.347	207	1.03503
0 : 5.585	43.3664	38.2328	204.925	1.03989
0 : 5.758	43.0865	38.0341	202.955	1.03694
0 : 5.93	43.1273	37.8824	201.3	1.03713

BLOW DP ATM	RPM	BLOW FLOW KG/SEC	BLOW TEMP K
1.67043E-2	6732.69	0	280.515
1.55438	12487.1	6.62744E-2	266.422
.306591	16975.6	2.73974E-2	275.267
.385453	17677.6	4.32699E-2	278.282
.388246	18322.1	4.97961E-2	278.995
.392436	17597.1	.0486952	279.144
.379867	18425.7	4.87197E-2	279.068
.389643	19391	5.10914E-2	278.843
.392436	18241.6	5.14985E-2	278.634
.372884	19580.2	4.99206E-2	278.495
.391039	18609.9	4.99626E-2	278.364
.392436	17999.9	4.97297E-2	278.222

TIME 0 : 6.115

DEWAR TEMP.

0	=	8.33433
1	=	8.57061
2	=	9.51496
3	=	23.2763
5	=	94.5953
7	=	142.649
8	=	152.221
9	=	155.264

DEWAR PRESS = 42.8415 ATM

TIME MIN SEC	DEWAR PR. ATM	NOZ PR. ATM	NOZ T. K	NOZ FL. KG/SEC
0 : 8.019	45.0608	-.805837	227.027	-1.47369E-4
0 : 8.193	45.3622	2.04678	223.103	7.25008E-2
0 : 8.367	45.8716	1.49027	220.936	5.86066E-2
0 : 8.541	46.3809	1.05715	223.134	4.72939E-2
0 : 8.715	47.1813	1.00427	225.774	4.56779E-2
0 : 8.889	47.7011	1.00723	227.39	4.559E-2
0 : 9.063	48.5951	.954054	228.016	4.41878E-2
0 : 9.237	49.0316	1.04086	228.484	4.63269E-2
0 : 9.411	49.9776	.929317	228.987	.0434722
0 : 9.585	50.6117	1.0413	229.353	4.62503E-2
0 : 9.759	51.4329	.942649	229.737	4.37357E-2
0 : 9.933	52.2229	1.0099	230.041	4.53935E-2

BLOW DP ATM	RPM	BLOW FLOW KG/SEC	FLOW TEMP K
2.63657E-2	4822.22	7.34297E-3	279.354
.190763	13983.3	4.21549E-2	279.343
.257361	16423.2	5.34828E-2	279.397
.245011	18045.9	5.89278E-2	279.341
.259064	18230.1	5.88067E-2	279.133
.303186	18425.7	6.10488E-2	278.762
.312526	18586.8	6.08463E-2	278.482
.308118	18022.9	6.21581E-2	278.274
.294851	18517.8	6.43304E-2	277.964
.295549	17654.6	6.21838E-2	277.772
.298386	18138	6.89799E-2	277.449
.271065	17907.8	.0672002	277.089

TIME 0 : 10.12

DEWAR TEMP.

0 = 8.96445
1 = 9.20841
2 = 10.585
3 = 27.2269

5 = 129.312

7 = 168.172
8 = 168.233
9 = 169.354

DEWAR PRESS = 52.8362 ATM

TIME 0 : .003

DEWAR TEMP.

0	=	9.62333	
1	=	9.64851	-.03
2	=	9.64126	-.02
3	=	9.60185	+.02
5	=	9.61616	-.00
7	=	9.62966	-.00
8	=	9.61244	+.01
9	=	9.57848	+.04

Thermocouple zero check.

DEWAR PRESS = 49.7385 ATM

TIME 0 : .002

DEWAR TEMP.

0	=	10.2059
1	=	10.7276
2	=	12.8895
3	=	28.258
5	=	107.518
7	=	142.544
8	=	160.9
9	=	172.307

Discharge No. 5

Time: 78 min.

Two successive discharges.

DEWAR PRESS = 52.0773 ATM

TIME MIN : SEC	DEWAR PR. ATM	NOZ PR. ATM	NOZ T. K	NOZ FL. KG/SEC
0 : .008	52.0773	.828739	284.762	3.67157E-2
0 : .197	49.5098	43.0633	263.199	1.02849
0 : .384	48.751	42.978	251.366	1.05038
0 : .565	48.2104	42.3902	248.266	1.04272
0 : .737	47.6491	42.1248	245.037	1.04301
0 : .909	47.3892	41.8025	242.258	1.04121
0 : 1.081	47.2749	41.6224	239.685	1.04236
0 : 1.253	46.7967	41.3759	237.147	1.04183
0 : 1.425	46.5161	41.0725	234.581	1.03998
0 : 1.597	46.4121	40.8639	232.168	1.04016
0 : 1.769	45.9755	40.6554	229.801	1.04027
0 : 1.941	45.6429	40.2667	227.439	1.03596

BLOW DP ATM	RPM	BLOW FLOW KG/SEC	BLOW TEMP K
-2.91861E-4	1133.26	0	277.83
.192094	13292.2	1.22167E-2	276.16
.379367	16641.8	3.02248E-2	275.288
.428747	18092	4.3094E-2	278.112
.43154	18218.6	4.73661E-2	278.631
.418971	19012.7	5.02243E-2	278.773
.43154	18886.1	.0483802	278.697
.432936	19012.7	.0494472	278.465
.416178	18575.3	4.92975E-2	278.348
.424557	18402.7	5.01816E-2	278.203
.42316	19104.7	5.12676E-2	278.035
.42735	18540.8	5.10527E-2	277.918

TIME 0 : 2.126

DEWAR TEMP.

0	=	12.4748
1	=	15.7593
2	=	31.2078
3	=	67.6929
5	=	126.811
7	=	140.838
8	=	148.615
9	=	154.89

DEWAR PRESS = 45.5597 ATM

TIME MIN SEC	DEWAR PR. ATM	NOZ PR. ATM	NOZ T. K	NOZ FL. KG/SEC
0 : 4.02	44.7073	.0583332	242.21	2.09798E-2
0 : 4.194	45.0504	1.59559	291.852	5.33423E-2
0 : 4.376	41.8436	36.5459	226.537	.943871
0 : 4.55	40.8664	35.6167	221.026	.931794
0 : 4.732	40.0296	34.9389	218.686	.919331
0 : 4.914	39.4059	34.3748	216.152	.910109
0 : 5.086	38.6471	33.8392	215.063	.898517
0 : 5.258	37.8623	32.9907	214.566	.877522
0 : 5.44	36.8228	31.91	215.145	.848313
0 : 5.622	35.5754	30.6728	215.821	.814948
0 : 5.804	34.2293	29.393	216.318	.780911
0 : 5.986	32.7792	27.9805	216.604	.743985

BLOW DP ATM	RPM	BLOW FLOW KG/SEC	BLOW TEMP K
3.10027E-2	4430.92	6.09737E-3	279.174
.197658	14616.3	5.86561E-2	271.961
.2976	16699.4	0	263.65
.379867	17884.8	2.35193E-2	272.454
.406402	18978.1	3.45155E-2	276.287
.388246	19519.1	4.42143E-2	276.974
.389643	19185.3	4.21106E-2	276.844
.38685	19967.9	4.1937E-2	276.574
.384057	20037	3.59065E-2	275.769
.395229	19864.3	3.16646E-2	274.882
.384057	19519.1	2.72297E-2	274.218
.398022	20474.3	.0259202	273.577

TIME 0 : 6.181

DEWAR TEMP.

0 = 97.7286
1 = 109.456
2 = 119.092
3 = 132.071

5 = 163.614

7 = 175.604
8 = 180.612
9 = 179.707

Reference thermometer outside calibration range; these temperatures meaningless.

DEWAR PRESS = 31.3655 ATM

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15. SUPPLEMENTARY NOTES

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Equipment to store supercritical helium at high density and to demonstrate pulsed discharge at high flow rates has been designed, fabricated and successfully tested. A storage density of 0.193 x 10^3 kg/m^3 (12.03 lb/ft^3) at 8.3 MPa (81 atm) was achieved in a 135 liter (35 gal) dewar. Pulsed discharges of 2 seconds and 4 seconds duration were demonstrated at a flow rate of 1.0 kg/s (2.2 lb/s), and flow fluctuations of less than $\pm$ 1 percent were achieved without feedback control. In general, the system operated in a very stable and well behaved manner.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Cryogenic helium supply system; cryogenic storage; helium; helium supply system; high density helium storage; liquid helium storage; supercritical helium.

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