Tank Applied Testing of Load-Bearing Multilayer Insulation (LB-MLI)

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Reduced Boil-Off

• For long duration storage of cryogenic propellants on orbit, boil-off is a significant problem
  – Reducing the boil-off through active refrigeration may be required if passive insulation systems cannot be built to meet mission requirements
• Lack of large scale 20 K class cryocoolers limits our current availability to do zero boil-off for liquid hydrogen
• Incorporating existing 90 K cryocoolers could still lower heat load by as much as 70% (theoretical)
  – Use a Broad Area Cooling (BAC) shield, similar to a vapor cooled shield, but attached to a cryocooler
  – Cool struts and plumbing in addition to insulation system
Problem Statement

• Demonstrate a system that can:
  – Support a Broad Area Cooling shield in the middle of an MLI blanket
  – Survive launch loads
  – Provide high thermal performance on orbit
  – Survive rapid depressurization

• Solution:
  – Load-Bearing Multilayer Insulation
    • Built by Quest Products & Ball Aerospace
    • Developed through several SBIR contracts
Load Bearing Multilayer Insulation

- Uses polymer based stand-offs to separate the layers as opposed to netting
  - Creates a simpler conduction heat transfer network for modeling
  - Allows for more accurate modeling of MLI system
- Can be arranged to provide structural support via stacking spacers
  - Previous testing used plastic stand-offs to support BAC shield
  - No stand-offs required with LB-MLI
- Currently at low (5 layer/cm) layer density
  - Based on current MLI theory, about optimum for 90 – 100 K warm boundary
  - Replaced 30 layer traditional blanket with 19 layer LB-MLI blanket
Test Program

Two tanks were fabricated to be as close to identical as possible

- Nearly identical insulation systems were installed on each tank
- One tank was tested with liquid hydrogen for thermal performance
- The other was tested with liquid nitrogen to determine the acoustic environmental effects on the cooled shield/MLI.
Test Configuration

Layered cut-away view

Cross-Sectional View

Support Ring

Titanium Struts

Outer MLI

BAC Shield

Tube on Shield (LH2 Test)

SOFI

Inner MLI

2x15 layers MLI 0.25-mil DAM, 20/cm

5-mil Aluminum BAC

Velcro attachment of LBMLI to BAC

19 layers LBMLI 1-mil DAM, 5.5/cm

Velcro attachment of foam to inner LBMLI

Foam Insulation

Tank Wall
Structural Testing

• In order to demonstrate structural integrity of the blanket, acoustic testing was selected over vibration testing
  – Insulation systems are large area, lightweight systems that respond more to acoustically input energy than vibrationally input energy

• Testing on coupons
  – Unloaded flat panel
  – Loaded curved panel
  – Post test examination for changes (damage)

• Testing on a Tank
  – Thermal testing before and after
  – Post test examination for changes (damage)

• All actual acoustic testing done when system was a room temperature
Coupon Test Results

- The dotted black line indicates input levels
- Colored squiggly lines indicate response
- Flat panel test (top)
  - Just LB-MLI, no load attached (i.e. BAC shield, other MLI)
  - Post test inspection revealed no issues (debonding, tearing, etc)
  - Indicated that LB-MLI can survive launch & ascent with no external load
- Curved panel test (bottom)
  - Included BAC shield mass simulator and outer MLI
  - Post test inspection revealed no issues
  - Indicated that LB-MLI can survive launch & ascent with load attached
- Both tests combined indicated that LB-MLI was ready to proceed with tank applied testing
Tank Applied Test Setup

![Graph showing pressure level vs. frequency]

<table>
<thead>
<tr>
<th>Accel #</th>
<th>Description</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>On gusset, near strut attach point</td>
<td>Triax</td>
</tr>
<tr>
<td>2</td>
<td>On tank, near strut attach point</td>
<td>Triax</td>
</tr>
<tr>
<td>3</td>
<td>On support column, top surface</td>
<td>Triax</td>
</tr>
<tr>
<td>4</td>
<td>On tank surface, mid-barrel section</td>
<td>Uniaxial</td>
</tr>
<tr>
<td>5</td>
<td>Same as #4, clocked 120 degrees around tank</td>
<td>Uniaxial</td>
</tr>
<tr>
<td>6</td>
<td>On top of tank</td>
<td>Uniaxial</td>
</tr>
<tr>
<td>7</td>
<td>On bottom of tank</td>
<td>Uniaxial</td>
</tr>
<tr>
<td>9</td>
<td>On gusset, near strut attach point</td>
<td>Triax</td>
</tr>
<tr>
<td>10</td>
<td>On tank, near strut attach point</td>
<td>Triax</td>
</tr>
</tbody>
</table>
Tank Applied Acoustic Testing Results

- Pre and Post Test Thermal testing using LN2
  - Heat load of 7.5 W on both tests
  - When running chilled GN2 through BAC shield tubing, heat load of 4.5 W on both tests
    - No gas leaks in tubing degrading performance
- Post test inspection found no issues
  - No debonding of spacers, no tears of MLI, no warping of MLI blanket
- Maximum acceleration level on BAC shield: 8.7 $G_{RMS}$
  - Original level for concern was 6 $G_{RMS}$
  - After no damage found, at 8.7$G_{RMS}$, level of concern was upped to 10 $G_{RMS}$

BAC Shield Response
Thermal Testing

• In order to demonstrate thermal viability, a thermal vacuum test was run using liquid hydrogen
  – Broad Area Cooled (BAC) Shield was integrated on top of the blanket
  – BAC shield was coupled to a cryocooler
  – Testing with and without cryocooler operational
• Pre-test coupons were tested using liquid nitrogen
## Thermal Coupon Results

<table>
<thead>
<tr>
<th>layers</th>
<th>Tc, K</th>
<th>Th, K</th>
<th>Measured $Q_i$, W/m²</th>
<th>Model $Q_i$, W/m²</th>
<th>% difference</th>
<th>SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ball</td>
<td>10</td>
<td>76</td>
<td>296</td>
<td>0.95</td>
<td>0.91</td>
<td>-4.3%</td>
</tr>
<tr>
<td>KSC</td>
<td>20</td>
<td>77</td>
<td>292</td>
<td>0.41</td>
<td>0.43</td>
<td>5.6%</td>
</tr>
<tr>
<td>KSC</td>
<td>20</td>
<td>77</td>
<td>305</td>
<td>0.57</td>
<td>0.51</td>
<td>-11%</td>
</tr>
<tr>
<td>Ball</td>
<td>3</td>
<td>76</td>
<td>296</td>
<td>3.62</td>
<td>3.02</td>
<td>-16%</td>
</tr>
<tr>
<td>KSC</td>
<td>9</td>
<td>78</td>
<td>293</td>
<td>0.92</td>
<td>0.97</td>
<td>5.2%</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>78</td>
<td>325</td>
<td>1.36</td>
<td>1.41</td>
<td>4.0%</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>78</td>
<td>316</td>
<td>1.23</td>
<td>1.28</td>
<td>3.5%</td>
</tr>
<tr>
<td>KSC</td>
<td>5</td>
<td>78</td>
<td>293</td>
<td>1.77</td>
<td>1.75</td>
<td>-1.3%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>78</td>
<td>305</td>
<td>1.99</td>
<td>2.02</td>
<td>1.5%</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>78</td>
<td>325</td>
<td>2.61</td>
<td>2.54</td>
<td>-2.6%</td>
</tr>
<tr>
<td>KSC</td>
<td>19</td>
<td>78</td>
<td>293</td>
<td>0.55</td>
<td>0.46</td>
<td>-16%</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>78</td>
<td>305</td>
<td>0.77</td>
<td>0.51</td>
<td>-34%</td>
</tr>
<tr>
<td></td>
<td>19</td>
<td>78</td>
<td>327.8</td>
<td>0.85</td>
<td>0.69</td>
<td>-19%</td>
</tr>
<tr>
<td>FSU</td>
<td>4</td>
<td>20</td>
<td>85</td>
<td>0.18</td>
<td>0.11</td>
<td>-42%</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>20</td>
<td>85</td>
<td>0.13</td>
<td>0.048</td>
<td>-63%</td>
</tr>
</tbody>
</table>

**Scale Factor** = \( \frac{Q_{MLI,\text{test}}}{Q_{MLI,\text{predict}}} \)
# Tank Applied Thermal Test Matrix

<table>
<thead>
<tr>
<th>Test #</th>
<th>BAC Set (K)</th>
<th>Shield Point</th>
<th>Bypass Valve (open/closed)</th>
<th>Fill (%)</th>
<th>Environmental Temperature (K)</th>
<th>Test Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80 K</td>
<td>Open</td>
<td></td>
<td>90</td>
<td>220</td>
<td>Steady State</td>
</tr>
<tr>
<td>2</td>
<td>80 K</td>
<td>Open</td>
<td></td>
<td>25</td>
<td>220</td>
<td>Steady State</td>
</tr>
<tr>
<td>3</td>
<td>N/A</td>
<td>Open</td>
<td></td>
<td>90</td>
<td>220</td>
<td>Steady State</td>
</tr>
<tr>
<td>4</td>
<td>N/A</td>
<td>Closed</td>
<td></td>
<td>90</td>
<td>220</td>
<td>Steady State</td>
</tr>
<tr>
<td>5</td>
<td>90 K</td>
<td>Open</td>
<td></td>
<td>90</td>
<td>220</td>
<td>Steady State</td>
</tr>
<tr>
<td>6</td>
<td>90 K</td>
<td>Closed</td>
<td></td>
<td>90</td>
<td>220</td>
<td>Steady State</td>
</tr>
<tr>
<td>7</td>
<td>N/A</td>
<td>Open</td>
<td></td>
<td>90</td>
<td>300</td>
<td>Rapid Evacuation</td>
</tr>
<tr>
<td>8</td>
<td>N/A</td>
<td>Open</td>
<td></td>
<td>90</td>
<td>300</td>
<td>Steady State</td>
</tr>
</tbody>
</table>

Note: Bypass Valve was to allow for testing with and without Thermo-Acoustic Oscillations (TAO)
## Tank Applied Thermal Test Results

<table>
<thead>
<tr>
<th>Test #</th>
<th>Heat Load to Tank (W)</th>
<th>Conduction Heat Loads (W)</th>
<th>Net Remainder (W)</th>
<th>MLI Penetrations (W)</th>
<th>MLI Heat Load (W)</th>
<th>MLI Heat Flux (mW/m²)</th>
<th>Predicted MLI Heat Flux (mW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.67</td>
<td>0.94</td>
<td>0.73</td>
<td>0.17</td>
<td>0.56</td>
<td>79</td>
<td>19</td>
</tr>
<tr>
<td>2</td>
<td>1.68</td>
<td>0.97</td>
<td>0.71</td>
<td>0.17</td>
<td>0.54</td>
<td>76</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>3.32</td>
<td>1.69</td>
<td>1.63</td>
<td>0.17</td>
<td>1.46</td>
<td>207</td>
<td>116</td>
</tr>
<tr>
<td>5</td>
<td>1.83</td>
<td>1.01</td>
<td>0.82</td>
<td>0.17</td>
<td>0.64</td>
<td>92</td>
<td>21</td>
</tr>
<tr>
<td>8</td>
<td>6.12</td>
<td>2.77</td>
<td>3.35</td>
<td>0.28</td>
<td>3.07</td>
<td>436</td>
<td>310</td>
</tr>
</tbody>
</table>

*Scale Factor* = \( \frac{Q_{\text{MLI, test}}}{Q_{\text{MLI, predict}}} \)
Rapid Depressurization

- Rapid Depressurization was performed
  - Simulates the first few minutes to hours of mission
  - Attempted twice, both times got through the rough pumping portion but had trouble switching to turbo/diffusion pumps
    - Issues with gaseous nitrogen evacuation due to the formation of solid nitrogen at the bottom on the MLI blanket
    - Attempted with helium gas and was fully successful
Post Test Evaluation

• Post test evaluation showed divoting and cracking of the SOFI, further investigation yielded:
  – Tank was stainless steel, not aluminum, SOFI shrinkage optimized for aluminum
  – SOFI was up to 4” thick in some places, recommend not greater than 1.5” to 2” thick in future
  – Velcro may have added extra stresses to cause more cracking
Conclusion

• Demonstrated a system (LB-MLI) that can:
  – Support a Broad Area Cooling shield in the middle of an MLI blanket
  – Survive launch loads
  – Heat load of less than 0.1 W/m² through the MLI with the cryocooler on and 0.2 W/m² with the cryocooler off.
  – Survive rapid depressurization

• Noticed increasing scale factor with decreasing temperature, first cut analysis indicates it is a radiation issue
  – This is not an LB-MLI specific problem
  – Was worse on previous traditional MLI blanket testing

• SOFI had issues handling combined loads during rapid depressurization
  – partially a design issue
  – more investigation needed to fully understand
Acknowledgments

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