Performance of MLI Seams between 293 K and 20 K

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Abstract. The performance of multilayer insulation systems (MLI) are often determined not by the bulk acreage insulation but rather by the design details that allow the insulation to be attached to the hardware it is insulating. To help understand the impacts of multiple different types of seams on blanket performance, calorimeter testing was performed at Glenn Research Center. Seams investigated included interleaved seams, butt seams, and overlapped seams; the latter two types of seams with multiple sub-blanket offsets built into the seam. Results showed that the interleaved seam had the best performance, and butt seams outperformed overlapped seams. Furthermore, if overlap seams are used, the sub-blankets should be overlapped by less than two inches.

1. Introduction
The recommended solution to minimize radiative heat loads on cryogenic propellant tanks in the space vacuum environment is to insulate them with multilayer insulation (MLI). MLI is constructed with layers of metallized (aluminum, gold) substrate films (Mylar, Kapton), which act as low emissivity radiation shields. Low thermal conductivity spacers separate the layers. The total number of layers is variable but can be on the order of 50 for long duration missions. MLI is known as “super insulation” and is the best known insulation for cryogenic tanks in space.

Loss of performance in MLI systems due to joints and seams in the insulation blankets has been recognized as a concern since the introduction of MLI. When attempting to insulate large tanks, seam numbers increase as tank dimensions exceed the roll widths available for insulation materials. Early studies focused more on quantifying the effect of seams in an MLI blanket than understanding the mechanisms. Hinckley [1] provides an early analytical model of heat loss through seams. Over the years, mitigation techniques have been developed. However, these mitigations such as overlapping every layer (interleaving) or precision cutting to minimize the gap are labor intensive and time consuming. Sumner [2] made one of the early studies quantifying the seam leak of a specific multilayer insulation design concept under development by NASA Glenn (then known as NASA Lewis). Sumner’s work is noteworthy in that use of a large calorimeter enabled higher precision. He also recognized that the impact of the seam is not only radiation leak of the joint, but also includes degraded performance of the surrounding MLI due to less than optimal temperature gradients in the nearby insulation layers. Shu, as part of the superconducting supercollider effort, developed a theoretical model of seam behavior [3] and validated it against a series of tests between liquid nitrogen and room temperature [4]. Recently, Fesmire and Johnson [5] re-examined the seam issue with a liquid nitrogen test apparatus at Kennedy Space Center (KSC) and experimentally verified the work by Hinckley. The effort documented in this report represents an effort to extend this work into liquid hydrogen temperatures and study a broader range of seam configurations.
Hinckley [1] derived a general set of equations for direct radiation through an open-butt seam. These equations are shown below and are somewhat typical of radiation terms:

\[ \frac{Q_{\text{seam}}}{L_{\text{seam}}} = \delta \varepsilon \sigma \left( T_H^4 - T_C^4 \right) \left( \frac{2}{\varepsilon - 1} \right) ^n \]  

(1)

\[ \frac{\delta \varepsilon}{t} = \left( \frac{2}{\varepsilon - 1} \right) n \times f_n \left( \frac{\delta}{t} \right) \]  

(2)

\[ f_n \left( \frac{\delta}{t} \right) = \sqrt{1 + \varphi^2 \left( \frac{1}{3} - 2 \varphi^2 \right) + \varphi^2 \ln \left( \frac{1 + \sqrt{1 + 4 \varphi^2}}{\varphi} \right) } \]  

(3)

\[ \varphi = \frac{\delta}{t} \]  

(4)

where \( Q/L \) is the heat leak through the seam, \( \delta \) is the seam width, \( t \) is the seam depth, and \( L \) is the length of the seam. \( T_H \) and \( T_C \) are the warm and cold boundary temperatures of the insulation, \( n \) is the number of MLI layers, \( \sigma \) is the Stefan-Boltzmann constant \((5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4)\), and \( \varepsilon \) is the emissivity of the MLI layers. However, with the addition of multiple staggers of a seam (see figure 1), the thermal models increased in complexity.

![Diagram of overlapped seams (a) vs butt seams (b)](image)

**Figure 1.** Diagram of overlapped seams (a) vs butt seams (b)

2. Test Setup

Testing was conducted at the NASA Glenn Creek Road Cryogenic Complex (CRCC) using the Calorimeter for the Measurement of thermal Performance At Cryogenic Temperatures (CoMPACT) [6]. Unlike conventional calorimeters that use liquid cryogens to determine heat transfer rates via measurement of boil-off rates, CoMPACT is cooled by cryocoolers and relies on a calibrated conduction rod (CCR) to determine heat flow similar to that developed by Celik and Van Sciver [7]. A conceptual drawing of the calorimeter is shown in figure 2.

The calorimeter consists of a cold and a warm surface which are a pair of nested cylinders with flat ends inside a cylindrical vacuum vessel. The warm (outer) cylinder is 0.610 m diameter and 1.473 m long. The cold (inner) cylinder is 0.457 m diameter by 0.914 m long and has 0.457 m diameter by 0.140 m long cylinders attached at the top and bottom ends, acting as guards intercepting heat coming into the top and bottom to minimize the effects of heat transfer at the ends of the test section. The guards are controlled to the same temperature as the test section, but copper sections are thermally separated from the test section by a 0.006 m gap to minimize any undesired heat transfer into the test section. The guards are structurally connected with thermally insulating G10 tabs (see figure 2). The inside of the warm cylinder and outside of the cold cylinder are painted with Aeroglaze Z306 (room temperature emissivity 0.90, solar absorptivity > 0.95, 90 K emissivity approximately 0.7 [8]) to provide a black body surface for the insulation to view. The warm cylinder, test section of the cold cylinder, and the pair of guarded ends on the cold cylinder are each cooled by a cryocooler (3 total, the two guards are controlled by a separate cryocooler than the test section). The MLI test specimen is wrapped around the outside of the cold cylinder.

The conduction rod was calibrated via experimental measurements to uncertainties less than 3%, confirmed using the aluminum thermal conductivity recently published by Tuttle [9].
2.1. Test coupons

Two sets of coupons were fabricated for testing: one 50 layer set and one 20 layer set. Both were made of two sub-blankets and had coversheets to ease handling. The 50 layer blanket was on hand from previous testing. The 20 layer blanket was fabricated by Yetispace for this effort. The blankets are summarized in Table 1. The Yetispace coupons were similar in design to those tested by Vander Laan [10].

Table 1. Description of Yetispace built and existing coupons.

| Feature                        | Yetispace   | Existing Blankets |
|-------------------------------|-------------|-------------------|
| Number of layers (total)      | 20          | 50                |
| Number of sub-blankets        | 2           | 2                 |
| Number of layers per sub-blanket | 10        | 25                |
| Reflector Substrate           | Polyester   | Polyester         |
| Reflector Deposited Metal     | Aluminum    | Aluminum          |
| Reflector thickness           | 0.00635 mm (0.25 mil) | 0.00635 mm (0.25 mil) |
| # spacers thicknesses per reflector | 2          | 2                 |
| Spacer Material               | Dacron B2A  | Polyester         |
| Spacer Thickness              | 0.1778 mm   | 0.1778 mm         |
| Covers thickness              | 5 mil       | 5 mil             |
| Design Sub-blanket Thickness  | 0.42 cm     | 1.59 cm           |
| Design layer density          | 24 lay/cm   | 16 lay/cm         |

2.2. Calorimeter test matrix

A total of nine tests were run, five with the 50 layer blanket and four with the 20 layer blanket. Similar seam concepts were tested on both blankets. The completed test matrix is shown in Table 2. The configuration of butt seams and overlapped seams are shown in Figure 1. The interleaved seam was assumed to be the same as no seam based on the work by Johnson [5].
Table 2. Test Matrix as completed

| Test Number | Description       | MLI Layers | Seam Construction | Offset, x, (in) |
|-------------|-------------------|------------|-------------------|----------------|
| 1           | Overlap seam      | 50         | 1 stagger         | 2              |
| 2           | Interleaved Seam  | 50         | N/A               | N/A            |
| 3           | Butt seam         | 50         | No stagger        | 0              |
| 4           | Butt seam         | 50         | 1 stagger         | 2              |
| 5           | Butt seam         | 50         | 1 stagger         | 4              |
| 6           | Interleaved Seam  | 20         | N/A               | N/A            |
| 7           | Overlap Seam      | 20         | 1 stagger         | 2              |
| 8           | Butt Seam         | 20         | 1 stagger         | 2              |
| 9           | Butt Seam         | 20         | No stagger        | 0              |

3. Test Results
The raw test data is shown in table 3. $T_{chamber}$ is the averaged temperature of the vacuum chamber wall sensors over the duration of the steady state period of the test, and $Q_{total}$ is the conduction heat load down the CCR. Figure 3 shows the temperature sensor layout of the calorimeter, while only two sensors are shown on the vacuum, in fact 9 sensors are spaced around the vacuum chamber wall. In general, the calorimeter was quite stable. Plots of various temperature locations are shown in figure 4 (environmental temperatures), figure 5 (differential calibration rod temperatures referenced to SD-31), and figure 6 (cold boundary temperatures). Figure 5 and figure 6 do show a slight increase in temperature during the test time frame (180 hr to 210 hr) at less than 1 mK/hr, or a heating rate of 0.28 mW. On figure 6, SD-16 ran slightly warmer than the rest of the sensors for an unknown reason. During tests 6 – 7, SD-31 was not functional, so SD-32 and SD-33 were used to calculate the heat load going down the CCR.

![Figure 3. Temperature sensor locations for use in data plots.](image-url)
Table 3. Raw test data from seams testing.

| Test No. | Configuration       | # of layers | layer density, lay/cm | # of staggerers | Tchamber, K | Tclad, K | Qtotal, W |
|----------|---------------------|-------------|-----------------------|-----------------|-------------|----------|-----------|
| 1        | Overlap             | 50          | 17.4                  | 1               | 299.7       | 22.6     | 0.788     |
| 2        | Interleave          | 50          | 17.1                  | 0               | 305.5       | 21.4     | 0.748     |
| 3        | Butt                | 50          | 18                    | 0               | 290.9       | 21.3     | 0.806     |
| 4        | Butt - 1 stagger, 2 in | 50          | 19                    | 1               | 289.9       | 21.3     | 0.806     |
| 5        | Butt - 1 stagger, 4 in | 50          | 17.9                  | 1               | 292.2       | 21.8     | 0.810     |
| 6        | Interleave          | 20          | 16.6                  | 1               | 286.8       | 24.0     | 1.033     |
| 7        | Overlap             | 20          | 16.6                  | 0               | 286.2       | 22.5     | 1.035     |
| 8        | Butt - 1 stagger, 2 in | 20          | 18                    | 1               | 289.1       | 21.9     | 1.222     |
| 9        | Butt - 0 stagger    | 20          | 18                    | 0               | 288.7       | 21.6     | 1.160     |

Figure 4. Environmental temperatures and cold vacuum pressure during Test 9.
Figure 5. Calibration rod differential temperatures, referenced to SD-31, during test 9.

Figure 6. Cold Boundary temperatures during test 9.
3.1. Results of 50 layer seams tests

Measured heat loads for the five tests conducted are shown in table 4. The interleaved seam is assumed to be the “ideal” seam. Other seam heat loads are calculated as the difference from that seam with the delta shown in the final column.

| Test Number | Run                | Q<sub>total</sub>, watts | T<sub>avg</sub>, K | K<sub>avg</sub>, W/m/K | ΔT, K | Q<sub>net</sub>, W | dQ, W | dQ, W/m |
|-------------|--------------------|--------------------------|------------------|-----------------------|-------|------------------|-------|---------|
| 1           | Overlap Seams      | 0.788                    | 21.06            | 29.8                  | 2.56  | 0.786            | 0.040 | 0.044   |
| 2           | Interleaved        | 0.748                    | 19.16            | 27.3                  | 2.43  | 0.746            | 0.000 | 0.000   |
| 3           | Full Butt          | 0.806                    | 18.85            | 26.9                  | 2.51  | 0.802            | 0.056 | 0.061   |
| 4           | Butt 2” Offset     | 0.806                    | 18.85            | 26.9                  | 2.52  | 0.803            | 0.057 | 0.062   |
| 5           | Butt 4” Offset     | 0.810                    | 19.37            | 27.8                  | 2.56  | 0.807            | 0.061 | 0.067   |

3.2. Results of 20 layer seams tests

Test results for the 20 layer blankets are shown in table 5. The interleaved seam is assumed to be the “ideal” seam. Other seam heat loads are calculated as the difference from that seam with the delta shown in the final column.

| Test Number | Run       | Q<sub>total</sub>, watts | T<sub>avg</sub>, K | K<sub>avg</sub>, W/m/K | ΔT, K | Q<sub>net</sub>, W | dQ, W | dQ, W/m |
|-------------|-----------|--------------------------|------------------|-----------------------|-------|------------------|-------|---------|
| 6           | Interleaved | 1.033                    | 20.38            | 28.9                  | 3.49  | 1.012            | 0.000 | 0.000   |
| 7           | Overlap   | 1.035                    | 18.62            | 26.6                  | 3.65  | 1.015            | 0.003 | 0.003   |
| 8           | Butt 2” Offset | 1.222                    | 17.52            | 25.0                  | 4.21  | 1.199            | 0.187 | 0.205   |
| 9           | Full Butt | 1.160                    | 17.25            | 24.7                  | 4.09  | 1.146            | 0.134 | 0.147   |

4. Discussion of Results

As expected on the 50 layer test, the layer by layer interleaved joint had the lowest heat leak. The overlap joint had a slightly better performance than the straight and staggered butt joints. Surprisingly, staggering the butt joint did not decrease the heat load, and increasing the stagger distance did not help. In fact, the test with the largest stagger was worse than the straight butt joint; although, this may be due to damage incurred by repeated handling rather the joint itself. Even for the worst performing seam, the results are only 5% more heat leak than the best performing seam.

Results with the 20 layer testing are a bit less conclusive; however similar results are seen. The overlap seam still performs very well; in this case, performing nearly identical to the baseline interleaved blanket. The poor performance of the offset butt joint is as yet unexplained being 20% worse than the interleaved blanket. The full butt joint slightly outperforms the offset butt joint and is within 15% of the interleaved blanket.

The theoretical butt seam heat load from Hinckley is on the order of 0.094 W/m for a 20 layer blanket and 0.050 W/m for a 50 layer blankets similar to those tested in this test campaign. Those values are on the same order of magnitude of the 0.15 W/m and 0.06 W/m measured.

5. Conclusions

Experimentation on different seams within multilayer insulation blankets has shown the thermal penalties of various seaming approaches. This penalty decreases with increasing layers as is theoretically expected and matches rather well the predictions from Hinckley. Sub-blanket overlapped joints have
less thermal penalties than butt joints. The testing has shown both better than expected performance for the blanket overlap seam and the performance of a carefully constructed butt seam within 15% of a seam of individually interleaved. The experimental heat loads due to seaming are more than the approximately 8% uncertainty that has been shown due to repeatability testing of a similar number of layers as demonstrated by Vander Laan [10] and Johnson [11], and thus should be considered significant.

6. References

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Acknowledgements

This work was funded by the Evolvable Cryogenics Technology Demonstration Mission, a part of the Space Technology Mission Directorate of the National Aeronautics and Space Administration. The authors would also like to acknowledge Mr. Mark Springowski for his patience with them during the installation of the blankets and testing as well as Mr. Helmut Bamberger, Mr. David Pike, Mr. Chris Detardo, Mr. Bill Vaccariello, and Mr. Keith Johnson for their work in developing and setting up the calorimeter and keeping it running.