Arcjet Testing of Advanced Conformal Ablative TPS

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Outline

• Technology Description
  – Conformal Ablative TPS
  – CA250 Project

• Arcjet Test Design
  – SPRITE

• Results
  – Temperature Response
  – Recession
  – Thermal Modeling

• Summary
Description: Conformal Ablative TPS

- **Substrate:** Low density carbon or polymer felts
  - High strain to failure eliminates need for strain isolation (SIP or large gap) upon attachment to rigid aeroshell (required for PICA & Si-based Tile)
  - Allows for large acreage application (reduced part count)
  - Reduced gaps and gap filler issues present with rigid TPS
  - Near-net-shape fabrication with preferred thermal orientation

- **Resin:** Modified phenolic (CPICA), modified silicone (CSICA), cyanate ester, etc.

- **First developed under Hypersonics EDL Project 2009-11**
  - Patent Pending 13/357,248

- **Transferred to CA250 Project in 2011**
CA250 TPS Project

• **Goal**
  – Development of Conformal PICA (CPICA) to TRL 5 by 2015

• **Activities**
  – 2013: Demonstrate (via ground testing) a conformal ablator capable to at least 250 W/cm²
  – 2014/15: Demonstrate process/fabrication scale-up via industrial partner

• **Motivation**
  – Commercially available felt systems come in 60-inch wide rolls
    • Larger parts, reduced part count
      (e.g. 30 pieces CA for MSL size vehicle vs. 120 PICA tiles)
  – Less complex to integrate across a variety of carrier structure
    • Insensitive to surface finish or rigidity of substructure
    • Does not require RTV or other “gap” filler between TPS segments
  – Less expensive “system” to manufacture and integrate
CA250 TPS Project

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Test Objectives

1. Assess the thermal performance of CPICA over a broad range of conditions
2. Develop TPS-C instrumentation for developing and validating thermal response models from TPS materials testing in the arcjet
3. Develop mid-fidelity material response model for CPICA that can predict recession and in-depth temp response in support of mission design and analysis
4. Address how to attach CPICA to a rigid structure while also evaluating seam designs between gore panels
CPICA Material Properties

- **Previous Work 2011-12**
  - Stagnation arcjet tests and screening test with SPRITE geometry 2 conditions
  - Limited material property data
    - Many properties guessed and/or scaled from those of PICA
  - Preliminary ablation and thermal response model developed for use with FIAT
- **Based on new 2013 data, the following were updated**
  - Small changes to
    - Virgin and char densities
    - Elemental composition
  - Preliminary CPICA FIAT model adjusted with new property data
    - Virgin specific heat
    - Virgin and char thermal conductivity
  - Recalculated based on above
    - Pyrolysis gas enthalpy
Aerothermal: MSL Peak Design

**MSL Aerothermal Entry Environments**

<table>
<thead>
<tr>
<th>Location</th>
<th>+3-sigma Value</th>
<th>09-TPS-02</th>
<th>Edquist, JPL D-34661, Rev B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak Heat Rate (W/cm²)</td>
<td>Peak Shear (Pa)</td>
<td>Peak Pressure (atm)</td>
<td>Peak Heat Load (J/cm²)</td>
</tr>
<tr>
<td>HS Leeside Flank</td>
<td>220.1</td>
<td>393.4</td>
<td>0.246</td>
</tr>
<tr>
<td>HS Leeside Shoulder</td>
<td>225.7</td>
<td>465.4</td>
<td>0.242</td>
</tr>
<tr>
<td>HS Leeside Shoulder</td>
<td>203.2</td>
<td>490.2</td>
<td>0.208</td>
</tr>
<tr>
<td>Stagnation Point</td>
<td>59</td>
<td>5.4</td>
<td>0.332</td>
</tr>
<tr>
<td>HS Nose Apex</td>
<td>119.2</td>
<td>127.4</td>
<td>0.239</td>
</tr>
<tr>
<td>HS Windside Shoulder</td>
<td>114.4</td>
<td>216.7</td>
<td>0.242</td>
</tr>
<tr>
<td>HS Windside Shoulder</td>
<td>103.8</td>
<td>240.5</td>
<td>0.172</td>
</tr>
</tbody>
</table>

250 W/cm², 0.33 Atm, 490 Pa Shear
SPRITE Test Article Detail

SPRITE¹ – Small Probe Reentry Investigation for TPS Engineering

- 8-inch diameter
- 55° sphere cone

LI-2200 INSULATION RING (HIDDEN) TO BACK OF STING ADAPTER FLANGE (HIDDEN)

RTV 560

RTV only on bottom half of TPS

STING ADAPTER ATTACHES TO THIS SURFACE

TO BACK OF LI-2200 INSULATION RING

3.689
3.945
4.1945

SIZE
CAGE CODE
DWG NO.

B
25307
#
Pre-Test CFD

High Condition “MSL+”
~ 400 W/cm², ~ 24 kPa
Press. ~ 210 Pa shear on
Flank and ~ 550 Pa shear
On 0.8” Rₜ corner

CFD - Dinesh Prabhu
Test Description

- 8 Articles tested at 4 conditions: 40, 150, 180 & 400 W/cm\(^2\)
- Standard rigid PICA & CPICA: both 0.5-inch thick & 0.28g/cm\(^3\)
- 4-inch hemispherical calorimeters were used to characterize the flow
- 4 TR models had TC plugs in each TPS segment at depth of: 0.15, 0.30 & 0.50-inch
- 4 seam models had TC plug in PICA segment and TC’s at 0.50-inch behind CPICA segments

```
<table>
<thead>
<tr>
<th>Condition</th>
<th>Cold Wall Heat Flux (W/cm(^2))</th>
<th>Pressure (atm)</th>
<th>Shear (Pa)</th>
<th>Exposure Duration (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Condition 1</td>
<td>400</td>
<td>0.25</td>
<td>210</td>
<td>30</td>
</tr>
<tr>
<td>Condition 2</td>
<td>180</td>
<td>0.15</td>
<td>120</td>
<td>60</td>
</tr>
<tr>
<td>Condition 3</td>
<td>150</td>
<td>0.07</td>
<td>100</td>
<td>80</td>
</tr>
<tr>
<td>Condition 4</td>
<td>40</td>
<td>0.09</td>
<td>60</td>
<td>100</td>
</tr>
</tbody>
</table>
```
Detail: Seam Models
Models During Testing

Uniform Heating (Conditions 1-3)

Non-Uniform Heating due to RTV expansion and flow (Condition 4)
Model During Testing @ 400 W/cm² on flank

IR image of model during testing illustrating uniform heating on the flank
Post-Test – $400 \text{ W/cm}^2$, 30 sec

C-PICA

PICA

Thermal Response Model

Seam Model
Backface Temp – TR Model

Backface Temperature Response $q_{flank} = 400 \text{ W/cm}^2$, 30-s

- **Standard PICA**
  - $\Delta T = 318 \degree C$

- **Conformal PICA**
  - $\Delta T = 145 \degree C$
Backface Temp – Seam Model

Backface Temperature Response $q = 400 \text{ W/cm}^2$, 30-s

- Standard PICA
  - $\Delta T = 400 \degree C$

- Conformal PICA
  - $\Delta T = 150 \degree C$

Test Time sec

Backface Temperature $\degree C$
# Post-Test Thermal Response

<table>
<thead>
<tr>
<th>Surface Temp</th>
<th>400 W/cm² – 30 sec.</th>
<th>180 W/cm² – 60 sec.</th>
<th>150 W/cm² – 80 sec.</th>
<th>40 W/cm² – 100 sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PICA</td>
<td>C-PICA</td>
<td>PICA</td>
<td>C-PICA</td>
</tr>
<tr>
<td>Temp C</td>
<td>2361</td>
<td>1039</td>
<td>677</td>
<td>151</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>25</td>
<td>124</td>
<td>23</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>0.30”</td>
<td>0.50”</td>
<td>0.30”</td>
<td>0.50”</td>
</tr>
<tr>
<td></td>
<td>1374</td>
<td>966</td>
<td>628</td>
<td>213</td>
</tr>
<tr>
<td>Std. Dev.</td>
<td>15</td>
<td>66</td>
<td>33</td>
<td>10</td>
</tr>
</tbody>
</table>

*TC’s at 0.15-in not listed as they all burned out*
## Post-Test Recession

<table>
<thead>
<tr>
<th>Material</th>
<th>Heat Flux (W/cm²)</th>
<th>Exposure Time (s)</th>
<th>Recession* (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PICA</td>
<td>400</td>
<td>30</td>
<td>2.8</td>
</tr>
<tr>
<td>C-PICA</td>
<td></td>
<td></td>
<td>3.5 +/-0.17</td>
</tr>
<tr>
<td>PICA</td>
<td>180</td>
<td>60</td>
<td>4.1</td>
</tr>
<tr>
<td>C-PICA</td>
<td></td>
<td></td>
<td>4.7 +/-0.04</td>
</tr>
<tr>
<td>PICA</td>
<td>150</td>
<td>80</td>
<td>4.0</td>
</tr>
<tr>
<td>C-PICA</td>
<td></td>
<td></td>
<td>4.7 +/-0.37</td>
</tr>
<tr>
<td>C-PICA</td>
<td>40</td>
<td>100</td>
<td>3.0</td>
</tr>
<tr>
<td>C-PICA</td>
<td></td>
<td></td>
<td>3.4 +/-0.50</td>
</tr>
</tbody>
</table>

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**Laser Scan of Post-Test Model**

**Recession Analysis – Jose Santos**
FIAT run with ±10% of nominal heating
  – Recession was ok at both nose and TC plug
  – Temperatures matched fairly well for Tw, TC1, and TC2
  – Could not match time TC3 response in this test series

*Temperature predictions for nose not shown (no data acquired)
CPICA – Condition 1

- Recession, Tw, and TC1 match model well
- Model a bit low for TC2, but high for TC3
Summary

- Fabricated CPICA using commercially available carbon felt
- Demonstrated applicability of CPICA on a curved structure at range of conditions from 40-400W/cm²
  - MSL-heat flux, pressure and shear
- Demonstrated advanced instrumentation of CPICA and gathered in-situ temperature & recession data in a representative shear environment
- Evaluated 5 seam designs between CPICA gores
  - All designs performed well
  - TPS performance not affected by any particular seam design
- CPICA material response model created based on new arcjet and thermal property data
  - Developed a mid-fidelity model that compares favorably with recession and temperature data
  - Errors tend toward over-prediction of surface recession and/or in-depth temperature, to be investigated
Initial and Ablated Shapes

- Models were scanned to get post-test shape in bisecting plane of each quadrant
- Although shape change around nose is significant, did not affect conditions on flank

[Graphs showing radial vs. axial coordinate for different power densities: 400 W/cm², 180 W/cm², 150 W/cm², 40 W/cm². Each graph compares PICA and CPICA results.]
DPLR – Pre & Post-Test

- For each arc jet condition, DPLR was run using the initial shape and the smoothed final shape
  - Results show only a small change in pressure and heat flux at the TC plug as a result of shape change