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CRYOGENIC TESTING OF DIFFERENT SEAM CONCEPTS FOR MULTILAYER INSULATION SYSTEMS

Test Summary Report
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ABSTRACT

Recent testing in a cylindrical, comparative cryostat at the Cryogenics Test Laboratory has focused on various seam concepts for multilayer insulation systems. Three main types of seams were investigated: straight overlap, fold-over, and roll wrapped. Each blanket was comprised of 40 layer pairs of reflector and spacer materials. The total thickness was approximately 12.5-mm, giving an average layer density of 32 layers per centimeter. The blankets were tested at high vacuum, soft vacuum, and no vacuum using liquid nitrogen to maintain the cold boundary temperature at 77 K. Test results show that all three seam concepts are all close in thermal performance; however the fold-over method provides the lowest heat flux. For the first series of tests, seams were located 120 degrees around the circumference of the cryostat from the previous seam. This technique appears to have lessened the degradation of the blanket due to the seams. In a follow-on test, a 20 layer blanket was tested in a roll wrapped configuration and then cut down the side of the cylinder, taped together, and re-tested. This test result shows the thermal performance impact of having the seams all in one location versus having the seams clocked around the vessel. This experimental investigation indicates that the method of joining the seams in multilayer insulation systems is not as critical as the quality of the installation process.

INTRODUCTION

Many different companies have their own preferred methods of designing multilayer insulation (MLI) systems. One of the more difficult areas of analysis for these systems is the effects of the seams and supports on the overall heat leak to the cryogenic tank. In 1975, Sumner attempted to directly measure this effect for a crude butt-seam as well as a penetration on a flat plate calorimeter and compared them to a seamless insulation system. (1) Sumner found a heat leak of 0.3 W/m for this butt joint, this seam was relatively similar to what is termed an overlap joint by the authors, but Sumner overlapped the entire blanket. Other recent tests of MLI systems assume some of their performance is due to their treatment of the seams or elimination of seams (2) (3), though no specific calculations are given. Additionally, many companies within the industry claim their method to be the best method of minimizing the performance impact of insulation seams.

The goal of this test matrix was to determine the performance impacts of various seams as installed on a cylindrical cryostat using a standard test method. The subsequent development of a seam performance database will help serve the interests of all who design and produce cryogenic multilayer insulation.

Figure 1. Cryostat-3, cryogenic insulation test apparatus for cylindrical specimens, with test specimen removed.

EXPERIMENTAL

The steady-state liquid nitrogen boil-off (evaporation rate) calorimeter methods established by the Cryogenics Test Laboratory were used to determine apparent thermal conductivity (k-value) of insulation material systems. The cylindrical test apparatus, Cryostat-3, shown in Figure 1, includes a cold mass of overall dimensions 5.2-inch diameter by 21.0-inch length and provides comparative k-values for insulation systems. The ten inch liquid nitrogen tank has five aerogel disks on both top and bottom of it to minimize the parasitic heat leak into the tank. The insulation system is wrapped around both the liquid nitrogen tank and the aerogel disks so that the total heat leak into the liquid nitrogen tank can be measured. A simplified schematic of the insulation test article is given in Figure 2. Comparison of results to results of the same material tested on Cryostat-100, an absolute calorimeter, can be used to calibrate the results from Cryostat-3 (4).

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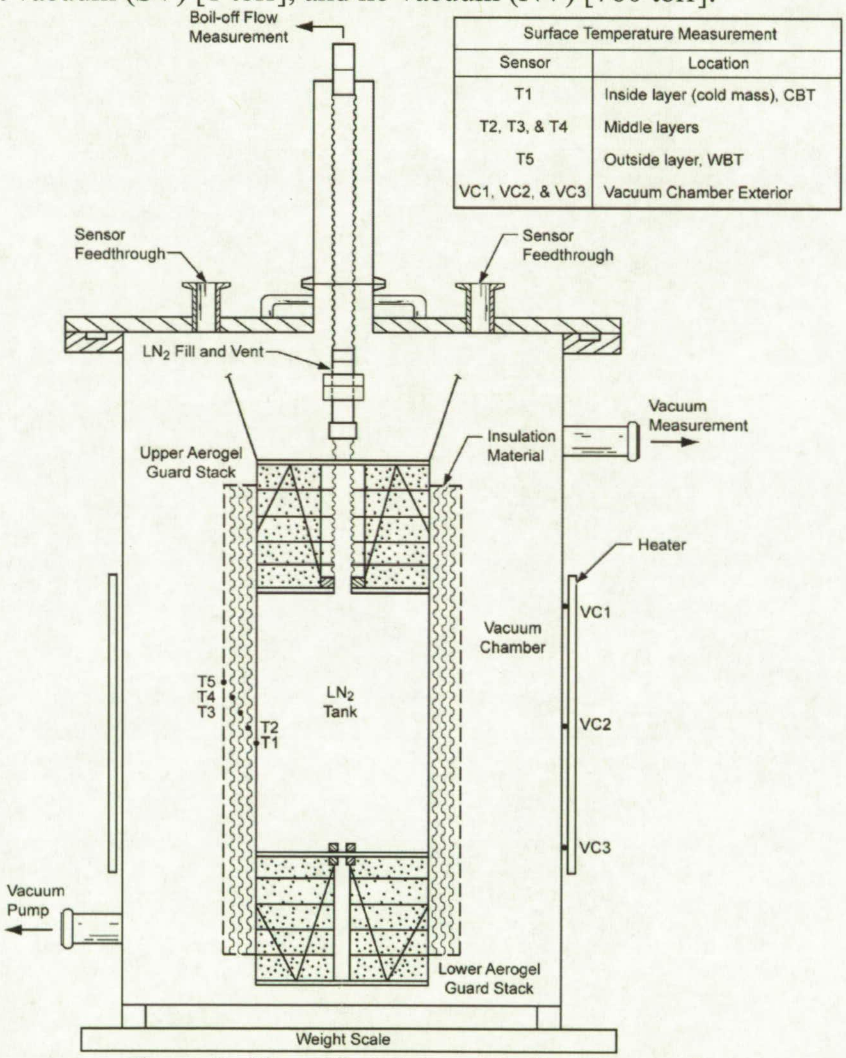
The liquid nitrogen cold mass maintained the cold boundary temperature (CBT) at approximately 78 K (-319°F). The warm boundary temperature (WBT) was maintained at approximately 293 K (+68°F) using an external heater. The difference between the WBT and CBT (ΔT) was therefore 215 K (387°F) while the mean temperature was 186 K (-125°F). Vacuum environments, or cold vacuum pressures (CVP), included the following three basic cases: high vacuum (HV) [below $1x10^{-4}$ torr], soft vacuum (SV) [1 torr], and no vacuum (NV) [760 torr].



Surface Temperature Measurement	
Sensor	Location
T1	Inside layer (cold mass), CBT
T2, T3, & T4	Middle layers
T5	Outside layer, WBT
VC1, VC2, & VC3	Vacuum Chamber Exterior

Figure 2. Simplified Schematic for Cryostat 3.

Additional tests were performed at cold vacuum pressures from 1×10^{-4} torr to 760 torr. Nitrogen was the residual gas within the vacuum chamber for all tests. All tests on Cryostat-3 are calibrated using the known thermal performance of glass bubbles. (5)

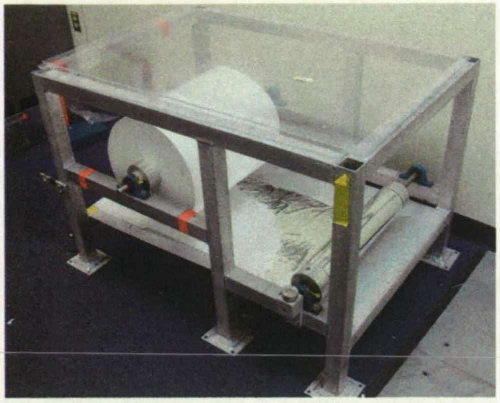


Figure 3: Cryostat – 3 rolling machine

INSULATION TEST MATERIALS

Five test series were run to test the comparative insulation value of various combinations of aerogel and multilayer insulation. Three different seam options were tested with 40 layers at one half of an inch thick. The last two were tested with 20 layers and identical thicknesses. Roll-wrapped MLI was tested at both 40 and 20 layers. All tests were run with double aluminized mylar as the reflectors and tissuepaper as the spacer. Thermocouples were included throughout each of the blankets on the same layers every time.

For the first test series (T204), 40 layers were roll-wrapped (continuously wrapped) around the cryostat cold mass using the roll-wrapping machine seen in Figure 3. The second (T205) and third (T206) test series were laid up layer by layer using overlapped and fold-over methods for handling the seams. These methods are illustrated in Figures 4 and 5. The insulation set-ups were tested at various vacuum levels from high vacuum to soft vacuum, generally ending at 1 Torr, where the heat flux through the insulation was higher than the external heaters could maintain. This caused the warm boundary temperature to be lower than 293 K.

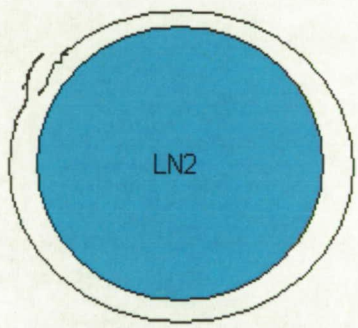


Figure 4: Overlapped seams

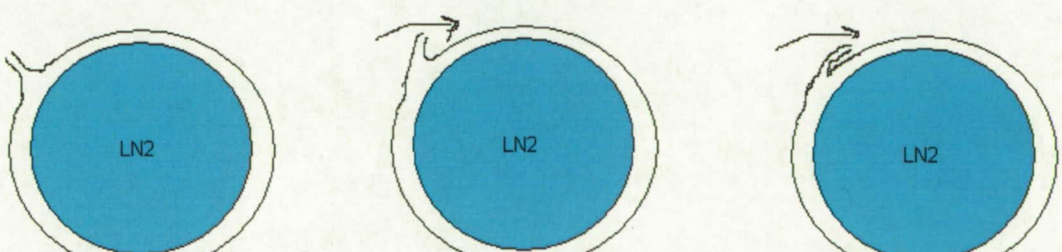


Figure 5: Method of fold over seam installation

Next a series was run with a 20 layer MLI blanket (T211). The original blanket was continuously wrapped around the cryostat for testing. After that test, a 28 cm seam was cut into the side of the MLI then completely taped over and the specimen was retested (T212 test 1). Then two more seams were added approximately 120 degrees apart from the original seam, additionally, the original seam was extended (T212 test 2-3). The original seam was extended to 33.5 cm in length and 1 mm in width while the new seams were 33.5 and 34 cm in length respectively and 1 mm wide. Each seam was closed with a single 1 inch piece of aluminized tape as shown in figure 6.

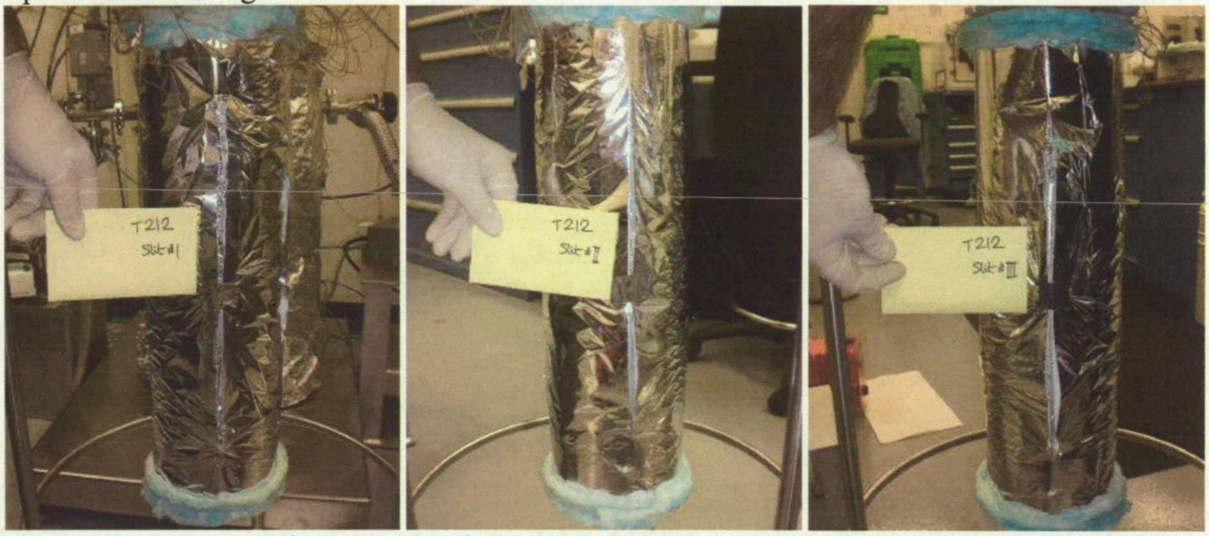


Figure 6: The three seams cut into the T212 test article.

ANALYSIS

Using the Lockheed equation for double aluminized mylar with tissuepaper spacers (eq. 1), the flat plate heat flux for 40 layers with a thickness of half of an inch (the layer density would then be 80 layers per inch or 31.5 layers per cm) is 1.3 W/m^2. (ref 6) When the number of layers is decreased to 20 layers, the heat flux increases to 2.6 W/m^2 at a pressure of 0.3 microns.

(1)

As the pressure is reduced to high vacuum, the heat flux approaches 0.44 and 0.90 W/m^2 respectively. Similarly equation 2, from a previous Lockheed report to NASA suggests the flat plate heat fluxes are approximately 0.80 and 0.38 W/m^2. However, this report contained no factor to account for pressure. Equation 2 from Reference 7 uses the English system of units.

(2)

Which is then converted to total cylindrical heat transfer by:

(3)

Table 1 contains a summary of the various results compared to the actual measured heat transfer from T204 (roll wrapped, 40 layers) and T211 (roll wrapped 20 layers). The roll wrapped blanket is used for reference because it was tested at both 20 and 40 layers.

Reference	Flat Plate	Flat Plate	Cylindrical	Measured	Measured

(number of layers)	Heat Flux (High Vacuum)	Heat Flux (0.3 microns)	Total Heat (0.3 microns)	Total Heat (0.3 microns)	Correction Factor (Roll Wrap)
Reference 6 (20)	0.49	2.7	0.31	0.18	0.58
Reference 6 (40)	0.24	1.3	0.16	0.15	0.96
Reference 7 (20)	1.0	3.1	0.36	0.18	0.50
Reference 7 (40)	0.38	1.4	0.17	0.15	0.86

Table 1: Summary of Analytical Results and Correction Factors

Similarily, analytical equations have been derived for seams in MLI. A group led by Hinckley[8], derived this equation for the heat input per unit length along a seam by defining an effective width, δ_{eff}:

$$\frac{\dot{Q}_{seam}}{L_{seam}} = \frac{\delta_e \sigma (T_H^4 - T_C^4)}{\left(\frac{2}{\varepsilon} - 1\right) n}$$

Where $$\frac{\delta_e}{t} = \left(\frac{2}{\varepsilon} - 1\right) n * fn\left(\frac{\delta}{t}\right)$$

And $$fn\left(\frac{\delta}{t}\right) = \sqrt{1+\varphi^2}\left(\frac{1}{3} - \frac{2\varphi^2}{3}\right) + \left(\frac{2\varphi^3}{3} - \frac{1}{3}\right) + \varphi^2 \ln\left(\frac{1+\sqrt{1+\varphi^2}}{\varphi}\right)$$

$$\varphi = \frac{\delta}{t}$$

The seams cut in the second portion of the test were approximately 1 mm wide, while the thickness of the blanket was 5 mm thick yielding $\varphi = 0.2$. Solving for Q/L using the appropriate dimensions from the blanket tested, returns 0.16 W/m.

RESULTS

The first three tests with 40 layers were all fairly close for the extent of the pressure range tested. Figure 7 shows the calibrated (accounting for the extra heating through the top and bottom of the cryostat) data for the various seam configurations. In the soft vacuum range, all three MLIs performed approximately the same, as the cold vacuum pressure dropped below 10 millitorr, the fold-over seams began to distinguish themselves as slightly better than both the overlap and the roll-wrap. At high vacuum (10^{-5} Torr), the fold-over configuration was approximately twice as efficient as the other two. Both the roll-wrap and overlap configurations were nearly identical for the whole range of pressures.

Figure 8: An as cut seam for T212 Tests 2 and 3

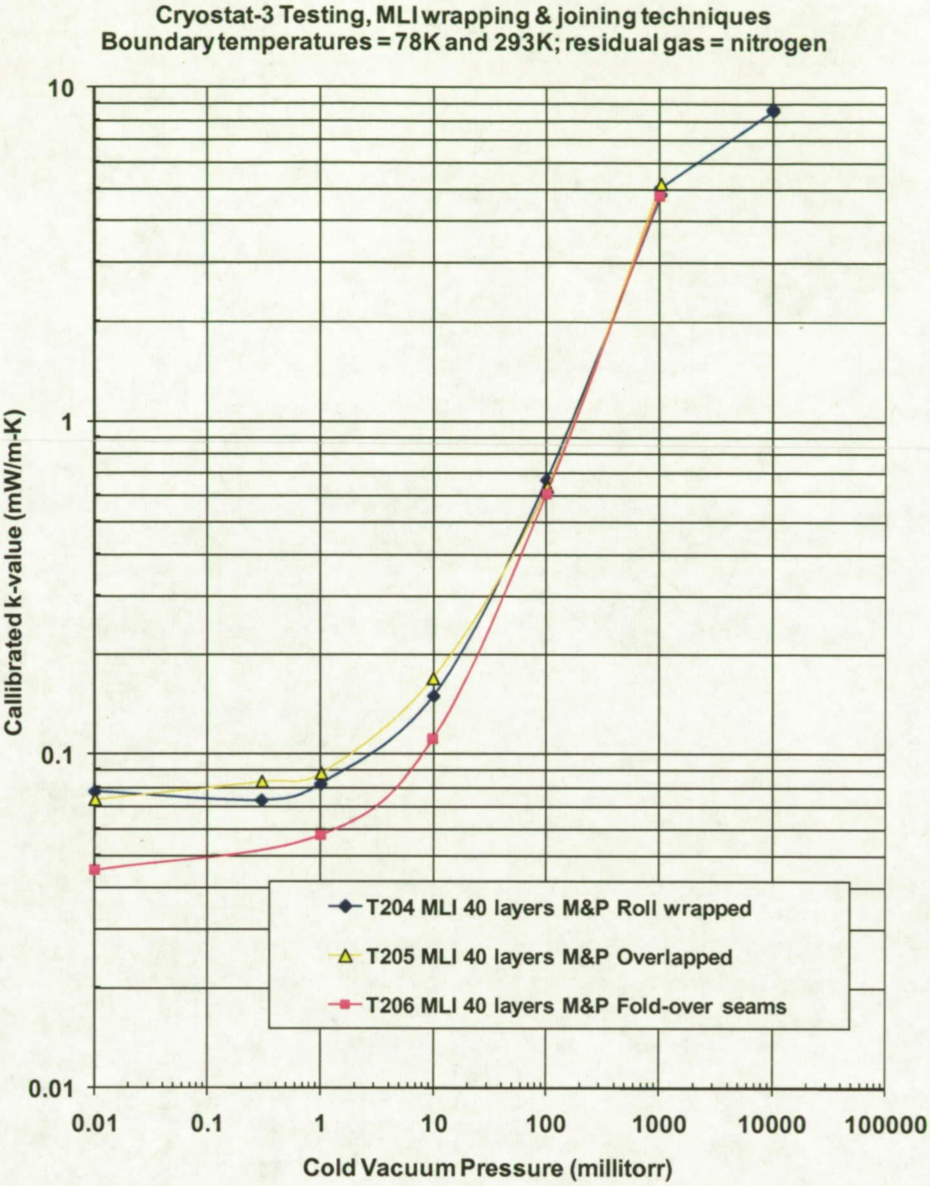


Figure 7: Heat Leak for Various seams as a function of Cold Vacuum Pressure

The second portion of testing involved mechanically cutting seams into roll-wrapped insulation blankets. The initial seam that was entirely closed with a single piece of aluminized tape showed no degradation. However, the second set of seams that were cut added 50% to the heat leak (see Figure 8). Upon disassembly, it was discovered that even after the enlargement of the first seam for the second test, it was not fully cut through to the cold mass as the other two seams were. This was due to the presence of thermocouples in the area of the seam. The authors were much more cautious cutting into the original seam than the other seams due to concern over cutting a thermocouple wire and losing temperature data through the blanket. Figure 9 shows how these temperature sensors near the first seam were affected. It is thought by the authors that there was no apparent change in thermal conductivity because the bottom few layers were not well cut, therefore minimizing the effects of the seam during T212, Test 1 even though there was a slight change in the layer temperatures close to the cold mass. These temperatures then changed drastically when the seam was widened and the other two seams cut for Tests 2 and 3. This was obviously a large enough difference to be noticed as a change in thermal conductivity.

Test Name	Number of Seams	Total Seam Length (m)	Comparative Heat Leak (W)	Excess Heat per Seam Length (W/m)
T211, Test 1	0	0	0.45	N/A
T212, Test 1	1	0.28	0.45	0.00
T212, Test 3	3	1.01	0.63	0.18

Table 2: Additional data for various seam configurations, all have 20 layers of MLI (DAM and paper)

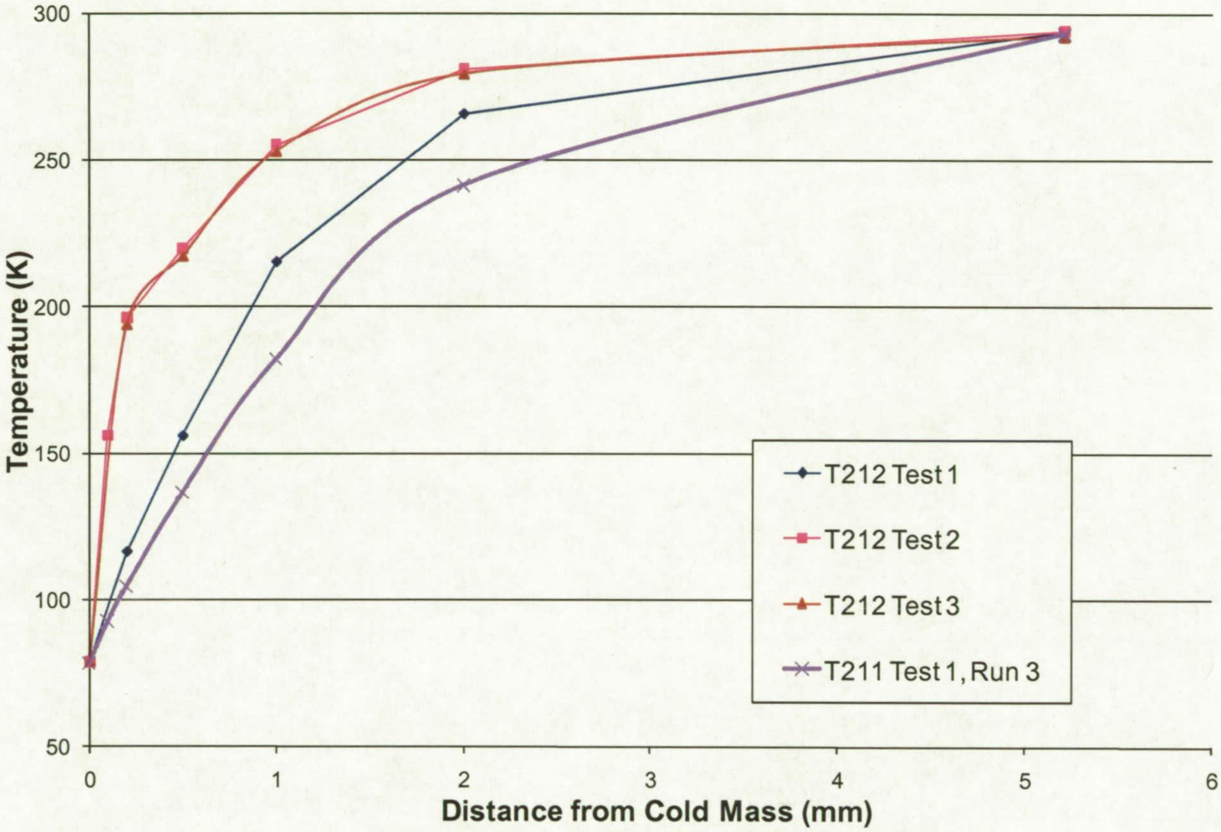


Figure 9: Temperature Profiles for T212 Seam Tests.

CONCLUSIONS

A thorough, scientific study of the effect of multilayer insulation system seams has been conducted at the Cryogenic Test Laboratory at the Kennedy Space Center. This study has led to the beginning of a database containing various seam installations and their effect on the total installation performance. All testing was done using the standard test procedure developed at for use with KSC's Cryostat-2/3.

It can be concluded from the first series of three tests, that if handled properly, seams will not degrade the thermal performance of an MLI system. For these insulation systems, the layers were hand applied individually to the cold mass. Additionally, the seams were offset 120 degrees around the cold mass to prevent direct radiation tunneling through the seam. Such well prepared seams showed little to no decrease in thermal conductivity; in fact the fold over seam improved the thermal conductivity of the insulation system.

The seam that was cut originally showed a small amount of degradation due to the seam, but the aluminized tape that was placed over the entire seam held the seam together and minimized any effects that were seen. This reinforces the notion that the insulation that is closest to the cold mass is the most important portion of the insulation system. When the seam was opened up further, with the exterior tape removed, the temperature profile changed drastically with much more of the temperature change occurring over the first few layers. With the additional 2 seams that were cut, a 50% increase in comparative thermal conductivity was measured. The measured heat leak per length of seam was predicted by Hinckley. Sumner's measurement was different by a factor of two due to the method of his seam. Sumner's use of the full blanket overlap allowed the top and bottom radiation shields to touch and caused a direct short to the cold mass.

ACKNOWLEDGEMENTS

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Symbols:

- C – Constant depending on the subscripts
- L – length
- k - thermal conductivity
- n – number of radiation shields
- $\bar{N}$– layer density of radiation shields (layers/cm or layers/in)
- P – gas pressure within the MLI
- Q – Heat input
- q - Heat flux (Heat input per unit area)
- T – Temperature
- t – thickness of MLI blanket

Greek:

- δ – seam width
- ε - total hemispherical emissivity
- σ – Stefan-Boltzman constant ($5.67*10\text{-}8\ W*m^{-2}*K^{-4}$)
- φ – ratio of seam width to blanket thickness

Subscripts:

- C – Properties of the cold boundary
- e – effective property (as in one that is from a correlation)
- g – Gaseous conduction coefficient
- H – Properties of the warm boundary
- i – inner radius
- o – outer radius
- r - Radiation coefficient
- s1 – First solid conduction coefficient
- s2 – Second solid conduction coefficient