NBSIR 73-344

HEAT TRANSFER AND MIXING OF SLUSH HYDROGEN

C. F. Sindt
P. R. Ludtke

Cryogenics Division
Institute for Basic Standards
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Heat Transfer and Mixing of Slush Hydrogen*

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Heat transfer to slush hydrogen and mixing were investigated in a 1 m^3 cylindrical vessel. The effects of heat transfer rates on thermal stratification and on self-pressurization were measured. Temperature profiles in thermal stratification were found to be more dependent on slush level and slush settling rates than on liquid level. Solids in the slush appear to be involved in the heat transfer mechanism as slush level affected the amount of warm liquid reaching the top of the dewar and therefore affected the self-pressurization rates.

Mixing effectiveness and power requirements to mix slush hydrogen were determined for two configurations of turbine mixers and one paddle mixer. Mixing power requirements were found to be sensitive to the mixer location and configuration.

Key words: Heat transfer; liquid hydrogen; mixing; mixing power; paddle mixers; slush hydrogen; turbine mixers.

1. Introduction

Liquid and slush hydrogen are the selected propellants for current and future space exploration rockets and more recently have become of great interest as fuel for the aircraft industry because of impending shortages of hydrocarbon fuels. Slush hydrogen has the advantage over liquid hydrogen of additional heat capacity and greater density. Slush hydrogen characterization studies have been conducted at the Cryogenics Division of NBS over the past decade. These studies have included preparation, flow, pumping, aging, solid particle configuration, and instrumentation of slush hydrogen.

Characteristics that have not been extensively investigated but are required to get maximum benefits from the increased heat capacity are heat transfer and mixing. Heat transfer and mixing investigations to date have been very limited in scope. Basic heat transfer to slush has been previously measured in a small scale laboratory apparatus as phase I of this program and was reported by C. Sindt [1972, 1973]. The objective of this phase of the program was to determine larger scale heat transfer characteristics, thermal stratification, and mixing energy requirements.

* This research was performed under NASA Contract No. W13300.

2. Experimental Apparatus

The experimental apparatus consisted of two vacuum insulated vessels. One vessel of 0.4 m^3 capacity was used as a slush generator. The second vessel of approximately 1 m^3 capacity was the experimental vessel. This vessel was cylindrical and was 0.76 m in diameter and 2.34 m deep. It was vacuum insulated at the bottom and side walls. The inner wall of this dewar was 0.9 mm thick stainless steel. These thin stainless steel walls were well suited to allow thermal stratification in the liquid. The top cover was a 25.4 mm thick stainless steel flat plate. The top plate had two 110-mm-diameter windows--one for lighting, the other for visual observation. Also included in the top plate was a 230-mm-diameter access hole. The access hole cover plate was used as a mounting base for an experimental mixer drive. The mixer drive and the mixer instrumentation were mounted externally on the access cover. The mixer was suspended on a driving shaft.

Thermal insulation for the top plate of the experimental vessel consisted of a 75-mm-thick layer of high density polystyrene foam, which was suspended below the top plate on three 1/4-inch bolts, and a radiation shield suspended at 25 mm below the foam on three separate 1/4-inch bolts. The radiation shield was chromium plated stainless steel. Incorporated in the shield were two hinged, closable doors to cover the window areas. The radiation shield had 13 mm radial clearance. With this arrangement the vent gas passed around the outside edge of the shield and flowed across the shield to the vent which was located near the center of the top plate. The vent gas, therefore, helped to cool the shield.

Liquid hydrogen for the experiments was provided from a portable dewar. This dewar was connected to the generator and the experimental

dewar with a vacuum insulated transfer line. The transfer line was also used to transfer slush from the generator to the experimental dewar.

In the process of filling the experimental dewar with slush, several batches of slush were made in the generator. These were transferred to the experimental dewar; then the excess liquid over the settled slush was back transferred to the generator to be used in preparation of the next batch. This process required two transfer lines and valves into the experimental dewar, one for transferring slush into the dewar and one for back transferring liquid. Both lines connected to the main transfer line outside the dewar; both extended to near the dewar bottom and were vacuum insulated to near the end. The liquid return line was enlarged at the end and covered with a 30 mesh[1] screen to prevent back transfer of the solid hydrogen particles. Upgrading techniques and slush production reported by Sindt and Ludtke [1970] were developed in this system which is shown in figure 1.

2.1 Heat Transfer System

Temperature controlled thermal radiation heaters were used to get uniform heat transfer to the thin stainless steel walls of the experimental dewar. The heaters consisted of a cylinder and a dished head to cover the dewar bottom and were 25 mm in diameter larger than the experimental vessel. The two sections were thermally insulated from each other, as the lower head was suspended by four 16 mm by 3.2 mm tetrafluoroethylene straps. The radiation heaters were both 1 mm thick copper plate. They were heated to the desired temperature electrically. The heaters are shown in figure 2.

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[1] A 30 mesh screen has 0.59 mm square openings.

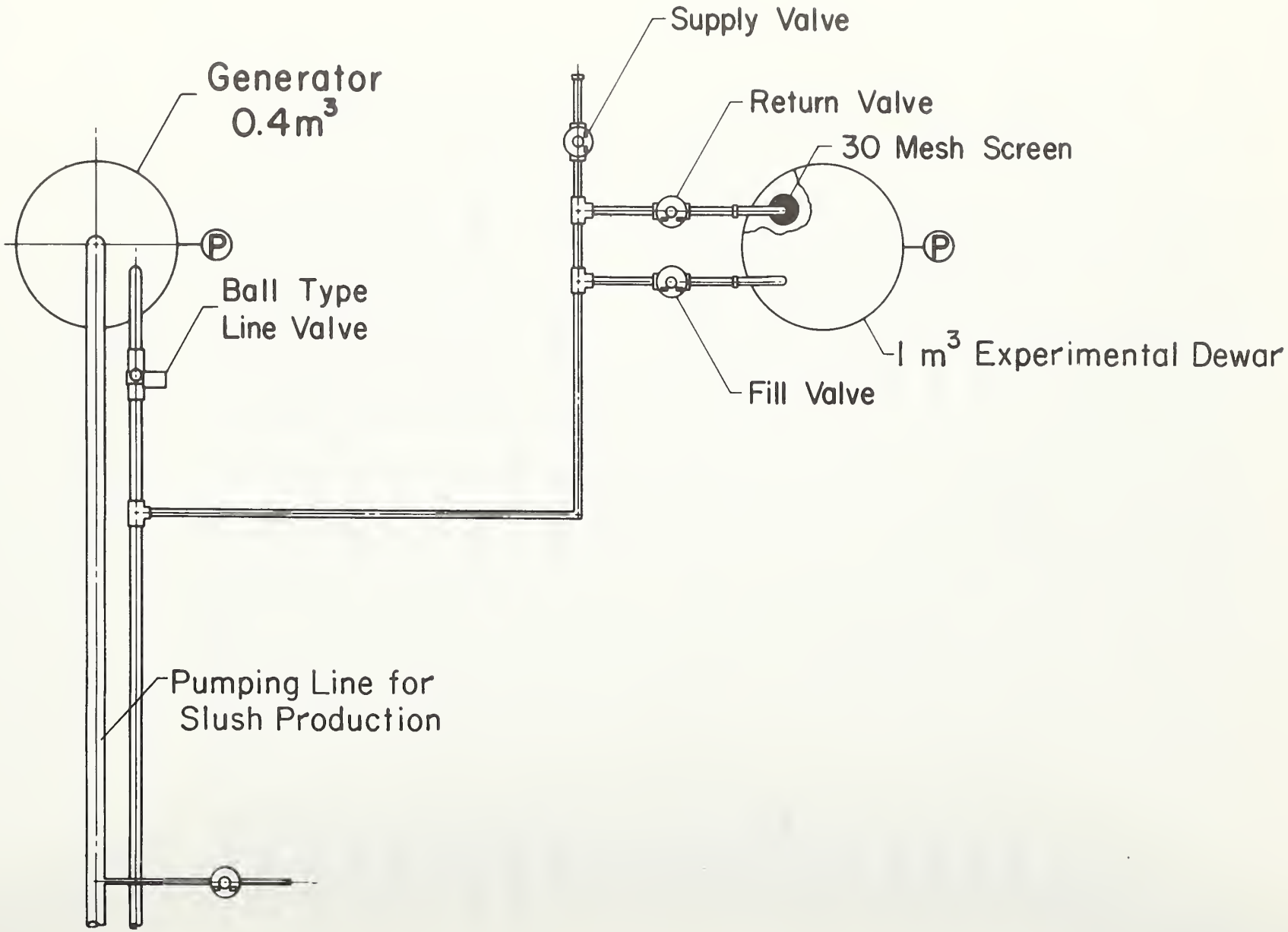

Figure 1. Schematic of experimental system.

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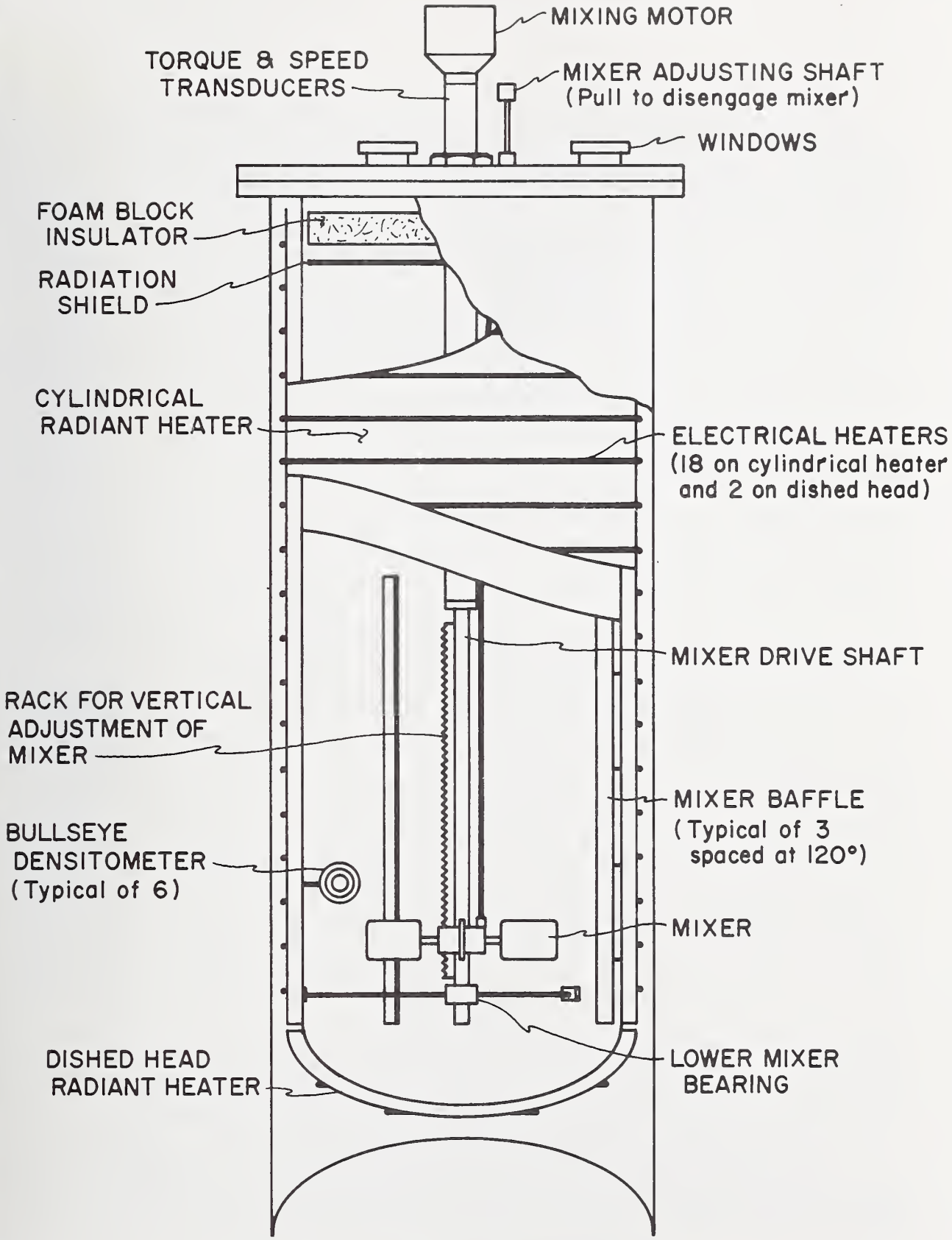

Figure 2. Experimental dewar schematic.

Electrical resistance units were applied to the heaters using a filled epoxy. They were spaced approximately 130 mm apart and were wrapped around the cylinder and laid in a spiral on the dished head. The electrical connections were made so that the cylindrical heater was heated by three separate circuits and the dished head by one circuit. Type T thermocouples were mounted on the copper between heating units and in the epoxy at the units. These thermocouples, which were referenced to an ice bath, were used for temperature control of the radiation heaters.

To reduce heat transfer from the outer shell to the radiation heaters, the heaters were wrapped on the outer surface with one sheet of aluminum foil after they were assembled and instrumented. To increase heat transfer from the radiation heaters to the experimental dewar walls, the outer surface of the dewar wall and the inner surface of the radiation heaters were coated with a "velvet textured" black paint which is commercially prepared for improving radiant heat transfer [ASTM, 1973].

The actual heat transfer by the radiation heaters to the inner vessel was determined in a series of tests conducted prior to the heat transfer tests. The method used to measure total heat transfer to the inner vessel was to measure the amount of liquid hydrogen boiled away at a constant pressure while the temperature of the radiation heaters was controlled at different levels. The temperature of the heaters was easily controlled, and the difference in temperature indicated by thermocouples on the copper walls and thermocouples in the mounting epoxy of the electrical units was less than two K at the maximum heating rate. Therefore, the radiation heaters were assumed to be of constant temperature throughout when all of the thermocouples mounted on the copper gave the same reading.

The mass of liquid that boiled away and the heat of vaporization of the liquid hydrogen at the dewar pressure were used to calculate the total

heat input. The mass was calculated from measurements of the gas volume with a dry gas meter and with a calibrated gas holder. Pressure and temperature of the gas were measured with a manometer and mercury filled thermometer respectively. The manometer accuracy was estimated to be ± 12 Pa. The temperature was estimated to be accurate to ± 0.2 K. The pressure in the vessel was controlled by the back pressure of the gas holder, which was susceptible to ambient pressure changes. Therefore, the barometer was read frequently, and if a change larger than 20 Pa occurred, the data prior to the change was excluded.

Some heat entered the dewar from the top plate. Calculations of the heat transferred to the liquid from the top revealed that the heat flux was less than one percent of the total at the lowest heater temperatures and was therefore considered negligible.

The radiant heaters were calibrated using liquid hydrogen in the experimental vessel. They floated at a temperature of about 110 K with the experimental vessel full of liquid and no electrical energy input.

Data from the calibration of the radiation heaters were reduced to the form of heat transfer per unit area versus the radiation heater temperature. Two sets of data were taken, one with the bottom heater on, the other with the bottom heater off. These data are in agreement and are shown in figure 3 with the calibration curve that was used for all of the slush heat transfer data reduction.

2.2 The Mixer

The mixer was supported and driven from a shaft through the access plate as previously noted. The mixer was driven with an air motor capable of delivering 2050 watts at 304 rad/s (2900 rpm). A gear reduction unit was installed on the motor for the last group of tests. The maximum power of 2050 watts was then produced at 75 rad/s (720 rpm).

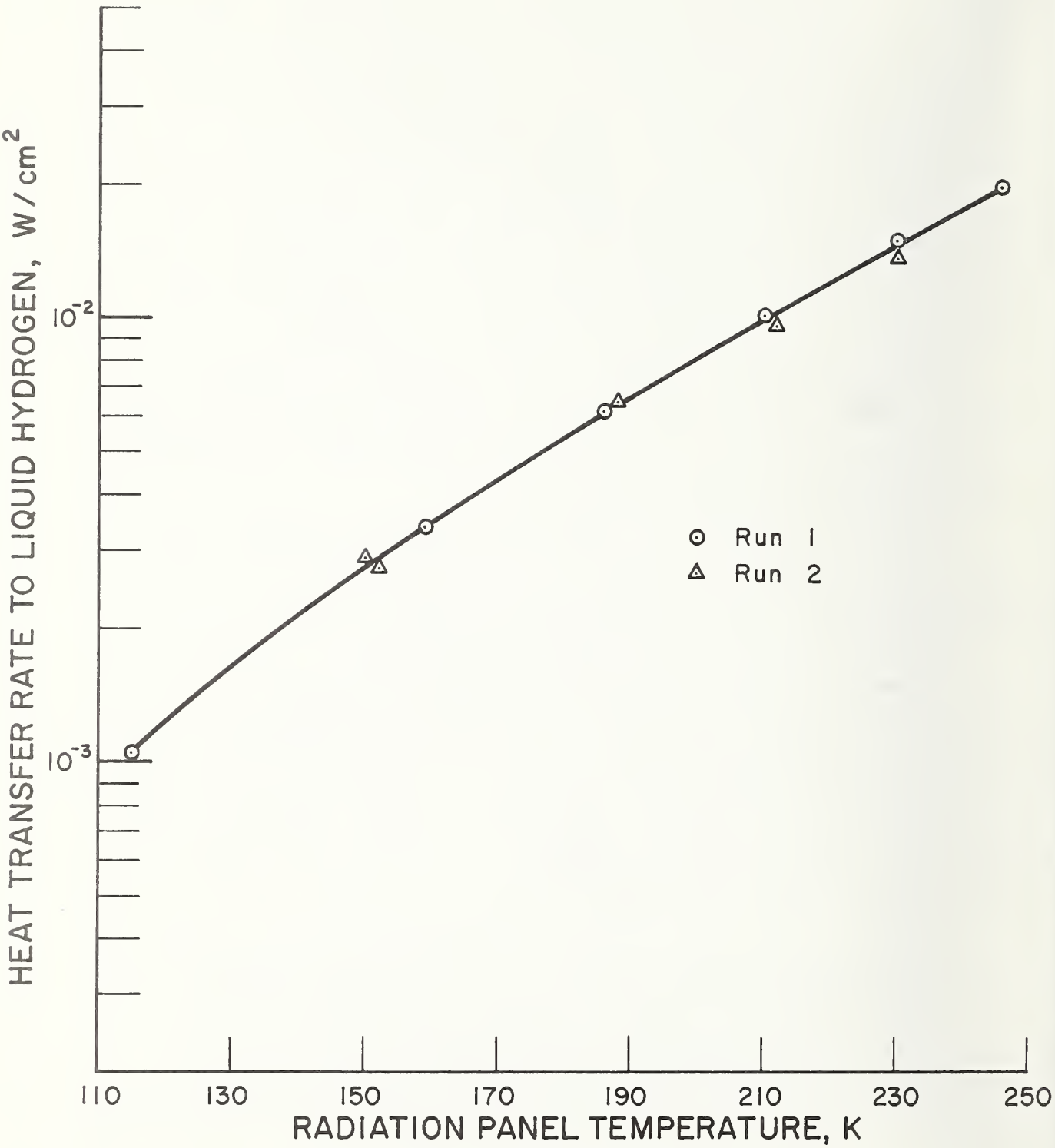

Figure 3. Heat transfer rate from the radiation panel.

A torque meter and speed sensor were mounted in the shaft above a hermetic seal that was mounted in the access plate. The hermetic seal was a commercially available unit that seals with magnetically controlled fluid suspension of ferrous particles held between the rotating element and the stationary element.

The mixer shaft extended to the bottom of the dewar where it was supported radially by a bottom mounted bearing. A concentric tube extended down from the access plate around the shaft for 1.52 m and had two bearings to provide more radial support and prevent shaft whip. The mixer was mounted on the shaft in such a way as to allow vertical adjustment using a rack and pinion gear. The adjustment was from 0.22 m to 0.82 m off the dewar bottom. The mixing head also contained gearing to allow adjustment of the mixer blade angle through 180 degrees of rotation. The two adjustments were made with a rod supported from the top plate, and adjustments could be made at any time that the mixer was stopped and the slush level was below the mixer such that the operation could be observed through the view port. Figure 4 shows the mixer with the blades set at 45°.

The blades selected were 100 mm long by 76 mm wide and rectangular. The center hub was 84 mm square and 64 mm thick. The mixer was 305 mm in overall diameter and had four blades. The diameter is larger than recommended for turbine mixing of low viscosity fluids [Uhl 1966]; however, the hub of the mixer is large because of the adjusting features. The large hub resulted in shorter blades for the same diameter, and considering the actual blade length, the blade diameter to vessel diameter ratio was 0.26 which is about that recommended. With the blades set at an angle of 45°, the mixer is an axial flow turbine, and with the blades set at 90°, the mixer is a paddle or a radial flow turbine. From the review of mixing as reported by McConnell[1971], these mixers are two of the more preferred mixers for mixing slush hydrogen in a one "g" environment.

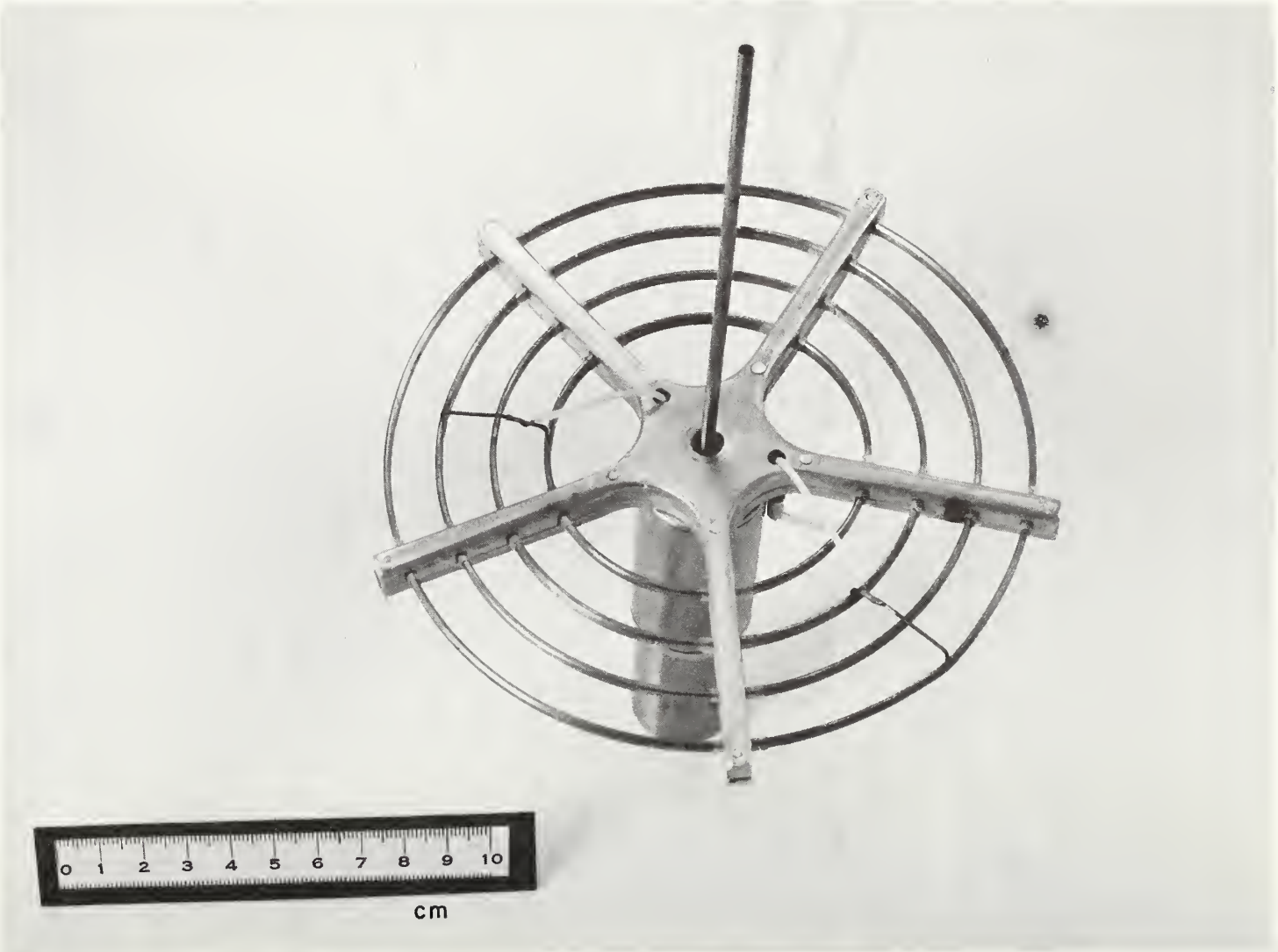

Figure 4. Slush mixer.

Mixing in low viscosity fluids requires baffling. Three equally spaced baffles 76 mm wide were mounted 15 mm from the dewar walls. The baffles extended the full length of the used dewar volume. The width of 76 mm satisfied the recommended ratio of one-to-ten for baffle width to vessel diameter in low viscosity fluids [Uhl, 1966].

3. Instrumentation

All of the data for the heat transfer and the mixing experiments were recorded using an automatic data acquisition system (ADAS) with a 56 channel input multiplexer. The ADAS output was recorded on magnetic tape which was then processed in a large computer for final data reduction.

3.1 Heat Transfer Instrumentation

One vertical and three radial thermocouple rakes were mounted in the experimental dewar. The radial rakes had eight thermocouples spaced at 1, 3, 6, 10, 40, 100, 200, and 380 mm from the dewar wall. They were located at 0.55, 1.27, and 1.73 m from the dewar bottom. The first of 10 thermocouples on the vertical rake was 1.38 m from the bottom. The 10 thermocouples were spaced 50 mm apart and were 200 mm from the dewar wall. All of the thermocouples were copper vs gold (0.07 atomic percent iron) and were referenced to the thermocouple located at 0.55 m from the bottom and 100 mm from the dewar wall. This reference thermocouple was attached to a calibrated carbon resistance thermometer. The outputs from the thermocouples were amplified 1000 times, then fed to the ADAS. The resistance thermometer used 20 μa constant current, and the voltage across the thermometer was measured directly by the ADAS.

It was not necessary to use the output of the resistance thermometer for the tests since the reference thermocouple was always surrounded by slush and therefore was always at triple-point temperature, 13.80 K.

Thermocouples were also mounted on the outside wall of the dewar inner vessel. Because the ADAS would not accept a grounded input, the decision was made to electrically isolate these thermocouples from the dewar. They subsequently failed and dewar wall temperatures were not available for data reduction.

The estimated error of the thermocouple measurement based on the output of thermocouples always surrounded by slush hydrogen is ± 0.25 K accuracy and ± 0.1 K precision with the largest single contribution to uncertainty in precision being the drift in the amplifiers. The drift of the amplifier in two hours was equivalent to ± 0.05 K; however, the day-to-day drift was twice as large. Since the reference thermocouple and the resistance thermometer were always in slush, these temperatures were always assumed to be 13.803 K [Roder, 1965]. Based on this assumption, the resistance thermometer and the associated electronics, which did not include an amplifier, indicated a maximum uncertainty of ± 0.05 K over the entire test program of more than a month duration.

Pressure in the experimental vessel was measured with a variable reluctance type of pressure transducer which was calibrated using a mercury manometer. The transducer was referenced to vacuum. The mercury manometer used for calibration was readable to ± 40 Pa, and the pressure transducer was linear and repeatable to ± 0.25 percent of the used range, or ± 250 Pa. Therefore, the pressure measurements are estimated to be accurate and precise to ± 290 Pa.

3.2 Mixer Instrumentation

The mixer torque, speed, position and blade angle were measured. The torque was measured with a torque meter which used a torsion

member with a photoelectric sensing device for determining the torsion member displacement. The meter was calibrated prior to the test program. The estimated accuracy of the torque meter from the manufacturers specification is ± 0.06 Nm.

The mixer speed was measured with an inductance pick up which was converted to volts dc using a frequency to voltage converter. Frequent calibration of this system indicated a maximum drift of ± 1 percent at frequencies near those produced by the pick up at mixing speeds. This translates into uncertainty in power measurement of 5% at low power (30 watts) to 2% at powers near 600 watts.

The mixer position was measured with a steel tape measure prior to running the tests. Blade angle was determined from the number of turns made on the adjusting gear train. Neither of these measurements was considered critical, so no precise method of measurement was devised.

Six slush densitometers were installed in the dewar to assist in determining the effectiveness of the mixer. These densitometers used capacitance as the measurement method and were bullseye in shape. A typical capacitance measurement densitometer is shown in figure 5. The densitometers were located at 0.36, 0.43, 0.71, 1.12, 1.47, and 1.78 meters off the bottom and at 0.1 to 0.18 m from the dewar wall. Four were perpendicular to the wall, one was parallel to the wall, and the top one was parallel to the liquid surface.

The densitometer signal conditioning units were capacitance bridges with circuits to convert capacitance unbalance to a dc voltage. This voltage was fed to the ADAS. Stability of the circuits was a problem, and short term drift limited the duration of accurate measurements to less than one hour. This problem precluded their use as

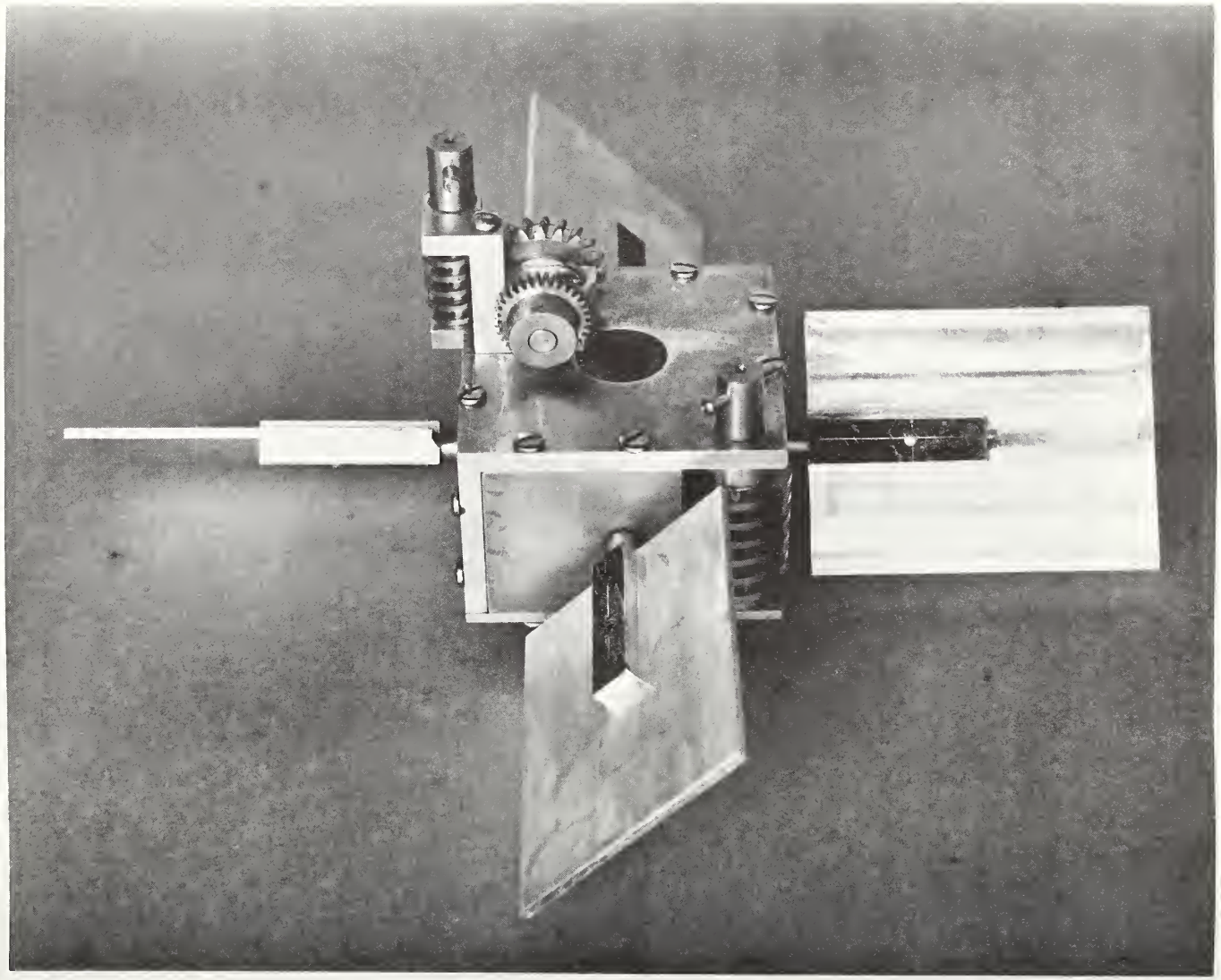

Figure 5. Bullseye capacitance densitometer.

absolute density measuring instruments. However, they proved effective in determining when mixing of the slush was thorough. When the densitometer readings remained relatively stable with increased mixer speed, and visual observation substantiated that mixing was apparent, the mixing was assumed complete. Marginal mixing was evident by large fluctuations in the densitometer signal and was also verified by visual observation of the fluid near the surface and around the top bullseye densitometer.

4. Experimental Procedure

4.1 Heat Transfer Test Procedure

Three types of heat transfer experiments were conducted. They were 1) heat transfer to slush with the dewar pressure starting at triple-point and self-pressurizing to approximately one atmosphere pressure, 2) heat transfer to slush with the dewar pressurized to one atmosphere with warm helium gas immediately after the final slush solid fraction upgrading cycle, and 3) heat transfer to slush with mixing to drop the dewar pressure when it reached 26.7 k Pa. In each experiment slush was made in the generator and transferred to the experimental dewar with warm helium gas as the pressurant. Liquid was returned to the generator through the 30 mesh screen until the liquid level was 100 mm above the settled slush level. Batches of slush were made in the generator and transferred into the experimental dewar until the slush and liquid level was very near the top thermocouple in the vertical rake. When the experimental dewar was about half filled, the radiation heaters were energized so that by the time the dewar was full, the heaters were at the desired temperature.

For the self-pressurization experiments, the experimental dewar was pumped to triple-point pressure after filling and the vent was closed. The dewar was allowed to self-pressurize, and data were taken automatically at intervals of 20 to 60 s.

The experiments where the slush was mixed when the pressure reached 26.7 k Pa were identical except that the mixer was run when the pressure reached 26.7 k Pa, and it continued to run until the pressure dropped below 13.3 k Pa. Mixing was then stopped, but the pressure frequently continued to fall to near triple-point pressure, 7.042 k Pa [Roder, 1965]. This continuing loss of pressure was attributed to residual turbulence after the mixer was stopped.

The experiments where the dewar was pressurized with helium gas were conducted in the same way as those described above except that warm helium gas was introduced immediately after the last slush transfer. Helium gas was introduced until the vent relief valve opened at about 93 k Pa pressure. Helium gas was continuously introduced until it was no longer required to maintain the pressure at vent pressure. Data were taken during the pressurization and for the duration of the test at 20 to 60 s intervals. The test duration was one hour or until the slush level was well below the second radial thermocouple rake.

4.2 Mixer Test Procedure

Two different types of mixing tests were run with three mixer configurations and two mixer positions. Mixing tests were performed in freshly prepared slush prior to heat transfer tests, and in aged slush after the heat transfer tests. The mixer configurations were mixing with the blades at 45° pushing down, mixing with the blades at 90°, and mixing with the blades at 45° pushing up. The two mixer locations were at 0.25 m and 0.71 m above the bottom of the dewar.

5. Test Results and Discussion

5.1 Heat Transfer Test Results and Discussion

The objectives of the heat transfer experiments were: 1) measure the thermal stratification rates in the liquid over settled slush and

correlate stratification rates with heat transfer rates; 2) measure self pressurization rates in a vessel filled with slush hydrogen and determine the effects of heat transfer rates on pressurization; 3) determine if the dependence of heat transfer rate on wall temperature was the same as reported for the small scale heat transfer experiments [Sindt, 1973]. The long range objective of the heat transfer experiments was to obtain enough data to enable development of an analytical model to predict pressure rise and thermal stratification for various heat transfer rates in vessels used for slush hydrogen storage.

Seven tests were conducted in which the pressure in the experimental vessel was raised to near one atmosphere with helium gas immediately after the last slush transfer. These tests were conducted to determine thermal stratification rates in the dewar at one "g" and at one atmosphere pressure. This series of tests covered heat transfer rates from 0.001 to 0.0175 W/cm^2. Several significant characteristics were evident during the series of tests. First, the thermal stratification profiles that developed were dependent on initial slush level and the age of the slush in the dewar. The age of the slush affects stratification because it determines the settling rate of slush level as a function of time. The instrumentation did not include a liquid level or slush level indicator, therefore, these levels were estimated by visual observation. Initial slush levels could be observed to $\pm$ 5 cm; however, the inaccuracy as well as the infrequency of visual observation as slush level dropped resulted in increased dispersion of this data from test to test.

The second significant characteristic observed was that all of the liquid over the settled slush increased in temperature with time. The thermal stratification followed the slush level as it dropped due to melting and settling. Figure 6 shows the typical temperature profiles at even time intervals as indicated by the vertical temperature rake.

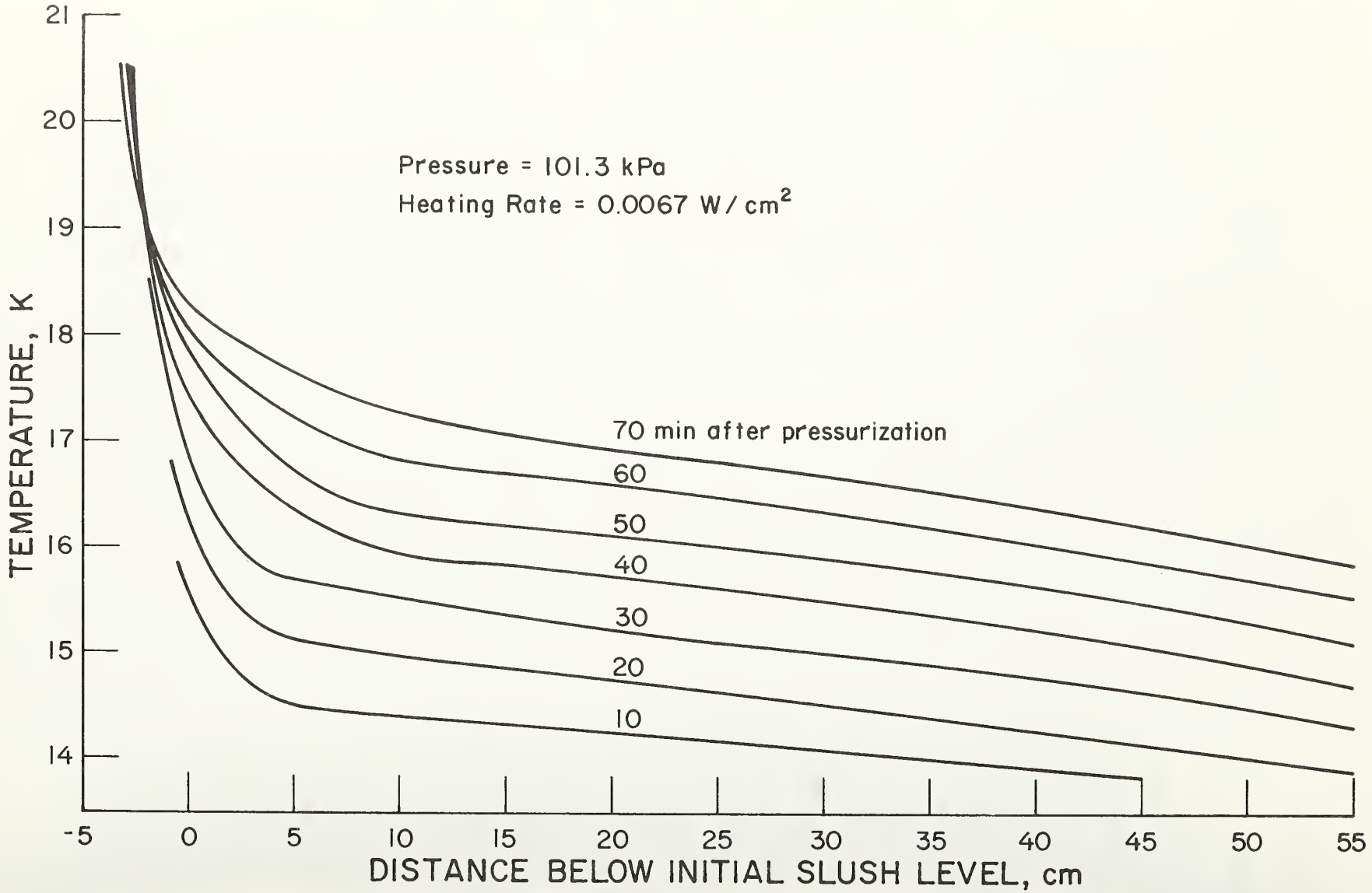

Figure 6. Vertical temperature profile in liquid over settled slush.

Graphs similar to those shown in figure 6 were prepared for each heat transfer rate. Then, to correlate the effects of heat transfer rate, a cross plot was made of temperature versus heat transfer rate for selected levels and times. The best correlation resulted when the levels were referred to the initial slush level and not the liquid level. Figure 7 shows a plot of temperature for different levels below the initial slush level at times of 10, 30, and 50 minutes after pressurizing with helium gas. From these data it appears that the relation between heat flux and stratification temperature at a prescribed location is linear over most of the range investigated. The data for levels between 0 and 0.1 m were very inconsistent. This inconsistency is probably caused by the previously mentioned slush settling rate, especially in the top .05 m of slush. Also, the initial heating in the liquid over settled slush is dependent on the manner of pressurization with the warm helium gas. Ideally, it would be desirable to start with the liquid and slush at the same levels after pressurizing with cold helium gas. Liquid and slush level indicators and a helium precooler should be used in future experiments.

Three tests were conducted to determine self-pressurization rates. These were at 0.001, 0.0045 and 0.0067 W/cm^2 heat rates. The data are shown in figure 8. A trend in increased pressure rise rate versus increased heat flux is evident, but the data are not sufficient to define this trend well enough to establish a correlation. The similarity between the pressure rise rate for the 0.0045 and 0.0067 W/cm^2 heat rate may be attributable to the variance of the initial slush levels.

The significance of liquid and slush levels on pressurization rate is more closely shown by the test where the slush was mixed when the pressure reached 26.7 k Pa. Pressure rise versus time for this test are shown in figure 9. Pressure over-shoot at both high and low pressure

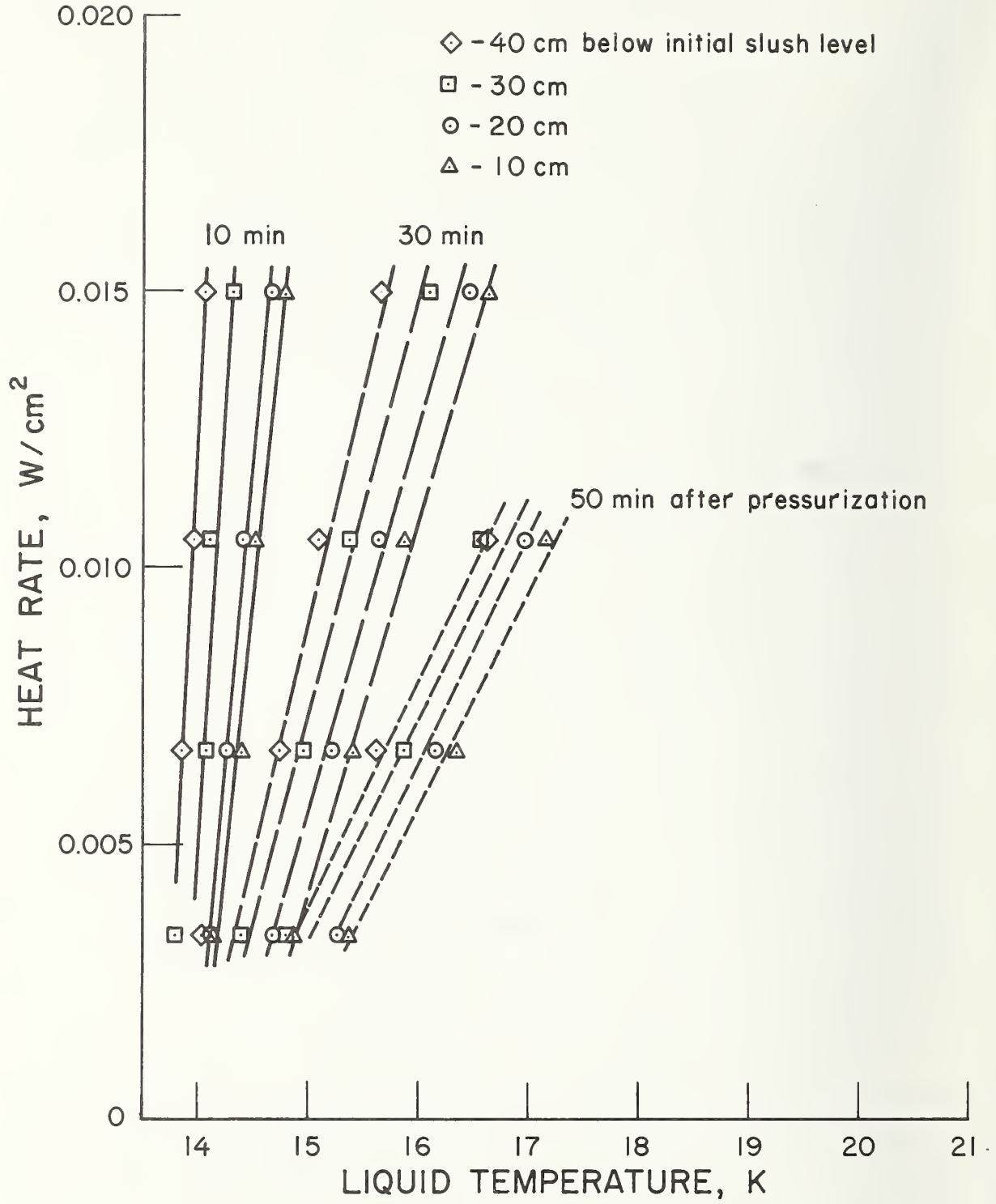

Figure 7. Liquid temperature versus heat transfer rates in liquid over settled slush.

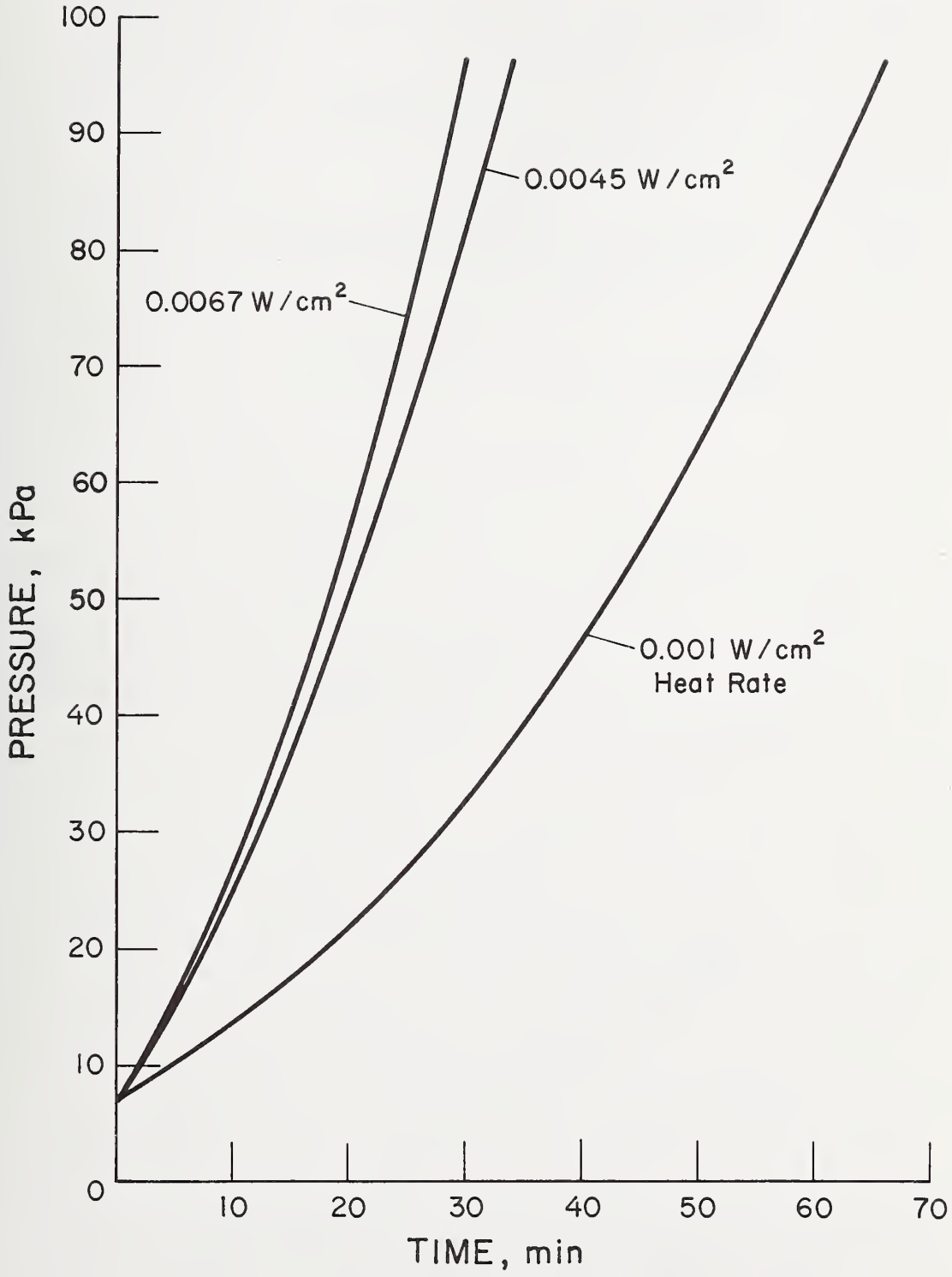

Figure 8. Self-pressurization of the ullage over settled slush.

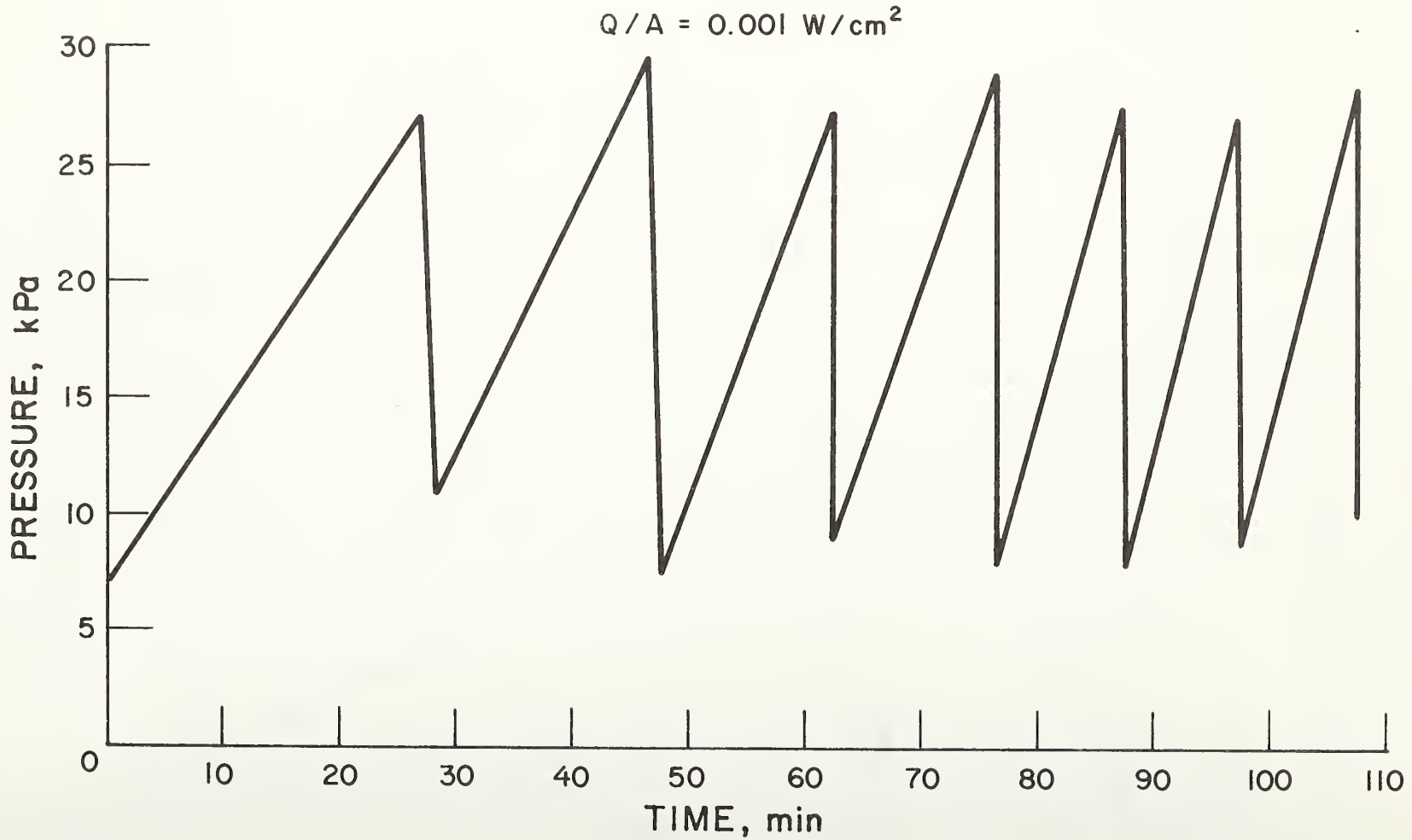

Figure 9. Self-pressurization with intermittent mixing.

resulted because the mixing operation was not controlled by a pressure sensing device but was controlled manually from visual observation of pressure. To eliminate the effects of this overshoot in the data, a second curve was drawn showing the time required for a given pressure rise of 13.4 k Pa from 13.3 to 26.7 K Pa. This is shown in figure 10. The significance of these data are twofold. First, mixing is an effective means of holding pressure in a slush container within a desired range; and second, pressure rise over settled slush due to self-pressurization is dependent on both the liquid and slush levels. The fact that the self-pressurization rate increases with lower slush levels has significant implications about the heat transfer mechanism to slush. In a vessel containing liquids, the heat flows from the wall to the liquid, and the liquid then flows up the wall in an ever increasing thickness boundary layer. This warmed liquid then flows across the top of the liquid. The resulting model is a thin layer of warmed liquid flowing up the wall and counter-flowing down the center, [Schwind and Uhet, 1964; Evans and Reed, 1968]. If this were the case in slush, the time to repressurize after each mixing cycle should be about constant since the liquid starts each cycle at about the same temperature. However, what appears to be occurring in the slush system is that the heat that flows in below the slush level is actually being absorbed by the slush at the expense of solid melting. If this were the case, the amount of heat flowing up the wall above the slush would increase as the slush level decreased and, therefore, the top layer of liquid would heat faster, resulting in an increased pressurization rate. This increase in pressurization rate was observed in the experiments. The implication is that the solid particles near the dewar do participate in the heat transfer mechanism.

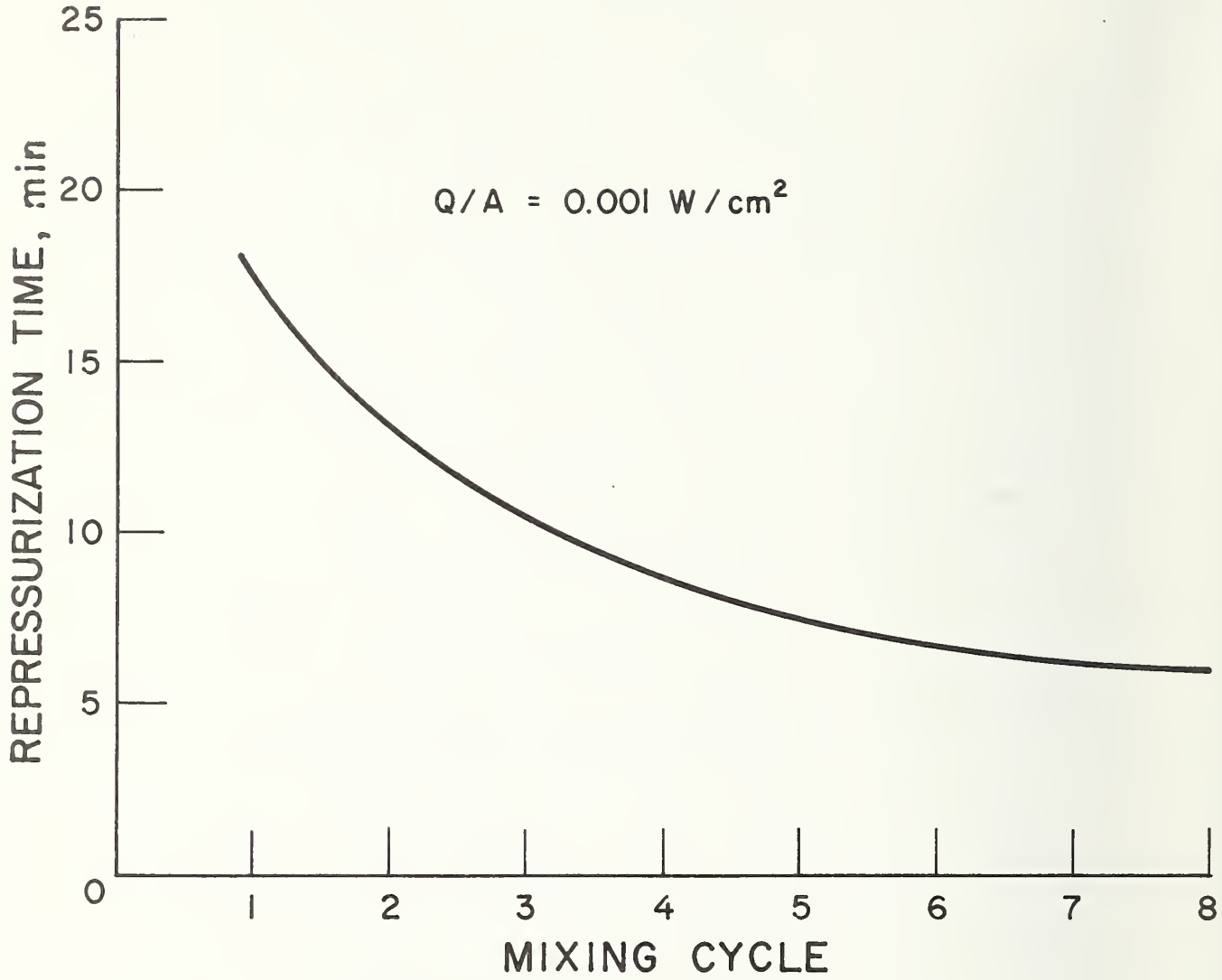

Figure 10. Self-pressurization versus mixing cycle.

This premise is further substantiated by thermal gradients that develop over settled slush. This gradient at any one time looks like the gradient in a vessel of liquid with the bottom displaced to the slush level. More data and a more detailed analysis of this observation seems warranted to confirm this observation before attempts are made to develop an analytical model of heat transfer to vessels containing slush hydrogen.

Another significant result from the heat transfer tests was that no radial temperature gradient was ever measured in any of the tests. This was the case whether the radial thermocouples were in slush or in liquid over settled slush. Apparently the warm liquid flowing up the wall does not develop a stream as thick as 1 mm, which was the location of the closest thermocouple to the wall.

5.2 Mixer Test Results and Discussion

The mixing tests were conducted in conjunction with the heat transfer tests. A mixer test was conducted immediately before starting each heat transfer test. These were considered to be tests in mixing of fresh slush. Other tests were conducted after completion of a heat transfer test. These were considered mixing tests in aged slush. The fresh slush was really a mixture of solids that were from 15 minutes to 2 hours old, as this was the time required to fill the experimental dewar with settled slush. The aged slush was one to two hours older than the fresh slush. Although this is a relatively short aging period significant aging effects did occur as was evident by the drop in slush level in excess of that caused by melting.

Very early in the experimental program it was discovered that slush which had been upgraded in the experimental vessel without mixing during transfer tended to pack to very high solid fraction in the bottom of the vessel. The slush densitometer that was located in the plane of

the mixer indicated solid fractions as high as 0. 8 during one attempt to mix after upgrading was completed. This is the highest solid fraction observed in slush to date. The increase in density at the mixer plane was not observed in the slush that was mixed during transfer.

A very significant development that accompanied the high solid fraction was that on several occasions transfer of slush from the generator to the experimental dewar was blocked. This occurred when the experimental dewar was nearly full of settled slush and only if the slush had not been mixed during any of the previous transfers. The slush transfers were made using pressure differences with a total available pressure difference of 100 k Pa. The apparent blockage could be relieved immediately by running the mixer if and only if the mixer mixed the entire dewar of slush.

A second very significant observation was that the power required to mix a dewar nearly filled with previously unmixed slush was much greater than was required to mix a dewar of slush previously mixed.

The data for fresh slush mixing with the mixer blades at 45° are shown in figure 11. The curve is from the mixing data and gives the power required to run the mixer in all cases except when the slush was not mixed during transfer. The symbols indicate the point where total mixing started. The one point at 575 watts power was for slush not premixed. As is indicated, this point is not on the curve for all other mixing data. The second high power point shown is for slush that was mixed for all but the last two transfers during upgrading. As is indicated, the power to initiate mixing is considerably greater than that for premixed slush, but in this case it does fall on the same power curve as the other mixing data.

The data for mixing of aged slush with the blades at 45° is shown in figure 12. The power versus speed relationship was found to be the

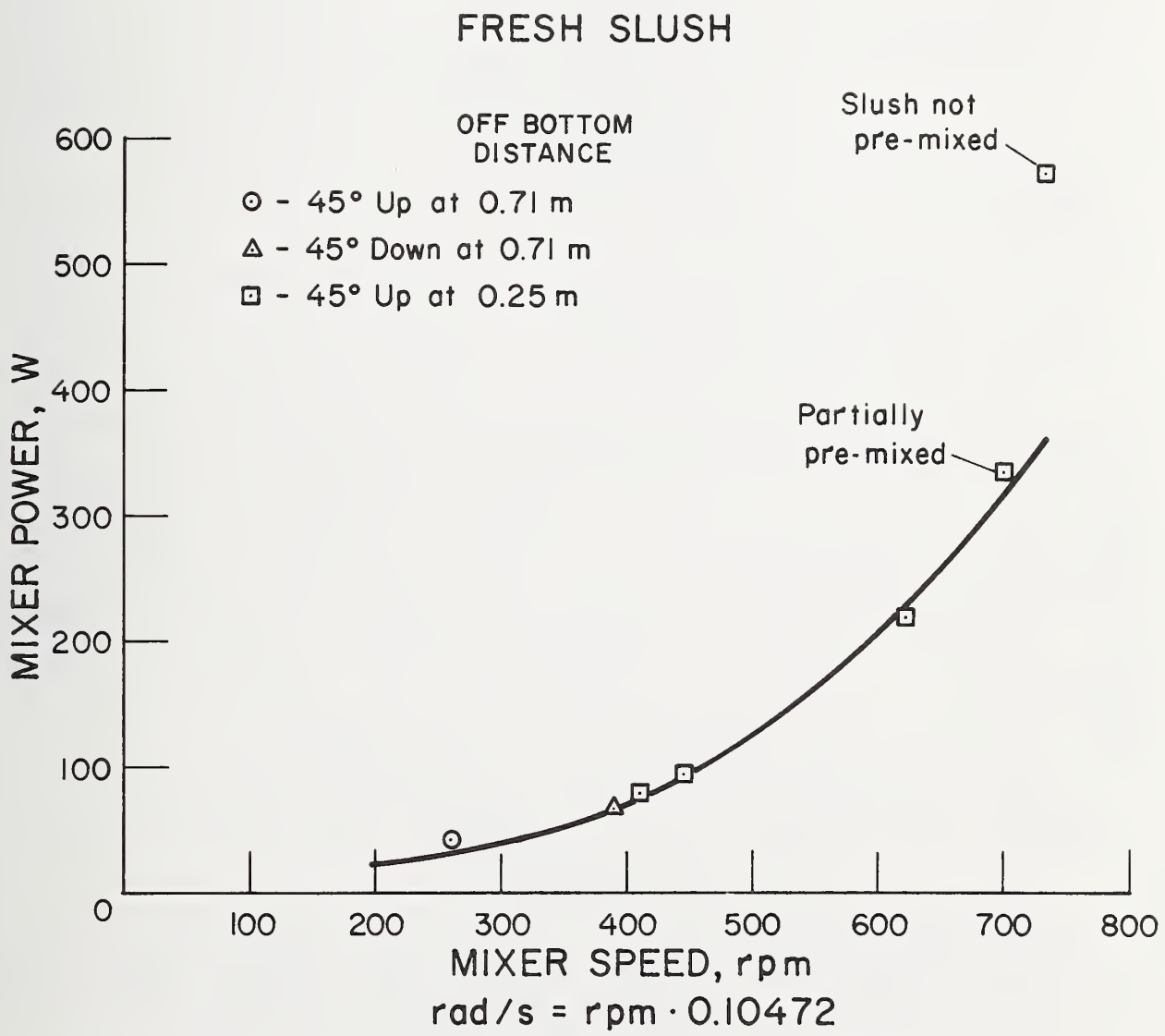

Figure 11. Mixing of fresh slush with a turbine mixer.

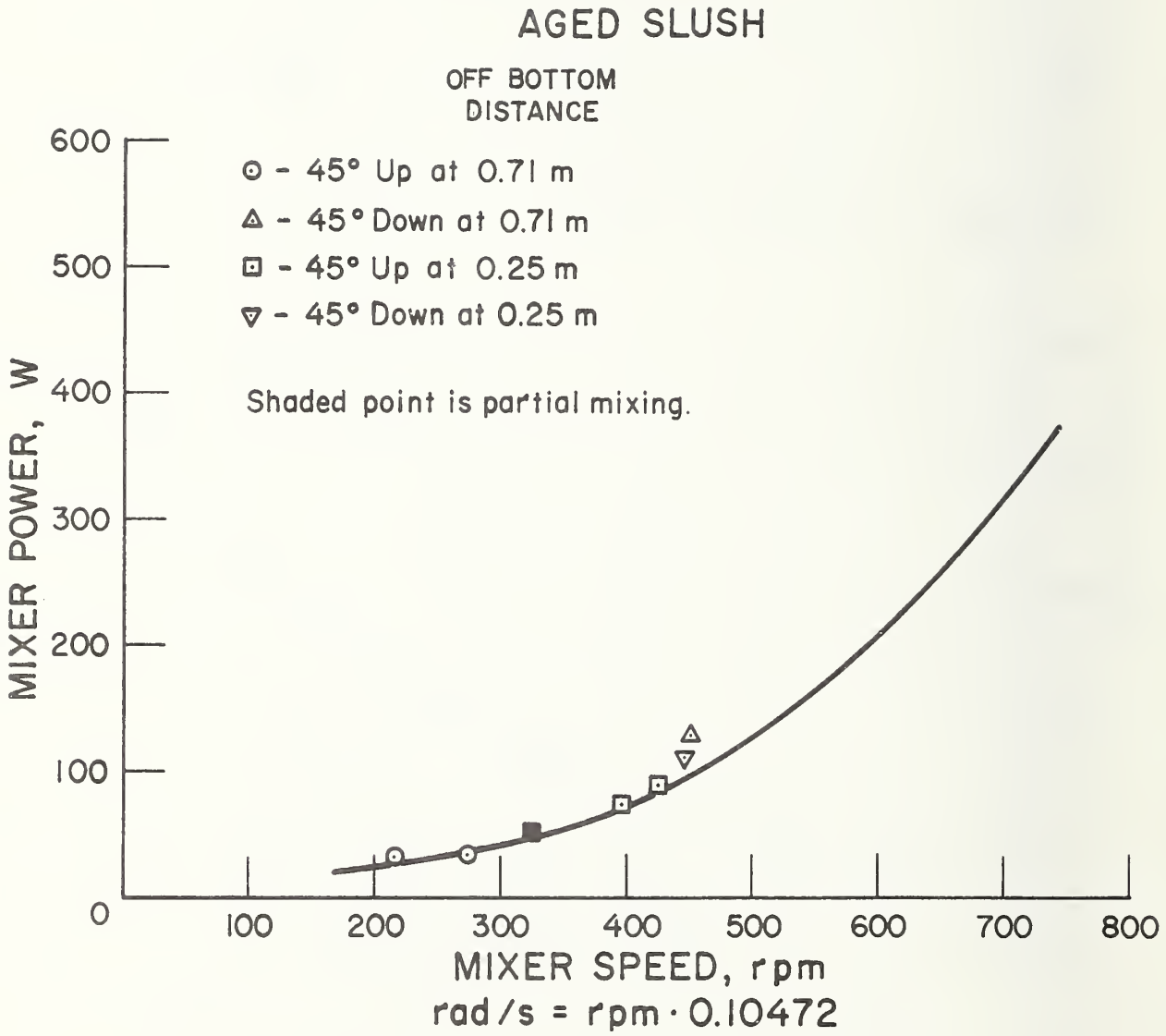

Figure 12. Mixing of aged slush with a turbine mixer.

same as for fresh slush. The speed required to start mixing is in general less for the aged slush than for fresh slush. This inference, that aged slush mixes with less speed and power than fresh slush, may be false because the aged slush settled solid level was always less than fresh slush, since settling and solid melting had occurred. To get an accurate comparison, the levels and solid fraction of the aged and fresh slush should be the same; however, no such equal comparison was made primarily because neither an accurate slush level device nor accurate densitometers were included in the instrumentation.

Figure 13 shows the mixing characteristics for the blades at 90° . For this configuration the mixing power was sensitive to the distance of the mixer from the bottom. As for the other figures, the symbol indicates when total mixing is developed, except for the point at 650 watts. This point was the maximum speed the mixer would run, but total mixing did not develop. This was in slush that had not been previously mixed.

From the mixing experiments it is apparent that the least power and speed are required for the mixer blades at 45° pushing up and with the mixer at 0.7 m off the bottom. Because of the difficulty in transferring slush without mixing, this configuration was not evaluated with unmixed slush.

6. Conclusions and Recommendations

Several significant results were obtained from the heat transfer and mixing experiments. These results lead to the following conclusions:

Heat Transfer

1. Thermal stratification develops in liquid over settled slush, and the stratification characteristics are similar to those in a vessel of liquid except that the stratification develops starting at the slush level instead of the bottom of the vessel.

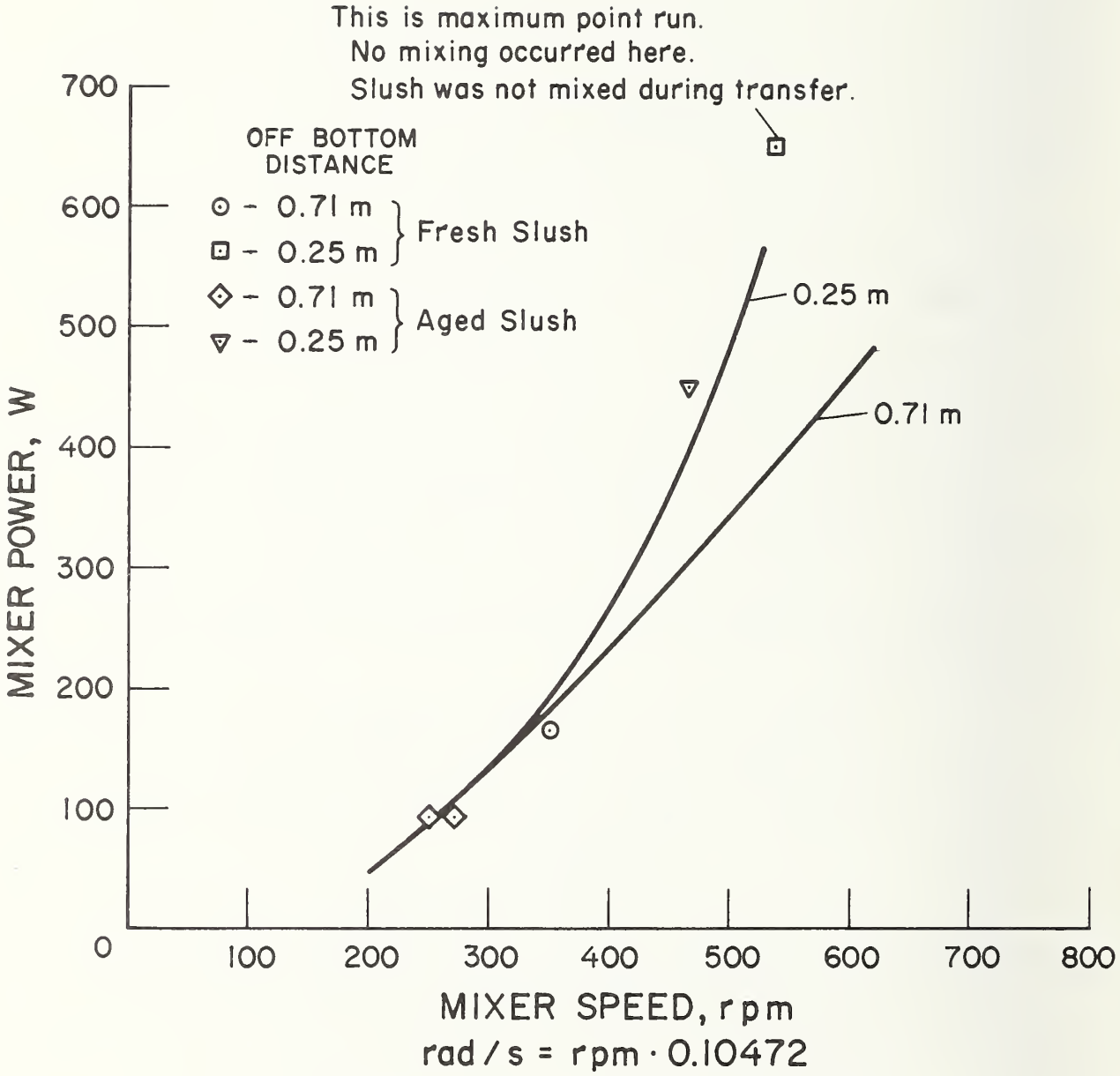

Figure 13. Mixing slush with a paddle mixer.

2. Heat entering below the slush level is apparently absorbed at the expense of melting solid and is not carried up the vessel wall in the boundary layer as in liquid.

3. Temperatures at specific locations in the stratified liquid are linearly dependent on heat transfer rates at the dewar walls.

4. Shapes of temperature profiles in the liquid over settling slush are more dependent on the initial slush level and on slush settling rate than on liquid level.

Mixing

1. Mixing of slush is an effective way to reduce pressures to near triple-point. However, pressure control with mixing at some level above triple-point pressure may be difficult because of the tendency for the slush, once mixing starts, to mix immediately and therefore condense ullage gas until the pressure is very near triple-point pressure.

2. Mixing power required to initiate mixing is greatly increased if slush solid fraction is upgraded without mixing.

3. Slush solid fraction upgrading as reported by Sindt and Ludtke [1970] may require effective mixing to prevent flow stoppage at the end of transfer lines, especially in freshly prepared slush.

4. Mixing power required to initiate mixing is very dependent on mixer configuration and location. Of the three configurations and two locations tested, a turbine mixer with blades at 45° pushing up and located at about 1/4 the depth of the slush mixed the best with the least power. The power required for mixing fresh slush with this configuration was 45 W/m^3.

5. Mixer and baffle design used in commercial applications for low viscosity fluids are effective for slush hydrogen. Designs other than those recommended [McConnell, 1971] were not evaluated to determine if other configurations may perform better.

The heat transfer experiments would have been more productive had the temperature measurements at the dewar been successful. Because of the failure of these thermocouples, data from these tests could not be compared to the basic heat transfer data reported in phase I [Sindt, 1973].

From these experiments several recommendations are evident. Instrumentation techniques to obtain accurate wall temperature in vacuum environments needs verification before more tests of this type are conducted. More testing is needed to verify and understand the apparent different heat transfer mechanism in slush than in liquid. More testing is needed to determine the relationship of pressure rise rate, slush levels, and heat transfer rates at the dewar walls. The need for more testing is also indicated before any reliable analytical models can be verified for cylindrical tank configurations.

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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.)

Heat transfer to slush hydrogen and mixing were investigated in a 1 m^3 cylindrical vessel. The effects of heat transfer rates on thermal stratification and on self-pressurization were measured. Temperature profiles in thermal stratification were found to be more dependent on slush level and slush settling rates than on liquid level. Solids in the slush appear to be involved in the heat transfer mechanism as slush level affected the amount of warm liquid reaching the top of the dewar and therefore affected the self-pressurization rates.

Mixing effectiveness and power requirements to mix slush hydrogen were determined for two configurations of turbine mixers and one paddle mixer. Mixing power requirements were found to be sensitive to the mixer location and configuration.

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Heat transfer; liquid hydrogen; mixing; mixing power; paddle mixers; slush hydrogen; turbine mixers.

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