Repeatability of Cryogenic Multilayer Insulation

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By accounting for each item separately, LOX ZBO testing accurately predicted total MLI performance. More information is available through the project documentation:

Penetration Integration:
- NASA-TP-2012-216315

MLI Blankets
- Traditional
- SS-MLI
- Hybrid

Seams

Skirt Integration

Tape, Pins & Attachments

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
Coupons to FSU for Phase 1

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
Results – Phase 2

The diagram shows the relationship between Heat Flux (W/m²) and Layer Density (layers/mm). The data points are represented by different colors: blue for one set of data and red for another. The x-axis represents Layer Density ranging from 1.6 to 2.8 layers/mm, while the y-axis represents Heat Flux ranging from 2.0 to 4.5 W/m².
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
\[ T.DIST(((Q_{avg} - Q)/(St.Dev/\sqrt{j}),j,TRUE) \]
- Bottom curve
\[ T.DIST.RT(((Q_{avg} - Q)/(St.Dev/\sqrt{j}),j) \]

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

\[ t = \frac{(\dot{Q}_{avg} - \dot{Q})}{s/\sqrt{j}} \]
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**