Repeatability of Cryogenic Multilayer Insulation

W L Johnson¹, M Vanderlaan², J J Wood³, N O Rhys³, W Guo²,⁴, S Van Sciver²,⁴ and D J Chato¹
¹Glenn Research Center, Cleveland, OH, 44135 USA
²National High Magnetic Field Laboratory, Tallahassee, FL 32310 USA
³Yetispace, Huntsville, AL 35802 USA
⁴Florida State University, Tallahassee, FL, 32310 USA
July 12, 2017
Cryogenic Engineering Conference
By accounting for each item separately, LOX ZBO testing accurately predicted total MLI performance. More information is available in the NASA-TP-2012-216315 report.

- **Skirt Integration**
- **Seams**
- **MLI Blankets**
  - Traditional
  - SS-MLI
  - Hybrid
- **Tape, Pins & Attachments**
- **Penetration Integration**
- **Repeatability**
The objective is to quantify variation in thermal performance due to the blanket fabrication process and due to standard blanket installation processes on a well-controlled system and to determine if there is a difference in this repeatability due to the value of the warm boundary temperature. For implementation this is broken out into two objectives

• Measure the thermal performance repeatability of multiple identical MLI blankets on the same calorimeter under the same conditions with a cold boundary temperature of 20 K or 77 K and a “high” warm boundary conditions (~300 K).

• Measure the thermal performance repeatability of the same MLI system installed and reinstalled on a calorimeter multiple times.
Two phases of MIRE:

- Phase 1: Directed work via Grant to Florida State University (FSU)
  - GRC provided test coupons (5)
    - 25 reflective layers
  - Two Temperature Ranges:
    - 20 K and 300 K (first series - completed)
    - 20 K and 100 K (second series – not completed)
  - Two types of repeatability
    - Between coupons
    - With same coupon

- Phase 2: Competed testing (awarded to Yetispace, completed)
  - Fabrication of 10 coupons
    - 10 reflective layers
    - 2 Thermocouples within each blanket
  - Temperature boundaries: 77 K to 300 K
  - Calorimeter selected by proposer (Yetispace working with FSU)
  - Testing each blanket once
Cut out of previously procured MLI blankets for Multilayer Insulation Mitigation Experiment (MIME)

- Six coupons fabricated in 2010 by Sierra Lobo
  - 25 layers
  - Designed for SMiRF LH2 calorimeter
  - 60” wide, 96” long
- MIME stopped when CPST started and the old SMiRF liquid hydrogen calorimeter had too many problems to fix
- MLI blankets were stored in “bonded” storage since then
  - All coupons have since been used by IFUSI in one way or another
  - Added cover sheets to ease in handling
  - Added tapered ends for tighter radius
  - Left instrumentation in blankets (preventing damage from removal)
Results – Phase 1

- Power, W vs. Coupon #
- Heat Flux (W/m²) vs. Layer Density (layer/mm)
Results – Phase 2

![Graph showing relationship between heat flux and layer density.](image-url)
**Statistical Analysis**

**ASTM E 2586**

- For samples sizes less than 12, the standard deviation can be estimated by the range divide by a constant, $d_2$ (provided in the standard, for $n = 5$, $d_2 = 2.326$)
  - Adjusted standard deviation: $0.083$ W
- $Z$-score: how many standard deviations the individual tests are from the mean
  
  $Z_i = \frac{(Q_i - \bar{Q})}{s}$

<table>
<thead>
<tr>
<th>300 K to 20 K testing</th>
<th>MLI 1</th>
<th>MLI 2</th>
<th>MLI 3</th>
<th>MLI 4</th>
<th>MLI 5</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.159</td>
<td>1.118</td>
<td>1.113</td>
<td>1.268</td>
<td>1.075</td>
</tr>
<tr>
<td>$Z$-score</td>
<td>0.15</td>
<td>-0.34</td>
<td>-0.40</td>
<td>1.46</td>
<td>-0.86</td>
</tr>
<tr>
<td>$Z$-score (trad s)</td>
<td>0.19</td>
<td>-0.43</td>
<td>-0.51</td>
<td>1.83</td>
<td>-1.08</td>
</tr>
</tbody>
</table>

- Estimated Standard Errors
  - Mean:
    - Note: $0.017$ W is $1.5\%$ of the average
  - Standard Deviation:
    - $C_4(n=5) = 0.939986$
    - $0.083 - 0.066 = 0.017 < 0.028$
  - Suggests data is statistically significant

\[ se(\bar{Q}) = \frac{s}{\sqrt{n}} = 0.017 \]

\[ se(s(Q)) = s \sqrt{1 - c_4^2} = 0.028 \]
# Results

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Mean, W</th>
<th>Min, W</th>
<th>Max, W</th>
<th>St. Dev, W</th>
<th>Range, W</th>
<th>Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 K to 300 K, All Five</td>
<td>1.15</td>
<td>1.08</td>
<td>1.27</td>
<td>0.066</td>
<td>0.19</td>
<td>+/-8.4%</td>
</tr>
<tr>
<td>20 K to 300 K, Coupon 3</td>
<td>1.06</td>
<td>0.98</td>
<td>1.15</td>
<td>0.061</td>
<td>0.17</td>
<td>+/-8.0%</td>
</tr>
<tr>
<td>77K to 293K, First Five</td>
<td>2.40</td>
<td>2.05</td>
<td>2.80</td>
<td>0.27</td>
<td>0.75</td>
<td>+/- 15.6%</td>
</tr>
<tr>
<td>77 K to 293 K, Second Five</td>
<td>2.90</td>
<td>2.20</td>
<td>3.35</td>
<td>0.41</td>
<td>1.15</td>
<td>+/- 19.8%</td>
</tr>
<tr>
<td>77 K to 293 K, All ten</td>
<td>2.65</td>
<td>2.05</td>
<td>3.35</td>
<td>0.43</td>
<td>1.30</td>
<td>+/- 24.5%</td>
</tr>
</tbody>
</table>
### Statistical Results

<table>
<thead>
<tr>
<th>Test Series</th>
<th>Mean Standard Error, W</th>
<th>Mean SE as Percent of Mean</th>
<th>Calculated St. Dev, W</th>
<th>St. Dev Standard Error, W</th>
<th>St. Dev Calc – Meas, W</th>
<th>St. Error Greater?</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 K to 300 K, All Five</td>
<td>0.017</td>
<td>1.2%</td>
<td>0.083</td>
<td>0.023</td>
<td>0.017</td>
<td>YES</td>
</tr>
<tr>
<td>20 K to 300 K, Coupon 3</td>
<td>0.015</td>
<td>1.1%</td>
<td>0.074</td>
<td>0.021</td>
<td>0.013</td>
<td>YES</td>
</tr>
<tr>
<td>77K to 293K, First Five</td>
<td>0.064</td>
<td>2.7%</td>
<td>0.322</td>
<td>0.092</td>
<td>0.053</td>
<td>YES</td>
</tr>
<tr>
<td>77 K to 293 K, Second Five</td>
<td>0.099</td>
<td>3.4%</td>
<td>0.494</td>
<td>0.140</td>
<td>0.085</td>
<td>YES</td>
</tr>
<tr>
<td>77 K to 293 K, All ten</td>
<td>0.042</td>
<td>1.6%</td>
<td>0.422</td>
<td>0.099</td>
<td>-0.006</td>
<td>YES</td>
</tr>
</tbody>
</table>

All Data Sets are Statistically Significant!
Probabilities of Next Coupon

- **Heat Flux Greater Than** (traditional)
- **Heat Flux Less Than** (traditional)
- **Heat Flux Greater Than** (small sample)
- **Heat Flux Less Than** (small sample)
Equations (from Microsoft Excel)

- Top curve
  \[ T.DIST\left(\frac{Q_{\text{avg}} - Q}{\text{St.Dev}/\sqrt{j}}, j, \text{TRUE}\right) \]

- Bottom curve
  \[ T.DIST.RT\left(\frac{Q_{\text{avg}} - Q}{\text{St.Dev}/\sqrt{j}}, j\right) \]

\[ j = \text{number of samples (5)} \]
Repeatability Summary

- **25 layer systems repeatability around +/- 8%**
  - Phase 1A showed repeatability of +/- 8.4%
  - Phase 1B showed repeatability of +/- 8.0%
  - Five coupons between 300 K and 20 K
  - Statistics line up with standard errors associated with small sample sizes, suggests that data is meaningful
  - Indicates that ir-repeatability mostly due to installation (layer density)

- **10 layer systems repeatability +/- 15 – 25%**
  - Similar layer density trend (though not nearly as distinct)
  - Installation technician played a role too

- Indicates repeatability a function of number of layers