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PRODUCING LIQUID-SOLID MIXTURES OF HYDROGEN USING AN AUGER

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Prepared for:
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CONTENTS

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

Key words: Cryogenic; hydrogen; production efficiency; scraping auger; slush; slush production.

1.0 INTRODUCTION

Liquid-solid mixtures (slushes) of hydrogen 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 hydrogen, we must be able to produce it economically, to store and transfer it successfully and to measure stored mass and mass flow rates. This paper reports test results of an auger system used to produce slush hydrogen.

During the late 1960's and early 1970's [1-9] slush hydrogen production, transfer, storage and measurement technologies were investigated. Although other production methods were tried, the freeze-thaw method was the most thoroughly investigated and it was used to produce test quantities of slush hydrogen. The freeze-thaw method of producing slush 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 mass fractions, the pumping-mixing or freeze-thaw cycle must be repeated numerous times. The freeze-thaw method produces small solid particles so that the resulting mixture can be transferred and stored in conventional cryogenic systems.

The freeze-thaw production method is technically feasible and fully developed, however, it has disadvantages. These disadvantages include:

1) The freeze-thaw process is a batch process.
2) The freeze-thaw process operates at the triple point pressure of the cryogen. For hydrogen this pressure is 0.0695 atmospheres absolute, a pressure that draws air through inadvertant leaks in the system. The air can become a safety problem in a hydrogen system.
3) The freeze-thaw process requires either costly equipment to recover the generated triple point vapor or the loss of about 16 percent of the normal boiling point liquid hydrogen if the vapor is simply discarded.
4) The freeze-thaw production process becomes even more difficult to apply to oxygen (another cryogen used in the space program) because the triple point pressure for oxygen is 0.0015 atmospheres; this pressure is nearly 50 times less than the triple point pressure of hydrogen.

In this study an auger that scraped frozen solid from the inside of a refrigerated brass tube was used to produce slush hydrogen. The auger system can continuously produce slush hydrogen 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 hydrogen. The auger system produced particles in the size realm of the particles produced by the freeze-thaw method so that the auger produced slush can be readily transferred and stored.

The surface freezing occurring in the freeze-thaw production process is thermodynamically reversible. In contrast, the freezing process in the auger is irreversible since a temperature difference must exist between the refrigerant and the freezing cryogen, and work energy added to scrape the solid cryogen out of the brass tube must be removed by the refrigerant. In spite of these irreversibilities, the auger system required less energy to produce a quantity of slush hydrogen than a practical freeze-thaw system. The temperature difference requires refrigeration temperatures below the triple point temperature of hydrogen so a gaseous or liquid helium refrigerator is required for the auger. In the experiment described here, liquid helium was used as the refrigerant.

The auger production method was initially based on the technology of the commercial shaved water-ice maker. However, during this investigation two patents describing an auger for making slush hydrogen were discovered [10,11]. The description in the patents confirmed the general conclusions of this investigation.

2.0 DESCRIPTION OF THE AUGER

A cross section of the auger and heat exchanger assembly used to produce slush hydrogen 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 the brass tube, the radial clearance decreases to 0.0127 cm (0.005 in) at the operating temperature. Since solid hydrogen has a low thermal conductivity, this annular clearance should be small to produce 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 eliminates heat transfer to the exterior surface. Vacuum insulated refrigerant lines are provided at the top and bottom of the heat exchanger.

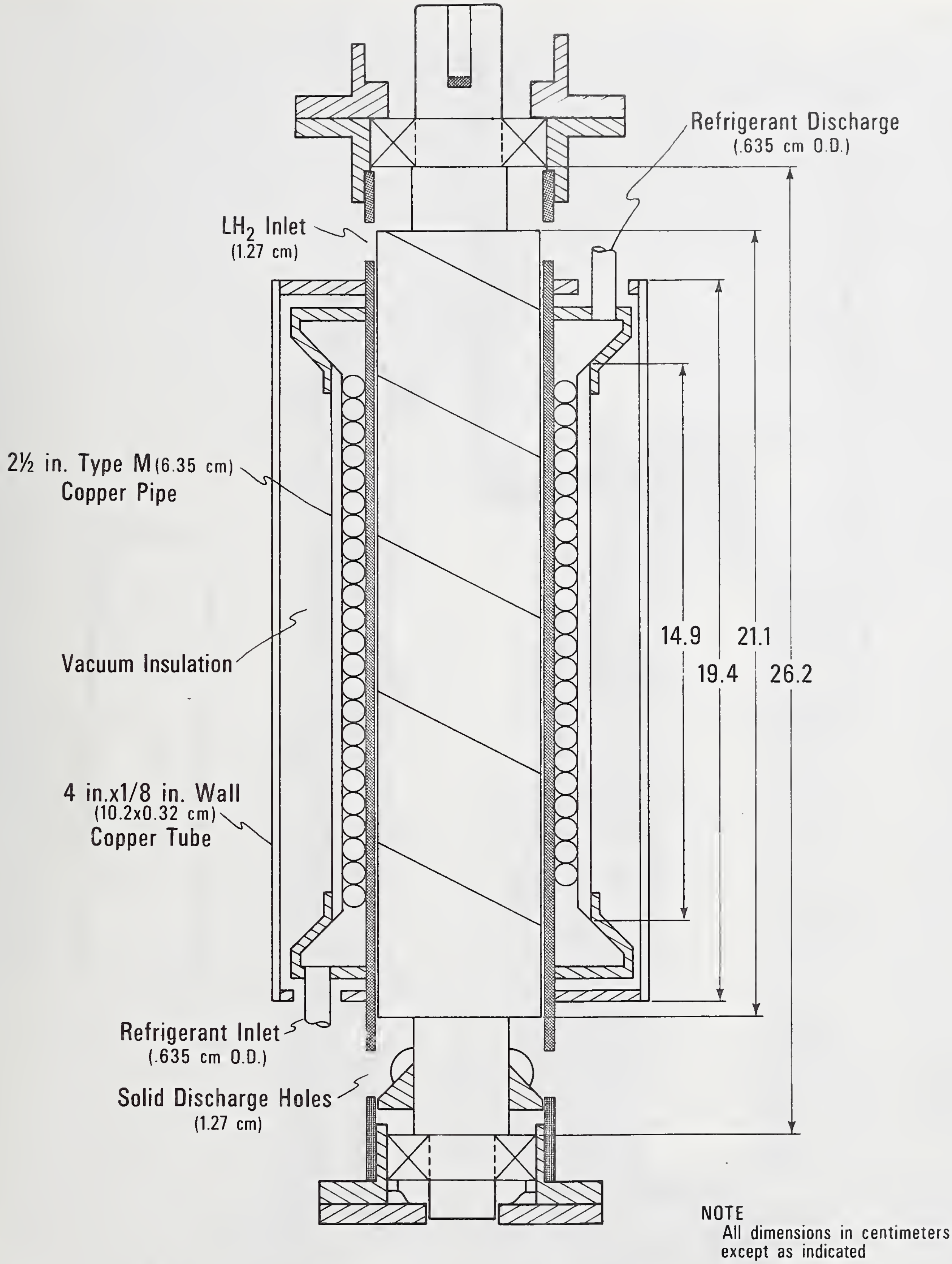

Figure 1. Cross section of auger and heat exchanger assembly.

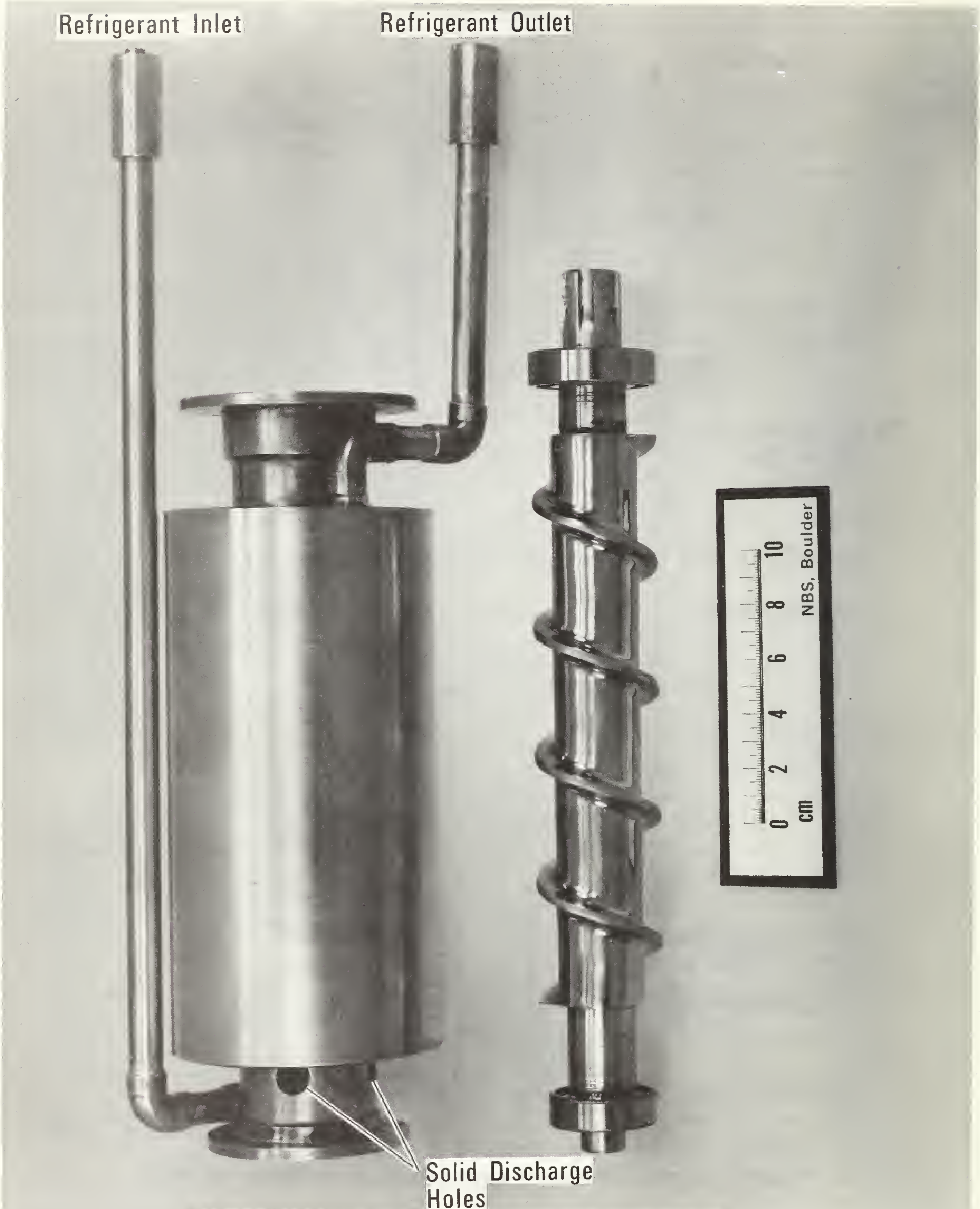

Figure 2. Partially disassembled auger unit.

The auger assembly was 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 rotating shaft seal using 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.

During operation the auger assembly is immersed in the liquid to be frozen and liquid is drawn into the holes hear the top of the brass tube and frozen hydrogen particles are discharged through holes near the bottom. In some of the tests with hydrogen, the bottom support bearing was removed to allow the solid particles to discharge from the bottom of the brass tube. Solid particle size was not affected by this alteration, but auger torque with no freezing (tare torque) was reduced significantly.

The instrumentation used with the auger system measured the refrigerant inlet and outlet temperatures, 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. Clear glass dewars were used to contain the auger system so that the slush production could be viewed and photographed.

3.0 RESULTS OF TESTS PRODUCING SLUSH HYDROGEN 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 hydrogen could be stored and transferred easily. As a secondary result the auger power requirements at various rotational speeds versus refrigeration supplied to the auger were measured to obtain an efficiency figure that could be compared to the efficiency of the freeze-thaw production method. Also, the slush was held in the settled condition for approximately 3 hours to determine if particle size changed with age.

Figure 3 shows freshly produced solid particles floating past a 2 mm square grid (the grid and shovel used to move the slush is shown in figure 4). The fresh slush particles are random in size varying from approximately 0.1 mm to 8 mm in the largest dimension. The particle size for freeze-thaw produced slush has been extensively measured [9] and the sizes of both fresh and aged particles varied from 0.5 to 10 mm with 2 mm being the most common size. The particles produced by the auger appear smaller; however, a much more extensive measuring program than conducted during these tests is necessary to determine the actual size distribution. Aged auger produced slush particles, figure 5, appear to have about the same size distribution as the fresh particles although they are now more rounded and have a clearer texture.

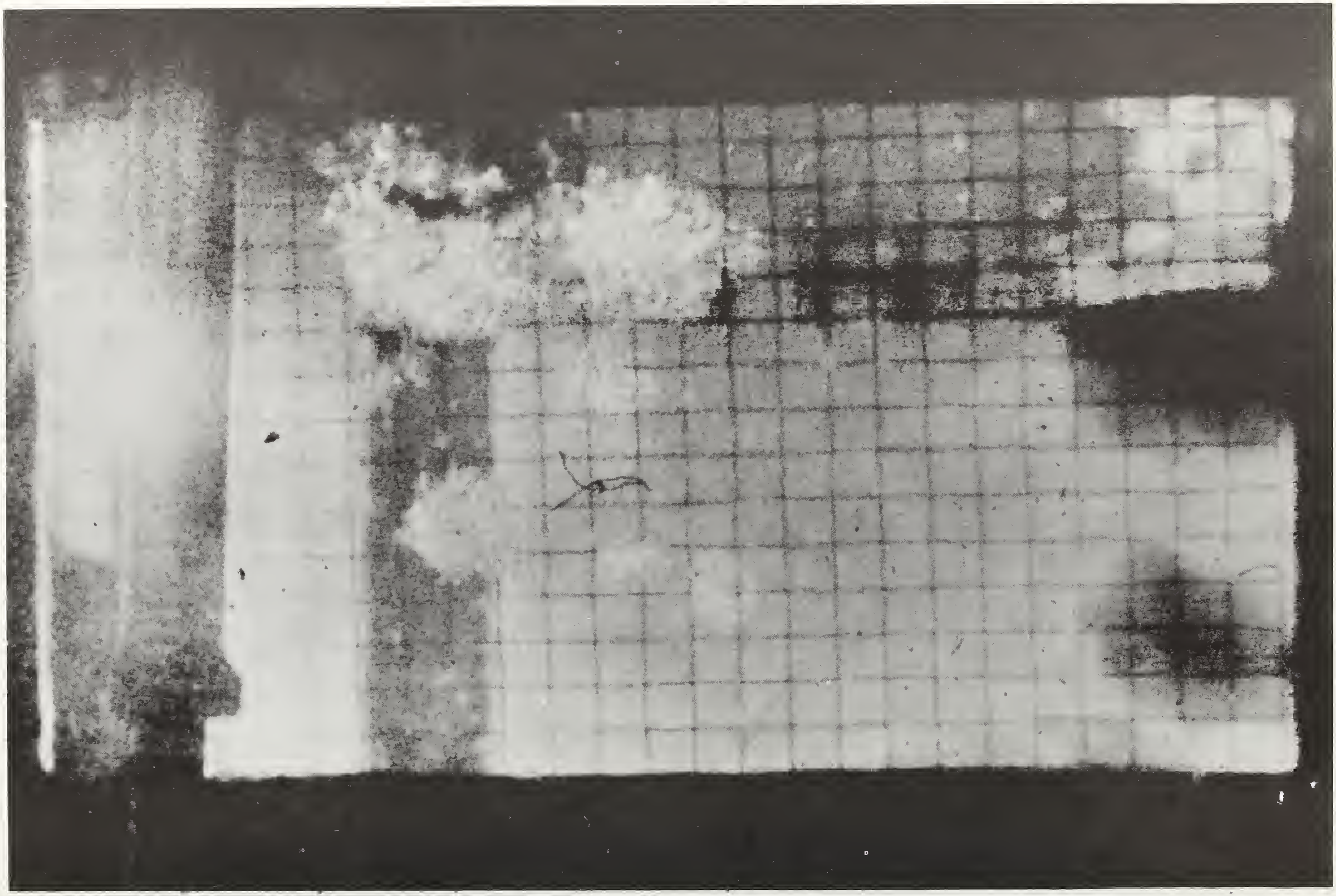

Figure 3. Fresh solid hydrogen particles photographed in front of a 2 mm square grid.

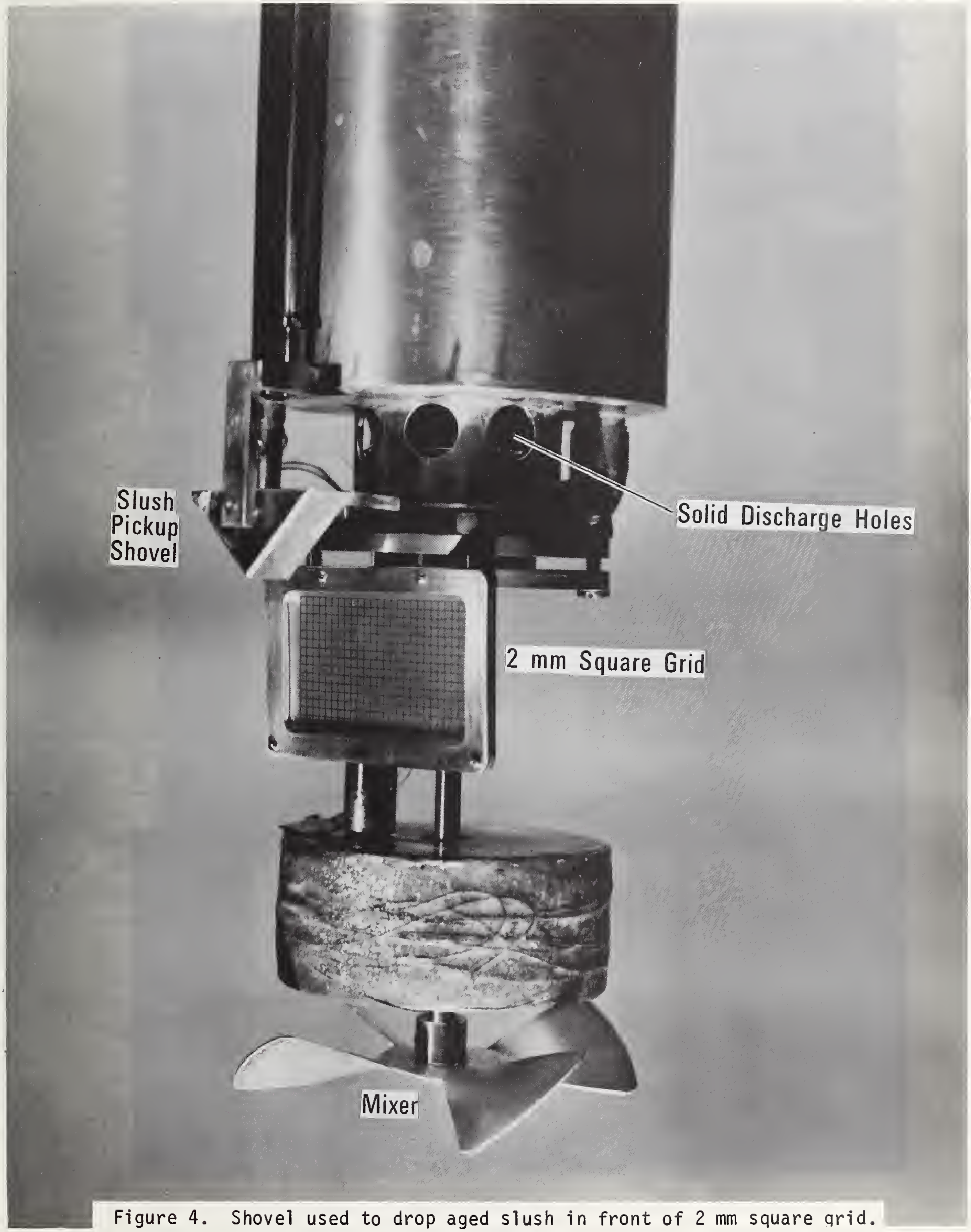

Figure 4. Shovel used to drop aged slush in front of 2 mm square grid.

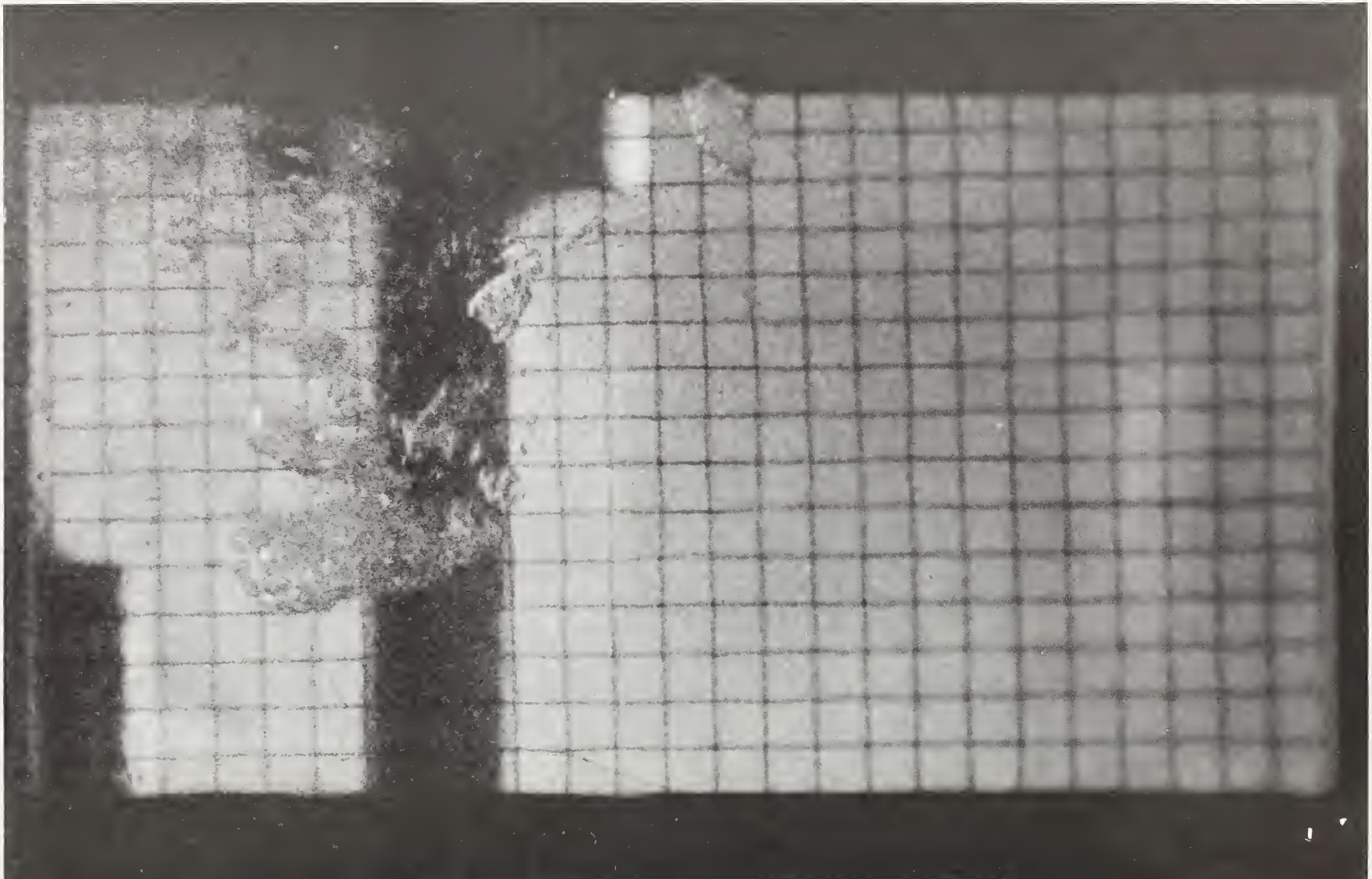

Figure 5. Slush particles about 3 hours old.

One would expect the particles produced by the auger to be curved to the same radius as the auger and not be the fine particles shown in figures 3 and 5. Actually the first particles produced from the auger are curved and quite large. But as the solid production rate increases (due to cooldown of the liquid hydrogen to triple point temperature) the curved needle shaped particles disappeared and the small particles shown in figure 3 were produced. This freezing phenomena is not understood, but the particles produced by the auger do become acceptably small during steady state operation.

The power required to rotate the auger is based on the torque and rotational speed measurements. During early tests when the bottom auger support bearing was in place, the rotational power increased with auger operating time. This increasing power with time was a result of clear solid hydrogen closing the solid discharge holes at the bottom of the auger assembly. As the hole size decreased the power required to extrude the solid increased. This problem was solved by removing the bottom bearing thereby increasing the solid discharge area. Without the bearing the solid could fall from the bottom of the auger assembly and the discharge holes were no longer necessary. Removing the bottom bearing also decreased the no freezing torque requirements (tare torque). Reducing the tare torque increased the amount of refrigeration available to freeze the hydrogen. The tare power (P_T) at 1.57 rad/s rotational speed decreased from 0.565 W with the bottom bearing in place to 0.282 W without the bearing. Tare torque is constant so that the tare power is directly proportional to rotational speed.

Scraping torque (the torque required by the auger to scrape off the solid hydrogen) is also nearly constant for a constant refrigeration rate to the auger. The constant torque is apparently due to a scraping force that does not depend on the thickness of the solid layer being removed. The constant torque measurement must be qualified however because theoretically the scraping power is now directly proportional to rotational speed and the scraping power approaches zero as the rotational speed approaches zero. In actual tests the torque would remain constant as the auger rotational speed was reduced until the auger would suddenly stop (freeze in place) with the torque increasing to a very high value.

The scraping torque does increase, however, as the refrigeration to the auger increases. This increase in scraping torque reflects the increased area over which solid hydrogen is formed. Since liquid helium is the refrigerant, heat is rapidly removed at the refrigerant inlet near the bottom of the auger because of a high helium boiling heat transfer coefficient and a relatively large temperature difference. Above the liquid helium level in the refrigerant heat exchanger, gas velocities are quite low so that the heat transfer coefficient is low and the temperature difference is also decreasing. Thus, at low refrigeration levels the liquid helium level in the heat exchanger is low and the area where the majority of the solid hydrogen is formed is low. As the refrigeration level is increased due to increased liquid helium supply flow, the liquid helium level in the heat exchanger rises increasing the area where frozen hydrogen accumulates. The increased area of freezing hydrogen requires an increased scraping torque.

Figure 6 shows the scraping power as a function of the refrigeration supplied to the auger assembly. The points shown are the experimental points taken at 1.57 rad/s or experimental points adjusted by direct proportion from a slower or faster rotational speed to 1.57 rad/s. The straight line is a hand fit of the data and is expressed by

$$P_s = 0.015 \, (P_R), \tag{1}$$

where P_s is the scraping power at a rotational speed of 1.57 rad/s in Watts, and P_R is the refrigeration supplied to the auger assembly in Watts.

The total power required to rotate the auger is the sum of the tare power and the scraping power. Since this power is proportional to the rotational speed this power can be expressed as

$$P_a = R/1.57 \, (P_s + P_T) \tag{2}$$

where

P_a = total auger power requirement, W

R = auger rotational speed, Rad/s

P_s = auger scraping power at a rotational speed of 1.57 rad/s (equation 1), W

and P_T = auger tare power at a rotational speed of 1.57 rad/s, W.

By substituting P_s from (1) and the tare power with the bottom bearing removed (0.282 W) while using 1.57 rad/s for R results in

$$P_a = 0.015 \, P_R + 0.282 \tag{3}$$

4.0 ENERGY REQUIRED TO PRODUCE SLUSH HYDROGEN

Producing slush appears to be a reasonable way of increasing the density and heat capacity of hydrogen, however, the cost of producing the slush must be acceptable. When large quantities of slush are produced, the cost of the energy required to produce the slush becomes significant. The production energy depends on the thermodynamic reversible energy requirements to produce slush and the energy required to overcome irrversibilities in a practical system. In this section the energy required to produce slush with a 0.5 solid mass fraction is determined for four practical slush producing systems. Three of the systems use the freeze-thaw production method and the fourth uses an auger and helium refrigerator to produce slush from normal boiling point liquid hydrogen.

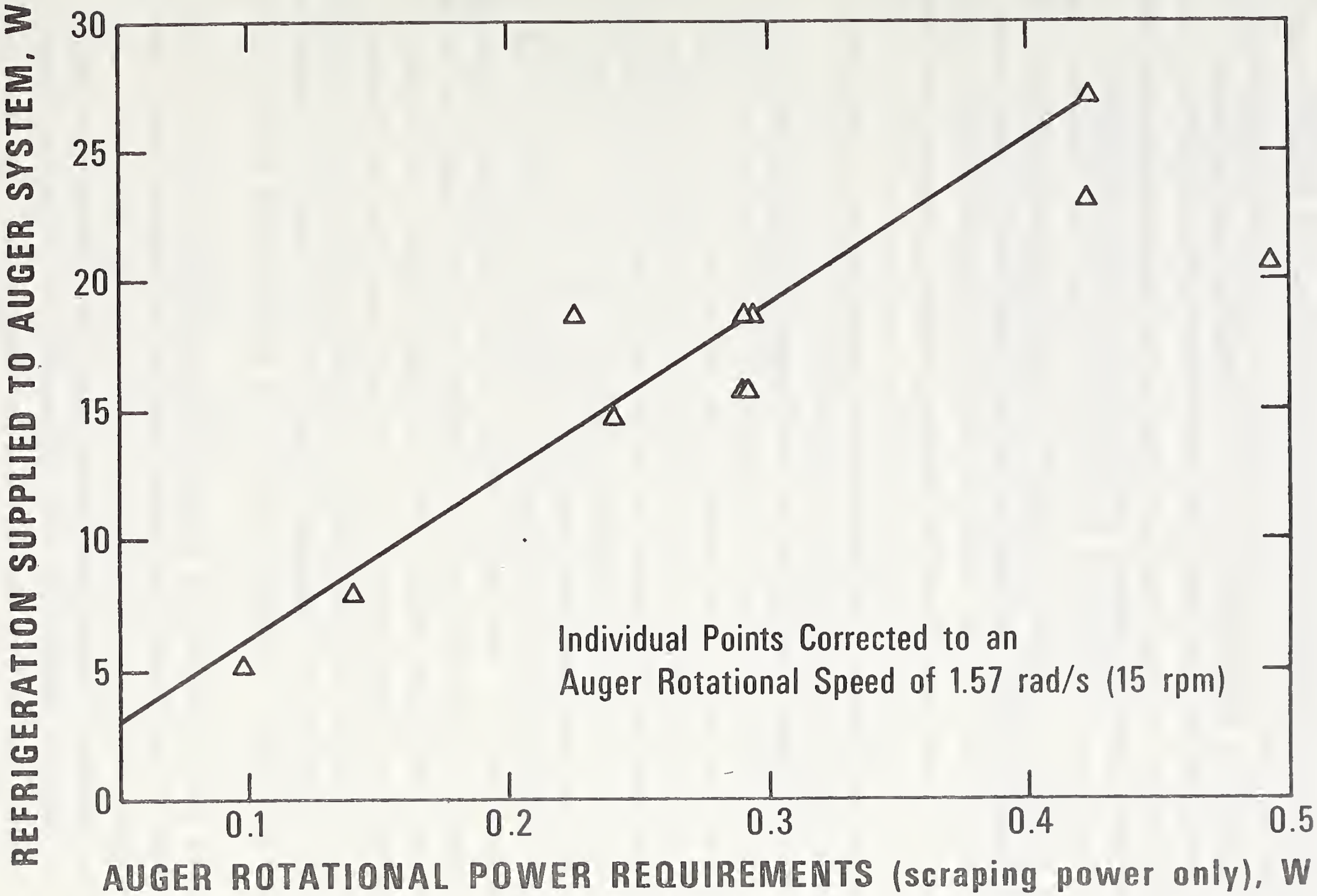

Figure 6. Scraping power required by the auger to produce slush hydrogen.

The thermodynamic reversible energy required to produce slush is equal to the thermodynamic availability of the slush. Using normal hydrogen at a temperature of 300 K and a pressure of one atmosphere as the base fluid, the reversible energy required to produce normal boiling point parahydrogen is 3971.4 W-hr/kg, and the reversible energy required to produce slush with a solid mass fraction of 0.5 is 4372.8 W-hr/kg. The energy required by practical systems is higher because of the component inefficiencies. The calculated energies for the four cases are based on liquefier and refrigerator efficiencies of 40 percent of Carnot. The vacuum pumps required by the freeze-thaw production method are assumed to have an efficiency of 50 percent of isothermal. Heat leak into the containers and transfer lines would also increase the required energy but these increases have not been included because they are difficult to calculate without a firm system definition and because, to at least the first approximations, the heat leak would be nearly equal for all of the systems studied. Because heat leak is not included, the calculated energies for the four cases will be lower than those of an actual system, but, the calculations do allow a comparison between the various slush production systems.

Besides the higher energy due to inefficient liquefiers and refrigerators in the system, the auger introduces additional irreversibilities because of the rotational power added to the slush generator, and the temperature difference between the refrigerant and freezing hydrogen. The ratio of total supplied refrigeration to the refrigeration available for freezing hydrogen in the auger system varies from 1.15 at low refrigeration rates to 1.015 for very high refrigeration rates (eq (3)). A ratio of 1.05 will be used to determine the refrigeration required to produce slush with a solid fraction of 0.5. The input energy to the refrigerator connected to the auger depends on the refrigeration temperature; the lower the temperature the higher the input energy. For the auger system, we assumed the lowest refrigeration temperature to be 10 K and since the refrigerator is also cooling the normal boiling liquid to triple point liquid, the highest refrigeration temperature is assumed to be 19.76 K. These refrigeration temperatures are within the capabilities of a closed cycle helium refrigerator.

While the power required to produce slush hydrogen using the auger is relatively easy to calculate, the power required to produce slush hydrogen using the freeze-thaw production method is very system dependent. For instance, the simplest freeze-thaw method vents the hydrogen gas after warming it to ambient temperature and compressing it to ambient pressure. Much more complex freeze-thaw systems can be visualized. The most complex system uses the refrigeration available in the vapor to precool a reliquefier. In table 1 five cases used to calculate power requirements are defined,

Table 1. Description of cases.

CASE 1	Hydrogen liquefier produces sufficient NBP liquid so one kilogram remains after the slush hydrogen is produced by the freeze-thaw method. The vapor removed during slush production is vented.
CASE 2	Hydrogen liquefier produces the NBP liquid. Slush is produced by the freeze-thaw method. Vapor removed during production is warmed, pumped to ambient pressure and then reliquefied.
CASE 3	Hydrogen liquefier produces the NBP liquid. Slush is produced by the freeze-thaw method. Vapor removed during production enters a liquefier as a cold gas and is reliquefied.
CASE 4	Hydrogen liquefier produces the NBP liquid. Slush is produced using a helium refrigerator and the auger. Refrigerator temperatures are between 19.76 and 13.303 K to produce triple point liquid and between 13.7 and 10 K to produce the slush.
CASE 5	Hydrogen liquefier produces the NBP liquid.

Liquefier efficiency = refrigerator efficiency = 40 percent of Carnot for all cases.

Vacuum pump efficiency = 50 percent of isothermal.

and table 2 shows the calculated energy required to produce one kilogram of slush hydrogen with a solid fraction of 0.5 for four cases compared to the energy required to produce normal boiling point liquid. The first three cases employ the freeze-thaw production method, the fourth case employs the auger production method, and the fifth case shows the power necessary to produce NBP liquid. Producing NBP liquid (Case 5) requires the least amount of energy but for only 11.7 percent more energy slush hydrogen with a 0.5 solid fraction can be produced using the auger. Case 1, the simplest freeze-thaw production system, requires the most energy and loses 0.19 kilogram of gaseous feed hydrogen for every kilogram of slush produced. The most energy economical freeze-thaw production system (Case 3) requires 516.4 W-hr/kg more energy than required by the auger method of producing slush. Case 3 would require a significant investment in slush generators and transfer equipment to achieve the energy economics while Case 1 and Case 4 would require the least capital for auxiliary equipment.

5.0 CONCLUSIONS

The auger successfully produces slush hydrogen with sufficiently small particles, so that the slush can be stored and transferred in cryogenic systems. Aging characteristics of the auger formed slush appear to be similar to the aging characteristics discovered for freeze-thaw produced slush. The energy required to produce 0.5 solid mass fraction slush is only 1.12 x the energy required to produce normal boiling point liquid hydrogen. This increase in energy input increases the density of hydrogen by 15.5 percent and the heat capacity by 18.3 percent when compared to normal boiling point liquid. Even though the auger system has some irreversibilities associated with the freezing and scraping processes, the overall evergy required to produce slush using the auger and a helium cycle refrigerator is less than the energy required by the freeze-thaw production method.

The auger method of producing slush eliminates many of the problems associated with the freeze-thaw production method. The auger can produce slush continuously versus the batch freeze-thaw process, and it can produce slush at raised pressures eliminating the air-intrusion safety problems associated with the production of slush hydrogen in the freeze-thaw production process.

Table 2. Energy required to produce one kilogram of 0.5 mass fraction slush hydrogen using four different systems

		Amount of Hydrogen Involved kg	Power to Produce W-hr/(kg of fluid)	Power to Produce Slush/ Power to Produce NBP Liquid
CASE 1	Freeze-thaw			
	Hydrogen liquefier energy	1.19	11,814.9	
	Vacuum pump energy	-.19	349.5	
	Total delivered	1.0	12,164.4	1.225
CASE 2	Freeze-thaw			
	Hydrogen liquefier energy	1.0	9,928.5	
	Vacuum pump energy	-.19	349.5	
	Reliquefier energy	+.19	1,886.4	
	Total delivered	1.0	12,164.4	1.225
CASE 3	Freeze-thaw			
	Hydrogen liquefier energy	1.0	9,928.5	
	Vacuum pump energy	-.19	349.5	
	Reliquefier energy	+.19	1,323.9	
	Total delivered	1.0	11,601.9	1.170
CASE 4	Auger			
	Hydrogen liquefier energy	1.0	9,928.5	
	Helium refrigeration energy		1,157.0	
	Total delivered	1.0	11,085.5	1.117
CASE 5	Normal Boiling Point Liquid			
	Hydrogen liquefier energy	1.0	9,928.5	
	Total delivered	1.0	9,928.5	1.000

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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.)*

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

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; production efficiency; scraping auger; slush; slush production.

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