NBSIR 79–1607

PRODUCING SLUSH OXYGEN WITH AN AUGER AND MEASURING THE STORAGE CHARACTERISTICS OF SLUSH HYDROGEN

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by

R. O. VOTH and P. R. LUDTKE

Part 1. PRODUCING SLUSH OXYGEN WITH AN AUGER

An auger rotating inside a brass tube refrigerated with liquid helium was used to produce liquid-solid (slush) mixtures of oxygen. The auger produced small particles of solid oxygen so that the resulting mixture could be transferred and stored. The auger could produce slush continuously in an appropriate system, and it could produce slush at pressures higher than the triple point pressure of the oxygen.

Part 2. STORAGE CHARACTERISTICS OF SLUSH HYDROGEN

Three long term storage tests were conducted on an Apollo hydrogen tank. The tank was filled to 88 percent with normal boiling point liquid hydrogen then the pressure rise rate to 17.6 bar and the venting rate at 17.6 bar were measured. The two other tests were similar except the vessel was filled with slush hydrogen. In one of these tests, the slush was mixed to eliminate thermal stratification. Filling with slush instead of liquid hydrogen increased the storage time before venting by 1.08 to 1.17 times and increased the mass loaded by 1.11 to 1.13 times.

Key words: Cryogenic; hydrogen; oxygen; scraping auger; slush; slush production; slush storage.

Part 1. PRODUCING SLUSH OXYGEN WITH AN AUGER

1.1 INTRODUCTION

Liquid-solid mixtures (slushes) of oxygen exhibit a higher density and heat capacity than the normal boiling point liquid. These characteristics are advantageous in space applications where longer storage times and higher storage densities are important. But to effectively use slush oxygen, we must be able to produce it economically, to store and transfer it successfully and to measure its stored mass and mass flow rates.

In this study, an auger previously used to produce slush hydrogen [1] was used to produce slush oxygen. The auger system can continuously produce slush, and since the auger system can be immersed in liquid, slush can be produced at pressures above triple point pressure. The increased pressure can be produced pneumatically or by generating a temperature stratification near the surface of the liquid. The auger system produced oxygen particles smaller than the particles produced in slush hydrogen, so the auger produced slush oxygen should be capable of being transferred and stored in a conventional cryogenic system.

The auger scraped frozen oxygen from the inside of a liquid helium refrigerated tube. The safety of such a device could be questioned because high forces and therefore high energies could be present in the scraping process. The general ground rules for an oxygen system are that the temperature generated by energy input to a system should be less than the ignition temperature of the fuels and oxygen present. In the auger system, the auger and wall are metal with high ignition temperatures and the total input energy to rotate the auger is less than 5 watts. Therefore, the precautions taken with this system were the same as those taken for liquid oxygen systems in general. The system was cleaned to remove hydrocarbons with low ignition temperatures and to remove particulate matter where energies could be concentrated, resulting in high temperatures. No evidence of rapid oxidation occurred during the production of slush oxygen.

Producing slush oxygen by the thoroughly investigated freeze-thaw method is difficult because of the low triple point pressure of oxygen [2]. The freeze-thaw method uses the latent heat of vaporization to freeze the cryogen. By removing vapor at the optimum rate from a container of triple point liquid, a porous solid layer is formed on the liquid surface. Stopping the vapor removal and mixing this solid layer into the remaining liquid produces a liquid-solid mixture of the cryogen. To obtain high solid fractions, the pumping-mixing or freeze-thaw cycle must be repeated numerous times. While with hydrogen, the freeze-thaw production method successfully produces slush with small solid particles, oxygen has a much lower triple point pressure than hydrogen (.0015 bar versus .07 bar for hydrogen), thus requiring a large vapor removal tube. The large tube must be sized to allow large volumes of vapor to flow at a low pressure drop. Because of this requirement, slush oxygen would be difficult to produce using the freeze-thaw method--the production of slush oxygen has not been reported in the literature before the current study. The direct freeze method in the auger overcomes the problem of removing vapor at the low triple point pressure of oxygen, and it produces slush with sufficiently small particles so that the slush can be transferred and stored in conventional cryogenic systems.

1.2 DESCRIPTION OF THE AUGER

A cross section of the auger and heat exchanger assembly used to produce slush oxygen is shown on figure 1. A photograph of the partially disassembled unit is shown on figure 2. The 400 series stainless steel auger with an outside diameter of 4.676 cm (1.841 in) is supported within a close fitting brass tube by a ball bearing at each end. The radial clearance between the auger and brass tube is 0.0178 cm (0.007 in) at ambient temperature. Because of the difference in thermal expansion between the stainless steel auger and brass tube, the radial clearance decreases to 0.0127 cm (0.005 in) at the operating temperature. Since solid oxygen has a low thermal conductivity, this annular clearance should be small to allow a high heat transfer rate.

A ribbon packed, vacuum insulated heat exchanger surrounds the brass tube. The ribbon packing increases the refrigerant heat transfer area while the vacuum insulation minimizes heat transfer to the exterior surface. Vacuum insulated refrigerant lines are provided at the top and bottom of the heat exchanger.

The auger assembly is suspended in the vertical position from a top plate by a stainless steel tube. Located concentrically within the support tube is the stainless steel torque tube used to rotate the auger. A shaft rotating in a magnetic fluid for a no-leak seal connected the torque tube to the ambient temperature drive mechanism. The drive motor is an air motor with numerous gear speed reducers. By changing the number of gear reducers and air supply pressure to the motor, the auger rotational speed could be varied from about 1 rad/s to 10 rad/s.

The instrumentation used with the auger system measured the torque and rotational speed of the auger drive, and the refrigerant flow rate. Refrigerant pressure and slush container pressure were also displayed on convenient gauges. Strip silvered glass dewars were used to contain the auger system so that the slush oxygen could be viewed and photographed.

1.3 RESULTS OF TESTS PRODUCING SLUSH OXYGEN WITH THE AUGER

Primarily, the auger tests were conducted to determine if the auger could produce sufficiently fine frozen particles so that the resulting slush oxygen could be stored and transferred easily. Secondarily, the auger

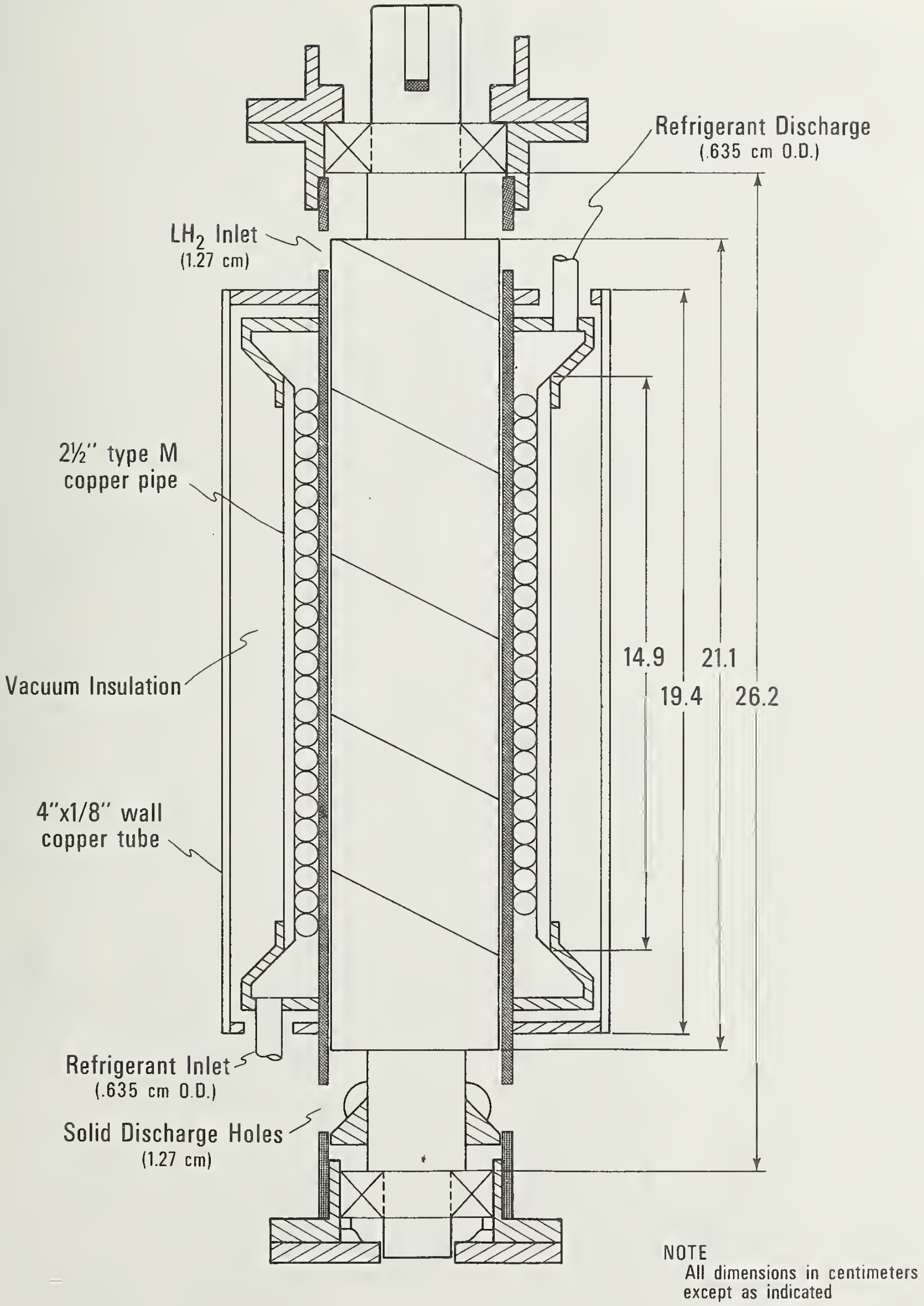


Figure 1. Cross Section of the Auger and Heat Exchanger Assembly.

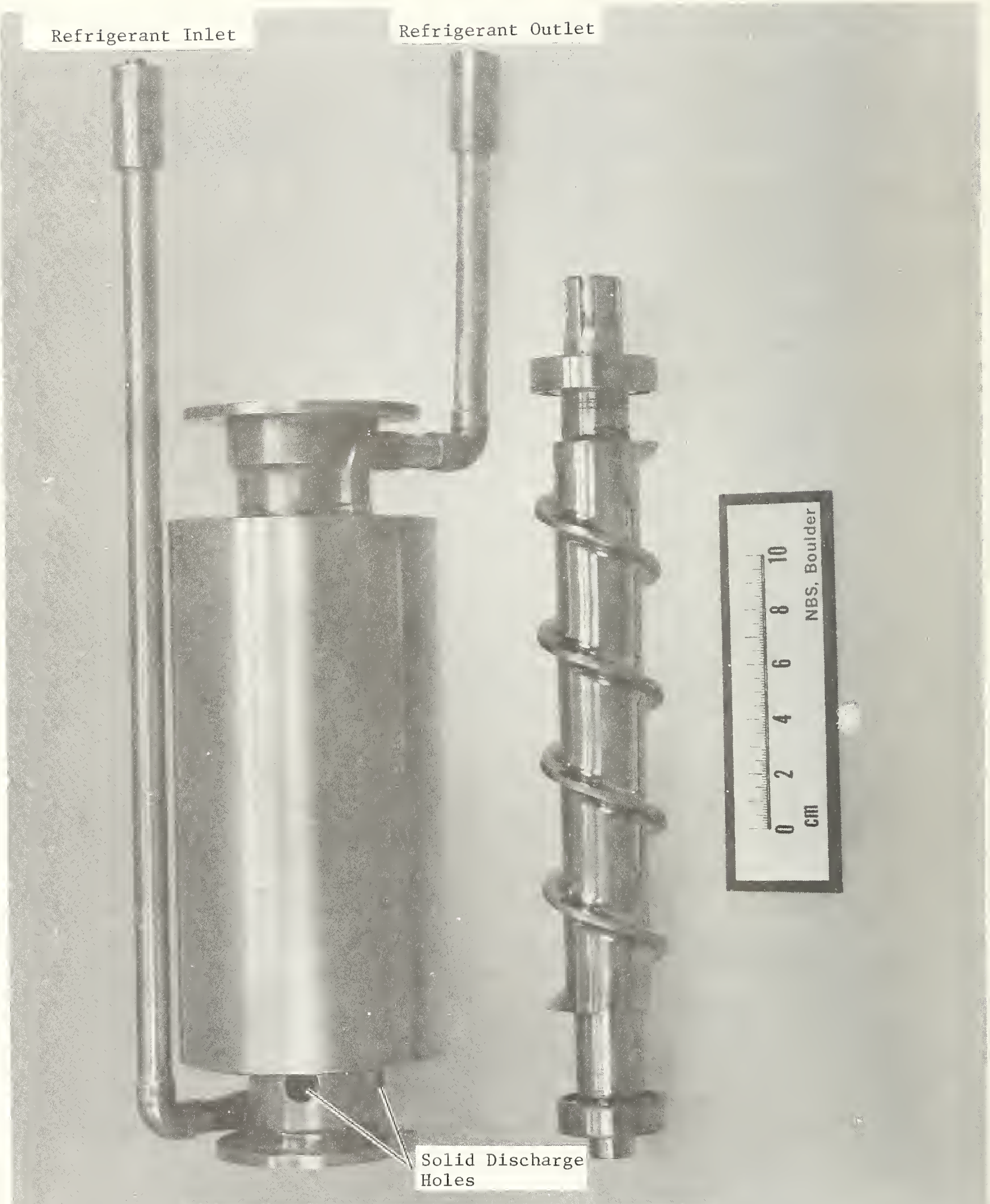


Figure 2. Partially Disassembled Auger Unit.

power required at various rotational speeds and refrigeration supplied to the auger were measured. Also, the slush was held in the settled condition for 56.5 hours to determine how the solid oxygen particles changed with time.

Figure 3 shows freshly produced solid particles floating past a 2mm square grid (the grid and the shovel used to move the slush are shown in figure 4). The fresh slush particles are random in size varying from approximately 0.1 mm to 5 mm in the largest dimension. This is smaller than the slush hydrogen particles produced by either the auger or the freeze-thaw production method [2]. Although the oxygen particles produced by the auger appear smaller, a much more extensive measuring program than conducted during these tests is necessary to determine the actual size distribution. Aged auger produced slush particles, figures 5, 6, 7, and 8 appear to have about the same size distribution as the fresh particles although they become more rounded and more transparent. The photographs of the aged particles were made by using the shovel (Figure 4) to reach into the settled slush and to lift the particles above the grid where they were slowly dumped allowing them to settle past the grid. The settling particles were photographed with a 16mm movie camera. The depression left by the shovel in the settled slush was filled immediately after the shovel was removed by the remaining slush particles. Especially in the aged condition, the particles were so spherical that they simply rolled into the depression, and the surface of the settled slush remained nearly horizontal throughout the test. This rolling action indicates that aged slush oxygen has a low angle of repose and it should transfer easily from a storage tank.

The total power required to turn the auger is the sum of the power required to turn the auger when no oxygen is freezing (tare power) and the power required to scrape the frozen oxygen from the brass tube (scraping power). The tare power was proportional to the auger rational speed or

$$P_t = .0359R$$

where

P_t = tare power, W (1)

R = auger rotational speed, rad/s

Figure 9 shows the scraping power as a function of the refrigeration supplied to the auger assembly. The points shown are the experimental points taken at various rotational speeds. The straight line is a hand fit of the data and is expressed by

$$P_s = 0.0392 (P_r), \tag{2}$$

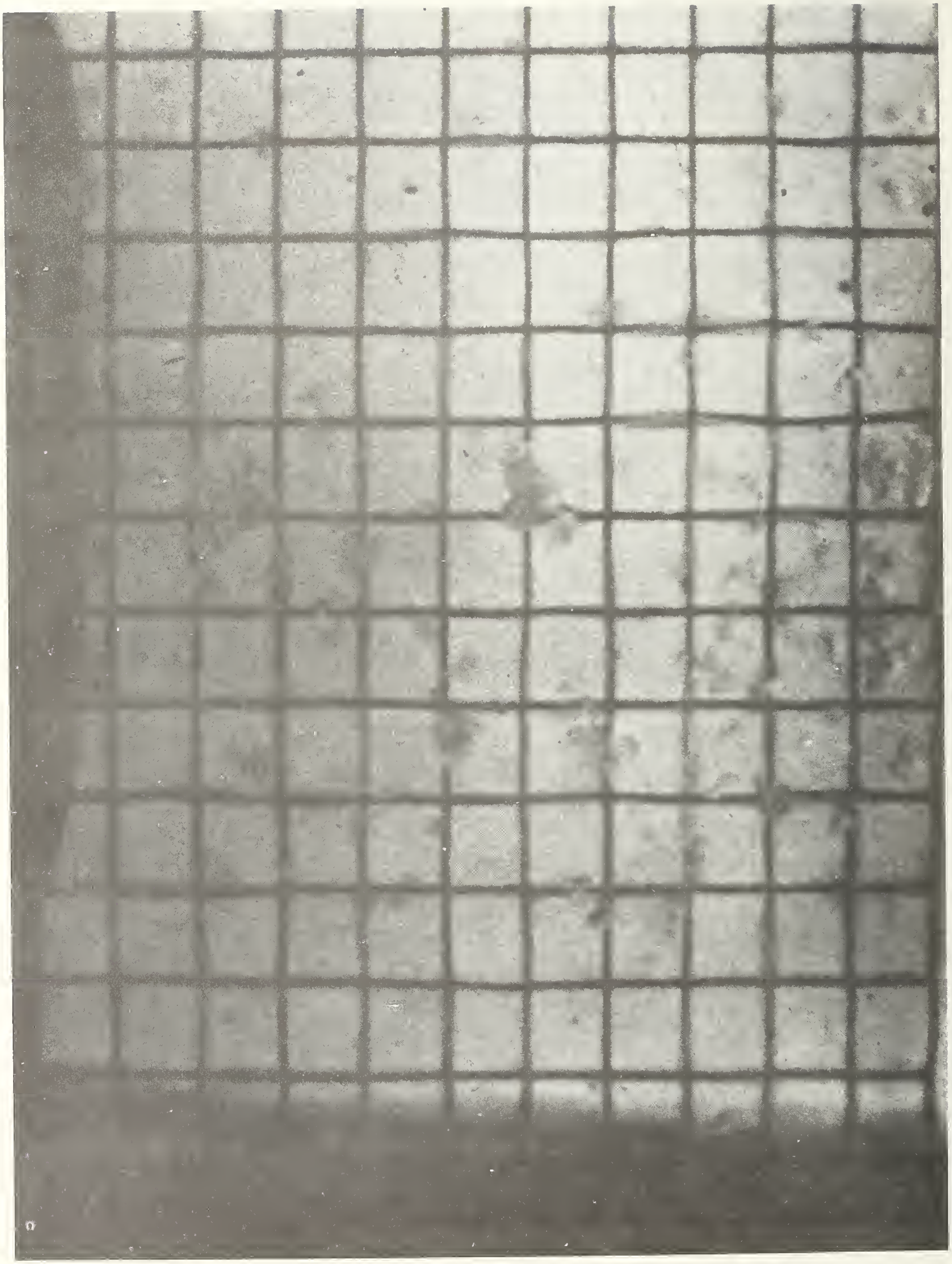


Figure 3. Fresh Oxygen Particles, Less than 1/2 Hour Old, Grid Size is 2mm square.

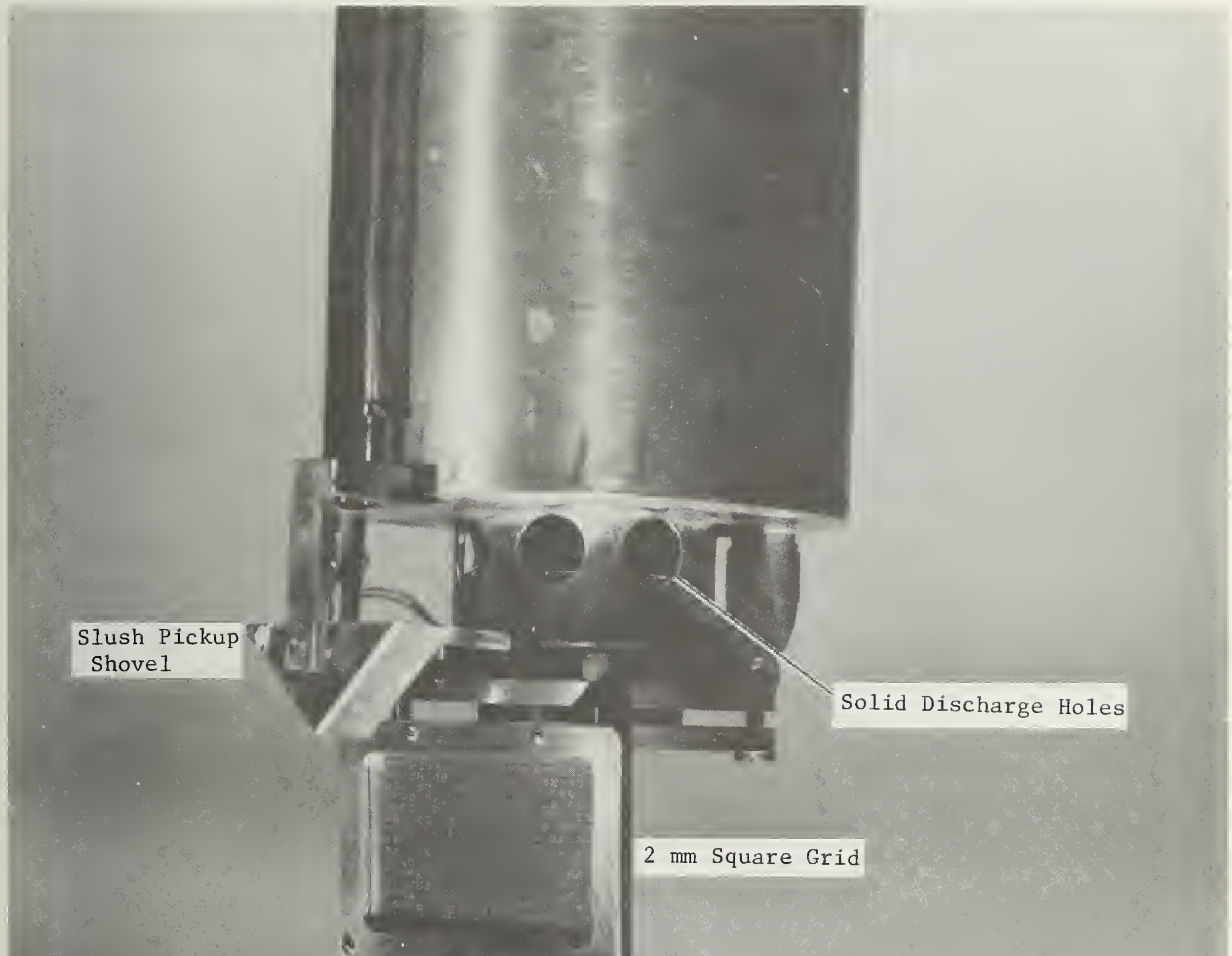


Figure 4. Shovel Used to Drop Aged Slush in Front of 2 mm Square Grid.

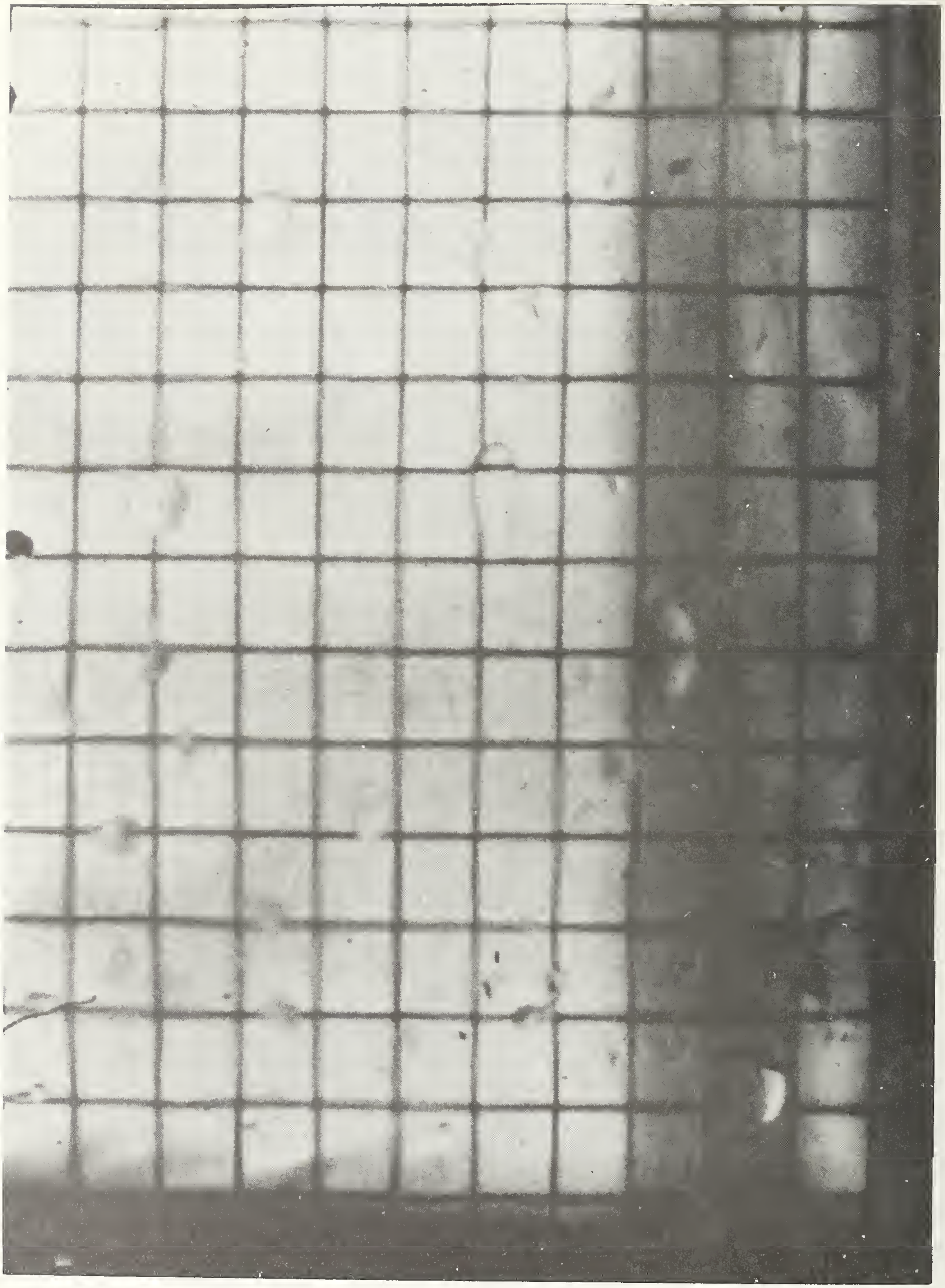


Figure 5. Aged Slush Oxygen Particles, Aged 12 Hours, Grid Size is 2mm square.

Figure 6. Aged Slush Oxygen Particles, Aged 24 Hours, Grid Size is 2mm square.

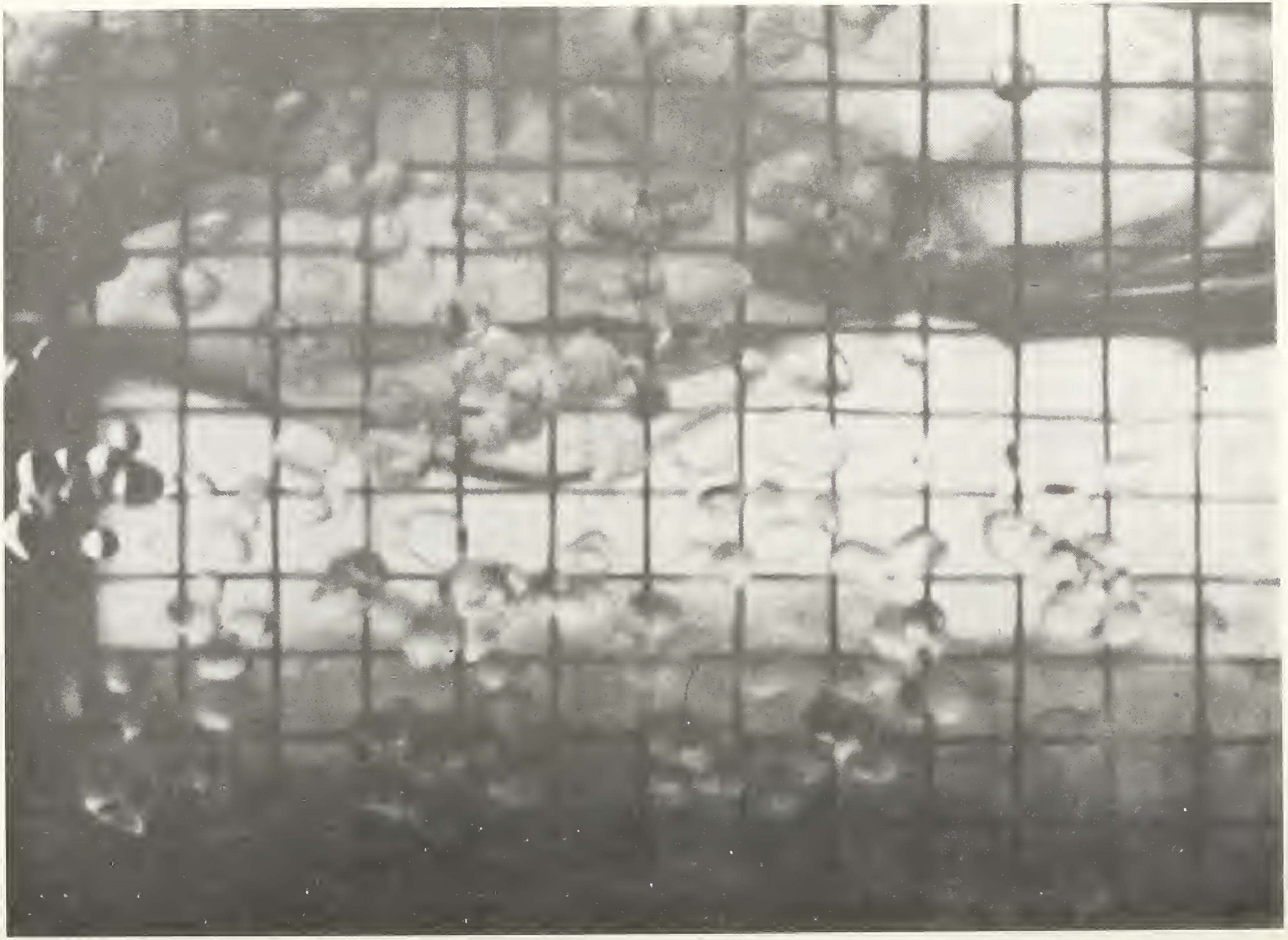


Figure 7. Aged Slush Oxygen Particles, Aged 27.5 Hours, Grid Size is 2mm square.

Figure 8. Aged Slush Oxygen Particles, Aged 56.5 Hours, Grid Size is 2mm square.

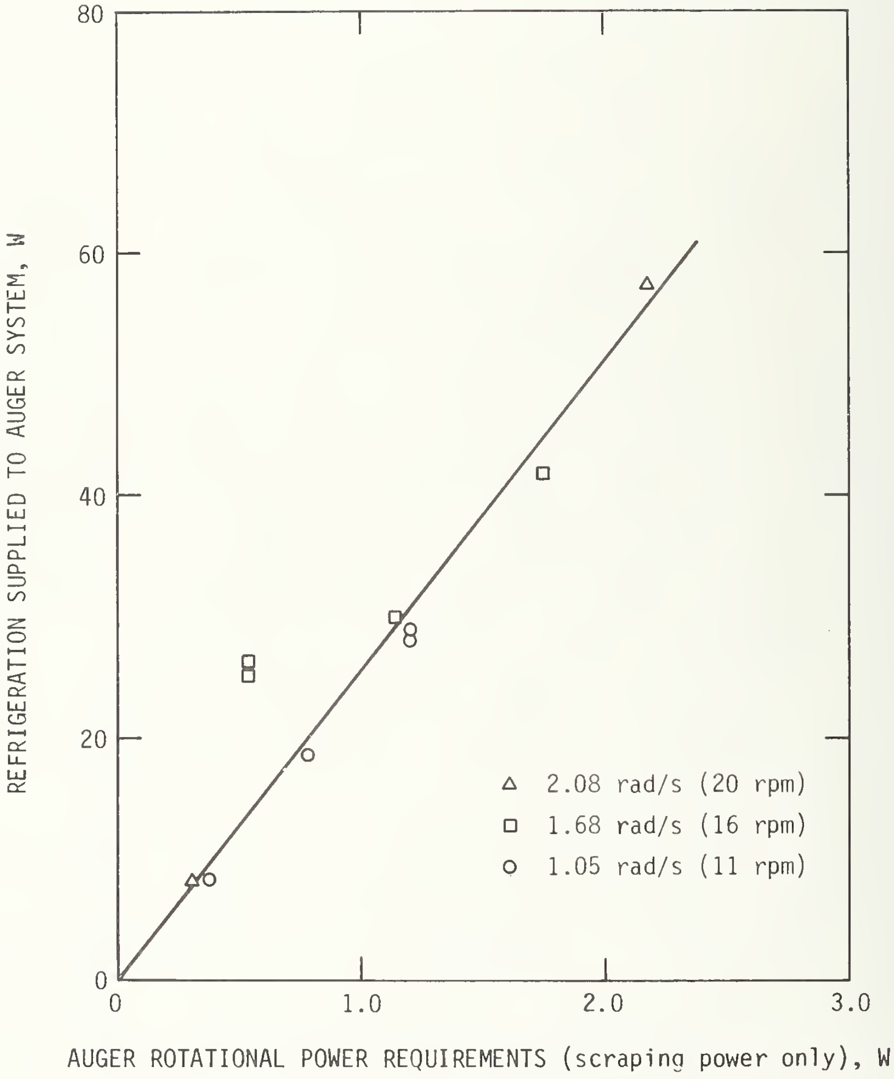


Figure 9. The Auger Scraping Power Requirement when Producing Slush Oxygen.

where P_s is the scraping power in Watts, and P_r is the refrigeration supplied to the auger assembly in Watts.

The total power required to rotate the auger during slush oxygen production is expressed by:

$$P_a = 0.0359R + 0.0392P_r \tag{3}$$

where

P_a = total auger power requirement, W

1.4 CONCLUSIONS FROM THE SLUSH OXYGEN PRODUCTION TESTS

The auger successfully produces a slush oyxgen with sufficiently small particles, so that the slush can be stored and transferred in cryogenic systems. Aged slush, in particular, contained spherical particles that easily rolled into any depression formed in the settled slush surface. Thus, the slush oxygen can probably be transferred from the bottom of a storage vessel with less agitation than that required to transfer a high mass fraction of slush hydrogen.

The auger system produces slush by direct freezing so that the low triple point pressure of oxygen has no effect on the production process. The slush can be produced by the auger system at pressures above the triple point pressure by pressurizing the liquid pneumatically or by utilizing a thermal stratification near the surface of the liquid oxygen and immersing the auger well below the surface.

Although producing slush oxygen required about 2.6 times the scraping power required to produce slush hydrogen, the oxygen scraping power is still only four percent of the total refrigeration power supplied to the auger.

Part 2. LONG TERM STORAGE OF SLUSH HYDROGEN

2.1 INTRODUCTION

Slush cryogens offer significant advantages when long term storage is required. The latent heat of fusion of the solid particles in the slush increases the amount of heat the fluid can absorb before venting must occur. In order to take advantage of the latent heat, an ullage volume in the storage vessel is required to allow for expansion during the melting process. Even though the required ullage volume decreases the stored fluid volume, the higher density of the slush maintains or increases the amount of mass stored in a vessel above that stored by an equal volume vessel completely filled with normal boiling point liquid. While these advantages can be shown theoretically, a practical system requires knowledge of a filling system, a filling procedure and a measuring system to achieve the correct ullage and slush mass fraction at loading. In order to determine areas where additional experimental work is required and to demonstrate the longer storage capabilities of slush, an Apollo flight weight tank was filled three times, and the pressure rise and venting characteristics were measured for an extended period of time for each filling. The first filling was with normal boiling point liquid hydrogen to provide data to judge the performance of the subsequent tests with slush hydrogen. During one slush test, the fluid was allowed to thermally stratify, and during the second slush test, the fluid was mixed using the in-tank electric fans. A radio frequency mass gauge was used during the tests to determine if its characteristics could be used to measure mass in a slush container.

An existing Apollo hydrogen tank was chosen for the experimental fills because no funds were available to custom design and build a better experimental container and because the results would apply to an existing flight weight tank similar to the fuel cell reactant tanks where slush could be used in the Space Shuttle flights. The use of the Apollo tank did, however, limit the accuracy of the experimental results because there was no slush compatible instrumentation in the tank. Since the radio frequency gauge is still being developed, it could not be used to determine mass in the tank. Therefore, the amount of hydrogen in the tank was determined by weighing the tank before and after the fill, and the ullage volume was determined by tilting the tank to locate the vent outlet at the required liquid level to provide the chosen ullage.

2.2 DESCRIPTION OF SLUSH STORAGE APPARATUS

The Apollo tank is constructed entirely of titanium making alterations to the tank difficult. The only changes were to the fill and vent lines. An epoxy joint to the titanium fill line was made using a high nickel alloy insert having thermal expansion characteristics similar to titanium. This joint was vacuum insulated to reduce heat leak. A similar epoxy joint was used on the uninsulated vent line. Valves were installed on both lines to isolate the tank after filling.

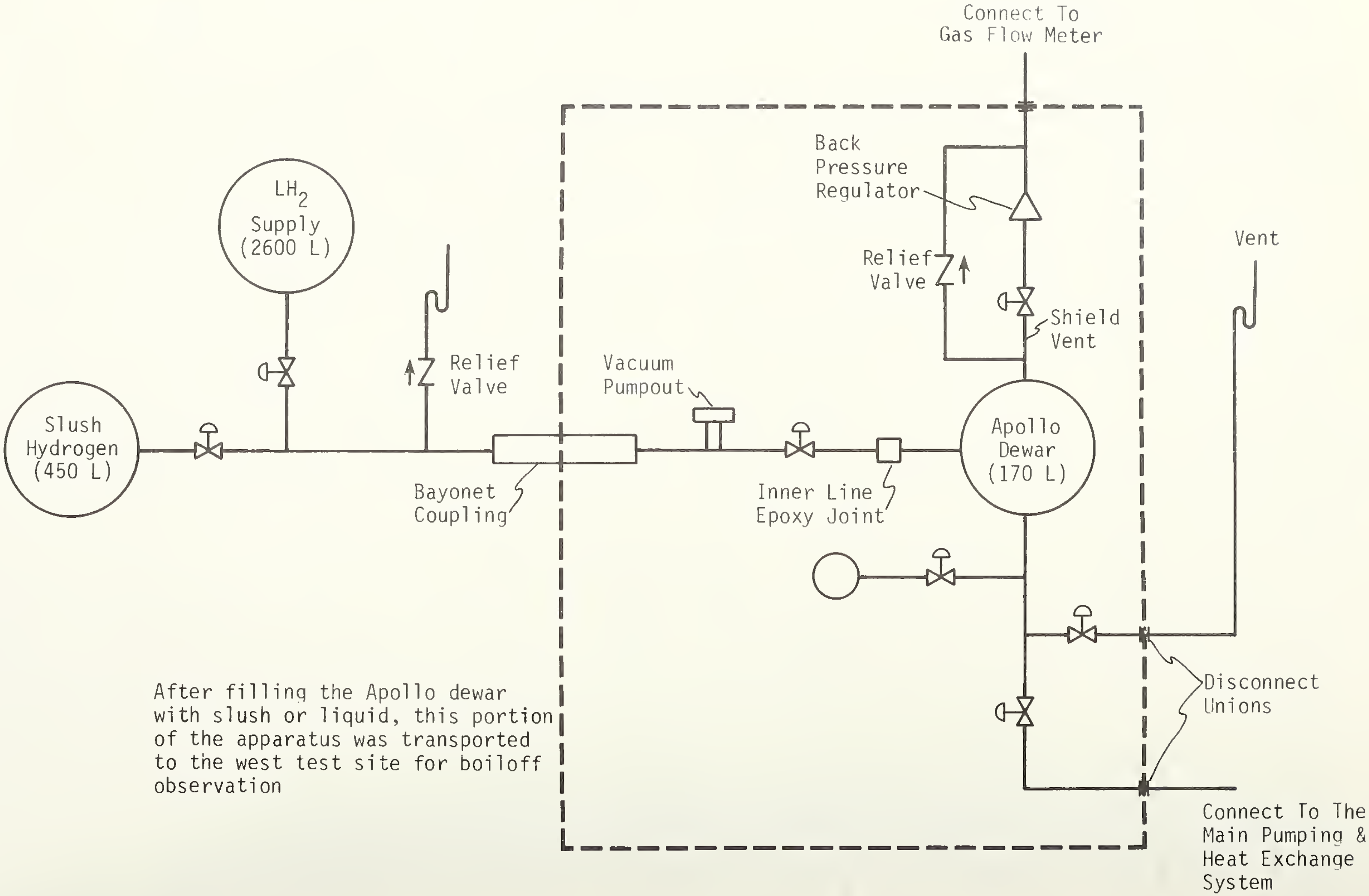
The radio frequency gauge was connected to an existing electrical connection to the interior of the tank. Because of the poor coupling obtained through this connection and because extraneous material existed in the tank (capacitance probe, mixing motors and electrical heater) the signals obtained from the resonant frequencies in the tank were weak.

Figure 10 shows a schematic of the system used to fill the Apollo tank. The fill line was short to limit the heat transfer to the fluid during the transfer. Two valves were located in the slush fill line to allow liquid hydrogen to enter either the slush generator or the Apollo tank. The Apollo tank could be vented either directly out a vent to the atmosphere or through a steam heat exchanger to a $34 m^3/min$ (1200 cfm) vacuum pump. The Apollo tank was mounted at an angle to achieve a 12 percent ullage volume. A photograph of the Apollo tank being filled is shown on figure 11.

The filling procedure included a fill to about half full with normal boiling point liquid at least 24 hours before the slush fill to temper the insulation. The boiloff gas generated during the 24 hour hold was vented through the vapor cooled shield to completely cool the insulation. Twenty four hours later when the slush hydrogen was being prepared by the freeze-thaw process, the remaining liquid in the Apollo tank was pumped to triple point pressure.

About 400 liters of slush were prepared, and after the vacuum insulated loading line was cooled with liquid hydrogen from the storage vessel, the slush transfer was started. The excess amount of slush prepared (the Apollo tank only held 170 liters) was used to provide some upgrading during transfer by transferring in slush and removing triple point liquid at the vent line. Also some solid melted during the pressurization of the slush generator during the slush transfer. The fill tube inside the Apollo tank is uninsulated and the ullage vapor condensed on the tube during the fill to maintain triple point pressure in the ullage. To insure that the slush level was below the vent line penetration, the venting pressure was maintained near triple point pressure during the fill. To establish the correct slush level, pumping on the vent line was continued a short time after the transfer was stopped. Since the vent line was uninsulated, large volumes of gas were removed during the transfer process, and the transfer took from 30 to 45 minutes depending on how much liquid was in the Apollo tank at the start of the transfer.

Heat leak to the Apollo vessel was established prior to the long term storage tests. The heat leak was measured by filling the vessel with normal boiling point liquid hydrogen and measuring the venting rate for an extended (2-3 day) period. Heat leak measurements were made for both a cooled shield



After filling the Apollo dewar with slush or liquid, this portion of the apparatus was transported to the west test site for boiloff observation

Figure 10. Schematic of the Liquid and Slush System Used to Fill the Apollo Vessel.

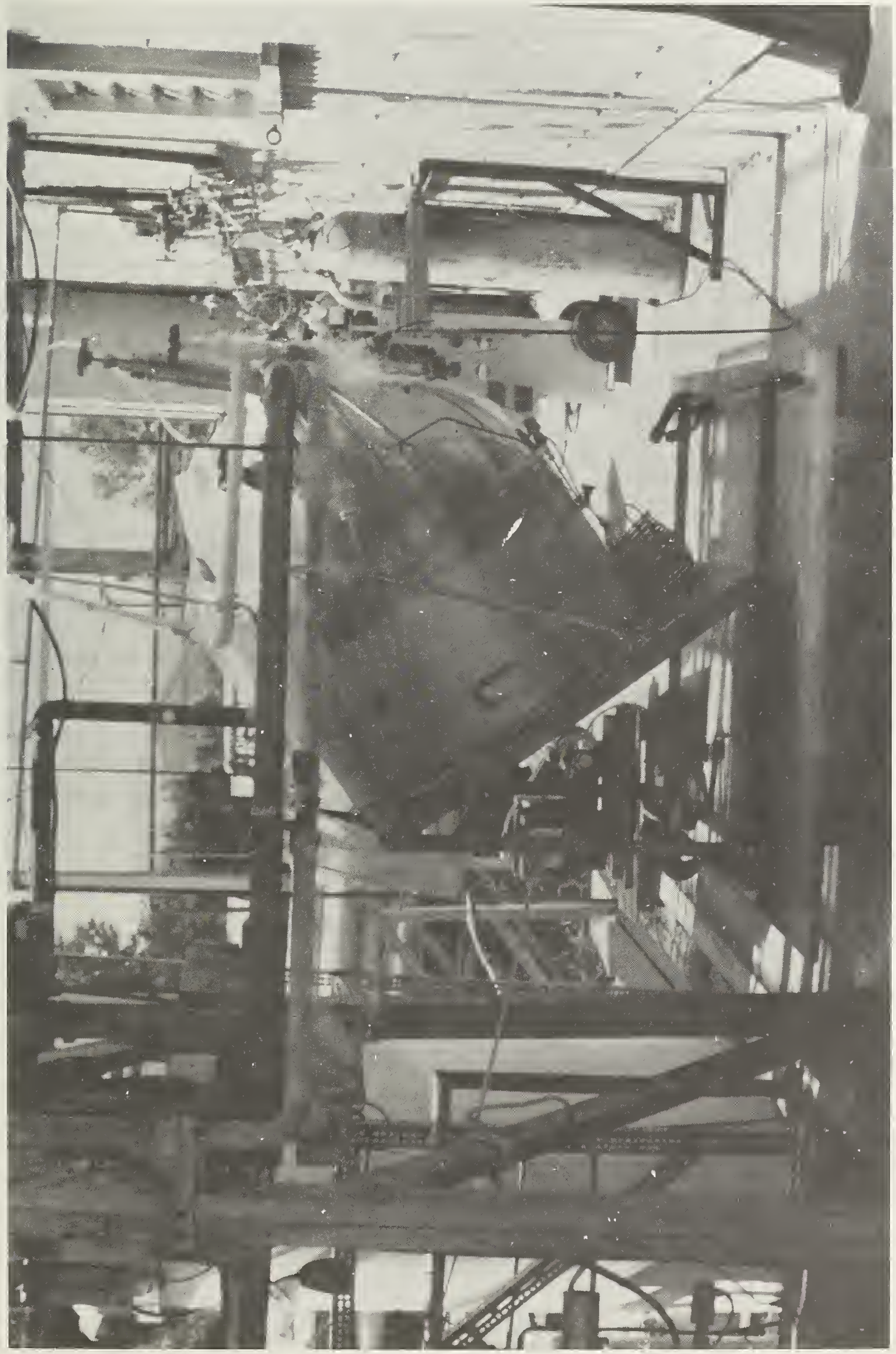


Figure 11. Apollo Tank Mounted at an Angle and Being Filled with Liquid Hydrogen.

and noncooled shield condition. The measured heat leak with a noncooled shield was 4.92 watts (16.79 Btu/h) and the heat leak with a cooled shield was 2.44 watts (8.33 Btu/h). Other parameters of the Apollo tank used in the theortical calculations for the tests are shown on table 1. Also shown is the estimated error in these parameters during the fill test.

TABLE 1

Important Parameters of the Apollo Tank

1. Volume*; Full at ambient Pressure 1 bar, 20.3 K	.19170 to .19190m^3 (.1918m^3 used in calculations)
2. Volume*; Full at 15.5 bars, 23.1 K	.19245 to 19259m^3 (.19252m^3 used in calculations)
3. Volume*; Full at 17.9 bars, 23.1 K	.1927 to .192720m^3 (.19264m^3 used in calculations)
4. Heat Leak	
With Cooled Shield	2.44 W ± .02W
With Noncooled Shield	5.92 W ± .02W
5. Tare Weight	
NBP Storage Test	67.81 kg ± .04kg
Unmixed Slush Test (changed electrical connector)	67.82 kg ± .04kg
Mixed Slush Test (changed electrical connector)	67.95 kg ± .04kg
6. Full Weight	
NBP Storage Test	79.61 kg ± .04kg
Unmixed Slush Test	81.11 kg ± .04kg
Mixed Slush Test	81.07 kg ± .04kg
7. Loaded Mass	
NBP Storage Test	11.80 kg ± .08kg
Unmixed Slush Test	13.29 kg ± .08kg
Mixed Slush Test	13.12 kg ± .08kg

*Volume figures obtained from Manual Number M-13532 of September 6, 1968

2.3 RESULTS OF THE HYDROGEN STORAGE TESTS

Three long term storage tests were conducted. The first test was with a normal boiling point liquid hydrogen fill. The second test was with a slush hydrogen fill and was conducted without mixing. The third test used a slush hydrogen fill and it was mixed at various times during the test.

After obtaining the weight of the empty Apollo tank (tare weight), the three tests were conducted following the general procedure outlined below.

1. The vessel was filled to the proper ullage volume.
2. The vessel was valved off.
3. The full weight was measured.
4. The pressure rise rate was measured to about 17.2 bar (250 psia)
5. When the pressure reached 17.2 bar the vessel was vented at nearly a constant pressure through the shield and a wet test gas meter.
6. After about 1 week, the venting valves were changed to vent without cooling the shield.
7. When the venting stopped, the Apollo tank was evacuated and purged and reweighed to check the tare weight.

The pressure rise rate for the three storage tests are shown in figures 12, 13, and 14. The NBP liquid test and the unmixed slush test were not mixed except for some movement as the vessel was weighed and moved to a remote site. This movement occurred during the first 2 hours after the fill. The third or mixed slush test was mixed using the internal fans at variable intervals as shown on table 2. The mixers were run until the pressure stopped decreasing for each interval. The heat generated by the fan motors was added to the measured heat leak of the vessel to calculate the theoretical pressure rise rate.

TABLE 2

Mixing Times During Pressure Rise Period

Total Time Since Filling	Mixing Time	Pressure, bar	
h	s	Before Mixing	After Mixing
19.25	63.7	1.360	.607
24.75	30	1.667	.748
40.73	202.2	4.630	1.184
47.00	150	9.664	9.243
59.25 (venting)	90	17.800	17.800

In every test, the measured pressure rise time was shorter than the theoretical time for a system in thermal equilibrium. For the unmixed case, the difference in time can be due to thermal stratification, but in the mixed test thermal stratification would not exist. The difference in

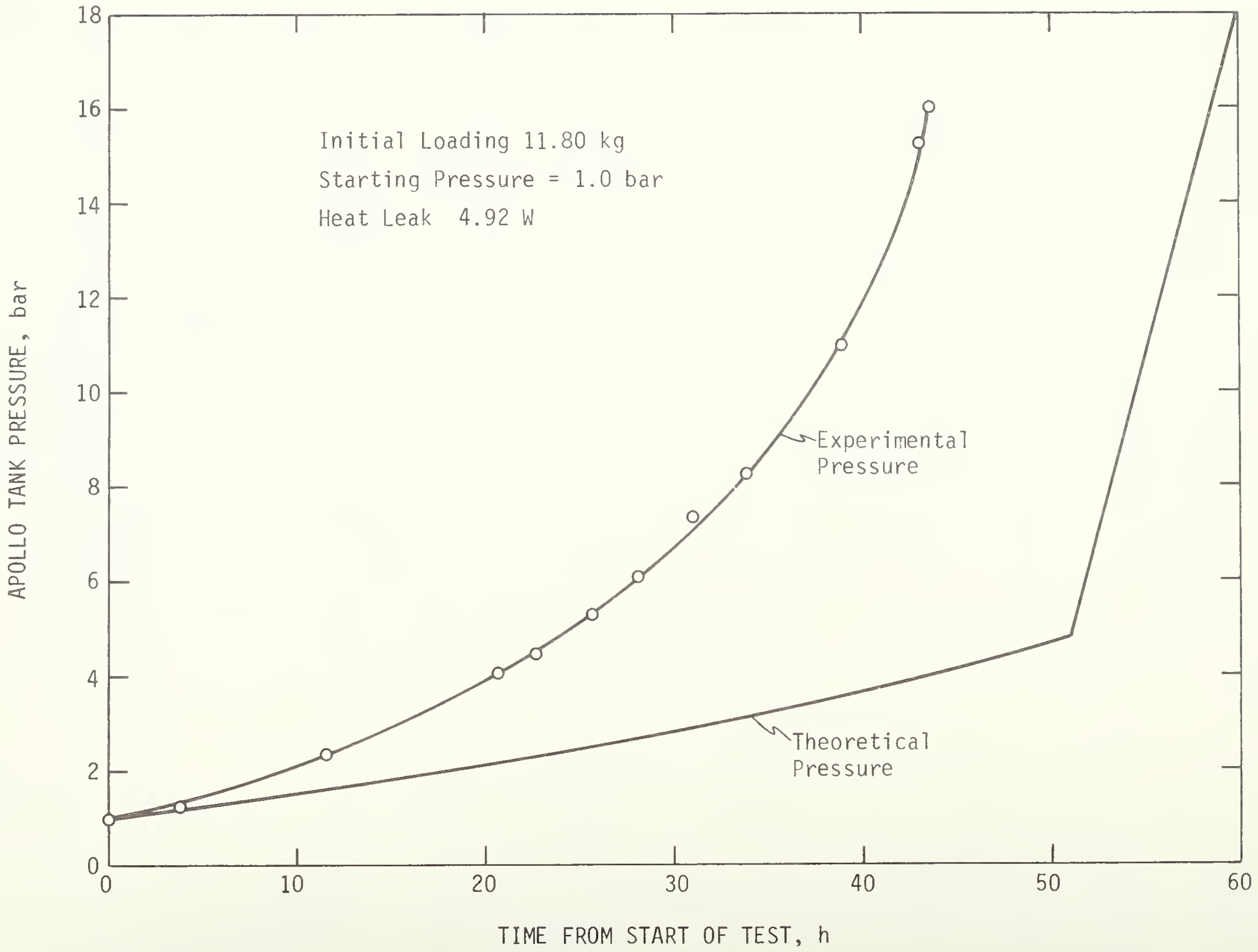


Figure 12. The Theoretical and Actual Pressure Rise for the Apollo Tank Filled with Normal Boiling Point Liquid Hydrogen.

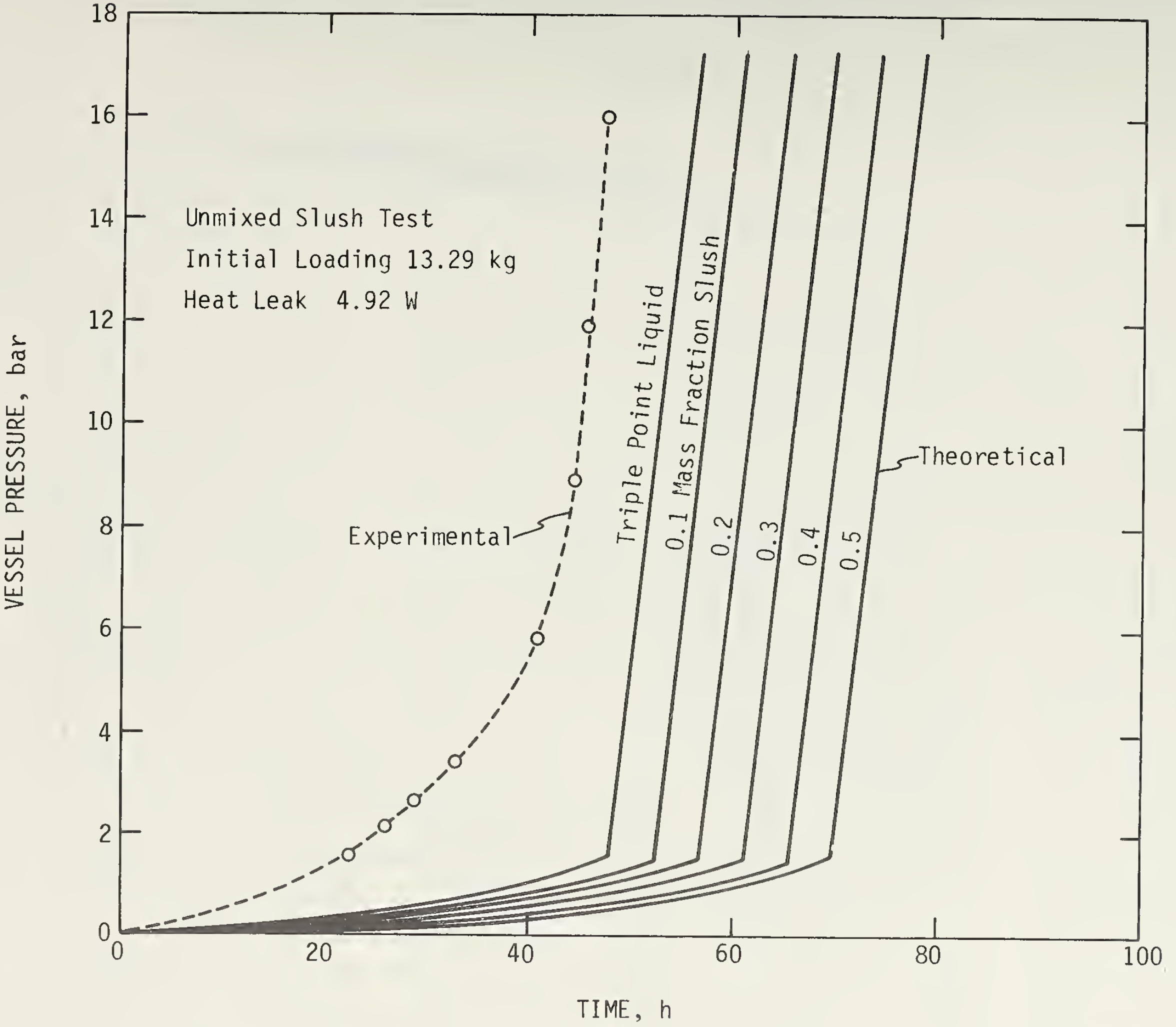


Figure 13. The Theoretical and Actual Pressure Rise for the Apollo Tank Filled with Slush Hydrogen. The Slush was not Mixed During the Test.

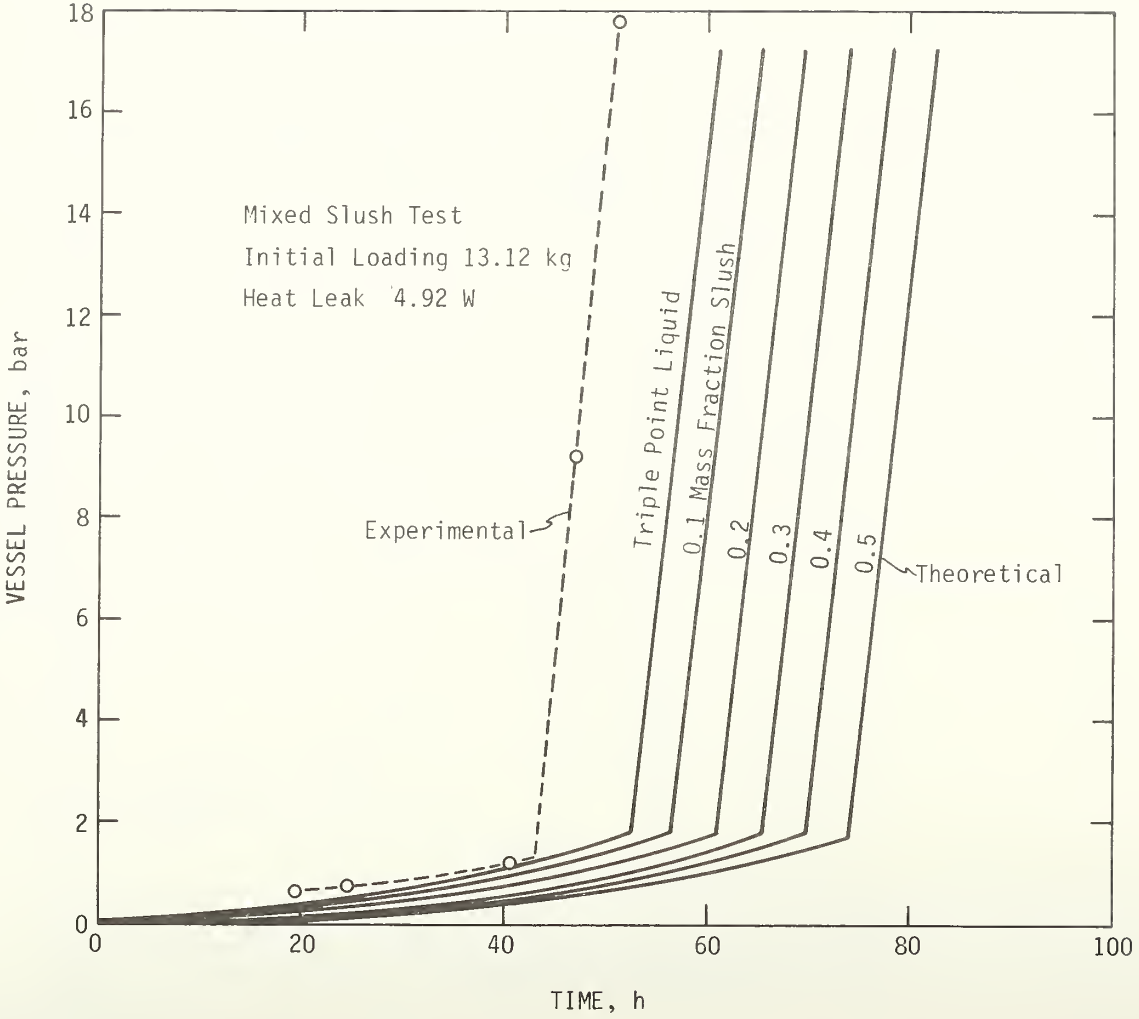


Figure 14. The Theoretical and Actual Pressure Rise for the Apollo Tank Filled with Slush Hydrogen. The Slush was Mixed at the Points Shown.

theoretical versus measured pressure rise time could be due to a combination of the following potential factors:

1. A higher heat leak than that measured prior to the storage tests.
2. The mixing fans stopped working near the end of the test (very little pressure reduction due to mixing occurred at 47 hours into the test--See table 2).
3. The Apollo vessel had a different volume than that used to calculate pressure rise time.
4. The inaccuracy in the weight measurement used to determine loaded mass was sufficient to cause the disagreement.
5. The experimental ullage volume was different than the ullage volume used in the theoretical calculations.

Analyzing the effect of heat leak on the pressure rise time shows that the calculated pressure rise time is inversely proportional to the heat leak to the tank. The heat leak could be increased by the changing pressure in the mixed slush test. Decreasing the vessel pressure by mixing will tend to allow warm gas from the vent and fill lines to be mixed into the cold fluid in the tank. This mixing will increase the heat input. Calculations, however, show this heat input to be insignificant when compared to the heat gain through the insulation. Since heat gain must be in error by nearly 20 percent to explain the shorter measured pressure rise time, an error in heat gain alone does not explain the discrepancy.

We have no reason to believe the mixing fans did not work during the test (they obviously worked in the early part of the test), and the measured pressure rise rate nearly duplicates the theoretical pressure rise rate calculated after the tank becomes full showing that the tank was probably mixed properly.

An error in the Apollo vessel volume used in the calculations leads to an approximate proportional error in pressure rise time. Figure 15 shows the effect of vessel volume on the total calculated pressure rise time for a tank filled with 13.29 kg of triple point liquid. The slope of the curve on this figure shows that a 1 percent error in volume yields a 1 percent error in pressure rise time. An error of 20 percent of the total volume is required to explain the difference between the measured and calculated pressure rise times. Therefore an error in the vessel volume does not explain the discrepancy.

A similar calculation can be made on the error involved in weighing the tank. The total weight of the tank was about 80 kg and measuring this weight to 0.1 percent (errors could accumulate in the tare measurement and the full measurement) yields an error of 0.08 kg or 0.6 percent in the weight of the hydrogen loaded. Figure 16 shows the change in calculated total pressure rise time versus mass loaded. An error in the loaded mass of

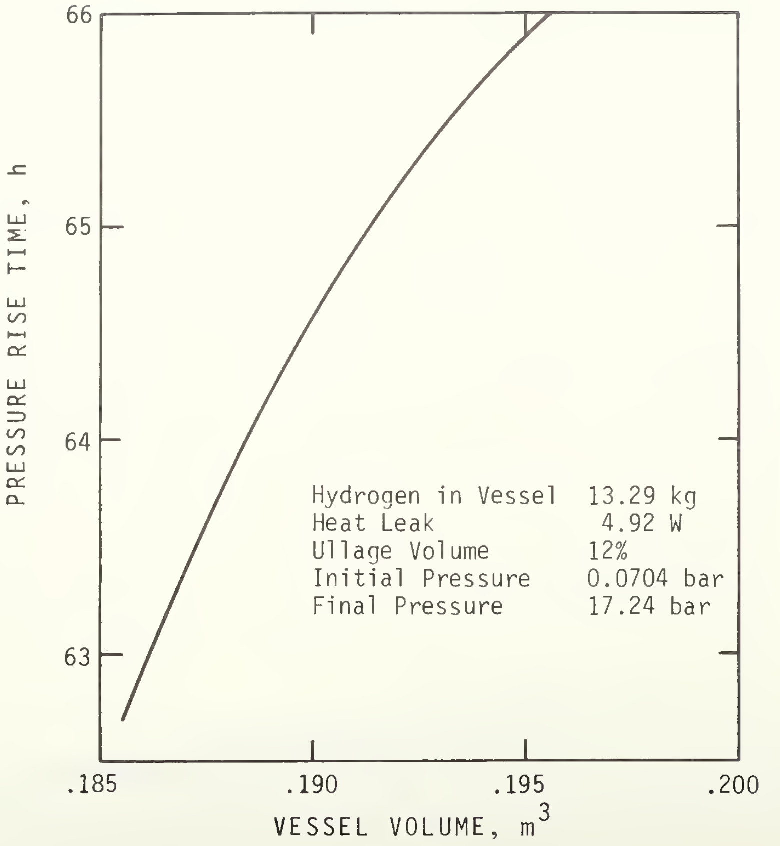


Figure 15. The Theoretical Pressure Rise Time Based on a Variable Apollo Tank Volume.

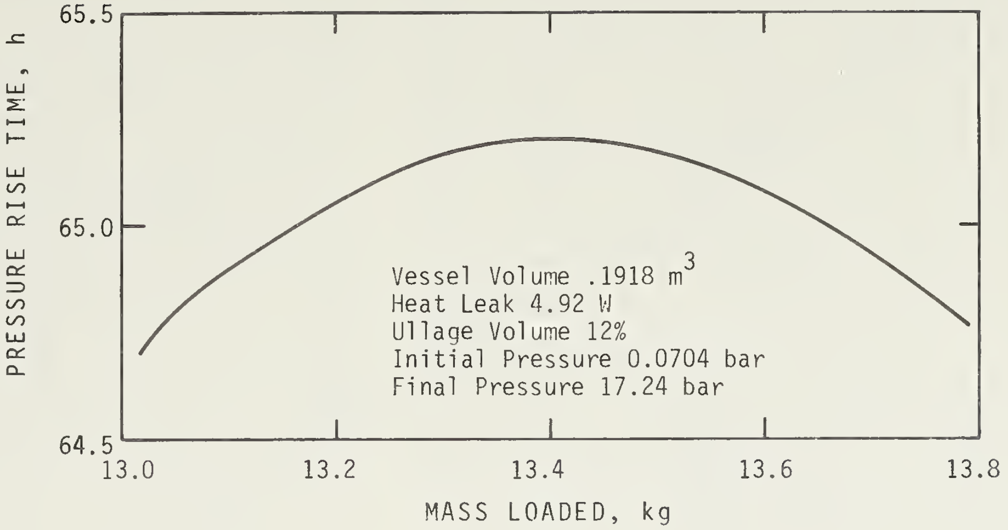


Figure 16. The Theoretical Pressure Rise Time Based on a Variable Apollo Tank Mass Loading.

13.29 kg results in very small changes in the calculated pressure rise times. Again the error in mass measurement cannot explain the difference between the measured and calculated pressure rise time.

Without instruments in the Apollo tank, it is impossible to tell the exact ullage volume in the filled container. Since the inlet tube to the vessel passes through the ullage volume, the ullage volume will always be at or near triple point pressure. Unless the venting pressure is below the triple point pressure, the ullage volume can fill, reducing its volume below that calculated by tilting the tank. We tried to insure a correct ullage volume by continuing to pump on the vent line after the transfer was complete. But even with all the precautions, the assurance of a correct ullage volume in the tank can not be proven because of the lack of instrumentation. Figure 17 shows the calculated pressure rise time versus ullage volume and mass fraction of the loaded slush for the Apollo vessel. An error of 1.5 cm in the fluid surface height yields a change of 10 hours in the pressure rise time. Thus, the difference between the measured and calculated pressure rise time is most likely due to an error in the loaded ullage volume. This result indicates that besides a mass meter, an accurate fluid level gauge would be required in the Apollo vessel to insure the correct loaded ullage volume to yield the desired pressure rise time.

Even though the results of the experiment differ from the theoretical calculation, the loaded slush mass was from 1.11 to 1.13 times the mass in the normal boiling point liquid fill and the slush pressure rise time was 1.08 to 1.17 times the pressure rise time of normal boiling point liquid hydrogen.

The venting rates at constant pressure are compared to calculated venting rates on figures 18 and 19. A fairly high scatter is apparent at the early part of the experiment with high remaining mass. This scatter results from the unknown heat leak during the early part of the experiment. When venting starts, the shield is warm, and heat leak decreases by a factor of 2 in about 24 hours as the shield is cooled. In order to decrease the time of the storage test, we later vented directly without cooling the shield so the heat leak increased by a factor of two over numerous hours. Also, the pressure in the Apollo vessel varied about 1 bar in a 24 hour period during the test so that instantaneous venting rates taken during a pressure rise were lower than average and venting rates taken during a pressure fall were higher than average. The experimental data appears to fit the calculated venting rates quite well establishing a further confirmation of the heat leak used for the theoretical calculation. Because of the good fit of the calculated and measured venting rates, slush was probably not present in the tank when venting started and thermal stratification was not effecting the data.

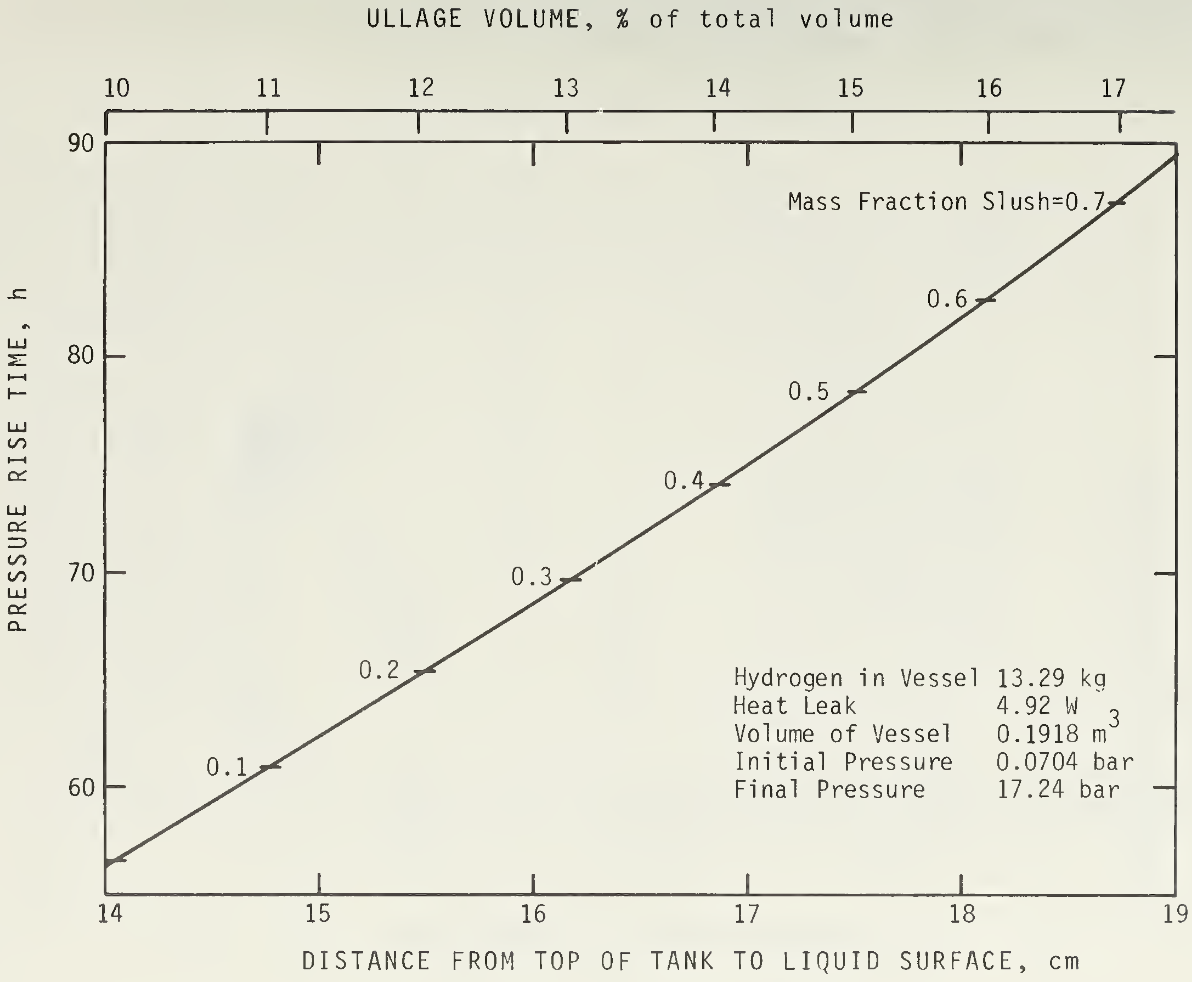


Figure 17. The Theoretical Pressure Rise Time with Various Ullage Volumes in the Apollo Vessel.

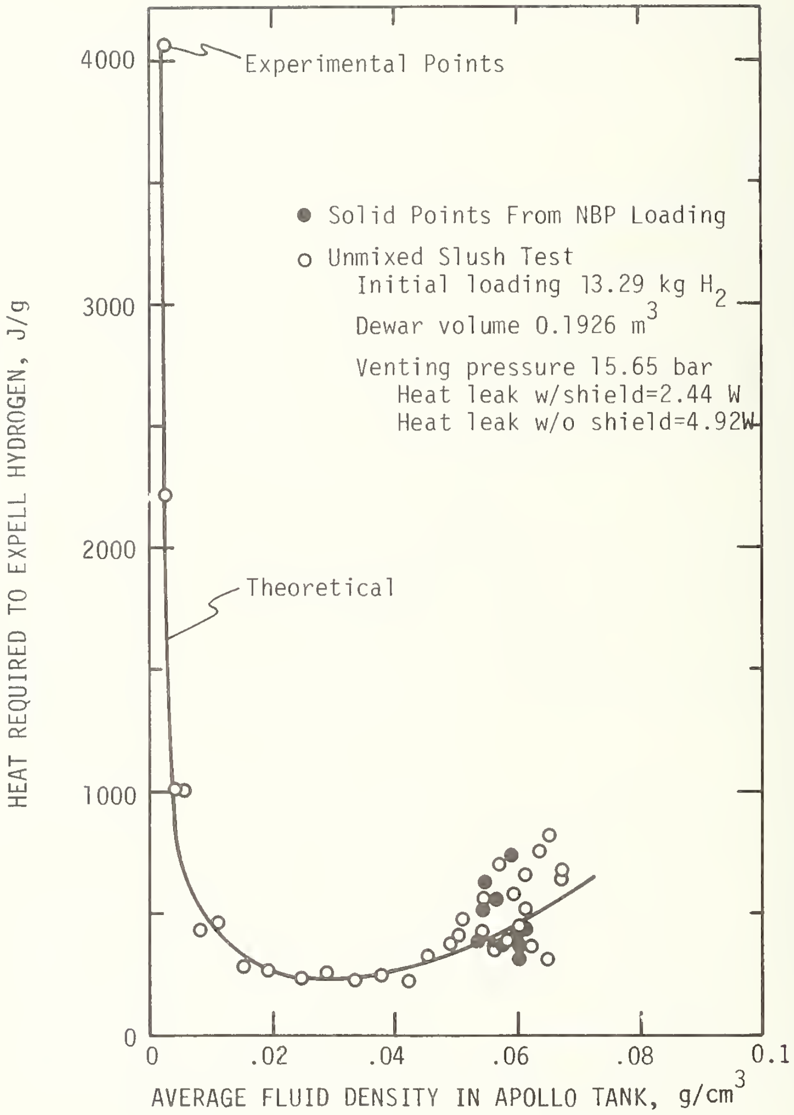


Figure 18. Venting Characteristics for the Apollo Vessel at a pressure near 15.65 bar.

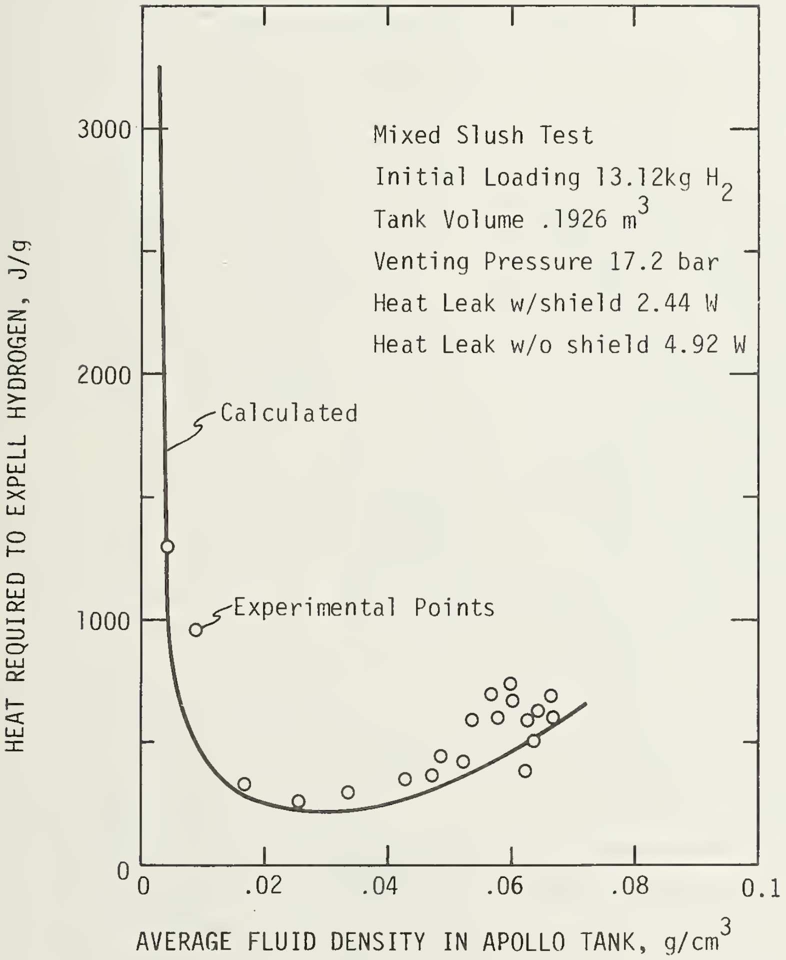


Figure 19. Venting Characteristics for the Apollo Vessel at a pressure near 17.2 bar.

2.4 THE RADIO FREQUENCY MASS GAUGE

The difficulty in determining the conditions in a loaded Apollo tank even when it is weighed confirm the need for a mass gauge for the slush storage vessel. (Also an accurate liquid level gauge to determine ullage volume is required.) The radio frequency gauge was connected to the tank through an existing wire to the capacitance gauge already in the tank. This connection provided a weak coupling to the tank interior and the weak coupling had two major effects on the results. First, the signal strength obtained was low making it difficult to differentiate between the resonance signal of the tank and the noise in the cables and measuring system. A block diagram of the system used to measure the tank resonant frequencies is shown in figure 20. Figures 21a, 21b and 21c compare the signals obtained from the Apollo tank to the signals from a clean (no internal capacitor, heater or mixers) sphere with a good internal antenna. The signal from the Apollo tank requires amplification, so the background noise becomes competitive with the resonance signal. The resonant signal from the clean sphere is much greater in strength, so less amplification is required and the background noise becomes insignificant. Figures 21b and 21c show the primary resonant frequency from the Apollo vessel, and figure 21a shows both the primary and secondary reasonances of the clean sphere.

The second effect of the weak coupling was apparent when the resonant frequencies of the unmixed slush test were compared to the resonant frequencies of the mixed test. In the second test, the mixing motors had been connected to the power supply, and this connection changed the empty resonant frequency of the vessel. Because of this effect it is impossible to compare the resonant frequency versus remaining mass for the two tests.

Figures 22 and 23 show the primary resonant frequency as determined from two peaks versus remaining mass for the two slush tests. Even with the difficulty of determining the resonant frequency, these results are encouraging. The frequency counter can be read to 5 significant digits with the fifth digit being questionable. With a four significant digit readout, the mass can be determined to within 1 percent if stratification and weak coupling do not affect the resonant frequency (from the slope of the curves on figures 22 and 23). In the mixed slush test, RF readings were taken before and after mixing. The resonant frequency readings changed by about ±.05 percent leading to a ±1 percent error in mass reading due to stratification. The overall error in contained mass should be well within ±2 percent for a properly designed radio frequency system.

One major unexplained frequency change occurred in the tests. The resonant frequency increased as the pressure increased in the nonventing pressure rise portion of the test. Since both the pressure and temperature of the vessel were increasing, the vessel volume was also increasing. The

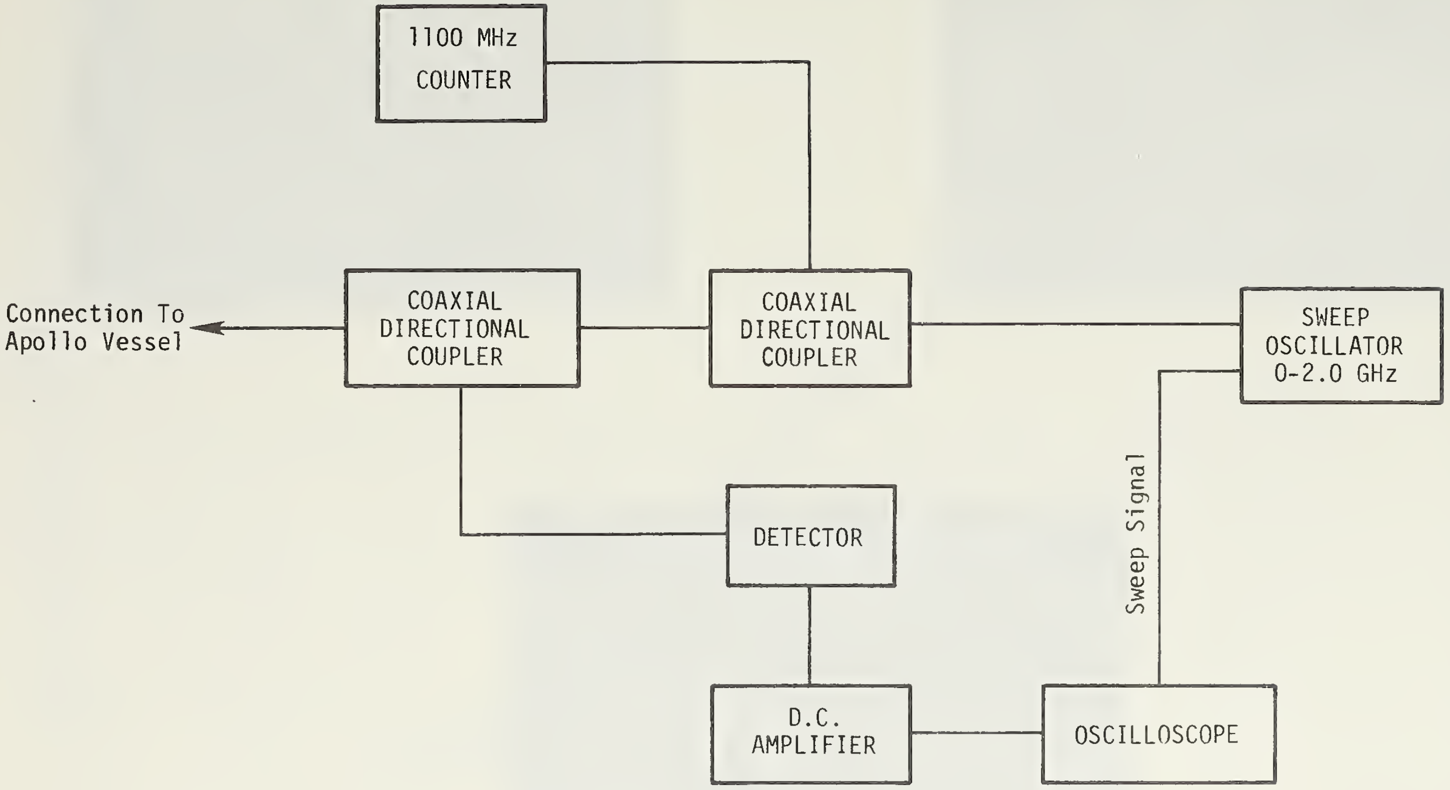


Figure 20. Block Diagram of the Instrumentation Used to Measure the Resonant Frequencies of the Apollo Vessel.

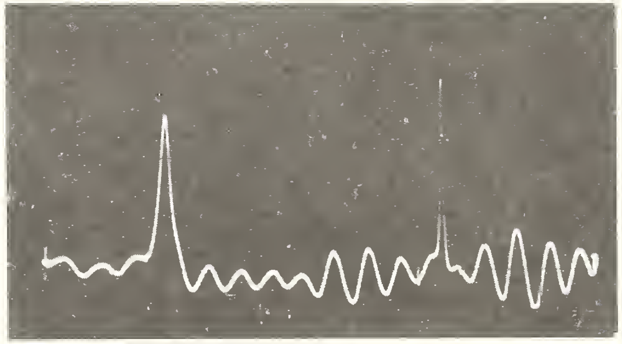


Figure 21a. The Primary and Secondary Resonance Signals for a Clean Sphere

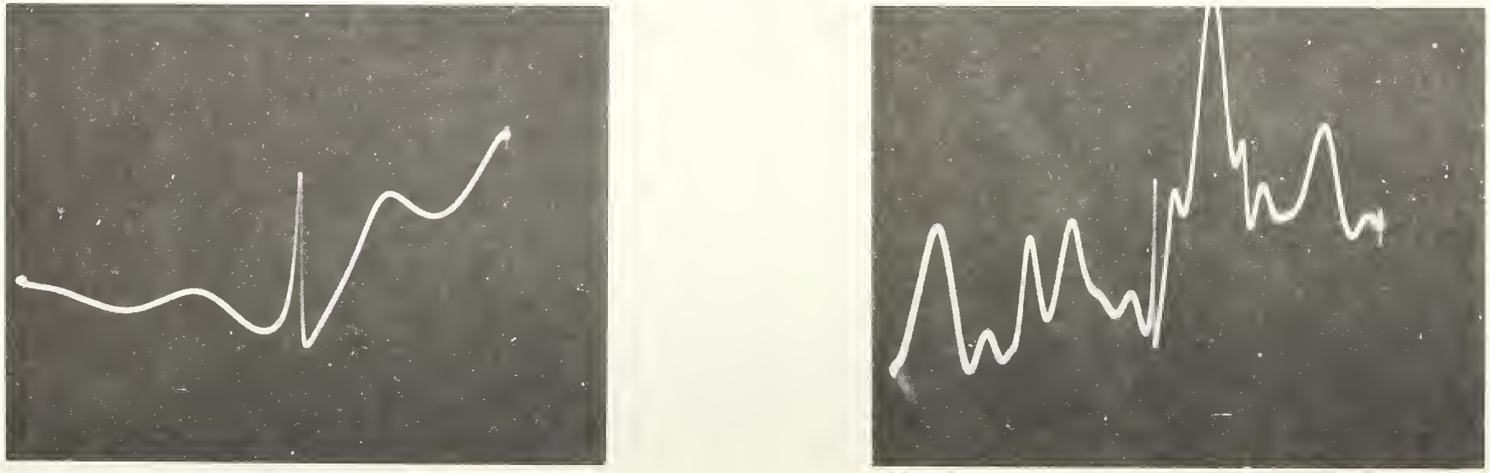


Figure 21b

Figure 21c

'The Primary Resonant Frequency and Background Noise Signals from the Apollo Vessel.

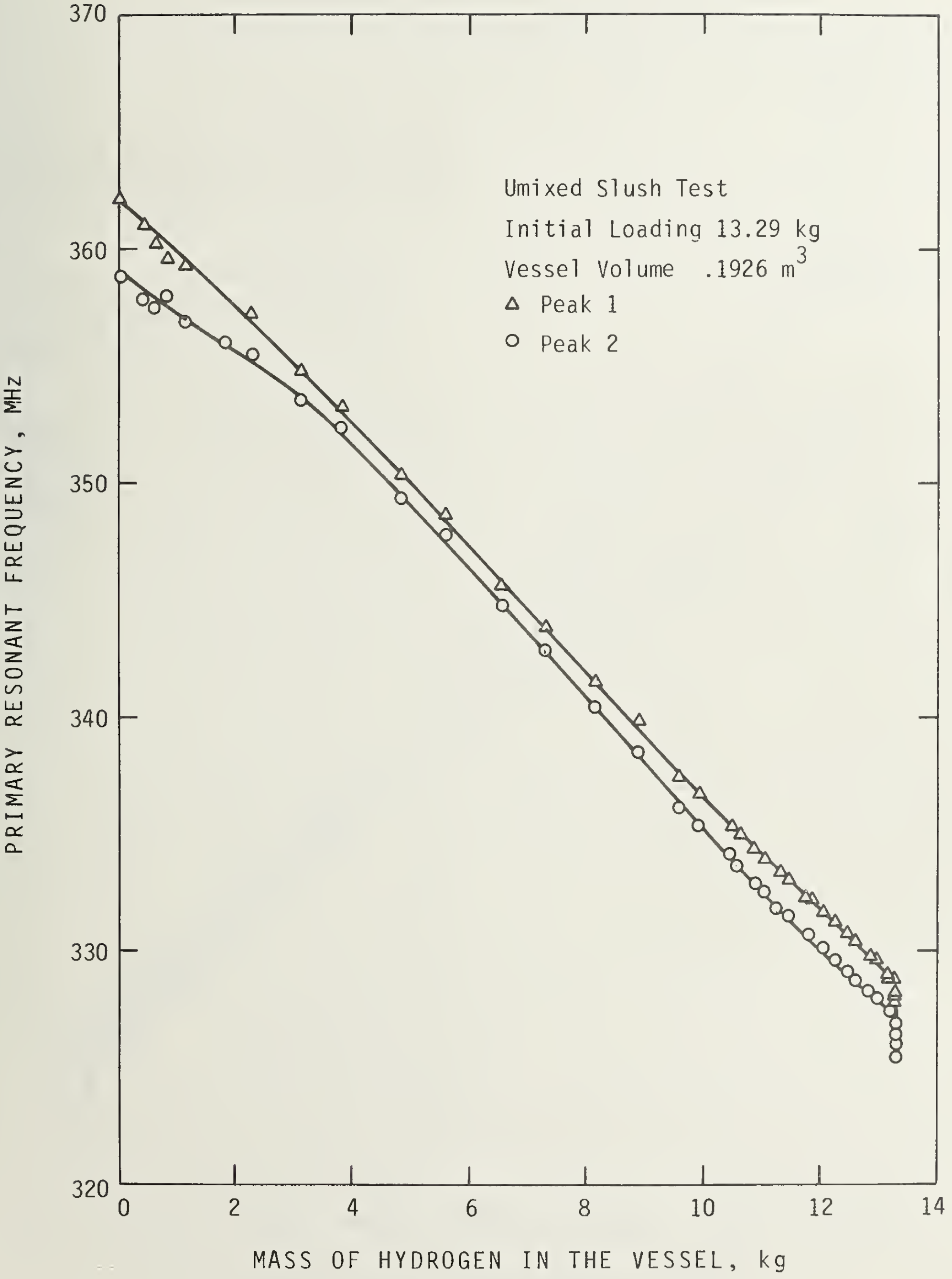


Figure 22. Resonant Frequency for Several Peaks Near the Primary Resonant Frequency of the Apollo Vessel Versus Remaining Hydrogen Mass.

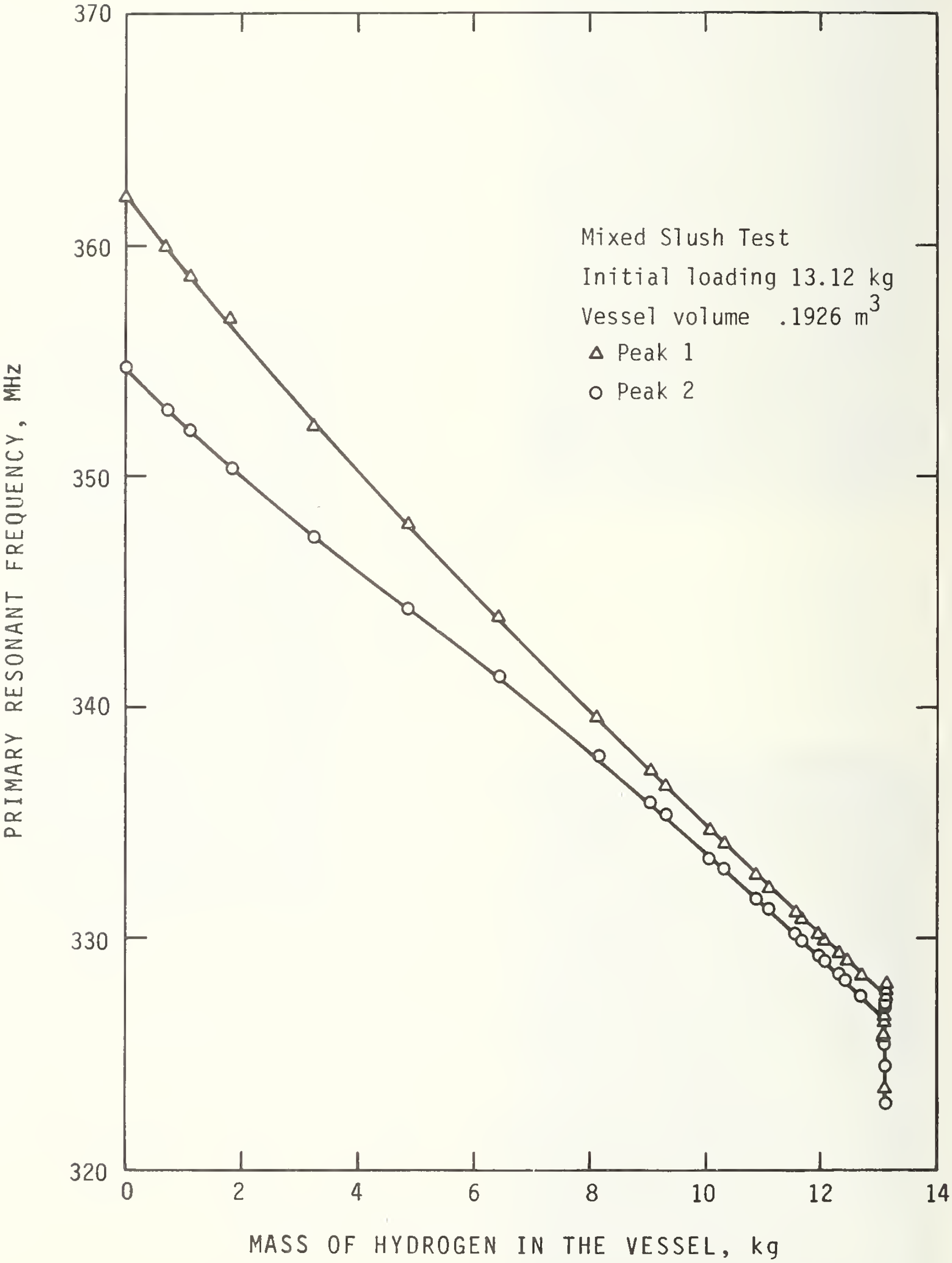


Figure 23. Resonant Frequency for Several Peaks Near the Primary Resonant Frequency of the Apollo Vessel Versus Remaining Mass.

resonant frequency is inversely proportional to the tank radius [3] so the larger volume should result in a lower resonant frequency. Mixing during this period had little effect on the resonant frequency rise and the only other explanation for the increasing frequency would be the poor coupling.

2.5 CONCLUSIONS FROM THE STORAGE TESTS

Even though the accuracy of the experimental results was limited by the lack of instrumentation in the Apollo tank, significant results were obtained. The slush pressure rise time was 1.08 to 1.17 times the pressure rise time for normal boiling point liquid hydrogen. The mass of slush hydrogen loaded was 1.11 to 1.13 times the normal boiling point liquid loaded in the vessel with the same ullage volume. Both the loaded mass and the tank volume had insignificant effects on the calculated pressure rise time while the ullage volume (the most difficult to measure) had a significant effect.

To use slush hydrogen in a practical application, the loading procedure and loading system must be carefully conceived. The latent heat of the solid hydrogen in slush with a mass fraction of 0.5 is comparable to the latent heat of vaporization for helium. Therefore, the loading system must be of helium transfer line quality. Not only must the heat leak be low, but since slush hydrogen exhibits nearly the same tendency to thermal oscillate as helium, the line penetrations should be similar to those used in a helium transfer system. The thermal oscillation develops at penetrations to the cold line that lead to ambient temperature conditions. These penetrations include gauge lines, pressure relief lines, and even valves used in the system. Secondly, the loading line inside the storage vessel should either enter the bottom of the vessel or be vacuum insulated as it passes through the ullage space. Otherwise, thermal stratification cannot develop on the fluid surface during the fill leaving the ullage volume at triple point pressure. With the ullage at triple point pressure, it is possible to overfill the tank unless the venting pressure is reduced to below triple point pressure at the completion of the fill. Finally, the venting system should be vacuum insulated to eliminate the higher pressures associated with flashing in the vent line and to conserve liquid hydrogen. Also an appropriately designed screen over the vent line penetration inside the tank would allow the slush to be upgraded in the vessel as it is being filled.

The radio frequency gauge does demonstrate a change in frequency with changing mass in the vessel. However, a vessel with a good antenna inside to achieve good coupling is necessary to yield good accuracy. Even without good coupling the R.F. gauge appears to be accurate to within 2 percent in mass loaded.

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NBS-114A (REV. 9-76)

U.S. DEPT. OF COMM.
BIBLIOGRAPHIC DATA SHEET

1. PUBLICATION OR REPORT NO.
NBSIR 79-1607

2. Gov't. Accession No.

3. Recipient's Accession No.

4. TITLE AND SUBTITLE
PRODUCING SLUSH OXYGEN WITH AN AUGER AND MEASURING THE STORAGE CHARACTERISTICS OF SLUSH HYDROGEN

5. Publication Date
March 1979

6. Performing Organization Code

7. AUTHOR(S)
Roland O. Voth and Paul R. Ludtke

8. Performing Organ. Report No.

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, DC 20234

10. Project/Task/Work Unit No.
[redacted]

11. Contract/Grant No.
CC-6253QA

12. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

NASA
Kennedy Space Center, Florida 32899

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

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.)*

Part 1. PRODUCING SLUSH OXYGEN WITH AN AUGER

An auger rotating inside a brass tube refrigerated with liquid helium was used to produce liquid-solid (slush) mixtures of oxygen. The auger produced small particles of solid oxygen so that the resulting mixture could be transferred and stored. The auger could produce slush continuously in an appropriate system, and it could produce slush at pressures higher than the triple point pressure of the oxygen.

Part 2. STORAGE CHARACTERISTICS OF SLUSH HYDROGEN

Three long term storage tests were conducted on an Apollo hydrogen vessel. The vessel was filled to 88 percent with normal boiling point liquid hydrogen then the pressure rise rate to 17.6 bar and the venting rate at 17.6 bar were measured. The two other tests were similar except the vessel was filled with slush hydrogen. In one of these tests, the slush was mixed to eliminate thermal stratification. Filling with slush instead of liquid hydrogen increased the storage time before venting by 1.08 to 1.17 times and increased the mass loaded by 1.11 to 1.13 times.

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; hydrogen; oxygen; scraping auger; slush; slush production; slush storage

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☒ Order From National Technical Information Service (NTIS), Springfield, VA. 22161

19. SECURITY CLASS (THIS REPORT)
UNCLASSIFIED

20. SECURITY CLASS (THIS PAGE)
UNCLASSIFIED

21. NO. OF PRINTED PAGES
42

22. Price
$4.00

☆U.S. GOVERNMENT PRINTING OFFICE: 1979-0-677-072/1284