Advanced Mirror Technology Development (AMTD) thermal trade studies

Thomas Brooks
(256) 544 – 5596
thomas.brooks@nasa.gov
Description of Primary Mirror

- 4m Circular Monolith
- 0.152m depth front to back
- Light-weighted with a back sheet
- Areal Density is 146 kg/m$^2$
- Optical face coated with $\varepsilon_{\text{aluminum}} = 0.03$
- Fixed Mount
- Material Properties:

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity [W/(m*K)]</th>
<th>Specific Heat [J/(kg*K)]</th>
<th>Density [kg/m$^3$]</th>
<th>Emissivity</th>
<th>CTE [1/K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ULE</td>
<td>1.31</td>
<td>766</td>
<td>2210</td>
<td>0.82</td>
<td>30x10$^{-9}$</td>
</tr>
<tr>
<td>Silicon Carbide</td>
<td>180</td>
<td>750</td>
<td>3100</td>
<td>0.9</td>
<td>2.2x10$^{-6}$</td>
</tr>
<tr>
<td>Zerodur</td>
<td>1.46</td>
<td>800</td>
<td>2530</td>
<td>0.9</td>
<td>7x10$^{-9}$</td>
</tr>
</tbody>
</table>
Heat Flow Through Mirror

- Most heat enters the mirror from the heated plate and exits through the optical surface.
- Heat is transported by radiation and conduction.
Description of Telescope Architecture

- Cylindrical Shroud; 60° Scarf
- No secondary mirror or baffles
- MLI on outer surface of shroud & sides of mirror $\varepsilon_{\text{MLI}} = 0.03$
- Inner surface of shroud painted black
- Heated plate behind mirror
- Placed at L2
Sample WFE Contour Plot (50mK, 140s Period)

Sample WFE with Focus, Tilts, and Astigmatisms Removed (50mK, 140s Period)
• Material: ULE
• Period of ACS: 5000s
• Controllability of ACS: Varied
• Density of Mirror: ULE Density
• Emissivity: 0.82
• Thicknesses: Baseline Design
• Conductivity: ULE Conductivity
WFE Stability versus Controllability

![Graph showing WFE stability versus controllability.](image)

- Control to 1mK
- Control to 5mK
- Control to 10mK
- Control to 50mK

**Equation:**

\[ y = 11.359x - 0.462 \]

**R²:** 1

**Points:**

- (1.0, 10.4)
- (5.0, 56.6)
- (10.0, 113.4)
- (50.0, 567.4)
WFE Stability versus Period

- Material: ULE
- Period of ACS: Varied
- Controllability of ACS: 50mK
- Density of Mirror: ULE Density
- Emissivity: 0.82
- Thicknesses: Baseline Design
- Conductivity: ULE Conductivity

\[
y = 0.1147x + 0.7095 \\
R^2 = 0.9999
\]
WFE Stability versus Conductivity

- Material: ULE
- Period of ACS: 140s
- Controllability of ACS: 50mK
- Density of Mirror: ULE Density
- Emissivity: 0.82
- Thicknesses: Baseline Design
- Conductivity: Varied

\[ y = -0.6341x + 17.649 \]
\[ R^2 = 0.9983 \]
• Material: ULE
• Period of ACS: 140s
• Controllability of ACS: Varied
• Density of Mirror: Varied
• Emissivity: 0.82
• Thicknesses: Baseline Design
• Conductivity: ULE Conductivity
• Material: ULE
• Period of ACS: 140s
• Controllability of ACS: 50mK
• Density of Mirror: ULE Density
• Emissivity: 0.82
• Thicknesses: Varied
• Conductivity: ULE Conductivity

RMS WFE Range (pm)

Normalized Rib Thickness (Simulated Rib Thickness/Design Rib Thickness)

\[ y = \frac{18.063}{x} - 0.31553x \]

\[ R^2 = 0.9991 \]
• Material: ULE
• Period of ACS: 140s
• Controllability of ACS: 20mK
• Mirror Density: ULE Density
• Emissivity: Varied
• Thicknesses: Baseline Design
• Conductivity: ULE Conductivity

![Graph showing WFE Stability versus Emissivity](image)

The graph shows the relationship between emissivity and RMS WFE range, with a linear regression equation given by:

\[ y = -1.9733x + 8.4309 \]

and an R² value of 0.9772.
WFE Stability versus Material

- Material: Varied
- Period of ACS: 140s
- Controllability of ACS: 50mK
- Mirror Density: Material Based
- Emissivity: Material Based
- Thicknesses: Baseline Design
- Conductivity: Material Based

![Graph showing RMS WFE Range (pm) for different materials: Silicon Carbide, ULE, Zerodur. Silicon Carbide has the highest range at 850.79 pm, followed by ULE at 22.78 pm, and Zerodur at 5.01 pm.]

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Quick Review

• RMS WFE Range is directly proportional to the ACS’s controllability and period.

• RMS WFE Range is inversely proportional to the mirror’s heat capacity and has a weak, negative linear relationship with conductivity and emissivity.

• For the material properties used, Zerodur causes the easiest to meet requirements on an active control system, followed closely by ULE, and distantly by Silicon Carbide.
1-D Rod Closed-Form Model

Rod with a mass, specific heat, thermal energy, temperature and coefficient of thermal expansion of \( m, c_p, Q, T, \) and \( \text{CTE} \) respectfully

- Equation 1 describes heat storage in the rod
  \[ Q = \rho V c_p T \]  
  \text{Equation 1}

- Equation 3 describes linear thermal expansion
  \[ (\text{CTE})L \Delta T = \Delta L \]  
  \text{Equation 3}

- Algebra and calculus then Equation 5

- Equation 5 shows variables that affect thermal strain rate
  - Geometry dependent: \( L, V, \) dQ/dt (surface area)
  - Material dependent: CTE, \( \rho, c_p, \) and dQ/dt (emissivity and absorptivity)

\[
\frac{dL}{dt} = \frac{(\text{CTE})L \; dQ}{\rho V c_p \; dt} \]  
\text{Equation 5}

Length of rod, \( L \)
Summary

• Numerical and analytical models agree that heat capacity and CTE have very strong affects on thermal deformation rates.

• For an actively controlled substrate, the following figures of merit are proposed:

  \[ \frac{dL}{dt} = \frac{(\text{CTE})L}{\rho V c_p} \frac{dQ}{dt} \]

  \[ y = 18.063/x - 0.31553x \]

  Massive Active Optothermal Stability, MAOS = \[ \frac{\rho c_p}{CTE} \]

  Active Optothermal Stability, AOS = \[ \frac{c_p}{CTE} \]
A data table of potential substrate materials is provided*

<table>
<thead>
<tr>
<th>Material</th>
<th>Massive Active Optothermal Stability (TJ/m³)</th>
<th>Active Optothermal Stability (GJ/kg)</th>
<th>Specific heat (J/kg/K)</th>
<th>Density (kg/m³)</th>
<th>Coefficient of thermal expansion (1/K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fused silica</td>
<td>2.91</td>
<td>1.32</td>
<td>741</td>
<td>2202</td>
<td>5.60E-07</td>
</tr>
<tr>
<td>ULE 7971</td>
<td>112</td>
<td>51.1</td>
<td>766</td>
<td>2200</td>
<td>1.50E-08</td>
</tr>
<tr>
<td>Zerodur</td>
<td>83.1</td>
<td>32.8</td>
<td>821</td>
<td>2530</td>
<td>2.50E-08</td>
</tr>
<tr>
<td>Cer-Vit C-101</td>
<td>140</td>
<td>56.0</td>
<td>840</td>
<td>2500</td>
<td>1.50E-08</td>
</tr>
<tr>
<td>Beryllium I-70A</td>
<td>0.298</td>
<td>0.161</td>
<td>1820</td>
<td>1850</td>
<td>1.13E-05</td>
</tr>
<tr>
<td>Aluminum 6061-T6</td>
<td>0.113</td>
<td>0.042</td>
<td>960</td>
<td>2710</td>
<td>2.30E-05</td>
</tr>
<tr>
<td>Silicon Carbide CVD</td>
<td>0.936</td>
<td>0.292</td>
<td>700</td>
<td>3210</td>
<td>2.40E-06</td>
</tr>
<tr>
<td>Borosilicate crown E6</td>
<td>0.595</td>
<td>0.255</td>
<td>830</td>
<td>2330</td>
<td>3.25E-06</td>
</tr>
</tbody>
</table>

Any Questions?

Contact Information
Email: thomas.brooks@NASA.gov
Phone Number: (256) 544-5596
Methodology

Thermal Analysis done in Thermal Desktop → Write NASTRAN input file → Run Thermal Deformation Analysis in NASTRAN → Post Processes Data for Optical Analysis

- Tasks boxed in red are handled entirely with a program written in Python.
- Program saves weeks of work per analysis.
- Program has been used to determine relationships between the telescope’s characteristics and technical performance parameters like stability.