NASA Technical Memorandum 107324

Comparison of the Continuous Freeze Slush Hydrogen Production Technique to the Freeze/Thaw Technique

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Prepared for the
1996 JANNAF Propulsion and Joint Subcommittee Meetings
sponsored by the JANNAF Interagency Propulsion Committee
Albuquerque, New Mexico, December 9–13, 1996

National Aeronautics and
Space Administration

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SUMMARY

Experiments were conducted to compare slush hydrogen production rates between the continuous freeze technique and the freeze/thaw technique. The continuous freeze technique involves pulling a continuous vacuum over triple point liquid and using a solid hydrogen mechanical ice-breaker to disrupt the surface of the freezing hydrogen. The data showed that the continuous freeze production technique had an average production rate that was 39 percent higher than the freeze/thaw methods tested. Gaseous helium was not used to disrupt solid hydrogen bridging in any of the slush production tests reported here. The continuous freeze tests however, did demonstrate the feasibility of using a mechanical ice-breaker to disrupt the solid hydrogen surface which could be applied to large scale slush hydrogen genererators that previously required the aid of expensive gaseous helium injection to melt the solid hydrogen bridge.

INTRODUCTION

With the introduction of spaceplanes in the next century, travel to low earth orbit (LEO) will become a frequent and relatively inexpensive practice compared with todays LEO launches. One of the key technologies that will allow this to happen is the use of slush hydrogen as the spaceplane fuel. Slush hydrogen is a mixture of liquid and solid hydrogen. A 50 percent solid content slush hydrogen mixture is 16 percent more dense than normal boiling point liquid hydrogen. The advantage of using slush hydrogen over normal boiling point liquid hydrogen as a spaceplane fuel is that vehicle size and weight can be reduced. According to Hans,[1] projected annual demand for slush hydrogen in the year 2010 is 584 million pounds to support a fleet of 20 spaceplanes. Therefore, a real need exists to develop slush hydrogen production techniques that have high production rates, are simple, inexpensive, efficient, safe, and easy to implement in large scale production facilities.

Several slush hydrogen production techniques such as the auger method presented by Voth[2] and the freeze/thaw method by Mann[3] produced small quantities of slush when initially tested. The freeze/thaw method was chosen to be used in the first large scale 800 gallon slush production facilities; the STF facility at Martin Marietta Astronautics in Denver, Colorado and the K-site facility at the NASA Lewis Research Center's Plum Brook Station in Sandusky, Ohio. These production facilities were the first to produce slush hydrogen in large quantities in support of the National Aerospace Plane slush hydrogen technology development program.[4]

The K-site testing showed that a solid hydrogen bridge would form at the surface during the freeze/thaw process from solids adhering to the generator walls.[5] The solid hydrogen bridge caused the production rate to decrease because the bridge acted like a barrier keeping vapor from being pulled out of the liquid. It was found that the solid hydrogen bridge could be eliminated by adjusting the magnitude of the pressure swing inside the slush generator during the freeze/thaw process. The swing pressure is the change in generator pressure from the thaw cycle to the freeze cycle. The swing pressure was accomplished through the addition of helium gas during the thaw cycle. In general, the larger the swing pressure the less adhesion of the solids to the generator wall. The addition of helium gas is detrimental because it also adds energy to a process that is trying to remove energy. In addition, a review of

the costs to produce a batch of slush hydrogen at K-site conducted by the author showed that expensive helium costs were approximately 42 percent of the total cost of slush production. The other costs included in the analysis were: liquid hydrogen (43 percent), operator time (11 percent), and electric power (4 percent).

The continuous freeze slush production technique developed by Haberbusch[6] did not require the use of helium for slush production and provided the potential to improve the rate of slush production by eliminating the thaw cycle time. The continuous freeze slush production technique involves pulling a continuous vacuum over a dewar of triple point liquid to create solids on the surface. A mechanical ice-breaker is cycled above and below the surface to break-up the newly formed solids without the use of a thaw cycle and pressurant gas.

To demonstrate the potential improvements of the continuous freeze method over the freeze/thaw method, experiments were conducted at the NASA Lewis Research Center. The experiments involved obtaining and comparing production rates from 9 tests; 3 continuous freeze tests, 2 freeze/thaw long thaw cycle tests, 2 freeze/thaw long freeze cycle tests, and 2 freeze/thaw equal cycle tests. Each of the 4 types of tests were repeated to allow a statistical analysis to be conducted to determine if differences between the four types of tests were significant or not. This report presents the results of these experiments.

SYMBOLS

Cp	specific heat of wall material, Btu/lbm R
h	enthalpy, Btu/lbm
h_o	enthalpy of gas leaving system, Btu/lbm
m	mass, lbm
m_o	total mass leaving system, lbm
$\dot{m}_o$	mass flow rate out of system, lbm/sec
$\overline{\dot{m}}_o$	average mass flow rate out of system during 1 scan/sec data rate, lbm/sec
P	pressure, psia
Q	energy, Btu
Q_o	energy removed via vacuum pumping, Btu
$\dot{Q}$	heat rate, Btu/sec
R	slush production rate, %/min
t	time, sec
T	temperature, °R
t_p	time of slush production, sec
t_α	start time of 1 scan per second data rate, sec
t_β	end time of 1 scan per second data rate, sec
U	internal energy, Btu

X solid fraction of slush

Greek

ρ density, lbm/cu. ft.

ν specific volume, cu. ft./lbm

Subscripts

1 state 1, start of slush production

2 state 2, end of slush production

FL fluid in test dewar

HL heat leak

L liquid

MELT meltback state

MIX mixer in test dewar

S solid

TP triple point

ULL ullage, vapor space above liquid

V vapor

W wall of test dewar

APPARATUS AND INSTRUMENTATION

SMALL SCALE HYDROGEN TEST SYSTEM

The Small Scale Hydrogen Test System (SSHTS) located inside the main test building at the NASA Lewis K-Site facility, uses the existing K-Site propellant supply system, vacuum pumping systems, and remotely located control room for facility operations and data recording. The SSHTS consists of a test dewar, instrumentation box, vacuum jacketed transfer lines, and supporting equipment. For these experiments only the test dewar and the vacuum pumping system were utilized. The test dewar is shown in figure 1.

The test dewar which was used as the slush generator is a 90 in. tall, 26 in. diameter cylindrical vacuum jacketed dewar with a rounded bottom end cap. The vacuum space contains several layers of multilayer insulation material and a liquid nitrogen shield that surrounds the top 44 in. of the inner vessel. The liquid nitrogen shield was not used for these tests. The inner vessel wall consists of a low thermal conductivity G10 plastic for the first 24 in. from the top, with the remainder of the structure being aluminum.

The lid of the test dewar is an aluminum flat plate with multiple penetrations for liquid and gas supplies, pressure taps, and electrical and instrumentation feedthroughs. Below the lid are three layers of the low thermal conductivity plastic covered with aluminized mylar which act as shields to reduce the heat leak into the dewar from internal convection to the lid. These shields extend down into the tank for approximately

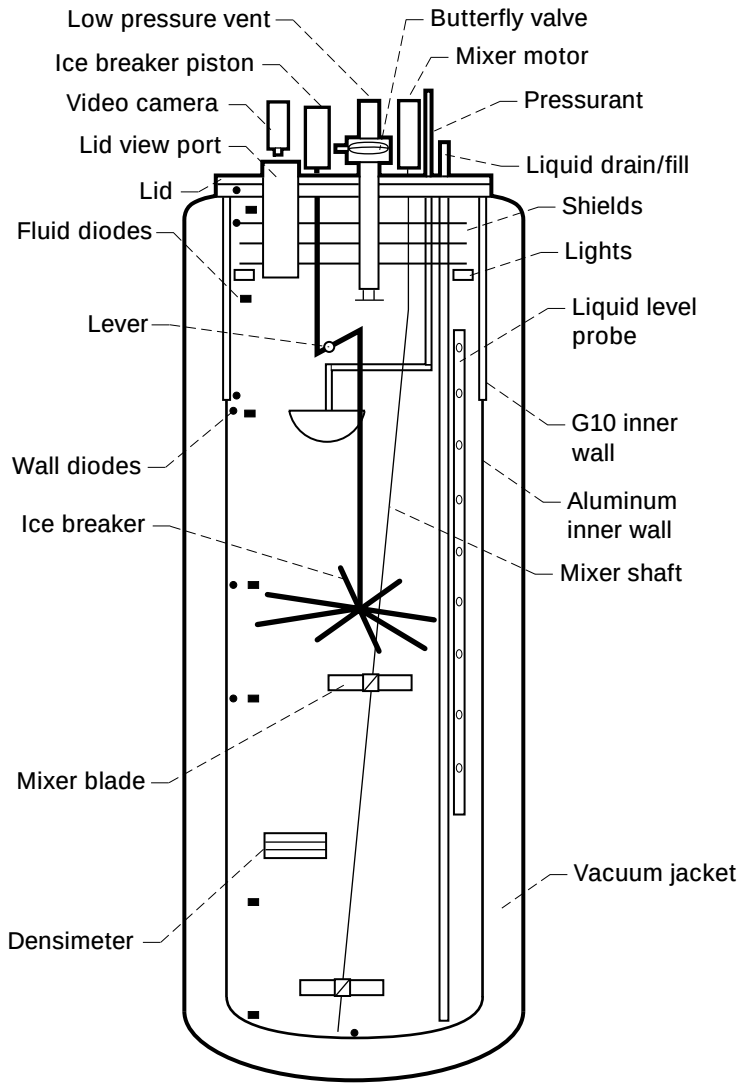

Figure 1.—Small scale hydrogen test system Dewar. Supporting structure excluded.

7.5 in. There is also a stainless steel support ring which hangs from the lid and provides support for internal hardware and instrumentation.

A viewport on the test dewar lid was utilized to video the inside of the test dewar during slush production. The viewport is constructed out of two Pyrex glass discs separated by an evacuated fiberglass tube. The top disc is sealed with an O-ring and the bottom disc is epoxied to the end of the fiberglass tube.

A mixer was used during testing to mix the solids into the liquid. The mixer has two sets of 9 in. diameter, 4 bladed, 45° pitch mixing blades attached to a shaft that runs the entire height of the dewar. The bottom mixer blade was located 5.5 in. from the bottom of the test dewar and the top mixer blade was located at 35 in. from the bottom. The top mixing blade is shown in figure 2. The mixer is driven by an electric motor located on the outside of the lid. The mixer speed was held constant at approximately 150 rpm for all tests.

The mechanical vacuum pump used to evacuate the ullage has a displacement of 778 cfm. The pump was connected to the test dewar through a 4 in. stainless steel vent line. The dewar was isolated from the vacuum pump by the dewar isolation valve which was a 4 in. butterfly valve mounted inline just outside of the test dewar. The

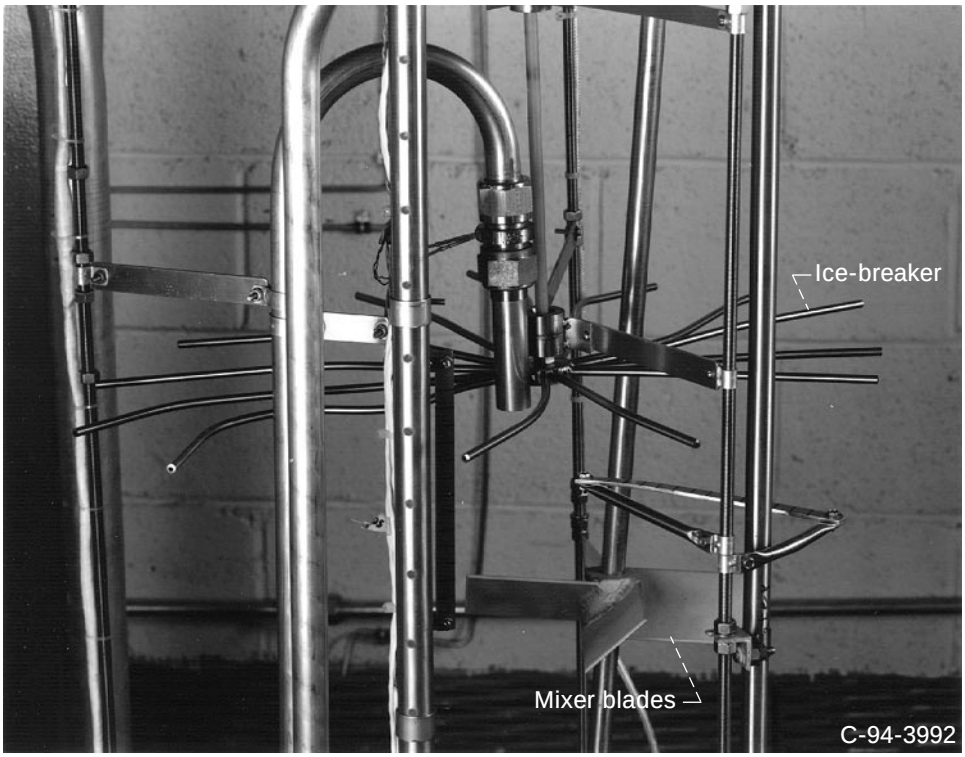

Figure 2.—Solid hydrogen mechanical ice-breaker.

dewar isolation valve was controlled by a PID controller that allowed automatic control of the valve during the freeze/thaw tests. A 36 kW heater/heat exchanger was available to warm the vent gas going to the vacuum pump inlet. The vacuum flowrate was measured using an orifice run.

Instrumentation within the test dewar provided indications of temperature, pressure, liquid level, and density. There were 7 silicon diodes spaced approximately 12 in. apart located on a vertical rake which provided both liquid and ullage gas temperatures. There were also 7 silicon diode temperature sensors mounted on the inner wall of the test dewar.

A capacitance type densimeter was used to measure the slush hydrogen density within the test dewar. The densimeter was located 18 in. from the bottom of the test dewar and was supported underneath the support ring.

The liquid level was measured using a capacitance type liquid level probe. The liquid level probe signal was compensated for changes in dewar pressure and fluid temperature which affect the accuracy of capacitance type devices.

HYDROGEN ICE BREAKER

The hydrogen ice breaker pictured in figure 2. consisted of thirteen 0.25 in. diameter stainless steel tubular spokes protruding horizontally from a central hub. The spokes were of various lengths and bent to various shapes to avoid contact with other pieces of hardware in the test dewar such as the liquid level probe and the all-thread rods that suspended the internal support structure from the lid.

The ice-breaker was fastened to the end of a fiberglass rod which acted as the plunger. The plunging rod was connected to one end of a lever located near the top of the dewar. The lever was designed to actuate the ice-breaker from a pneumatically actuated valve mounted to the top of the dewar. The actuating valve and the other end of the lever were connected via a separate fiberglass rod. The lever converted the 1 in. stroke of the pneumatic valve to a

6 in. stroke for the ice-breaker. The ice-breaker stroke went from 42 to 36 in. as measured from the bottom of the test dewar. The ice-breaker actuation was controlled manually from the control room.

TEST PROCEDURE

The test dewar was filled to approximately 51 in. with normal boiling point liquid hydrogen. Data recording was then initiated. The vacuum pump was turned on and the test dewar isolation valve was opened. The test dewar pressure was dropped from 14.4 psia to the triple point pressure at which point solids formed on the surface of the liquid indicating triple point liquid. The pressure eventually bottomed out at 0.95 psia. The isolation valve was closed. The mixer was ramped to 150 rpm and held constant throughout the slush production. The isolation valve was opened and vacuum pumping was continued. The 36 kW heater/heat exchanger used to warm the vacuum pumped gas was not required since the cold hydrogen vapor warmed in the vent line prior to reaching the vacuum pump.

For the continuous freeze tests the hydrogen ice-breaker was manually operated approximately 30 times/min to break the hydrogen ice forming on the surface during the vacuum pumping. As larger chunks of hydrogen ice formed the ice-breaker would be used to push the chunks into the liquid and mixed with the slush. The particular ice-breaker used in these experiments allowed some of the large chunks of ice to wedge up in between the spokes and ride on top of the ice-breaker. In order to get the chunks into the liquid, the isolation valve was closed to stop the vacuum pumping for a very short while to allow the large chunks to slip back through the spokes and into the liquid. The isolation valve was then opened and slush production resumed. The slush production was finally stopped when the ice-breaker could no longer reach the liquid/solid surface due to the lower travel limit of the ice-breaker stroke. The isolation valve was then closed, the vacuum pump turned off and the mixer turned off. After a minute hold period the meltback procedures were initiated. The mixer was turned on to increase the heat leak, and all of the solids were melted. Once the bottom rake diode began to rise in temperature indicating no more two phase fluid in the test dewar the mixer was turned off. A final liquid level measurement was made to be used in the final mass measurements and the data recording was then stopped.

For the freeze/thaw tests the freeze/thaw cycle times were programmed into the PID controller and verified through visual observation of the isolation valve prior to the start of the test. The valve was programmed to go fully open and fully closed in a specified time. The vacuum pumping to triple point procedures were the same as for the continuous freeze tests. Once triple point was reached the mixer was ramped to 150 rpm and held constant. The automatic freeze/thaw cycling of the test dewar isolation valve was initiated. The test dewar pressure during one freeze/thaw cycle ranged from 54.3 to 49.1 torr for a swing pressure of 5 torr. Slush production continued until the liquid/solid level reached approximately 36 in. The isolation valve was then closed, the vacuum pump turned off and the mixer turned off. After a minute hold the meltback procedures were conducted.

DATA ANALYSIS

PRODUCTION RATE

The slush hydrogen production rate (R) for each test is calculated by dividing the final solid fraction in percent (X) by the total time of slush production (t_p).

$$R = \frac{X}{t_p} \tag{1}$$

The final solid fraction is the percent of solid hydrogen by mass in the slush mixture at the end of the test. The total time of slush production is defined as the time from triple point liquid hydrogen to the end of slush production which occurred when the liquid/solid level reached approximately 36 in.

FINAL SOLID FRACTION

The final solid fraction is calculated from conservation of mass and energy. The mass and energy balance was conducted with the test dewar as the control volume. The equations for conservation of mass and energy are given below. State 1 is at the start of production and state 2 is at the end of production.

$$m_{L_1} + m_{V_1} = m_{L_2} + m_{V_2} + m_{S_2} + m_o \tag{2}$$

$$Q_{HL} + Q_{MIX} = (U_2 - U_1)_w + (U_2 - U_1)_{ULL} + (U_2 - U_1)_{FL} + Q_o \tag{3}$$

where

$$(U_2 - U_1)_{FL} = (h - P\nu)_{L_2} m_{L_2} + (h - P\nu)_{S_2} m_{S2} - (h - P\nu)_{L_1} m_{L_1}$$

Equations (2) and (3) are then solved for m_{L_2} and m_{S_2} and are given in equations (4) and (5). The liquid and solid ($P\nu$) terms are negligible compared to the enthalpies. The ullage mass (m_{V_1}, m_{V_2}) and ullage energy terms $(U_2 - U_1)_{ULL}$ are negligible compared to the other mass and energy terms.

$$m_{L_2} = \frac{Q_{HL} + Q_{MIX} - Q_o - (U_2 - U_1)_w - h_{S_2}\left(m_{L_1} - m_o\right) + h_{L_1} m_{L_1}}{h_{L_2} - h_{S_2}} \tag{4}$$

$$m_{S_2} = m_{L_1} + m_{V_1} - m_{L_2} - m_{V_2} - m_o \tag{5}$$

The terms in the right hand sides of equations (4) and (5) are calculated from measured parameters and are shown in Appendix A, Data Reduction.

The final solid fraction is then calculated from equation (6).

$$X = \frac{m_{S_2}}{m_{S_2} + m_{L_2}} \tag{6}$$

The final solid fraction calculation was checked by comparing the liquid mass inside the test dewar after the meltback $m_{L_{MELT}}$ to the sum of the calculated solid and liquid mass $\left(m_{S_2} + m_{L_2}\right)$ used in calculating the final solid fraction.

RESULTS AND DISCUSSION

A summary of slush production results for each test is given in table 1. The test number and run order are given at the top of the table. The tests were conducted in a random order to minimize the influence of any uncontrollable time varying factors that may have existed. The remainder of table 1 is divided into four parts: Controlled Parameters, Production Results, Mass Measurements, and Energy Measurements.

CONTROLLED PARAMETERS

Tests CF1J, CF1K, and CF1L are repeats of the continuous freeze production method using the ice-breaker. Tests F1B and F1C are repeats of the freeze/thaw method with approximately the same freeze and thaw cycle times.

TABLE 1.—SUMMARY OF SLUSH PRODUCTION RESULTS

Test number	Units	CF1J	CF1K	CF1L	F1B	F1C	F2B	F2C	F3B	F3C
Run order		1	2	6	4	5	3	8	7	9
Controlled parameters										
Ice-breaker		yes	yes	yes	no	no	no	no	no	no
Freeze cycle time	sec	no	no	no	10	10	11	11	21	19
Thaw cycle time	sec	no	no	no	12	14	25	25	15	17
Production results										
Slush production rate	percent/min	1.44	2.00	1.83	1.07	1.14	0.75	0.68	1.20	1.34
Production rate uncertainty (+/–)	percent/min	0.24	0.13	0.25	0.04	0.06	0.01	0.04	0.24	0.14
Calculated final solid fraction	percent	46	67	51	81	72	99	77	42	58
Total time of slush production	sec	1920	2009	1673	4553	3779	7940	6818	2100	2594
Total time spent freezing	sec	1860	1759	1413	2070	1574	2426	2083	1225	1369
Total time spent thawing	sec	60	250	260	2483	2205	5514	4735	875	1225
Percent of production time spent freezing	percent	97	88	84	45	42	31	31	58	53
Slush mass calculated from M & E balance	lbm	55.43	54.86	54.32	54.35	54.63	54.22	54.86	56.54	55.38
Difference between meltback and slush mass	percent	0	0	1	0	1	–1	–2	–1	1
Mass measurements										
Vacuum pumped mass	lbm	3.38	4.43	3.49	4.72	4.39	4.84	4.07	2.73	3.82
Liquid mass at start of production	lbm	58.80	59.29	57.81	59.07	59.02	59.06	58.93	59.27	59.33
Liquid mass after meltback	lbm	55.42	54.89	54.90	54.23	54.91	53.43	53.96	55.71	55.72
Energy measurements										
Vacuum pumped energy	Btu	351	482	355	785	655	1207	932	364	491
Wall energy at start of production	Btu	3164	3147	3094	3197	3110	3192	3112	3070	3152
Wall energy at end of production	Btu	3151	3154	3088	3231	3144	3284	3205	3091	3149
Mixer energy	Btu	64	68	48	146	121	250	207	61	75
Environmental heat leak	Btu	86	90	75	205	170	357	307	95	117

Tests F2B and F2C are repeats of the freeze/thaw method with a long thaw cycle. Tests F3B and F3C are repeats of the freeze/thaw method with a long freeze cycle. Variations in the freeze/thaw cycle times were due to the repeatability of the isolation valve response to the controller.

PRODUCTION RESULTS

The production results given include; the slush production rate, slush production rate uncertainty, the final solid fraction obtained from calculation, the total time of slush production, the total time spent freezing, the total time spent thawing, the percent of slush production time spent freezing, the slush mass calculated from the mass and energy balances, and the difference between the measured meltback mass and the calculated final slush mass. The uncertainty analysis of the calculated slush production rates yielded an average production rate uncertainty of $\pm$9 percent with the high being $\pm$20 percent and the low being $\pm$1 percent.

The total time of slush production, the total time spent freezing during slush production, and the total time spent thawing during slush production are given in seconds. These numbers were used to calculate the percent of slush production time spent freezing. Under ideal conditions the continuous slush production method would not require the stoppage of vacuum pumping. However, in these continuous freeze tests using the ice-breaker, it became necessary to stop vacuum pumping for a short period of time to allow the solid chunks of ice to fall through the spokes of the ice-breaker and into the liquid. Visual observation of the production process showed several very large chunks (6 to 12 in. in length) collecting on top of the ice-breaker. Even with these small periods of “thawing”, the average percent of time spent freezing during continuous freeze slush production was 90 percent. This is a 61 percent increase in the average time spent freezing over the long freeze cycle freeze/thaw tests (56 percent).

The mass of the slush produced as calculated from the mass and energy balance is compared to the measured fluid mass after conducting a meltback of the slush. The difference between the two masses is given in terms of percent of measured meltback mass. For all nine tests the maximum difference was 2 percent and the average difference was less than 1 percent thus providing a very good verification on the amount of slush calculated at the end of slush production.

MASS AND ENERGY MEASUREMENTS

Also presented in the summary of results are the mass and energy measurements that are used in the mass and energy balance calculations used to calculate final solid fraction. The mass measurements include vacuum pumped mass, liquid mass at the start of slush production, and the liquid mass after meltback. Gaseous helium injection into the ullage was not required in any of the slush production tests to aid the thawing of the solid hydrogen surface. This is due to the fact that the environmental heating rate per wetted surface area was an order of magnitude higher in the test dewar than in the slush hydrogen generator used at K-site[5] which did require helium injection to melt the solid hydrogen bridge. The higher environmental heat leak in the test dewar made it easier for the solids to melt away from the walls during the thaw cycle. The fact that helium was not introduced into the ullage during the production process helped to maintain an accurate vent gas flow rate measurement. The measurement would have been invalid had helium been introduced since the helium/hydrogen mixture ratio would have been an unknown.

A direct measurement of the slush density was made during testing with the densimeter. The densimeter data is not presented in this report because it was not used in the data analysis. The maximum density readings that were recorded were significantly lower than the density that was calculated. Density measurements indicated that the densimeter reached a plateau in the middle of the tests at about 40 percent solid fraction and would not read higher even though visual data indicated solids were still being formed. It is the opinion of the authors that the densimeter was “shielded” by the support ring from the bulk fluid and that the sample of slush inside the densimeter did not represent the overall density of the bulk fluid in the test dewar.

The energy measurements made include; vacuum pumped energy, wall energy at the start and end of production, mixer energy, and the environmental heat leak. The change in wall energy from start to end of production was a very small fraction of the total energy removed via vacuum pumping, typically 3 percent. The sum of the mixer energy and environmental heat leak into the liquid was on average 43 percent of the energy removed by vacuum pumping.

Values ranged from a high of 55 percent to a low of 33 percent. The mixer energy was typically 40 percent of the total amount of energy entering the test dewar through mixing and heat leak.

Even though the vacuum pumping efficiency seems lower than what would typically be found in a slush production facility, the rates of energy input by the mixer and heat leak are constant throughout testing thus allowing the different production methods to be compared.

STATISTICAL ANALYSIS

An Analysis of Variance (ANOVA) statistical analysis was conducted to compare the means and standard deviations of the production rates of the four production methods tested. The goal of the ANOVA was to determine if the production rates for each method were significantly different from one another. The data for each of the four methods were assumed to be normally distributed. The mean and standard deviation for each method was calculated. Using a Foster-Burr analysis it was determined that the standard deviations were not significantly different from one another. Therefore the standard deviations were “pooled” to give one strong reliable standard deviation to be used in the remainder of the analysis.

A comparison of the mean value of production rate for each method was conducted using a 1-way ANOVA F statistic. This analysis determined that the means were significantly different and that the analysis should continue to determine how the means were different. Therefore, a Student Newman Keuls (SNK) analysis was conducted to determine which mean production rates were significantly different from one another at a 95 percent confidence level.

A summary of the statistical analysis conducted is given in table 2. For each of the four production methods tested the table gives; the test numbers, the mean value of the production rate, the standard deviation of the production rate, the number of tests conducted, the degrees of freedom, the lower 95 percent bound and the upper 95 percent bound. The upper and lower 95 percent bounds for each production method bound the range in solid production rates that would occur 95 percent of the time for that production method in this facility based on the degrees of freedom. The degrees of freedom are quite small for each test thus causing the large 95 percent bounds.

The average slush production rates are presented graphically in figure 3. The average production rate for the continuous production method was 1.76 percent/min. The average production rates for the freeze/thaw equal cycles, long thaw cycle, and long freeze cycle were 1.11, 0.72, and 1.27 percent/min, respectively. The results of the SNK analysis indicate that the continuous freeze mean production rate of 1.76 percent/min was significantly greater than all other production rates. The SNK analysis also indicated that the long freeze cycle freeze/thaw production rate (1.27 percent/min) and the equal cycle freeze/thaw production rate (1.11 percent/min) are not significantly different from one another. The SKN analysis showed that both of these methods are significantly less than the continuous freeze production rate and both are significantly greater than the long thaw cycle freeze/thaw production rate (0.72 percent/min). The SNK analysis showed that the long thaw cycle freeze/thaw mean production rate was significantly less than all other mean production rates.

TABLE 2.—STATISTICAL ANALYSIS SUMMARY OF PRODUCTION RATES

Statistic	Units	Production methods			
		Continuous freeze	Freeze/thaw long freeze cycle	Freeze/thaw long thaw cycle	Freeze/thaw equal cycles
Test number		CF1J, CF1K, and CF1L	F3B and F3C	F2B and F2C	F1B and F1C
Mean production rate	percent solid/min	1.76	1.27	0.72	1.11
Standrad deviation of production rate	percent solid/min	0.29	0.10	0.05	0.05
Number of tests		3	2	2	2
Degrees of freedom		2	1	1	1
Lower 95 percent bound	percent solid/min	0.52	0.01	0.09	0.48
Upper 95 percent bound	percent solid/min	2.99	2.53	1.34	1.73

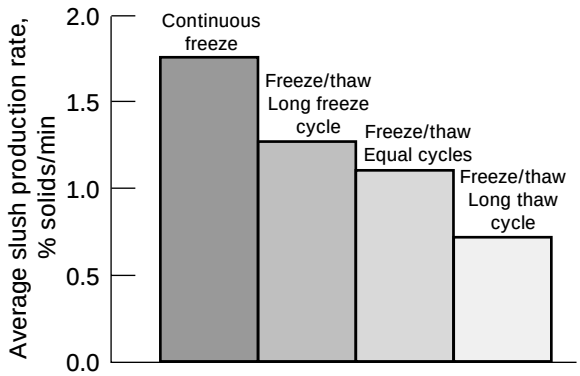

Figure 3.—Average slush production rate test results.

CONCLUDING REMARKS

Experiments were conducted to demonstrate the new and unique continuous freeze slush hydrogen production technique and to compare this technique to the freeze/thaw slush production technique. Tests were conducted in a 200 gallon slush hydrogen generator. The continuous freeze method involves pulling a continuous vacuum over a dewar full of triple point liquid and using a stainless steel tubular spoked ice-breaker to break up the solid hydrogen forming on the surface of the liquid.

The continuous freeze method along with 3 variations of the freeze/thaw slush production method were tested. The results of the statistical analysis comparing the production rates of each method proved that the continuous freeze slush production rate is significantly higher than all of the freeze/thaw slush production methods tested. The continuous freeze slush production method showed an increased production rate of 39 percent over the next best freeze/thaw method tested.

The continuous freeze slush production method and associated ice-breaker hardware tested here provide an engineering model that could be emulated in large production facilities. The continuous freeze method has demonstrated the feasibility of eliminating expensive gaseous helium injection and its associated heat addition in slush production facilitities that required helium for solid hydrogen bridge breaking.

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APPENDIX A
DATA REDUCTION

LIQUID MASS

The liquid mass at the start of production $\left(m_{L_1}\right)$ and the liquid mass after the meltback $\left(m_{L_{MELT}}\right)$ were calculated by dividing the test dewar up into seven volumetric nodes as shown in figure 4(a). The liquid level measurement defined the upper boundary of the top most liquid node. The fluid temperature at each node was represented by a silicon diode temperature sensor. The density of the fluid in each nodal volume was calculated using test dewar pressure and the nodal temperature. The total mass of liquid was obtained by summing the product of the nodal density and volume for each liquid node as shown in equation (7).

$$m_L = \sum_{\text{node } i=1}^{\text{node } i=\text{top}} V_i \rho_i \tag{7}$$

VACUUM PUMPED MASS

For the continuous freeze tests the total amount of mass removed from the test dewar was calculated by integrating the measured mass flow rate over the total time of slush production.

$$m_o = \int_1^2 \dot{m}_o dt \tag{8}$$

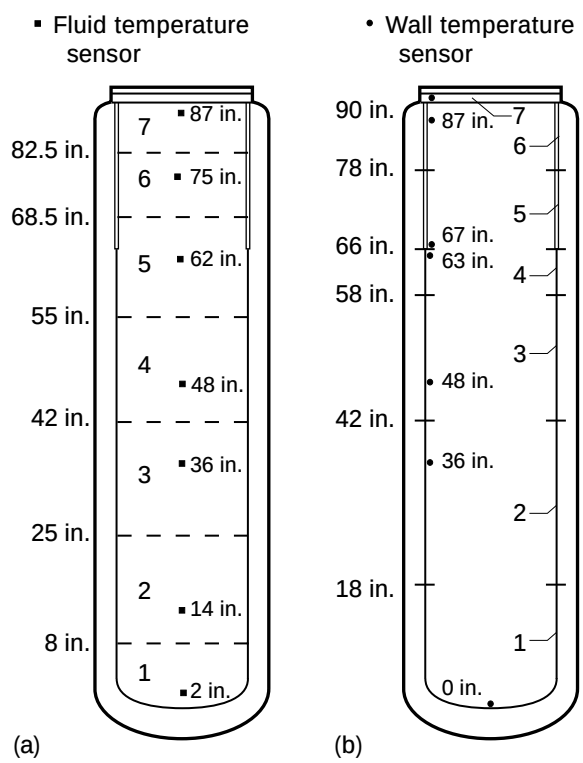

Figure 4.—Fluid and wall volume nodes. (a) Fluid nodes. (b) Inner wall nodes.

For the freeze thaw tests the total amount of mass removed from the test dewar was calculated by multiplying an average mass flow rate by the total time of slush production as shown in equation (9). The average mass flow rate was obtained by integrating the measured mass flow rate over several freeze/thaw cycles during the 1 scan/sec data recording rate at the beginning of slush production. This is shown in equation (10). The one scan/sec data rate was sufficient to capture the changes in the vacuum flow rate during the freeze/thaw cycling.

$$m_o = \overline{\dot{m}}_o t_p \tag{9}$$

$$\overline{\dot{m}}_o = \frac{\int_{t_\alpha}^{t_\beta} \dot{m}_o dt}{t_\beta - t_\alpha} \tag{10}$$

HEAT LEAK ENERGY

The environmental heat leak input shown in equation (11) was calculated from multiplying the total time of slush production by the measured heating rate of 0.045 Btu/sec. The measured heating rate was obtained from a separate boil-off test conducted prior to the start of the slush production tests.

$$Q_{HL} = 0.045\, t_p \tag{11}$$

MIXER ENERGY

The mixer energy input was measured from a watt meter that measured the power input to the electric mixer motor. The power was then integrated over the slush production time to obtain a total mixer energy input as shown in equation (12).

$$Q_{MIX} = \int_1^2 \dot{Q}_{MIX} dt \tag{12}$$

WALL ENERGY

To calculate the wall energy at a given state, the test dewar inner vessel wall was divided into seven volumetric nodes as shown in figure 4(b). The temperature at each node was represented by a wall mounted temperature sensor. The total energy in the wall was obtained by summing the product of the nodal volume, density, specific heat, and temperature of each node as shown in equation (13). Nodes 1, 2, 3, 4, and 7 were made out of 2219 Aluminum. Nodes 5 and 6 were made out of G10.

$$U_W = \sum_{\text{node } i-1}^{\text{node } i=7} \left(V_w \rho_w C_{pw} T_w\right) i \tag{13}$$

LIQUID ENERGY

The liquid energy at the start of slush production was calculated from multiplying the triple point liquid enthalpy $\left(h_{L_{TP}} = h_{L_1} = h_{L_2} = -132.9 \text{ Btu/lbm}\right)$ by the total amount of measured triple point liquid mass as shown in equation (14). The triple point solid enthalpy used in the energy balance calculation (equation (2)) was $h_{S_{TP}} = h_{S_2} = -157.9 \text{ Btu/lbm}$.

$$U_{L1} = h_{L_1} m_{L_1} \tag{14}$$

VACUUM PUMPED ENERGY

The energy leaving the system during vacuum pumping from state 1 to state 2 was calculated from multiplying the average enthalpy of the gas leaving the system by the total amount of vapor that left the system. The average enthalpy was calculated from the average gas temperature leaving the system and the test dewar pressure during slush production. The vacuum pumped energy is given by equation (15).

$$Q_o = \bar{h}_o m_o \tag{15}$$

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE
October 1996

3. REPORT TYPE AND DATES COVERED
Technical Memorandum

4. TITLE AND SUBTITLE
Comparison of the Continuous Freeze Slush Hydrogen Production Technique to the Freeze/Thaw Technique

5. FUNDING NUMBERS
WU–505–70–62

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER
E–10430

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, DC 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA TM–107324

11. SUPPLEMENTARY NOTES
Prepared for the 1996 JANNAF Propulsion and Joint Subcommittee Meetings sponsored by the JANNAF Interagency Propulsion Committee, Albuquerque, New Mexico, December 9–13, 1996. Mark S. Haberbusch, Ohio Aerospace Institute, 22800 Cedar Point Road, Brook Park, Ohio 44142, and Nancy B. McNelis, NASA Lewis Research Center. Responsible person, Nancy B. McNelis, organization code 5340, (216) 977–7474.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Categories 28, 15, and 14

This publication is available from the NASA Center for AeroSpace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***
Experiments were conducted to compare slush hydrogen production rates between the continuous freeze technique and the freeze/thaw technique. The continuous freeze technique involves pulling a continuous vacuum over triple point liquid and using a solid hydrogen mechanical ice-breaker to disrupt the surface of the freezing hydrogen. The data showed that the continuous freeze production technique had an average production rate that was 39 percent higher than the freeze/thaw methods tested. Gaseous helium was not used to disrupt solid hydrogen bridging in any of the slush production tests reported here. The continuous freeze tests however, did demonstrate the feasibility of using a mechanical ice-breaker to disrupt the solid hydrogen surface which could be applied to large scale slush hydrogen generators that previously required the aid of expensive gaseous helium injection to melt the solid hydrogen bridge.

14. SUBJECT TERMS
Slush hydrogen; Densified cryogens; Slush hydrogen production

15. NUMBER OF PAGES
14

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT
Unclassified

18. SECURITY CLASSIFICATION OF THIS PAGE
Unclassified

19. SECURITY CLASSIFICATION OF ABSTRACT
Unclassified

20. LIMITATION OF ABSTRACT