MSFC-307

2007 Space Cryogenic Workshop
July 12 – 13, 2007
Huntsville, Alabama

CRYOGENIC CAPILLARY SCREEN HEAT ENTRAPMENT

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July 2007

ABSTRACT

Cryogenic liquid acquisition devices (LADs) for space-based propulsion interface directly with the feed system, which can be a significant heat leak source. Further, the accumulation of thermal energy within LAD channels can lead to the loss of sub-cooled propellant conditions and result in feed system cavitation during propellant outflow. Therefore, the fundamental question addressed by this program was: "To what degree is natural convection in a cryogenic liquid constrained by the capillary screen meshes envisioned for LADs.?" Testing was first conducted with water as the test fluid, followed by LN2 tests. In either case, the basic experimental approach was to heat the bottom of a cylindrical column of test fluid to establish stratification patterns measured by temperature sensors located above and below a horizontal screen barrier position. Experimentation was performed without barriers, with screens, and with a solid barrier. The two screen meshes tested were those typically used by LAD designers, "200x1400" and "325x2300", both with Twill Dutch Weave. Upon consideration of both the water and LN2 data it was concluded that heat transfer across the screen meshes was dependent upon barrier thermal conductivity and that the capillary screen meshes were impervious to natural convection currents.

INTRODUCTION

If cryogenic propellants are used in orbital maneuvering and reaction control systems (OMS and RCS respectively) then surface tension liquid acquisition devices (LADs) are likely to be required to ensure the supply of vapor-free propellant in the reduced gravity environment. Despite the fact that LADs have been used extensively in space-based storable propellant systems, there has been no on-orbit application with cryogenic propellants. Although the principles of surface tension are the same for both storable and cryogenic liquids, and the LAD components should be similar, there are additional thermal control challenges inherent in the cryogen application.

Natural Convection and Thermal Stratification

Typically the heat leak into a cryogenic container must be carefully controlled to avoid excessive boil-off and assure adequate pressure control. In spite of careful thermal engineering intended to minimize heat leaks, significant natural convection can occur and result in circulation patterns which, in turn, affect the degree of thermal stratification. Stratification, or the distribution of thermal energy within the cryogenic tank and feed system, must be considered in assuring propellant sub-cooling sufficient to avoid cavitation and vapor formation during propellant outflow to the engine.

A common misconception is that natural convection is insignificant in microgravity. As an example, during the Apollo Program, convection was observed in the hydrogen tank under acceleration 0.8×10^{-4} g - 3.7×10^{-4} g of an orbiting Saturn S-IVB test stage during the Saturn AS-203 Flight Experiment (Ref.1). Temperature sensors within the hydrogen tank detected a 2.8°C (5°F) axial gradient or stratification within the liquid. This gradient was attributed to the development of a convective recirculation current in the liquid.

Liquid Acquisition Devices

Figure 1 shows a notional cryogenic propellant tank and associated LAD concept. Typical LAD design is intended to support:

- OMS engine firings at the start of tank operation, with the net acceleration vector aligned along the tank main axis
- Short-duration RCS engine firings, with acceleration vectors not necessarily aligned along the tank main axis.

The presence of the LAD can affect cryogenic propellant conditioning and vice versa. The presence of the solid barrier or a compartmented tank is significant since it can impede mixing and complicate reduced gravity pressure control; however the issue of concern for this effort is the localized accumulation of thermal energy within the LAD flow channels. Since the LAD interfaces directly with the feed system, which can be a significant heat leak source, the accumulation of thermal energy within the LAD channels is of special concern (Figure 2).

TEST HARDWARE and PROCEDURES OVERVIEW

The basic experimental approach was to heat the bottom of a cylindrical column of test fluid to establish stratification patterns measured by temperature sensors located throughout the tank. Testing was first conducted without the presence of a screen; then, the test condition was repeated with a screen placed horizontally across the test cylinder at about the halfway position of the liquid column (Figure 3). Finally, for reference purposes, a solid barrier was placed across the liquid column at the halfway position above the heater. The initial test series was conducted with water as the test fluid in a transparent container. The second test series was conducted with liquid nitrogen (LN2) in a Dewar. Further details regarding the testing with water and LN2 are presented in subsequent sections.

Two types of screen material were obtained for use in the tests. Both were of the stainless steel Twill Dutch Weave configuration that is typically used by surface tension LAD designers - "200 x 1400" and "325 x 2300", differ in wire size and the number of warp and shute wires per unit length.

During the beginning water experiments a significant problem was discovered. As the test progressed, gas bubbles began to accumulate on the underside of the screen sample. These bubbles, which originated in the region of the heater, grew in number until coalescence formed a large gas pocket. To mitigate this problem the water was "de-aerated" by heating the water for extended periods of time and avoiding agitation prior to testing.

TEST SETUP and APPROACH

Water Test

The water test setup is shown in Figure 4 and consisted of a double-walled transparent polycarbonate cylindrical container. The exterior cylinder was used to form a 2.54 cm annulus which could be evacuated, thereby minimizing sidewall heat leakage into

the liquid. Thermal energy was injected into the water through two independent heaters located at the bottom of the tank. Temperature sensors (thermo-couples) were located at four positions above and below the screen sample positioned 45.7 cm above the tank base. These four measurement levels are referred to as: Bottom, Lower Middle, Upper Middle and Top. As illustrated in Figure 4, five sensors were mounted on a cross-shaped support structure at each of the measurement positions.

Checkout testing was conducted first to assure that the test setup functioned satisfactorily. The baseline testing was performed after problems discovered during the checkout phase were corrected. In either case, the test matrix presented in Table 1 guided the test sequence

Test Type	Sample Type	Approximate Heater Power (Watts)
Low power baseline test with no barrier	None	920
High power baseline test with no barrier	None	1840
Low power baseline test with solid barrier	Aluminum Foil	920
High power baseline test with solid barrier	Aluminum Foil	1840
Low power test with coarse screen	"200x1400" screen	920
High power test with coarse screen	"200x1400" screen	1840
Low power test with fine screen	"325x2300" screen	920
High power test with fine screen	"325x2300" screen	1840

Table 1. Water Test Matrix

Liquid Nitrogen Test

For the LN2 testing a stainless steel Dewar with an internal polycarbonate cylinder installed was used (Figure 5). The inner cylinder was made with the same polycarbonate double-walled pipe used in the water tests but was shorter (61.9 cm vs. 106 cm). It contained the screen sample, temperature sensors (silicon diodes) and heater. It is within this restricted volume – wherein the heater was sufficient to establish an adequate level of convection and stratification – that the experiment was conducted. However, the entire vessel was filled with LN2 for each test.

The test matrix used to guide the testing is presented in Table 2. The basic experimental approach was to achieve stable conditions within the Dewar, then activate the heater at the bottom of the cylindrical column of test fluid to establish stratification patterns measured by temperature sensors located within the interior cylinder. Testing was first conducted to establish baseline stratification conditions without the presence of a screen and with and without heater activation. With this baseline condition, the cylinder was cleared of any significant obstructions (only the temperature instrumentation arrangement was present) so that unimpeded convection could occur. Then, the test condition was repeated with a screens placed horizontally across the test cylinder at about the halfway

position of the liquid column (Figure 5). Finally, for reference purposes, a solid barrier (aluminum foil supported by the 325x2300 mesh screen) was placed across the liquid column. In the process of testing it was observed that care had to be taken to establish consistent initial conditions or the temperature magnitudes for the various test conditions could not be compared.

Test Type	Sample Type	Approximate Heater Power (Watts)
No power baseline test with no sample	None	0
Baseline test with no sample	None	103
Test with coarse screen	"200x1400" screen	103
Test with fine screen	"325x2300" screen	104
Baseline test with solid barrier	Aluminum foil, supported by "325x2300" screen	104

Table 2. LN2 Test Matrix

TEST RESULTS

During initial testing it was found that because a considerable convective mixing occurred throughout the testing, a sensor-to-sensor comparison was impractical and misleading. Furthermore, due to complex mixing currents at the "Bottom" (near the heaters) and uppermost or "Top" positions, the temperature trends at these positions were not necessarily reflective of what was occurring at or near the screen position. However, the averaged temperatures at the positions or levels nearest the screen, i.e. the Lower Middle and Upper Middle positions enabled a clear evaluation of convective flow resistance due to the barriers. Also, it is emphasized that any temperature magnitudes presented herein are considered adequate to establish *relative*, but not absolute, heat transfer resistance characteristics.

Water tests

The water test results for the Lower Middle and Upper Middle positions (7.6 cm below screen and 15.2 cm above the screen respectively) are presented in Figures 6 – 9. Temperature-time histories for both screen meshes, the solid barrier, and no barriers for test durations ranging from 40 to 50 minutes are presented for the low heater setting (920 watts) in Figures 6 – 7 and for the high heater setting (1840 watts) in Figures 8 – 9. With a barrier, temperatures below the barrier position consistently increased more rapidly than without the barriers, indicating the accumulation of thermal energy or heat entrapment. For example, at the end of the 920 watt test period (~ 50 minutes), the Lower Middle temperatures (below the barrier position) were 5–10°C higher with the barriers (Figure 6). Similarly, at the 1840 watt setting, temperatures were 13-16°C higher due to the presence

of the barriers (Figure 8). Conversely, temperatures at the Upper Middle position (above the barrier position) were lower with the barriers. The Upper Middle temperatures at the end of the test with the 920 watt setting were 10-11°C lower with the barriers installed (Figure 7), and 16-19°C lower at the 1840 watt setting (Figure 9).

Therefore, it can be concluded that all the water tests with samples installed (whether coarse screen, fine screen or solid barrier) indicated greatly reduced thermal mixing. Also, although the solid plate represents a complete barrier against convective flow, it actually showed a *greater* amount of heat transfer than either of the two mesh samples. The reason for this is that the aluminum barrier has a higher thermal conductivity than that of the stainless steel screen mesh. Additionally, contrary to what one might expect, slightly more heat transfer occurred across the fine mesh screen than with the coarse mesh. Apparently neither mesh allowed the passage of convective currents, however the fine mesh – being considerably thinner – allowed a greater degree of thermal conduction from the lower to the upper compartment. Nevertheless, both the screen samples showed greater heat entrapment than the solid barrier. This appears to be conclusive proof that with water as the test fluid the screens effectively prevented the passage of natural convection.

Liquid Nitrogen tests

During the liquid nitrogen testing stratification created by the heater was somewhat obscured by the heat leak from the Dewar bottom and top. Due to the reduced temperature differences and even more complex mixing currents (compared with water) at the Lower Bottom (near the heaters) and Upper Top positions, the data could not be used to evaluate trends at or near the screen position. However, as in the water tests, the averaged temperatures at the positions or levels nearest the screen (the Lower Middle and Upper Middle positions) enabled an evaluation of convective flow resistance trends due to the barriers. Again, it is emphasized that any temperature magnitudes presented herein are considered adequate to establish relative, but not absolute, convective flow resistance characteristics.

Temperature-time histories for both the "200x1400" and "325x2300" mesh screens, the solid barrier, and no barriers for the Lower Middle and Upper Middle positions (8.7 cm below screen and 8.7 cm above the screen respectively) are presented for a 10 minute test period in Figures 10 and 11. The Dewar heat leak effects on the liquid temperature rise rate are clearly illustrated with the "no barrier, no heater" condition, i.e., increased about 0.39°C per minute. Therefore, it is evident that the temperature differences (stratification) produced by the heater were reduced by the heat leak from the Dewar bottom and top. However, even though the temperature differences are small, the trends with the barriers installed were like those observed in the earlier water tests. Referring to the Figures 10 – 11, the temperatures below the barrier position were consistently higher with the barriers installed, indicating heat entrapment. Conversely, temperatures above the barrier position were consistently lower with the barriers installed, indicating reduced stratification.

The solid barrier case represented the greatest thermal resistance condition. Although the solid barrier condition represented total resistance against convective flow,

the barrier-to-barrier temperature differences were small enough (~ .3°C) to have been caused by the thermal conductivity of the solid barrier (aluminum foil + screen) compared with that with the "screen only" conditions. Furthermore, the earlier water testing indicated that the solid barrier used in those tests (aluminum foil only) was actually less of a barrier than the screens, which was also attributed to barrier thermal conductivity differences. Therefore, upon consideration of both the water and LN2 data one can conclude that heat transfer across the screen meshes evaluated is dependent upon thermal conduction and that the passage of natural convection through the screens was effectively blocked. In conclusion, it is recommended that future LAD heat entrapment thermal analyses consider only thermal conduction across capillary screen barriers with either "200x1400" or "325x2300" meshes.

SUMMARY AND RECOMMENDATIONS

Despite the fact that capillary LADs have been used extensively in space-based storable propellant systems, there has been no on-orbit application with cryogenic propellants. Although the principles of surface tension are the same for both storable and cryogenic liquids there are additional thermal control challenges inherent in the cryogen application. Since the LAD interfaces directly with the feed system, which can be a significant heat leak source, the accumulation of thermal energy within the LAD channels is of special concern since it can lead to the loss of sub-cooled propellant conditions and result in feed system cavitation during propellant outflow.

Testing was first conducted with water as the test fluid, followed by LN2 tests. In either case, the basic experimental approach was to heat the bottom of a cylindrical column of test fluid (19.1 cm diameter by 106 cm high) to establish stratification patterns measured by temperature sensors located above and below a horizontal screen barrier position. Testing was conducted without barriers, with screens, and with a solid barrier. The two screen meshes tested were those typically used by LAD designers, "200x1400" and "325x2300", both with Twill Dutch Weave.

During the water checkout tests, air came out of solution and accumulated under the barriers, thereby affecting the test results. Subsequently the water was "de-aerated" by heating the water for extended periods of time and avoiding agitation prior to testing. Test results indicated that with a barrier, temperatures below the barrier position consistently increased more rapidly than without the barriers, indicating the accumulation of thermal energy or heat entrapment. Neither mesh allowed the passage of convective currents, however the fine mesh – being considerably thinner – allowed a greater degree of thermal conduction from the lower to the upper compartment. Also, although the solid plate represents the most complete barrier against convective flow, it actually showed a *greater* amount of heat transfer than either of the two mesh samples. Apparently this is due to the higher thermal conductivity of the aluminum barrier as compared with the stainless steel screen mesh. Therefore, with water as the test fluid, the "200x1400" and "325x2300" capillary screen meshes both represented barriers impervious to natural convection currents at two heater power levels, 920 watts and 1840 watts.

LN2 testing was conducted within a 56.0 liters stainless steel Dewar. An inner polycarbonate cylinder, which was the same as that used in the water tests, was installed inside the Dewar to shield the stratification created by the heater from the sidewall heating effects. It is within this restricted volume that the experiment was conducted. However, stratification created by the 104 watt heater was still somewhat obscured by the heat leak from the Dewar bottom and top heat leak. Even though the temperature differences were small, the trends with the barriers installed were like those observed in the earlier water tests. The temperatures below the barrier position were consistently higher with the barriers installed, indicating heat entrapment. Conversely, temperatures above the barrier position were consistently lower with the barriers installed, indicating reduced stratification.

Upon consideration of both the water and LN2 data one can conclude that heat transfer across the screen meshes evaluated was dependent upon barrier thermal conductivity and that the passage of natural convection through the screens was effectively blocked. In conclusion, future LAD heat entrapment thermal analyses should consider only thermal conduction across capillary screen barriers with either "200x1400" or "325x2300" meshes. Whether or not the constrained convection leads to an unacceptable degree of localized stratification was not the subject of this investigation since such a determination is dependent on specific engine operational requirements, tank/feed system thermal characteristics, the propellant, vehicle orientation, and mission profile. However, once the potential for accumulating thermal energy within LAD channels is quantified, measures to mitigate the problem can be devised with more confidence.

REFERENCES

1. "Evaluation of AS-203 Low Gravity Orbital Experiment", Chrysler Corporation, Space Division Technical Report HSM-R421-67, Contract NAS8-4016, January 1967.

2. Grayson, G. et al: "Cryogenic Tank Modeling for the Saturn AS-203 Experiment", AIAA paper 2006-5258, July 2006.

ILLUSTRATIONS

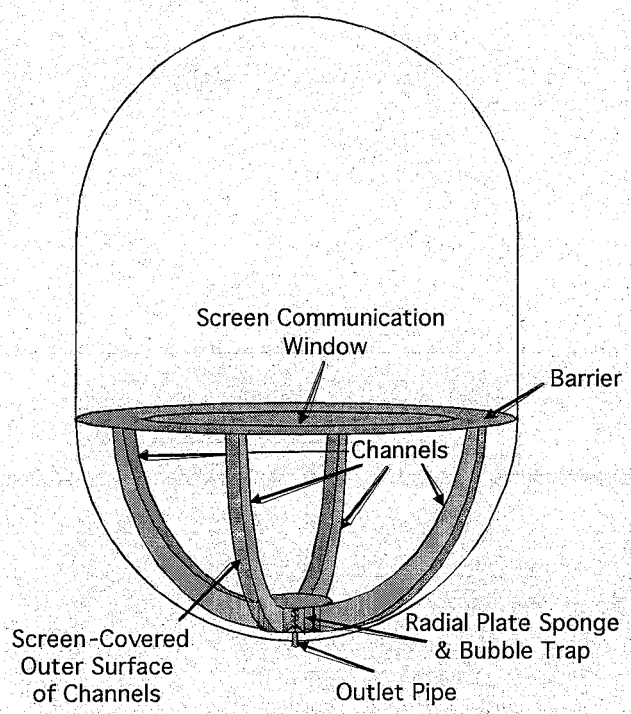

Figure 1. Representative LAD Concept

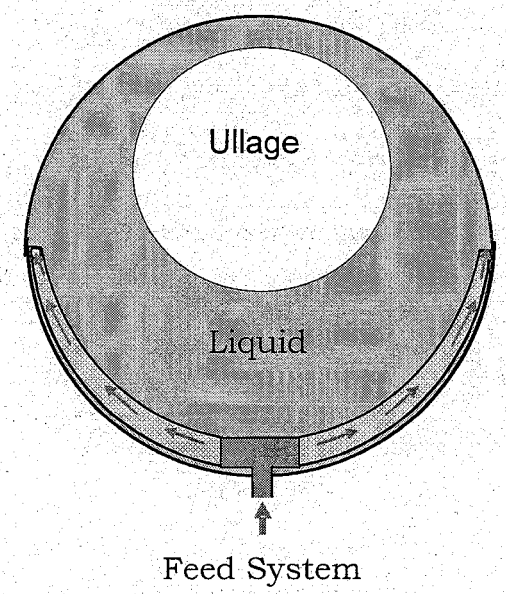

Figure 2. Thermal Energy Distributions within LADs

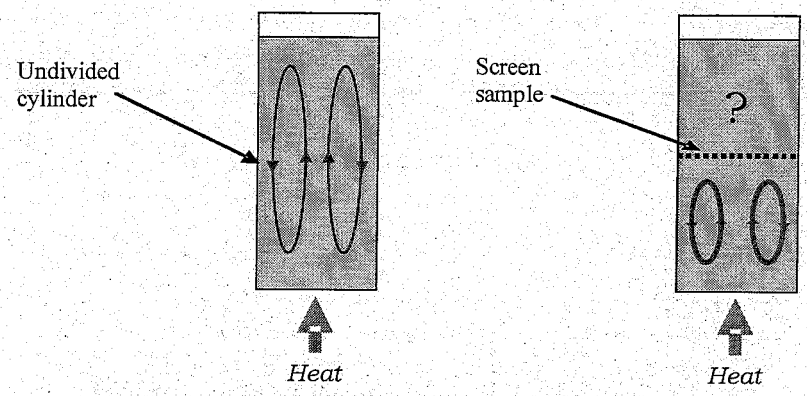

Figure 3. Heat Entrapment Experiment Concept

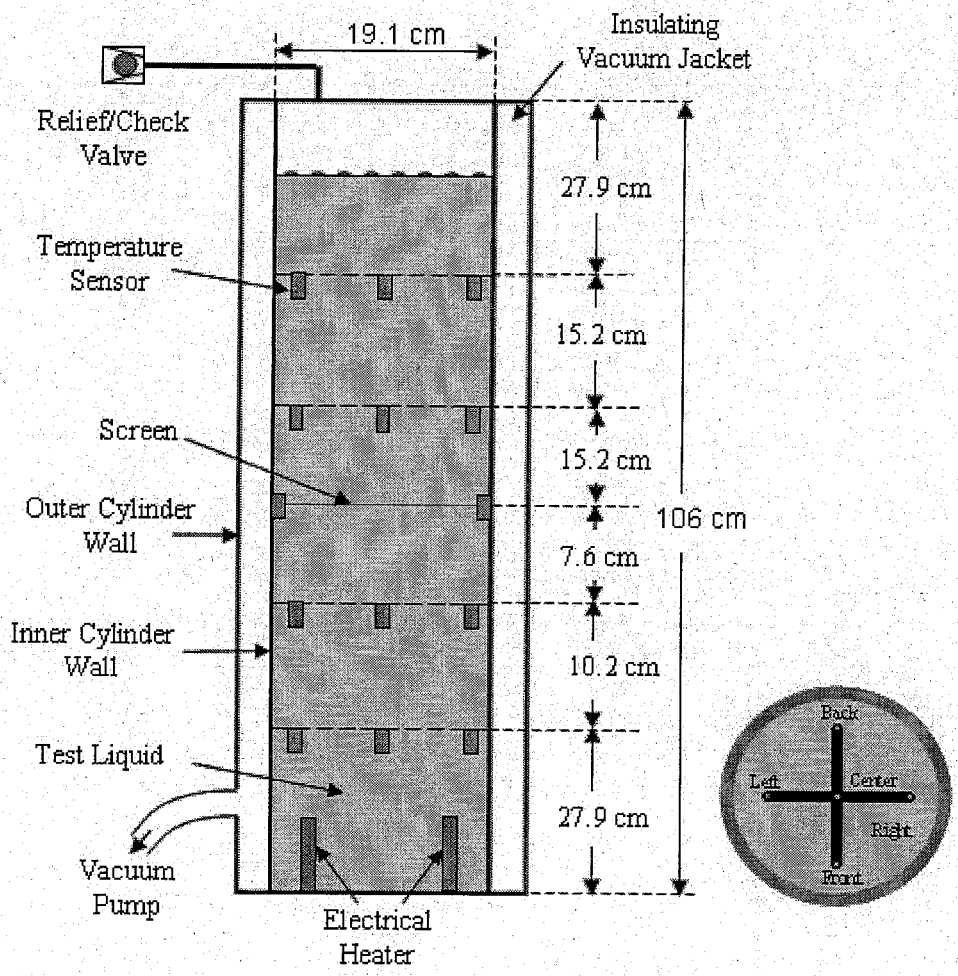

Figure 4. Heat Entrapment Water Experiment Configuration

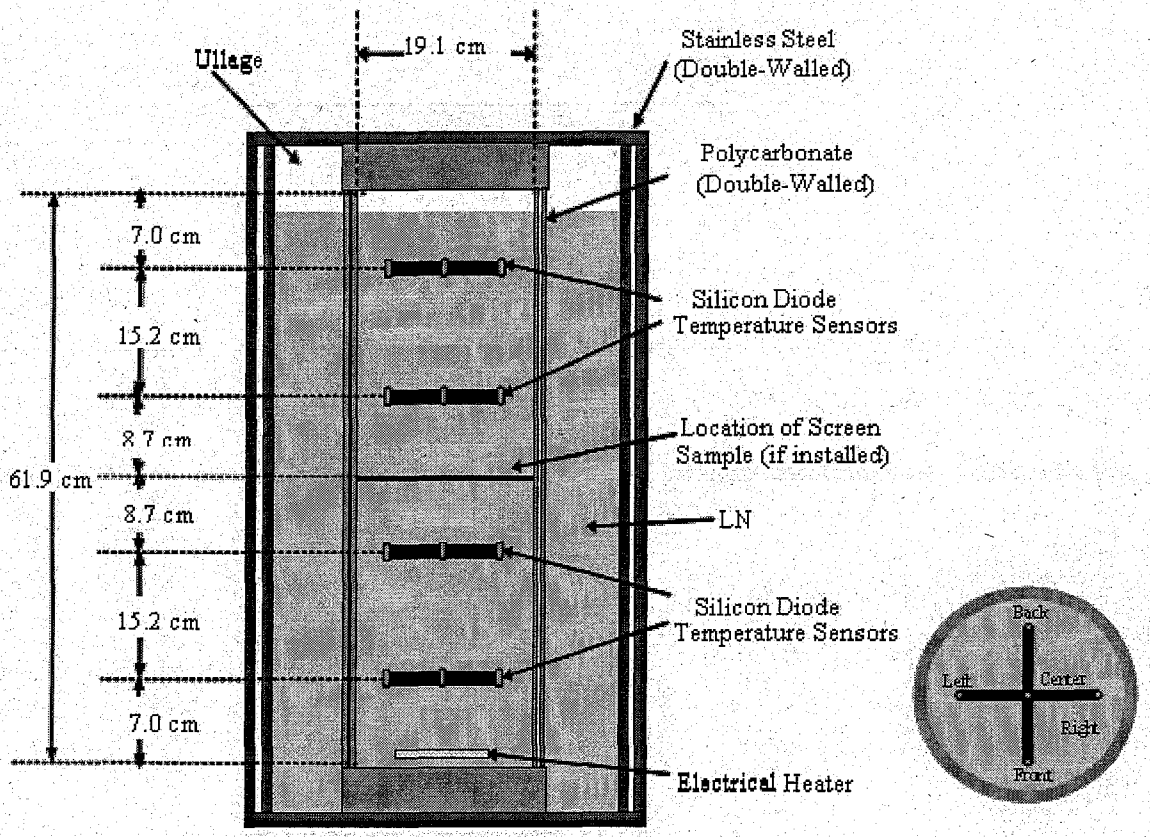

Figure 5. Heat Entrapment LN2 Experiment Configuration Schematic

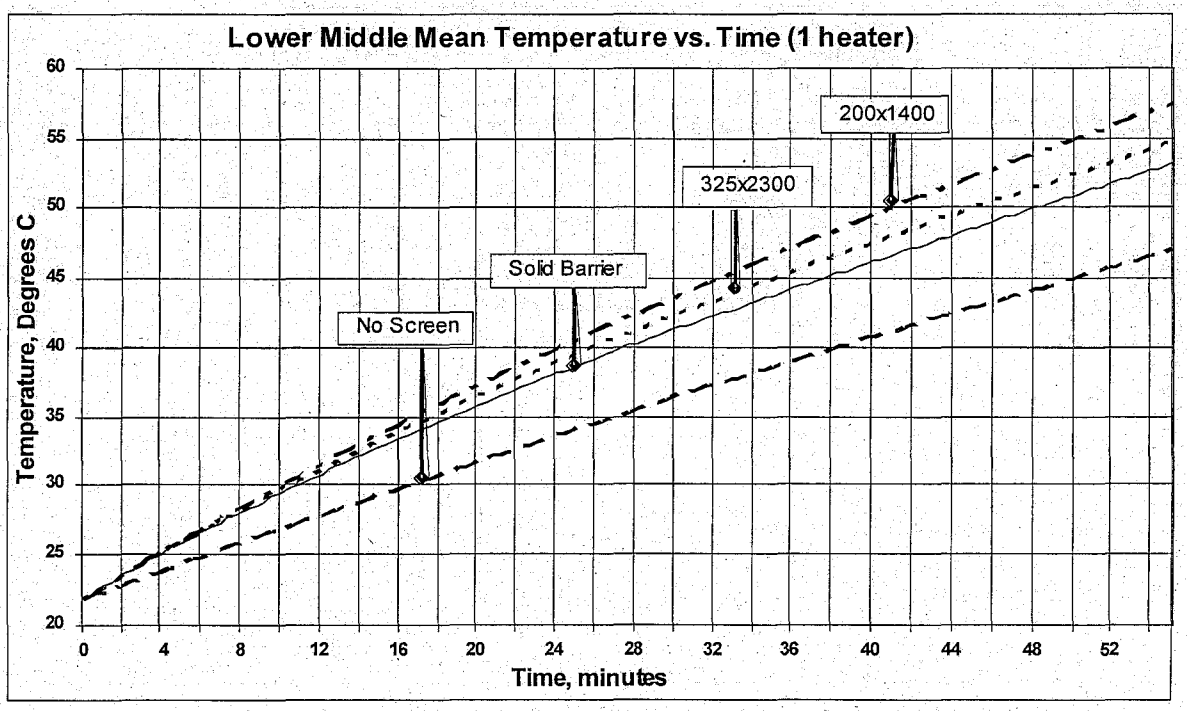

Figure 6. Water Average Lower Middle Temperature vs. Time (low power)

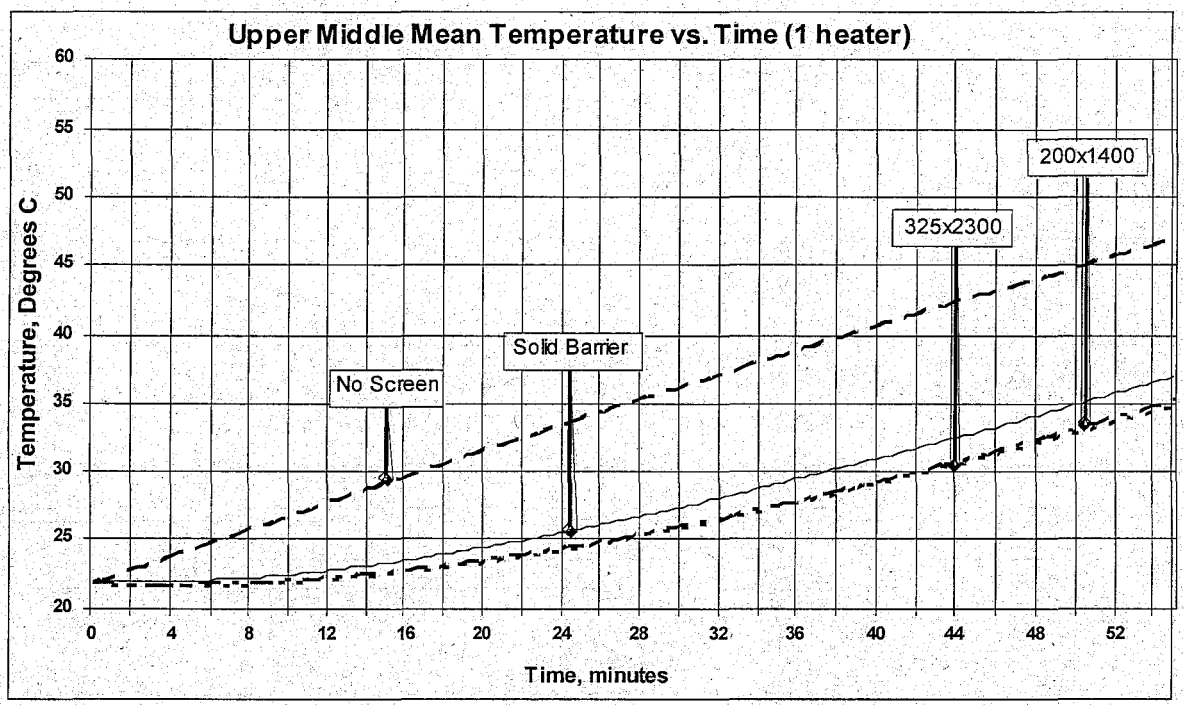

Figure 7. Water Average Upper Middle Temperature vs. Time (low power)

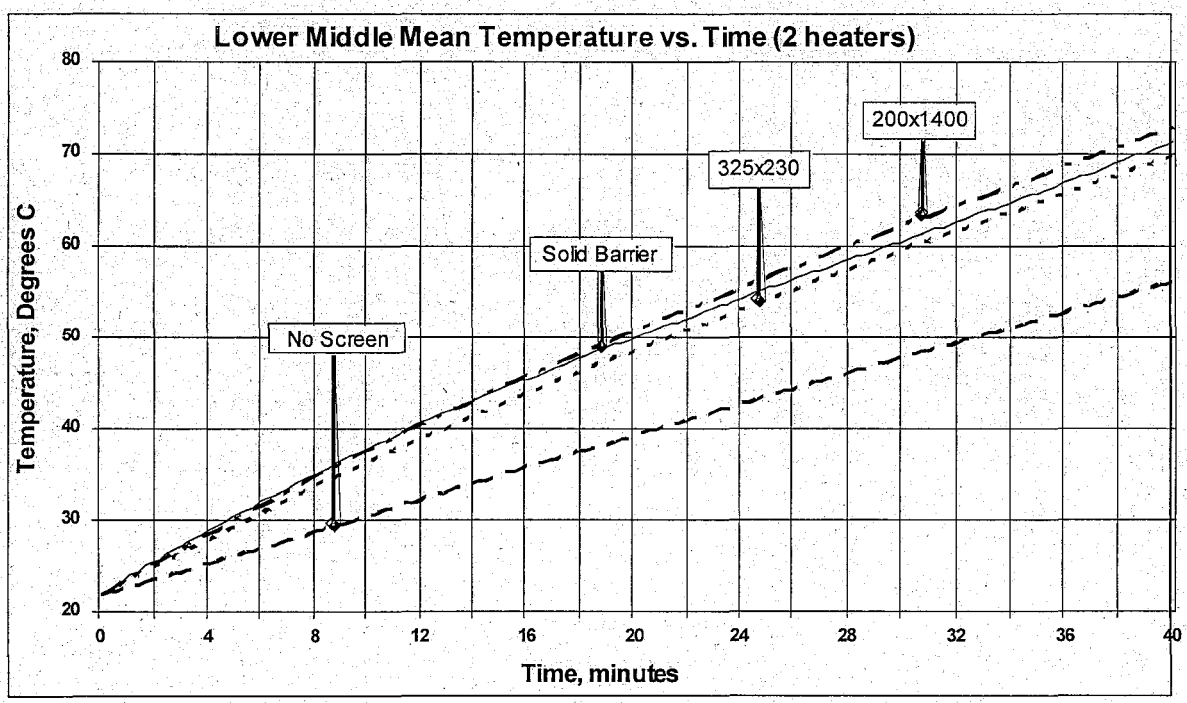

Figure 8. Water Average Lower Middle Temperature vs. Time (high power)

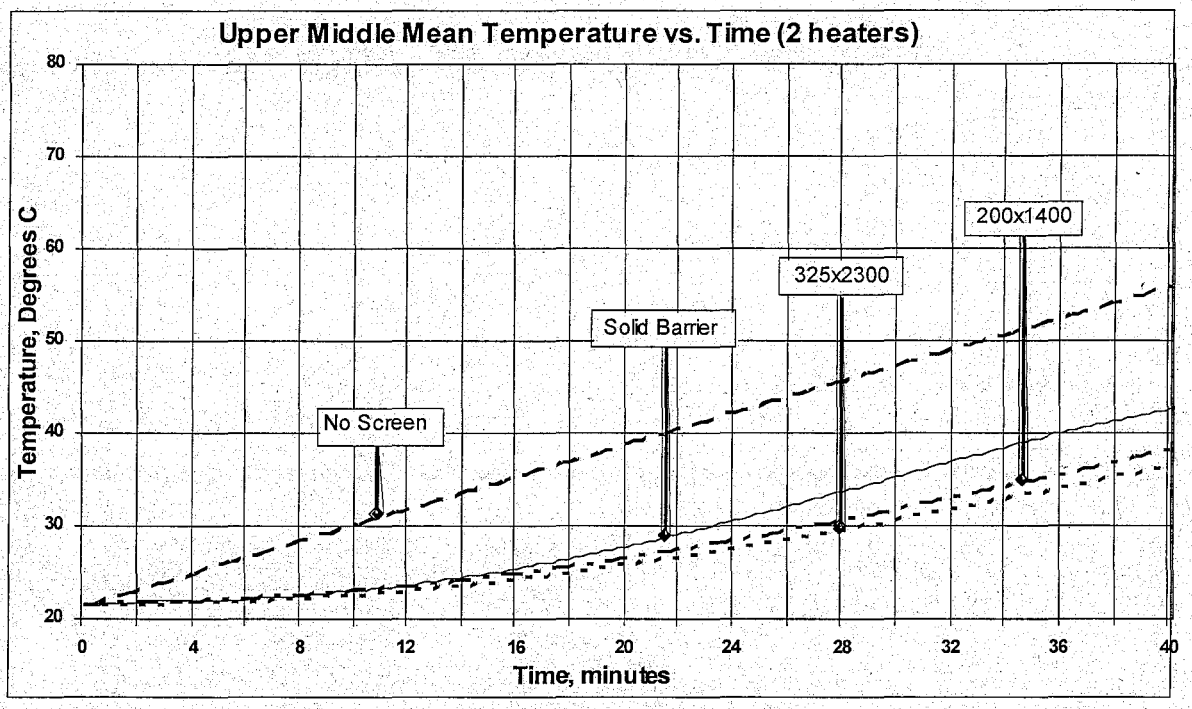

Figure 9. Water Average Upper Middle Temperature vs. Time (high power)

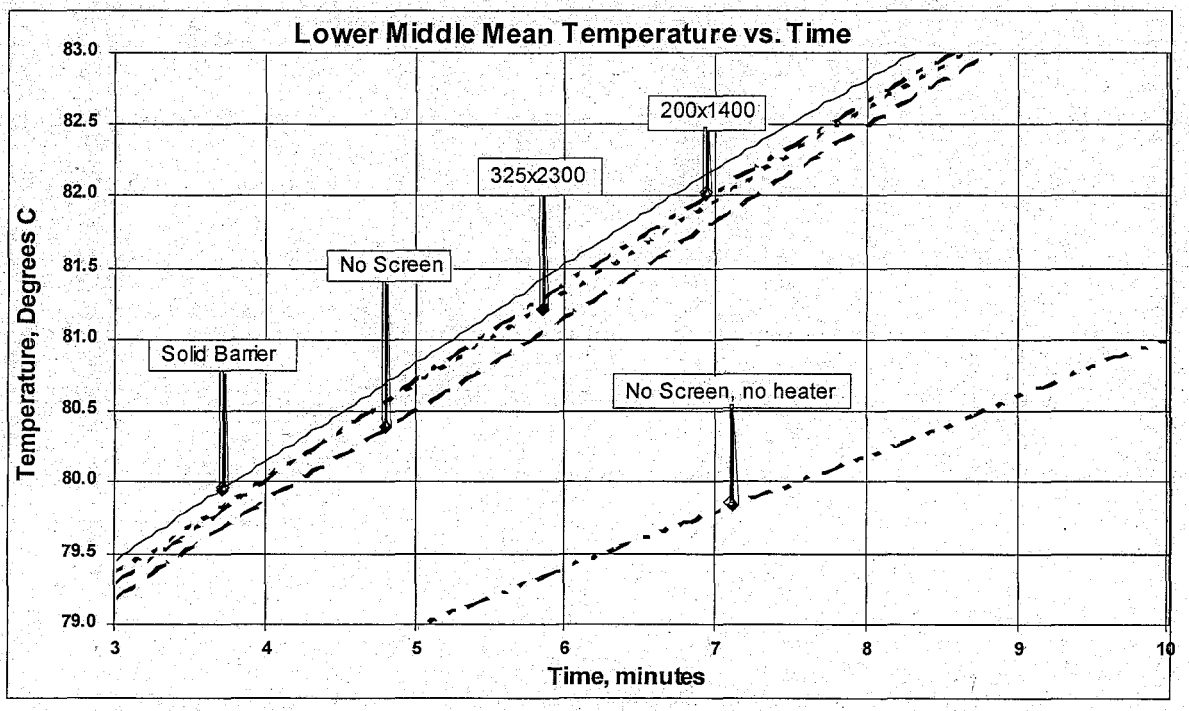

Figure 10. LN2 Average Lower Middle Temperature vs. Time

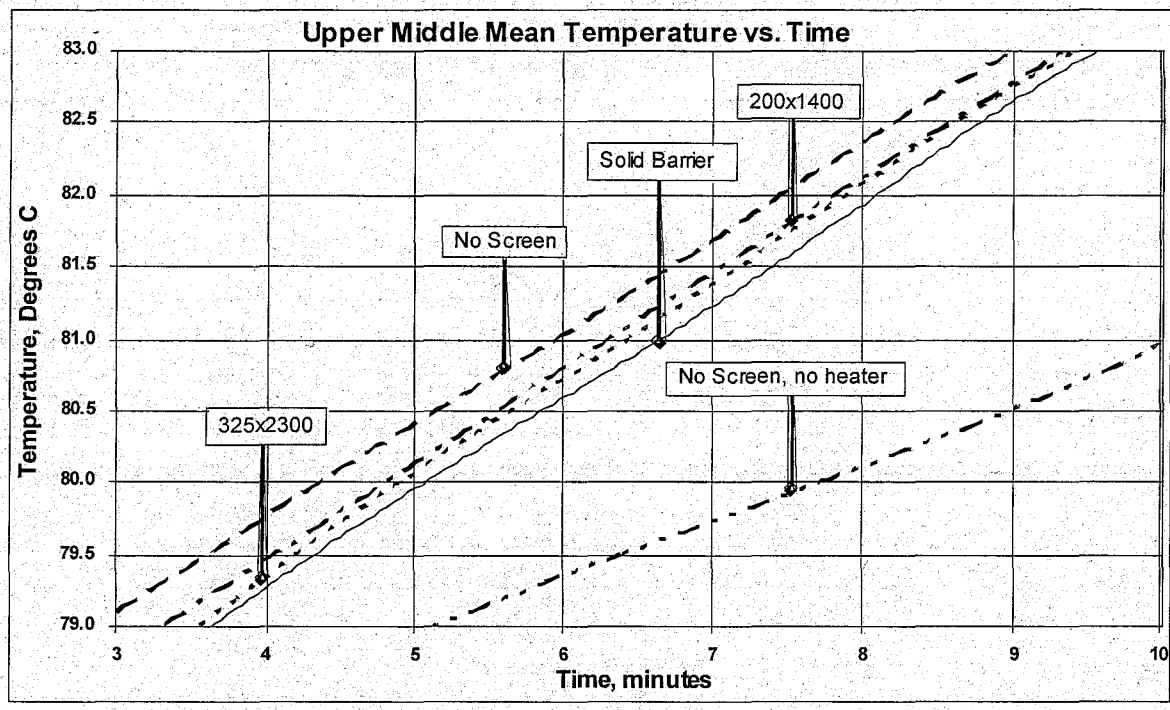

Figure 11. LN2 Average Upper Middle Temperature vs. Time