Quantifying MLI Thermal Conduction in Cryogenic Applications from Experimental Data

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Topics

- Motivated by very cold (6 K) space telescope applications
  - Large MLI uncertainties observed in test data for Hot-side temperatures below 40 K

- Using modeling equations to Quantify (Extract) key parameters of existing MLI designs from test data
  - Conductivity of S/C versus Dewar versus Cryo MLI
  - Understanding Role of Conductivity in MLI performance

- Conclusions and Lessons Learned
Cryogenic MLI Study Motivated by 6K MIRI Instrument on JWST

James Webb Space Telescope (JWST)

MIRI in its MLI
MLI Heat Transfer as a Function of Hot-Side Temperature

Key:
- SLI Radiation Absorbed ($\epsilon_h = 1, \epsilon_c = 6.8 \times 10^{-4} T_H^{0.67}$)
- Lines of constant Effective Emittance
- • JPL 20-layer Cassini (SSAK+5EK+15MN+AK)
- • JPL Duo-layup Cassini (SSAK+5EK/15MN+A) (20 layers in 2 blankets with staggered seams)
- • Unperf. DAM 1-SN MLI ($X =$ number of layers) (LMSC dewar minimum achiev. layer density)

Observations:
- Effective Emittance of Dewar MLI drastically degrades as hot-side temperature drops down to 40 K
- Spacecraft MLI has 10x greater effective emittance than dewar MLI
Lockheed Characterization of MLI Emittance as a Function of Temperature

Goldized Mylar

\[ \varepsilon_{TH} = 1.50 \times 10^{-3} (T)^{0.483} \]

\[ \varepsilon_{TH} = 1.19 \times 10^{-3} (T)^{0.509} \]

\[ \varepsilon_{TH} = 8.32 \times 10^{-4} (T)^{0.554} \]

\[ \text{ASE Bulk (} \varepsilon_{TH} \approx T^{2/3} \) \]

Symbols indicate various insulation blankets
• From Cunnington et al. (1971)

Aluminized Mylar

\[ \varepsilon_{TH} = 6.5 \times 10^{-4} (T)^{0.667} \]

\[ \varepsilon_{TH} = 5.6 \times 10^{-4} (T)^{0.667} \]

Predicted From ASE Theory for 400 Å

\[ \varepsilon \approx T^{0.67} \]

Symbols indicate various insulation blankets
• From Cunnington et al. (1971)
Lockheed Equation for Estimating MLI Thermal Radiation Loads

MLI Conductivity

Classic Lockheed MLI Equation

\[ q = q_c + q_r = \frac{C_c N^{2.56} T_m}{n} (T_h - T_c) + \frac{C_r \epsilon_o}{n} (T_h^{4.67} - T_c^{4.67}) \]

where

- \( q = \) total heat flux transmitted through the MLI (mW/m²)
- \( q_c = \) conductive heat flux transmitted through the MLI (mW/m²)
- \( q_r = \) radiative heat flux transmitted through the MLI (mW/m²)
- \( C_c = \) conduction constant = \( 8.95 \times 10^{-5} \)
- \( C_r = \) radiation constant = \( 5.39 \times 10^{-7} \)
- \( T_h = \) hot side temperature (K)
- \( T_c = \) cold side temperature (K)
- \( T_m = \) mean MLI temperature (K); typically \( (T_h + T_c)/2 \)
- \( \epsilon_o = \) MLI shield-layer emissivity at 300 K = 0.031
- \( N = \) MLI layer density (layers/cm)
- \( n = \) number of facing pairs of low-emittance surfaces in the MLI system

\[ \epsilon_o T^{0.67} \times T^4 \]
Estimation of Thermal Radiation Loads with Cryo MLI

Modified Lockheed MLI Equation

\[ q = q_c + q_r = \frac{k_o \kappa(T)}{n} (T_h - T_c) + \frac{C_r \varepsilon_o}{n} (T_h^{4.67} - T_c^{4.67}) \]

\[ C_c N^{2.56} T_m \]

Conduction

Radiation

Relative Conductivity, \( \kappa(T) \)

Mylar

Kapton

Nylon

\( k_c \propto T_m \)

TEMPERATURE, K

Relative Conductivity, \( \kappa(T) \)
Measured Thermal Radiation Loads with Room-Temperature MLI

Gold = JPL S/C MLI
Blue = LMSC Dewar MLI

Key:
- SLI Radiation Absorbed ($\varepsilon_H = 1, \varepsilon_C = 6.8 \times 10^{-4} T_H^{0.67}$)
- Lines of constant Effective Emittance
- 20 JPL 20-layer Cassini (SSAK+5EK+15MN+AK)
- 20 JPL Duo-layup Cassini (SSAK+5EK/15MN+A) (20 layers in 2 blankets with staggered seams)
- 10 Unperf. DAM 1-SN MLI ($X =$ number of layers) (LMSC dewar minimum achiev. layer density)

Observations:
- Room-temperature MLI quickly degrades at lower Hot-Side Temps.
- Spacecraft MLI 10x higher emittance than Dewar ML

Compute $k_0$ Using Datum

Gold = JPL S/C MLI
Blue = LMSC Dewar MLI
### Nonlinear Equation Set for Lockheed 37-layer Dewar MLI for $T_H = 40K$

\[
\begin{align*}
q_2 &= k_o \kappa(T_2) \frac{(T_2 - 4.2)}{2} + C_r \epsilon_o \left( T_2^{4.67} - 4^{4.67} \right) / 2 = 7.5 \\
q_3 &= k_o \kappa(T_3) \frac{(T_3 - T_2)}{3} + C_r \epsilon_o \left( T_3^{4.67} - T_2^{4.67} \right) / 3 = 7.5 \\
q_5 &= k_o \kappa(T_5) \frac{(T_5 - T_3)}{5} + C_r \epsilon_o \left( T_5^{4.67} - T_3^{4.67} \right) / 5 = 7.5 \\
q_{10} &= k_o \kappa(T_{10}) \frac{(T_{10} - T_5)}{10} + C_r \epsilon_o \left( T_{10}^{4.67} - T_5^{4.67} \right) / 10 = 7.5 \\
q_{17} &= k_o \kappa(40) \frac{(40 - T_{10})}{17} + C_r \epsilon_o \left( 40^{4.67} - T_{10}^{4.67} \right) / 17 = 7.5
\end{align*}
\]

<table>
<thead>
<tr>
<th>No. Layers</th>
<th>T</th>
<th>$\Delta T$</th>
<th>$k_o$</th>
<th>$q_c$</th>
<th>$q_r$</th>
<th>$q_{Total}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(v)</td>
<td>(K)</td>
<td>(K)</td>
<td>(mW/m²·K)</td>
<td>(mW/m²)</td>
<td>(mW/m²)</td>
<td>(mW/m²)</td>
</tr>
<tr>
<td>cold wall</td>
<td>4.0</td>
<td>Calc</td>
<td>Calc</td>
<td>99% Conduction!</td>
<td>Fixed</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>11.5</td>
<td>7.5</td>
<td>25</td>
<td>7.5</td>
<td>0.06</td>
<td>7.5</td>
</tr>
<tr>
<td>3</td>
<td>16.5</td>
<td>5.0</td>
<td>25</td>
<td>7.5</td>
<td>0.06</td>
<td>7.5</td>
</tr>
<tr>
<td>5</td>
<td>22.0</td>
<td>5.5</td>
<td>25</td>
<td>7.5</td>
<td>0.06</td>
<td>7.5</td>
</tr>
<tr>
<td>10</td>
<td>30.0</td>
<td>8.0</td>
<td>25</td>
<td>7.5</td>
<td>0.06</td>
<td>7.5</td>
</tr>
<tr>
<td>17</td>
<td>40.0</td>
<td>10.0</td>
<td>25</td>
<td>7.5</td>
<td>0.06</td>
<td>7.5</td>
</tr>
</tbody>
</table>
Measured Thermal Radiation Loads with Room-Temperature MLI

Gold = JPL S/C MLI

Blue = LMSC Dewar MLI

Key:

- Green: SLI Radiation Absorbed ($\epsilon_H = 1$, $\epsilon_C = 6.8 \times 10^4 T_H^{0.67}$)
- Blue: Lines of constant Effective Emittance
- Orange: JPL 20-layer Cassini (SSAK+5EK+15MN+AK)
- Yellow: JPL Duo-layup Cassini (SSAK+5EK/15MN+A) (20 layers in 2 blankets with staggered seams)
- Blue: Unperf. DAM 1-SN MLI ($X =$ number of layers) (LMSC dewar minimum achiev. layer density)

Next, Compute Heat Transfer for 278 K Point using $k_o = 25$

...and then compute for the other $T_{HOT}$ points
Nonlinear Equation Set for Lockheed 37-layer Dewar MLI for $T_H = 40$K

\[ q_2 = 25 \times \kappa(T_2) \left( T_2 - 4.2 \right) / 2 + C_r \varepsilon_o \left( T_2^{4.67} - 4^{4.67} \right) / 2 = Q_{278} \]

\[ q_3 = 25 \times (T_3) \left( T_3 - T_2 \right) / 3 + C_r \varepsilon_o \left( T_3^{4.67} - T_2^{4.67} \right) / 3 = Q_{278} \]

\[ q_5 = 25 \times (T_5) \left( T_5 - T_3 \right) / 5 + C_r \varepsilon_o \left( T_5^{4.67} - T_3^{4.67} \right) / 5 = Q_{278} \]

\[ q_{10} = 25 \times \kappa(T_{10}) \left( T_{10} - T_5 \right) / 10 + C_r \varepsilon_o \left( T_{10}^{4.67} - T_5^{4.67} \right) / 10 = Q_{278} \]

\[ q_{17} = 25 \times \kappa(40) \left( 40 - T_{10} \right) / 17 + C_r \varepsilon_o \left( 40^{4.67} - T_{10}^{4.67} \right) / 17 = Q_{278} \]

<table>
<thead>
<tr>
<th>No. Layers</th>
<th>T (K)</th>
<th>ΔT (K)</th>
<th>$k_o$ (mW/m²·K)</th>
<th>$q_c$ (mW/m²)</th>
<th>$q_r$ (mW/m²)</th>
<th>$q_{Total}$ (mW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cold wall</td>
<td>4.0</td>
<td>Calc</td>
<td>Fixed</td>
<td>Cond at low T</td>
<td>Calc</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>38</td>
<td>34</td>
<td>25</td>
<td>252</td>
<td>3</td>
<td>275</td>
</tr>
<tr>
<td>3</td>
<td>96</td>
<td>43</td>
<td>25</td>
<td>250</td>
<td>11</td>
<td>275</td>
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<tr>
<td>5</td>
<td>160</td>
<td>64</td>
<td>25</td>
<td>224</td>
<td>57</td>
<td>275</td>
</tr>
<tr>
<td>10</td>
<td>220</td>
<td>60</td>
<td>25</td>
<td>132</td>
<td>130</td>
<td>275</td>
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<tr>
<td>17</td>
<td>278</td>
<td>58</td>
<td>25</td>
<td>78</td>
<td>195</td>
<td>275</td>
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</table>
Computed Thermal Loads for Lockheed 37-Layer Dewar MLI

**Key:**
- **SLI Radiation Absorbed** ($\epsilon_r = 1$, $\epsilon_c = 6.8 \times 10^{-4} T_H^{3.67}$)
- **JPL 20-layer Cassini** (SSAK+5EK+15MN+AK)
- **JPL Duo-layup Cassini** (SSAK+5EK/15MN+A) (20 layers in 2 blankets with staggered seams)
- **Unperf. DAM 1-SN MLI** ($X$ = number of layers) (LMSC dewar minimum achiev. layer density)
- Modeled results for LMSC 37-layer DAM 1-SN
- Modeled results for LMSC 20-layer DAM 1-SN
- Modeled results for LMSC 10-layer DAM 1-SN
- Lines of constant Effective Emittance

**Bottom Line:**
- Room-temperature MLI quickly degrades at lower Hot-Side Temps. Avoid using at $T_H < 100K$
- Spacecraft MLI 10x higher emittance than Dewar ML
**Conductance and Thermal Gradient Calculation for 21-layer Cassini MLI**

Calculations for JPL 21-layer S/C MLI with 328 K hotbox and 87K coldwall

<table>
<thead>
<tr>
<th>No. Layers</th>
<th>T</th>
<th>ΔT</th>
<th>$k_o$ (mW/m²·K)</th>
<th>$q_c$ (mW/m²)</th>
<th>$q_r$ (mW/m²)</th>
<th>$q_{Total}$ (mW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>cold wall</td>
<td>87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MLI out surface</td>
<td>121</td>
<td>34</td>
<td>n/a</td>
<td>0</td>
<td>8720</td>
<td>8720</td>
</tr>
<tr>
<td>5</td>
<td>167</td>
<td>46</td>
<td>925</td>
<td>8635</td>
<td>85</td>
<td>99% 8720</td>
</tr>
<tr>
<td>15</td>
<td>304</td>
<td>137</td>
<td>925</td>
<td>8240</td>
<td>480</td>
<td>8720</td>
</tr>
<tr>
<td>1</td>
<td>313</td>
<td>9</td>
<td>925</td>
<td>7613</td>
<td>1107</td>
<td>87% 8720</td>
</tr>
<tr>
<td>inner hot box</td>
<td>328</td>
<td>15</td>
<td>vacuum gap ($\epsilon=0.08$)</td>
<td>0</td>
<td>8720</td>
<td>8720</td>
</tr>
</tbody>
</table>

JPL Cassini MLI is 37x more conductive than Lockheed's Dewar MLI
Measured Thermal Radiation Loads with Lockheed Cryo-MLI & SLI

= 9 Layer DAM with 3 silk nets

Key:
- SLI facing Black ($\epsilon_H = 1$, $\epsilon_C = 6.8 \times 10^{-4} T_H^{0.67}$)
- SLI facing SLI ($\epsilon_H = \epsilon_C = 6.8 \times 10^{-4} T_H^{0.67}$)
- Unperf. 9 Layer DAM with 3-SN (LMSC dewar minimum achiev. layer density)
- Bare tank taped with Double Alum Mylar (SLI)
- Lines of constant Effective Emittance

Observations:
- Cryo Dewar MLI is seen to improve upon SLI emittance down to 40 K Hot-Side Temps (but only by 2x)
- Spacecraft MLI has no hope at cryogenic Hot Side Temps
- 3M #425 tape is comparable to Cryo MLI

Compute $k_0$
Using Datum

1.2
### Calculations for Lockheed's 9-Layer 3-SN Cryo MLI with $T_H = 40K$

<table>
<thead>
<tr>
<th>No. Layers</th>
<th>$T$</th>
<th>$\Delta T$</th>
<th>$k_o$</th>
<th>$q_c$</th>
<th>$q_r$</th>
<th>$q_{Total}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K)</td>
<td>(K)</td>
<td>(mW/m².K)</td>
<td>(mW/m²)</td>
<td>(mW/m²)</td>
<td>(mW/m²)</td>
<td>(mW/m²)</td>
</tr>
<tr>
<td>cold wall</td>
<td>4.2</td>
<td>Calc</td>
<td>Calc</td>
<td>88% Conduction!</td>
<td>Fixed</td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11.5</td>
<td>8.3</td>
<td>1.5</td>
<td>1.07</td>
<td>0.14</td>
<td>1.2</td>
</tr>
<tr>
<td>1</td>
<td>16.5</td>
<td>4.0</td>
<td>1.5</td>
<td>1.07</td>
<td>0.14</td>
<td>1.2</td>
</tr>
<tr>
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<td>21.7</td>
<td>5.4</td>
<td>1.5</td>
<td>1.07</td>
<td>0.14</td>
<td>1.2</td>
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<td>25.7</td>
<td>4.0</td>
<td>1.5</td>
<td>1.07</td>
<td>0.14</td>
<td>1.2</td>
</tr>
<tr>
<td>3</td>
<td>30.0</td>
<td>4.3</td>
<td>1.5</td>
<td>1.07</td>
<td>0.12</td>
<td>1.2</td>
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<tr>
<td>hot wall</td>
<td>40.0</td>
<td>10.0</td>
<td>-</td>
<td>0</td>
<td>1.2</td>
<td>1.2</td>
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</tbody>
</table>

Lockheed Cryo MLI is 17x less conductive than Lockheed’s 37-Layer Conventional Dewar MLI
Measured Conductances of Various MLI Constructions

**600 to 1 Variability in MLI Conductance between Cryo-dewar MLI and S/C MLI**

<table>
<thead>
<tr>
<th>Constructions</th>
<th>Conductance Variability</th>
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</thead>
<tbody>
<tr>
<td>JPL 21-layer Cassini</td>
<td>600 to 1</td>
</tr>
<tr>
<td>Lockheed 37-layer DAM/1SN</td>
<td>37 to 1</td>
</tr>
<tr>
<td>Lockheed 9-layer DAM/3SN</td>
<td>17 to 1</td>
</tr>
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</table>
Conclusions

- Calculation technique provides very useful insights into MLI performance
  - Layer Conductance ($k_0$)
  - Conduction/Radiation/Temp gradient thru MLI

- Lessons Learned: Estimating cryogenic heat loads with cryogenic MLI has LARGE uncertainties
  - 600 to 1 range of conductances (tough job to pick correct value for predictions)
  - MLI quickly degrades to SLI at $T_H < 100$ K as MLI conductance totally dominates below 100 K