Advanced Mirror Technology Development (AMTD) thermal trade studies

Thomas Brooks, Phil Stahl, Bill Arnold

NASA/MSFC
What is AMTD?

• Efforts associated with this presentation are performed as part of the Advanced Mirror Technology Development (AMTD) program
• Larger aperture space telescopes are required to answer our most compelling science questions.

• AMTD’s objective is to mature to TRL-6 critical technologies needed to produce 4-m or larger flight-qualified UVOIR mirrors by 2018 so that a viable mission can be considered by the 2020 Decadal Review.

• To accomplish our objective, we:
  • Use a science-driven systems engineering approach.
  • Mature technologies required to enable highest priority science AND result in a high-performance low-cost low-risk system.
Description of Primary Mirror

- 4m Circular Monolith
- 0.152m depth front to back
- Light-weighted with a back sheet
- Areal Density is 146 kg/m²
- 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/m³]</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>
• Most heat enters the mirror from the heated plate and exits through the optical surface
• Heat is transported by radiation (56%) and conduction (44%)
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
WFE Contour Video
WFE Visualization

Sample WFE Contour Plot (50mK, 140s Period)

Sample WFE with Focus, Tilts, and Astigmatisms Removed (50mK, 140s Period)
WFE Stability versus Controllability

- 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 RMS WFE range and controllability](image)

- **Graph 1**: RMS WFE - Mean RMS WFE (pm) vs Time (s)
  - Control to 1mK
  - Control to 5mK
  - Control to 10mK
  - Control to 50mK

- **Graph 2**: RMS WFE Range (pm) vs Shroud Controllability (mK)
  - 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

\[
\begin{align*}
y &= 0.1147x + 0.7095 \\
R^2 &= 0.9999
\end{align*}
\]
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
WFE Stability versus Mass and Control

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

![Graph showing RMS WFE Range (pm) vs Shroud Controllability (mK) @ Period of 140s]

- 1x Mass
- 2x Mass
- 3x Mass
WFE Stability versus Thicknesses

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

![Graph showing RMS WFE Range versus Normalized Rib Thickness](image)
WFE Stability versus Emissivity

- Material: ULE
- Period of ACS: 140s
- Controllability of ACS: 20mK
- Mirror Density: ULE Density
- Emissivity: Varied
- Thicknesses: Baseline Design
- Conductivity: ULE Conductivity

\[ y = -1.9733x + 8.4309 \]
\[ R^2 = 0.9772 \]
- Material: Varied
- Period of ACS: 140s
- Controllability of ACS: 50mK
- Mirror Density: Material Based
- Emissivity: Material Based
- Thicknesses: Baseline Design
- Conductivity: Material Based
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 CTE respectfully

- Equation 1 describes heat transfer in and out of the rod
  \[
  \frac{dQ}{dt} = \rho V c_p \frac{dT}{dt} \quad \text{Equation 1}
  \]
- Equation 2 describes linear thermal expansion
  \[
  (\text{CTE})L \Delta T = \Delta L \quad \text{Equation 2}
  \]
- Algebra and calculus then Equation 5
- Equation 4 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)
  \[
  \frac{dL}{dt} = \frac{(\text{CTE})L dQ}{\rho V c_p} \quad \text{Equation 4}
  \]
Summary

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

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

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

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>
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<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.

![Graphs showing wavefront error and shroud temperature over time](image-url)