Testing of SHIIVER MLI Coupons for Heat Load Predictions

W L Johnson¹, D Oberg², D Frank³, V Mistry³, and F D Koci¹

¹Glenn Research Center, Cleveland, OH, 44135 USA
²Aerospace Fabrication and Materials, Farmington, MN, 55024 USA
³Lockheed Martin Advanced Technology Center, Palo Alto, CA, 94304 USA

E-mail: Wesley.L.Johnson@nasa.gov

Abstract. The Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) is designed to demonstrate the performance benefits of installing multilayer insulation (MLI) and structural vapor cooling onto a large hydrogen tank as a part of an upper stage. The intent of the 4 meter sub-scale demonstration is to design the MLI in a manner that its performance can be scaled to a full sized application. In order to predict the performance of the blankets as well as aid in the design, several features needed to be tested. Four different coupons were tested and evaluated for thermal performance relating to the number of layers, the seams, and the attachment mechanisms. The attachment mechanisms were further tested for structural strength at nominal application temperatures. From the testing, the number of layers were determined to be 30, and heat load penalties were determined for the seams and attachments. The attachment mechanisms passed all load testing with a margin of greater than 40%.

1. Introduction

Cryogenic propellant tanks are insulated with multilayer insulation (MLI) to minimize radiative heat loads in the space vacuum environment. 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 50 layers or more for long duration missions. Loss of performance in MLI systems due to joints, seams, attachments, and other design details of the insulation blankets has been recognized as a concern since the introduction of MLI. When attempting to insulate large tanks, even more seams may be required as the tank dimensions exceed the roll widths available for insulation materials.

In order to demonstrate the application of MLI and other technologies on a relative scale for upper stages, NASA is developing the Structural Heat Intercept, Insulation, and Vibration Evaluation Rig (SHIIVER) [1]. One of the objectives of SHIIVER is to demonstrate the benefits of MLI as applied to upper stage hydrogen and oxygen applications. In order to predict MLI performance for the SHIIVER test, some coupon thermal testing was required to assess thermal impact of design decisions. The data from the coupons also informs scaling methodologies that will use the SHIIVER data and extrapolate the SHIIVER results to larger tank sizes. The initial coupon provided a first look at the probable heat load range that can be expected on the SHIIVER test article. Subsequent articles focused on specific design details and their thermal effects on the expected performance. The testing was informed by the preliminary MLI system design. Of the many design details that could have been tested, the effect of the number of layers was thought to be most likely to change the actual design of the MLI system. This was followed by the seam performance and attachment method. All three factors were tested thermally.
to determine their effect on the thermal performance of the MLI system. The attachment method was also tested structurally to ensure the MLI would be able to withstand appropriate launch and depressurization loads.

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). Unlike conventional calorimeters that contain liquid cryogens and determine heat transfer rates via measurement of boil-off rates, CoMPACT is cooled by cryocoolers and relies on a calibrated conduction rod to determine heat flow similar to the method developed by Celik and Van Sciver [2]. A conceptual drawing of the calorimeter is shown in figure 1.

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 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 [3]) 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 [4].

![Figure 1. Calorimeter for the Measurement of thermal Performance At Cryogenic Temperatures (CoMPACT)](image-url)
2.1. Test coupons

The test coupons were designed and fabricated by Aerospace Fabrication and Materials (AFM), who is also under contract for design, fabrication, and installation of the SHIIVER MLI blankets. The first coupon (Coupon #1) was constructed of 50 layers split into 5 sub-blanks of 10 layers each and the remaining three coupons consisted of three sub-blanks of 10 layers each (30 total layers). The innermost side and outermost side of the MLI system had a cover sheet, however, after the first sub-blanket, the innermost side was netting that was laminated and held in place on the inside reflector to keep reflectors from consecutive sub-blanks from touching. Fastener tape was placed between the sub-blanks to hold them to each other, but the fastener tape pieces were not sewn all the way through each sub-blanket. Instead, each piece of fastener tape had pressure sensitive adhesive on the back of it and was stuck with clothing tags to hold the fastener tape in place. Fastener tape was also placed on each side of the sub-blanket to fasten it to itself. The inner sub-blanket was held to the calorimeter by six click-bond 9208 fasteners that were cut to length. Each click-bond went through an x that was cut in the blanket.

For the second test (Coupon #2), the outer three blankets of Coupon #1 were removed and only a new outer sub-blanket was installed. The new outer sub-blanket was built the same as the outer sub-blanket for coupon #1 with the exception of the width.

Each sub-blanket for Coupon #3 (for Test 3) had two halves that were joined with fastener tape strips similar to the joint on the edges on the single section sub-blanks (see figure 2). With this two seam configuration, the seams were spaced 180 degrees apart on the calorimeter.

Coupon #4 was the same as Coupon #2, except it had four tabs from which structural attachment of the blanket would be achieved (see figure 3) on the outside of the outer layer. These were oriented in two pairs of two around the calorimeter and at separations of 120 degrees from themselves and the seam. The tabs consisted of two rows of stitching with 13 holes in the first row and 14 holes in the second row for the stitching to go through. The stitching only goes through the outer sub-blanket. These tabs represented AFM’s structural attachments from the MLI to the SHIIVER test article.

Five separate coupons were made for structural pull testing of the SHIIVER structural attachments. These coupons were identical to a single sub-blanket in construction.

![Figure 2](image.png)
2.2. **Calorimeter test matrix**

The calorimeter test matrix is shown in table 1. This allowed for early testing of the elements that might change the design (i.e. number of layers) and later testing of elements that would be used to analyze the design. Initially test 4 was discussed as being a compressed MLI coupon test, however, when structural changes in the blanket from the Click-Bond to the grommet tabs were made that included stitching, a change was made to the test matrix to ensure the stitching was tested.

| Test (Coupon) Number | Description                | Number of MLI Layers | # of Seams | # of Structural Patches |
|----------------------|----------------------------|----------------------|------------|-------------------------|
| 1                    | Baseline Test              | 50                   | 1          | 0                       |
| 2                    | Reduced layer Count        | 30                   | 1          | 0                       |
| 3                    | Two Seams                 | 30                   | 2          | 0                       |
| 4                    | Structural Attachments     | 30                   | 1          | 4                       |

3. **Test Results**

The raw test data is shown in table 2 (the cold boundary is averaged over the six sensors on the test section). $T_{chamber}$ is the average of the nine temperature sensors on the vacuum chamber wall and $Q_{total}$ is the conduction heat load down the CCR, $Q_{net}$ is $Q_{total}$ minus the known structural parasitic heat loads. In general the calorimeter was quite stable, plots of the cold boundary temperature versus time are shown in figure 4. Figure 5 shows the differential temperatures along the calibrated conduction rod during testing. The top and bottom temperature sensors on the rod were used to calculate all heat loads down the calibration rod. As seen in Figure 4, several of the tests started to oscillate in a 24 hour period with the ambient temperature.

| Coupon Number | Configuration         | # of layers | layer density, lay/cm | Warm Boundary, K | $T_{chamber}$, K | $T_{cold}$, K | $Q_{total}$, W |
|---------------|-----------------------|-------------|-----------------------|------------------|------------------|----------------|-----------------|
| 1             | Baseline Test         | 50          | 18.5                  | 260              | 289.3            | 20.9           | 0.937           |
| 2             | Reduced layer Count   | 30          | 15.8                  | 260              | 287.4            | 20.8           | 0.928           |
| 3             | Two Seams             | 30          | 16.7                  | 261              | 287.1            | 21.7           | 1.062           |
| 4             | Structural Attachments| 30          | 16.7                  | 260              | 286.4            | 21.8           | 0.979           |
3.1. Results and discussion of the different number of layers

Measured heat loads for the two tests with different number of layers are shown in table 3. It can be seen that there are nearly identical heat loads and very similar heat fluxes for the two tests. Both tests were run with a single seam through the coupon. The test system was seen to perform almost identically.
for the two tests. The warm boundary for both tests was approximately 260 K. The main difference can be observed to be the layer density. Since the 20 inner layers for the second test were installed identically to the first test (the only change was the removal of the outer three sub-blanks and addition of an outer sub-blanket of the correct size), this would suggest that the first test had a lower layer density on the inner layers as well. This suggests that the trend of nearly identical heat fluxes is representative.

### Table 3. Test results for 50 layer blanket, component calibration

| Coupon Number | Configuration | \( Q_{total} \), W | \( Q_{net} \), W | Thickness, cm | Layer Density, Lay/cm | \( q_{net} \), W/m² |
|---------------|---------------|-------------------|-----------------|---------------|-----------------------|------------------|
| 1             | 50 Layers     | 0.937             | 0.931           | 2.7           | 18.5                  | 0.670            |
| 2             | 30 Layers     | 0.928             | 0.923           | 1.9           | 15.8                  | 0.674            |

3.2. Results of two seams test

Test results for the single and double seam blankets are shown in table 4. All tests were run with 30 layers and no attachments. The warm boundary for both tests was approximately 260 K. The change in the net heat load due to the addition of a seam was 135 mW, over an effective seam length of 0.91 m, that is 0.147 W/m. While the layer density of the system changed slightly, this was due to a circumferential measurement difference of 6 mm (0.25 inches). This suggests that just over 13% of the heat load through the single seam coupon was due to seam heating. This value is similar to recently reported values by Chato [5]. Temperature sensors for all three initial tests used type-E thermocouples to record warm boundary temperatures both near the seam and either opposite to the seam or between two seams. Typically the difference between the measurements on the two sides was 1 – 2 K, approximately the uncertainty of a type-E thermocouple.

### Table 4. Test results for single and double seams

| Coupon Number | Configuration | \( Q_{total} \), W | \( Q_{net} \), W | \( Q_{seam} \), W | % change |
|---------------|---------------|-------------------|-----------------|-----------------|----------|
| 2             | Single Seam   | 0.93              | 0.92            | 0.135           | 14.6%    |
| 3             | Double Seam   | 1.06              | 1.06            | 0.27            |          |

3.3. Results of attachment test

Test results for the proposed attachment mechanisms onto the SHIIVER tank compared to the thirty layer case (Test #2) are shown in table 5. Note that in the thermal testing, the attachment had the same optical properties as the outer coating, but in structural testing, where the optical properties didn’t matter, cheaper, non-aluminized materials were used. The total of four stitched attachments added a total of 52 mW to the measured heat load. Additionally, the temperature sensors (type-E thermocouples) were placed on the inside of the blanket, one right under the stitching of one attachment and the other halfway in between two attachments. These recorded a temperature difference of 28 K between the attachment and the sensor that was between the two attachments. This suggests that the stitching of the attachment caused significant shorting of the blanket in that area, although no warm boundary temperatures were measured as they were assumed to be similar to previous testing. Each attachment consisted of two rows of stitching, one row had 14 holes (13 stitches) and the second had 13 holes (12 stitches). Based on the recorded data, hole size, and model proposed by Johnson [6], the thermal penalty appears to be appropriate (see next section).

### Table 5. Test results stitched attachment

| Coupon Number | Configuration | \( Q_{total} \), W | \( Q_{net} \), W | \( Q_{attach} \), W | WBT, K | \( T_{stitch} \), K | \( T_{blanket} \), K |
|---------------|---------------|-------------------|-----------------|-----------------|--------|------------------|------------------|
| 1             | 30 layer, no attachment | 0.93              | 0.92            | 0               | 261    | N/A              | N/A              |
| 2             | Attachments   | 0.98              | 0.97            | 0.05            | 261*   | 235              | 207              |

*not measured, assumed to be identical to previous testing
3.4. Structural Test Results

Five coupons were tested structurally via pull testing at -80°C, representative of the expected temperatures on the outside of a cryogenic fuel tank in Earth orbit. These consisted of a strip of 10 layers of MLI that was wide enough to hold the patch and approximately 0.3 m long. The stitching was the same as was tested in the last calorimeter coupon (Coupon #4) test and the grommet only went through the tab. The expected load for each patch is 268 N. Using a safety factor of 1.4, the load requirement for the patches is 376 N. Due to a problem in the testing hardware, on three of the five test segments, the highest load that could be applied was 500 N—this was cyclically applied with the coupons surviving up to five cycles at 500 N. The other two coupons failed at 655 N.

4. Discussion of Results

Two specific investigations were conducted, the first insured that the seams coupon testing did not have any interaction between the two seams and the second compared the stitching heat loads to previously developed calculation methodologies.

4.1. Investigation into the Seams Testing

To determine if a significant disturbance in the blanket can propagate far away from the disturbance, a Thermal Desktop® model was created of the 30 layer calorimeter coupon with both perpendicular and parallel conductivities of the MLI between each layer, connected by radiation and conduction ties. The model took a longitudinal strip of a 42 layer/inch blanket and compressed it by a factor of two as shown in figure 6. The layer density is updated to twice the coupon value to simulate 50% compression in the area. The area compressed is approximately 6.4% of the total area of the blanket.

Figure 6 shows the temperature of a shield ¼, ½ and ¾ of the way through the 30-layer blanket. Each of the pictures shows the average temperature of the layer and the temperature gradient from the compressed location outward. The results show that the disturbance does not propagate more than a quarter way around the blanket. This would indicate that the test of the two seam coupon showed the entire effect of the second overlap should have been measured.

![Figure 6. Temperature profile through the 30 layer blanket with a strip compressed shows that the disturbance does not propagate more than a quarter of the way around the blanket.](image)

4.2. Calculations on the Stitching of the Structural Flaps

To calculate the suggested heat flow through the stitching, both a radiation model and a conduction model were set up as suggested by Johnson [6]. The conduction model was a 20 node model using NIST’s data for nylon thermal conductivity [7], a thread diameter of 0.25 mm, a length of 5 mm (the thickness of the sub-blanket), and given boundary conditions. The number of threads were two in half
of the holes and four in the other half, averaging 3 threads per hole from the stitching. The radiation calculations was set up assuming a 0.65 mm radius hole (in reality the hole could be approximated by a 0.5 mm x 0.8 mm ellipse due to tension in the threads pulling towards the next holes). The effective radius ($r_{\text{eff}}$) was calculated using equation 1, and then the radiation heat load was calculated using $r_{\text{eff}}$ (equation 2). The different boundary conditions and heat loads from the calculations are shown in Table 6. The warm boundary temperature was measured at 260 K and is not changed throughout the calculations. The cold boundary temperature was measured at 200 K between the patches and 230 K on the threading. This indicates that the conduction heat load should be calculated to a cold boundary temperature of 230 K and the radiation to a cold boundary temperature of 200 K because it is seeing the next sub-blanket as opposed to the back of the first sub-blanket (as shown in the mixed scenario in table 6). Based on those calculations, heat loss estimates are 14 mW per patch or 54 mW for the set of four.

$$r_{\text{eff}} = \frac{1}{x \cos \theta} + r_{\text{perf}}$$  \hspace{1cm} (1)

$$\dot{Q} = A_{\text{eff}} \varepsilon_{\text{layer}} \sigma (T_h^4 - T_c^4)$$  \hspace{1cm} (2)

| Heat Loads for one stitch or hole | WBT = 260 K CBT = 230 K | WBT = 260 K CBT = 200 K | WBT = 260 K CBT = mixed |
|---------------------------------|-----------------------------|-----------------------------|-----------------------------|
| Conduction (mW/thread)         | 0.10                        | 0.21                        | 0.10                        |
| Radiation (mW) all holes       | 3.4                         | 5.7                         | 5.7                         |
| Total (mW)                     | 11.8                        | 22.6                        | 13.8                        |

5. Conclusions

Testing of four coupons representative of SHIIVER MLI options has brought into light the thermal penalties of several design options. The calorimeter warm boundary temperature was 260 K, which is very similar to what may be expected in the SHIIVER test setup. The 30 layer coupon was found to perform essentially identically to the 50 layer coupon at approximately 0.67 W/m². The seam heat load as designed was 147 mW/m and comparable to seam loads measured previously on staggered overlap seams. The penalty for the attachments was approximately 10 mW per attachment, in close agreement with the measured values. Based on these results, the SHIIVER MLI heat loads can be predicted.

6. References

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