Development of Low Density Flexible Carbon Phenolic Ablators

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• **Background**
  SoA Low Density Carbon Phenolic Ablators
  Challenges with SoA Configurations
  What are flexible ablators?

• **Motivation**
  Why flexibles - what are the advantages?

• **Applications**
  Potential Applications

• **Testing**
  Preliminary Thermal and Mechanical Tests

• **Summary**
State of the Art (SoA) Low Density Carbon Phenolic Ablators

- Phenolic Impregnated Carbon Ablator (PICA) was an enabling TPS material for the Stardust mission where it was used as a single piece heatshield
- PICA has the advantages of low density (~0.27g/cm³) coupled with efficient ablative capability at high heat fluxes
- More recently, PICA was chosen as the primary heatshield for Mars Science Lab (MSL) and Space-X’s Dragon as a tiled configuration
Background

Challenges with SoA Configurations

• Under the Orion program PICA was shown to be capable of both ISS and lunar return missions
• Some unresolved issues remain for its application in a tiled configuration for the Orion-specific design including a brittle char and developing a suitable gap filler
• The problem of developing an appropriate gap filler resulted in the Orion program selecting AVCOAT as the primary heatshield material over PICA.
Char Cracking in System Level Tile Array Tests

- Solar Tower testing on an array of PICA tiles with various gap filler materials induced high in-plane compressive stresses (caused by the high temperature gradients) in the samples.

- Articles survived the heating, however additional loads caused char cracking and failure in the char. For the image shown the additional loading caused some of char to fall off adjacent tiles. This highlights the challenges when designing with gap filler materials not compatible with PICA.
Background

*Developing Suitable Gap Filler Solutions for PICA*

- Developing a suitable gap filler material that meets the thermal and structural requirements is not trivial

- Images to the right highlight the challenges with compatible gap filler materials. In the lower heat flux condition, fencing of the gap filler material is observed as it recedes slower than the PICA material, however in the higher test condition the gap filler material recedes faster leaving a gap
Making PICA Flexible

- PICA is a low density carbon phenolic
- Composition works very well up to 1000 W/cm²
- Retain the composition but change the architecture
Making PICA Flexible

Flexible PICA from a Felt Substrate

- Material is comparable in composition to PICA
- Material remains flexible after charring
- Material can be processed as large pieces
- Parameters such as thickness, density etc are tailor able

as processed demonstrating the flexibility of the material in the virgin state

as processed demonstrating the flexibility of the material in the charred state
Advantages of Flexible Ablators

- Flexible ablators have significant design, system integration, and performance advantages as compared to rigids
  - Manufacturability
  - Reduction in piece-parts
  - Ease of assembly
  - Enables larger diameter aeroshells
  - Eliminates gap and seam issues (thermo-mechanical, aero-physics phenomena)

- Orion and MSL aeroshell designs are at the upper limit with respect to mass and size for rigid ablators

Orion Heat Shield
(5 m diameter)

MSL Heat Shield
(4.5 m diameter)
Potential Conformal Applications for Flexible TPS

Potential applications for Heavy Mars Down-mass Concepts

<table>
<thead>
<tr>
<th>Location on Mid L/D Vehicle</th>
<th>Rigid TPS</th>
<th>( q ) (W/cm(^2))</th>
<th>Margin ( q )?</th>
<th>Pressure (kPa)</th>
<th>Shear (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windward cylinder</td>
<td>PICA/LI-900</td>
<td>437 / 130</td>
<td>YES</td>
<td>24 / 17</td>
<td>512 / 266</td>
</tr>
<tr>
<td>Windward cylinder</td>
<td>PICA/LI-900</td>
<td>301 / 87</td>
<td>no</td>
<td>21 / 15</td>
<td>373 / 194</td>
</tr>
<tr>
<td>Nose, max</td>
<td>LI-900</td>
<td>26 / 11</td>
<td>no</td>
<td>1 / 1</td>
<td>30 / 21</td>
</tr>
<tr>
<td>Cylinder side, max</td>
<td>LI-900</td>
<td>26 / 18</td>
<td>no</td>
<td>1 / 10</td>
<td>54 / 67</td>
</tr>
<tr>
<td>Cylinder, leeward max</td>
<td>LI-900</td>
<td>2 / 2</td>
<td>no</td>
<td>0 / 0</td>
<td>3 / 5</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Location on COBRA 14297 Vehicle</th>
<th>Rigid TPS</th>
<th>( q ) (W/cm(^2))</th>
<th>Margin ( q )?</th>
<th>Pressure (kPa)</th>
<th>Shear (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windward cylinder</td>
<td>PICA</td>
<td>174 / 63</td>
<td>no</td>
<td>13 / 13</td>
<td>175 / 114</td>
</tr>
<tr>
<td>Nose, max</td>
<td>LI-900</td>
<td>26 / 10</td>
<td>no</td>
<td>1 / 1</td>
<td>29 / 21</td>
</tr>
<tr>
<td>Cylinder side, max</td>
<td>LI-900</td>
<td>26 / 11</td>
<td>no</td>
<td>1 / 1</td>
<td>28 / 21</td>
</tr>
<tr>
<td>Leeward cylinder</td>
<td>LI-900</td>
<td>1 / 1</td>
<td>no</td>
<td>0 / 1</td>
<td>2 / 4</td>
</tr>
</tbody>
</table>

Analysis of heat rates suggest flexible ablators should be considered for windward cylinder and nose locations.
Potential Conformal Applications for Flexible TPS

Potential applications for Lunar Return and Robotic Mars missions

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Location</th>
<th>q (W/cm²)</th>
<th>Margin q?</th>
<th>Pressure (kPa)</th>
<th>Shear (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orion, LEO</td>
<td>Shoulder (pt 21)</td>
<td>65</td>
<td>no</td>
<td>101</td>
<td>88</td>
</tr>
<tr>
<td>Orion, Lunar</td>
<td>Shoulder (pt 21)</td>
<td>433</td>
<td>no</td>
<td>101</td>
<td>146</td>
</tr>
</tbody>
</table>

Flexible ablators can mitigate PICA integration issues

Flexible ablators are an attractive alternative to rigid PICA for future MSL class rigid aeroshells

Courtesy: J. Arnold ARC
Potential Applications for Flexible TPS

Flexible ablators are enabling for many other future entry missions

<table>
<thead>
<tr>
<th>Entry Vehicle Concept</th>
<th>Location</th>
<th>q (W/cm²)</th>
<th>Margin q?</th>
<th>Pressure (kPa)</th>
<th>Shear (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EDL SA, ADEPT</td>
<td>Peak Forebody</td>
<td>106 / 32</td>
<td>YES</td>
<td>11 / 8</td>
<td>42 / 25</td>
</tr>
<tr>
<td>EDL SA, ADEPT</td>
<td>Peak Forebody</td>
<td>67 / 21</td>
<td>no</td>
<td>9 / 6</td>
<td>27 / 16</td>
</tr>
</tbody>
</table>

1 Hypersonic Inflatable Aerodynamic Decelerator
2 Adaptive Deployable Entry-system Project

7.2 km/s entry, capable1 of delivering 3.4 mt to Mars surface2 (7.2 mt arrival mass)

1 EDL SA 2010 study
2 Viking (MSL) technology can deliver ~ 1.2 mt

1 HIAD Concept
(23 m diameter)

2 ADEPT Concept
(23 m diameter)

Exploration FeedForward (EFF) Concepts
(6, 8, 10 m diameters)

1 Courtesy: J. Arnold ARC
Results from Preliminary Screening Tests

• Candidate systems have been processed and are currently going through a series of screening tests that include mechanical, thermal and relevant environment screening (arc jet, LHMELE, HyMETs)

• Preliminary Results:
  – Mechanical
  – Thermal Conductivity
  – Microstructure
  – Arc Jet testing
  – LHMELE Testing
Samples were tested in tension in the IP direction to evaluate strength and strain to failure. (8” x 1”)

PICA flex failed very gracefully during the test and showed necking behavior – a phenomenon that is traditionally present in very ductile materials.

PICA flex was able to withstand about 8%-12% strain before onset of necking.

For comparison, a PICA stress strain curve is also provided - strain to failure of PICA is < 1% which leads to difficulties in designing with PICA.

While PICA has higher strength, in applications that are strain to failure driven, PICA flex has advantages.
• The laser flash method was used to evaluate thermal conductivity in PICA flex
• Data presented is an average of 3 samples
• For comparison, the thermal conductivity of PICA are also provided
• For this test series the PICA and PICA flex samples have comparable densities, however, the thermal conductivity of PICA flex is approximately a third of that of rigid PICA
Microstructure

- Characterizing the microstructure of a TPS material is important as the constituent distribution at the microstructural level will influence properties.
- PICA flex has a microstructure that resembles PICA in many aspects; distributed phenolic phase in a carbon matrix.

Representative PICA flex microstructure

Representative PICA microstructure
LHMEI Screening Tests

- Exposure 115 W/cm² for 30 seconds
- Comparable areal mass for all materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Max. Backface Temperature (°C)</th>
<th>Time to Reach Max. Backface Temperature (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIRCA</td>
<td>198</td>
<td>120</td>
</tr>
<tr>
<td>PICA Flex Variant 1</td>
<td>72</td>
<td>310</td>
</tr>
<tr>
<td>PICA Flex Variant 2</td>
<td>64</td>
<td>152</td>
</tr>
<tr>
<td>PICA Flex Variant 3</td>
<td>80</td>
<td>186</td>
</tr>
</tbody>
</table>

Pre test

Post test
LHMELEL Screening Tests

1st Exposure

- 450 W/cm² for 25 seconds

<table>
<thead>
<tr>
<th>Material</th>
<th>Max. Backface Temperature (°C)</th>
<th>Time to Reach Max. Backface Temperature (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PICA</td>
<td>240</td>
<td>93</td>
</tr>
<tr>
<td>PICA Flex Variant 1</td>
<td>118</td>
<td>213</td>
</tr>
<tr>
<td>PICA Flex Variant 2</td>
<td>75.5</td>
<td>246</td>
</tr>
<tr>
<td>PICA Flex Variant 3</td>
<td>133</td>
<td>143</td>
</tr>
</tbody>
</table>

2nd Exposure

- 115 W/cm² for 50 seconds

<table>
<thead>
<tr>
<th>Material</th>
<th>Max. Backface Temperature (°C)</th>
<th>Time to Reach Max. Backface Temperature (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PICA</td>
<td>276</td>
<td>108</td>
</tr>
<tr>
<td>PICA Flex Variant 1</td>
<td>128</td>
<td>223</td>
</tr>
<tr>
<td>PICA Flex Variant 2</td>
<td>84</td>
<td>232</td>
</tr>
<tr>
<td>PICA Flex Variant 3</td>
<td>173</td>
<td>144</td>
</tr>
</tbody>
</table>

- Comparable areal mass for all materials
Arc Jet Exposure

- Initial arc jet screening has been completed at the Johnson Space Center arc jet facility
- Samples were 3” diameter by ~ 1” thick and bonded to an LI 2200 tile holder and were instrumented with a backface thermocouple
- Initial arc-jet tests show PICA flex performing well at 520 W/cm², 35 kPA
- Performance limits for flexible ablators have yet to be determined

![Pre test](Image)
![Post test](Image)
Summary

- We are currently looking at alternative architectures to yield flexible and more conformal carbon phenolic materials with comparable performance to PICA.
- Flexible TPS concepts address some of the design issues faced in the application of a tiled PICA heat shield.
- Initial testing of flexible PICA concepts has been encouraging:
  - Substantially higher strain to failure than PICA.
  - Lower thermal conductivity than PICA.
  - Survived a 520 W/cm², 35 kPa arc jet exposure.
- Flexible ablator technology is enabling for upcoming NASA missions:
  - Rigid and deployable TPS applications.
  - For the 23 m HIAD and ADEPT deployable decelerators and for revolutionary ADEPT missions to Venus and Saturn.
- Testing will begin under Office of the Chief Technologist funding in Fiscal Year 2012.
Acknowledgement

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  - the Entry, Descent, and Landing Technology Development Project.

- The authors would also like to acknowledge Robin Beck, Jim Arnold, Kristina Skokova, Susan White and Jose Chavez-Garcia
Families of Ablators Under Development at Ames

- Advanced PICA-like ablators
- Conformable PICA
- Flexible PICA
- Graded Ablators
- Flexible SIRCA