Arc Jet Testing Of Carbon Phenolic For Mars Sample Return And Future NASA Missions

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The objective of the Mars Sample Return (MSR) mission is to return a sample of Martian soil to Earth.
The Earth Entry Vehicle (EEV) brings the samples through the atmosphere to the ground.
MSR EEV containment requirement

- **Strict containment requirement** by NASA’s Planetary Protection Officer: less than $10^{-6}$ probability of releasing any Martian material within Earth’s biosphere

- Survival of EEV depends greatly on TPS performance
  
  $\Rightarrow$ high reliability EEV $\Rightarrow$ heritage TPS

- Heritage TPS material would be one with a history of successful survival in one or more previous NASA missions
Objectives

- Model aerothermal environment during EEV flight

- On the basis of these modeling results and historic performance, select potential TPS materials for EEV forebody

- Fabricate selected heritage TPS materials, as well as few alternate non-heritage materials

- Test these materials in the arc jet environment representative of predicted flight environment

- Evaluate materials performance in the arc jet

- Compare results of modeling predictions with the test results
Anticipated stagnation point entry heating environment for EEV

- First step in TPS selection is analysis of aerothermal environment

Entry velocity 11.5 km/sec

- 1500 W/cm² peak stagnation point heat flux
- 9.7 kJ/cm² stagnation point integrated heat load
TPS selection: why ablators?

- For heating rates of 1500 W/cm² ablators are the main choice.

- Ablators can be used at extremely severe heating environments, where no other (ceramic-based) reusable materials can be used.

- Drawback is sometimes large recession -> change in aerodynamic shape.

TPS

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<table>
<thead>
<tr>
<th>Mission</th>
<th>TPS material</th>
<th>Integrated heat load, J/cm²</th>
<th>Stagnation heat flux, W/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pioneer Venus</td>
<td>Carbon phenolic, ρ = 1.49 g/cm³</td>
<td>11,800</td>
<td>4,500</td>
</tr>
<tr>
<td>Large Probe</td>
<td>Carbon phenolic, ρ = 1.45 g/cm³</td>
<td>300,000</td>
<td>55,200</td>
</tr>
<tr>
<td>Galileo Probe to Jupiter</td>
<td>Carbon phenolic, ρ = 1.5 g/cm³</td>
<td>9.7</td>
<td>1,500</td>
</tr>
<tr>
<td>Mars Sample Return</td>
<td>Carbon phenolic, ρ = 1.5 g/cm³</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **TPS selection:** Why fully dense carbon phenolic missions at conditions much more severe than expected for MSR EEV.
- **Silica-based tile**
- **Shuttle**
- Fully dense Carbon phenolic as TPS for MSR EEV.
TPS selection: fabrication of tested composites

- In order to fabricate "heritage" materials, original components and processes had to be found, i.e., ones that were used on Galileo probe
- All carbon phenolic composites were fabricated by outside vendors under NASA guidelines

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Rayon fabric → Carbon fabric → Prepregging with phenolic resin → Composite panels
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NASA was able to Acquire original Avtex rayon fabric used in previous successful missions (no longer commercially available)

Rayon was carbonized at the same facility as The heritage fabric

Military grade Phenolic resin 91LD

Original Galileo job procedures were followed, if existed

- Supply of heritage materials for carbon phenolic composites is disappearing -> alternate materials were also tested

Lyocell carbon fiber: staple, larger thickness
Other grade of phenolic resin SC1008

TPS

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TPS selection: fabrication of tested composites

Both Galileo probe and MSR EEV use two types of composites:
- Chopped Molded Carbon Phenolic (CMCP)
- Tape Wrapped Carbon Phenolic (TWCP)

Summary of fabricated and tested composite materials: 6 different materials

<table>
<thead>
<tr>
<th></th>
<th>Carbon Fabric</th>
<th>Phenolic Resin</th>
<th>Density, g/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tape Wrapped</td>
<td>CCA-3 (1641B) *</td>
<td>91LD*</td>
<td>1.47</td>
</tr>
<tr>
<td>30 °-angle ply</td>
<td>CCA-3 (1641B) *</td>
<td>SC1008</td>
<td>1.47</td>
</tr>
<tr>
<td></td>
<td>Lyocell</td>
<td>SC1008</td>
<td>1.33</td>
</tr>
<tr>
<td>Chopped Molded</td>
<td>CCA-3 (1641B) *</td>
<td>91LD*</td>
<td>1.45</td>
</tr>
<tr>
<td></td>
<td>CCA-3 (1641B) *</td>
<td>SC1008</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>Lyocell</td>
<td>SC1008</td>
<td>1.44</td>
</tr>
</tbody>
</table>

* Galileo pedigree fabric and resin systems

Galileo Pedigree fabric/resin system
Arc jet testing: Interactive Heating Facility (IHF)

- Materials were tested at IHF facility at NASA Ames
- 60 MW power

Materials are tested in hypersonic plasma flow
Arc jets simulate flight heating environment
Arc jet testing: summary of test conditions

• Each material was tested at two heating conditions:
  - Maximum heat according to modeling predictions (1500 W/cm²)
  - Half of maximum heat flux (750 W/cm²)
• Similar integrated heat load as during flight

<table>
<thead>
<tr>
<th>Condition</th>
<th>Heat flux, W/cm²</th>
<th>Exposure time, sec.</th>
<th>Total heat load, J/cm²</th>
<th>Stagnation pressure, atm</th>
<th>Stagnation enthalpy, MJ/kg</th>
<th>Model diameter, inch</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td>1500</td>
<td>6.5 (7)</td>
<td>9750 (10500)</td>
<td>1</td>
<td>28.1</td>
<td>1.25</td>
</tr>
<tr>
<td>Condition 2</td>
<td>750</td>
<td>13</td>
<td>9750</td>
<td>0.82</td>
<td>18.1</td>
<td>3</td>
</tr>
<tr>
<td>Flight</td>
<td>varying trajectory</td>
<td>9650</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Test specimen geometry

Sketch of cross section Attached to the holder

Different diameter for high and low conditions due to arc jet restrictions

3 inch for 750 W/cm²
1.25 inch for 1500 W/cm²
Criteria of material evaluation

1. Structural integrity post arc jet test
2. Surface recession

3. Bondline temperature and how close it can be predicted by modeling

4. Surface temperature

5. Weight loss
Arc jet test results: post-test visual appearance

Tape wrapped carbon phenolic

CCA-3/91LD
Sample ID: 91LD-7
Heritage material

Tested at high heat flux (1500 W/cm²)

Lyocell/SC1008
Sample ID: Lyocell-7

- Some delamination for heritage material
- Lyocell/SC1008 didn’t show much delamination
Arc jet test results: post-test visual appearance

Chopped molded carbon phenolic

CCA-3/91LD
Sample ID: 91LD-7
Heritage material

Lyocell/SC1008
Sample ID: Lyocell-7

Tested at high heat flux (1500 W/cm²)

• Both heritage and Lyocell materials showed slight delamination.
Arc jet test results: recession

CCA-3/91LD
Sample ID: 91LD-7
Heritage material

Resin pull-out
Plies separation

Lyocell/SC1008
Sample ID: Lyocell-7

- Very little or no recession was predicted.
- Due to resin pull-out, most of the samples increased in size (negative recession).
- Lyocell fiber composites didn't show much of plies separation due to staple character of Lyocell, and plies interlocking.

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Arc jet test results: recession

- Negative recession (increase in thickness) was observed in most cases due to swelling and/or delaminations.

- Lyocell fiber based composites showed the smallest size change.
Predicted bondline temperatures

- Modeling predicts that arc jet testing at half of maximum heat flux should result in bondline temperature close to the flight conditions.
- Testing at high heat flux should result in lower bondline temperature.
Examples of bondline temperature response

- Examples above are for the TWCP Lyocell/SC1008 material.
- Peak temperature is reached within a few minutes after the models are removed from the flow:
  ~ 100 sec. for the 1500 W/cm² condition;
  ~ 150 sec. for the 750 W/cm² condition.
Summary of peak bondline temperature

750 W/cm² heating condition

- All materials performed comparably to each other in terms of peak bondline temperature
- Slightly higher bondline temperature than predicted
Summary of peak bondline temperature

1500 W/cm² heating condition

Peak bondline temperature, °C

- Tape wrapped
- Chopped molded
- Predicted peak T

CCA-3/91LD  CCA-3/SC1008  Lyocell/SC1008

Heritage material

• All materials performed comparably to each other in terms of peak bondline temperature

• Much higher peak bondline temperature than predicted!
Discrepancy between measured and predicted bondline temperatures

1.25 inch diameter models tested  3 inch diameter models tested at 750 W/cm²
At 1500 W/cm²

- Two-dimensional heat transfer at the center ->
temperature is higher than predicted

- ~ One-dimensional heat transfer
  at the center -> experimental data
  agree with predictions

- Much higher peak bondline temperature than predicted for high heat flux

- This effect was expected due to the small model diameter resulting in
  2-dimensional heat transfer effects during the arc jet test.

(Small diameter models (1.25 inch) were chosen for this test because of limitations
of the IHF facility to achieve ~1500 W/cm² flux on larger size models).

- Modeling was done for one-dimensional case

- In order to correctly evaluate the backface temperature at high heat fluxes, larger
  size models need to be tested. (Small diameter models (1.25 inch) were
Summary

- Potential thermal protection materials for Mars Sample Return Earth Entry Vehicle were tested in a series of screening arc jet tests.

- Strict containment requirement for EEV dictated use of TPS with a heritage of successful flights in the past.

- Fully dense carbon phenolic ablative TPS was selected as one with successful flight heritage (Galileo probe to Jupiter).

- The performance of the Galileo heritage and two other candidate TPS materials were evaluated at 1500 and 750 W/cm² heat flux.

- The test series was successful and demonstrated that all the variant performed adequately at both heat fluxes and showed suitability for use as the forebody TPS for MSR EEV.

- Theoretical models satisfactorily predicted bondline and surface temperatures for 3 inch diameter models tested at 750 W/cm² condition. In order to fully characterize potential materials at high heat fluxes, testing of larger size models is necessary.