Arc Jet Testing of Thermal Protection Materials:
3 Case Studies

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Arc Jet Testing: TPS Case Studies

Arc Jet Testing

Other than an actual flight test, arc jet facilities are the best available tool for testing materials and systems in high speed entry environments.

Arc jets provide a controlled test environment that approximates the heat fluxes, surface temperatures, enthalpies, pressures, flow, and shear experienced during high speed entries.

While arc jet facilities cannot duplicate all of the relevant parameters in any single test, a well designed test matrix in concert with material modeling and analysis can offer Mission teams confidence in validating the performance of their thermal protection materials and systems.
Arc Jet Testing: TPS Case Studies

The following presentation discusses three illustrative cases involving material issues identified during arc jet testing.

Background

Case 1: PICA & MSL
Testing identifies material issue

Case 2: Advanced TUFROC
Test article or material?

Case 3: Conformal PICA
Testing guides material development
**Arc Jet Testing: TPS Case Studies**

### ArcJet Basics

- **High Energy Flow**
  - Mach 5 - 7 at exit
  - Bulk Temp $\sim 7,000^\circ$ K

- **Constrictor Segment**
  - Electrically isolated
  - Test gas (e.g. air, nitrogen)

- **Interchangeable Nozzles**
  - Cut-away cross-section
  - 99.99% pure copper

- **Sealed Test Chamber**
  - Capable of simulating extreme upper atmosphere (1 - 5 Torr)

- **Cooling Water**
  - Test gas
  - Cooling water
Arc Jet Testing: TPS Case Studies

NASA Ames Arc Jet Complex

- Nation's highest powered (150 MW DC) arc-heated hyper-thermal test facility
  - Aerodynamic Heating Facility (AHF) 20 MW
  - Turbulent Flow Duct (TFD) 20 MW
  - Panel Test Facility (PTF) 20 MW
  - Interactive Heating Facility (IHF) 60 MW

- Unique capabilities enable development of advanced TPS materials and concepts

- Large test articles (2.5 cm up to 60 x 60 cm)

- Pre-mixed test gas with continuous high enthalpy flows (2 - 40 MJ/kg in air)

- Plasma flow expands through selectable nozzles to hypersonic speeds

- Enthalpies similar to planetary entries

- Spectroscopic / LIF diagnostic capability

Every NASA flown thermal protection system has been tested in some capacity in the Ames Arc Jet Complex.
Arc Jet Testing: TPS Case Studies

Outline

Case 1: PICA & MSL
Testing identifies material issue

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* Phenolic Impregnated Carbon Ablator
** Mars Science Laboratory
Objective of NASA's Mars Science Laboratory (MSL) program was to place an SUV size rover (Curiosity) safely on the surface of Mars.

Too heavy for airbags, MSL utilized a Sky Crane for a powered descent.

3 m (long) x 3 m (wide) x 2 m (tall)
900 kg, 6 wheels, 90 m/hr
MSL Entry, Descent, and Landing (EDL) Phase
17 minutes of excitement

1. Entry Vehicle separation from Cruise Stage
2. Balance devices separation
3. Entry Interface
4. Peak heating
5. Peak deceleration
6. Hypersonic aero-maneuvering
7. Parachute deployment
8. Heat shield separation
9. Radar ground mapping
10. Backshell separation
11. Retro-propulsion
12. Tethered descent
13. Touchdown and cable separation
14. Sky Crane fly-away

Guided Entry
- 125 km 5.8 km/s

Parachute Descent
- 10 km 500 m/s

Powered Descent
- 1.8 km 100 m/s

Landing
- 8 m, 1 m/s

Approximate, non-linear time scale

T = 0 2 min 10 min 15 min 16 min 17 min
Prior to MSL, the heaviest Mars entry vehicle (EV) was Viking (980 kg). MSL (3380 kg) expected to be more than triple the EV mass of Viking.

Curiosity rover ~ 5 times the mass of MER Spirit / Opportunity rovers.

Given MSL's mass, geometry, and trajectory - turbulent flow was predicted on the primary heat shield (first for a Mars entry)

⇒ Entry heating projected to be 2x that of any previous Mars mission
## CASE 1: PICA & MSL

### Comparing MSL (design) with Prior Mars Entry Vehicles

<table>
<thead>
<tr>
<th></th>
<th>Viking 1 &amp; 2</th>
<th>Pathfinder</th>
<th>MER A &amp; B*</th>
<th>Phoenix</th>
<th>MSL (design)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Entry mass (kg)</strong></td>
<td>980</td>
<td>585</td>
<td>840</td>
<td>570</td>
<td>3,380</td>
</tr>
<tr>
<td><strong>Entry speed (km/s)</strong></td>
<td>4.5</td>
<td>7.6</td>
<td>5.5</td>
<td>5.5</td>
<td>5.6</td>
</tr>
<tr>
<td><strong>Heat shield diameter (m)</strong></td>
<td>3.5</td>
<td>2.65</td>
<td>2.65</td>
<td>2.65</td>
<td>4.5</td>
</tr>
<tr>
<td><strong>Heat shield (TPS) material</strong></td>
<td>SLA-561V</td>
<td>SLA-561V</td>
<td>SLA-561V</td>
<td>SLA-561V</td>
<td>SLA-561V</td>
</tr>
<tr>
<td><strong>TPS thickness (cm)</strong></td>
<td>1.3</td>
<td>1.9</td>
<td>1.6</td>
<td>1.4</td>
<td>TBD</td>
</tr>
<tr>
<td><strong>Peak heat flux (W/cm^2)</strong></td>
<td>20</td>
<td>120</td>
<td>50</td>
<td>55</td>
<td>200</td>
</tr>
<tr>
<td><strong>Turbulent (at peak heat flux)?</strong></td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Peak pressure (atm)</strong></td>
<td>0.1</td>
<td>0.2</td>
<td>0.1</td>
<td>0.08</td>
<td>0.37</td>
</tr>
</tbody>
</table>

**KEY** denotes MSL not in class with prior Missions  

* Spirit & Opportunity
**CASE 1: PICA & MSL**

**SLA Stagnation Testing for MSL**

- **MSL baselined SLA-561V**, which performed well in stagnation arc jet testing and was heatshield material for all previous Mars missions.

- Glass vaporization allowed material to withstand heat fluxes > 300 W/cm²

- **No failures observed**

- High fidelity SLA-561V material model matched stagnation arc jet tests

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**MSL Stagnation Test Articles (SLA-561V)**

- 30 W/cm²
- 90 W/cm²
- 150 W/cm²
- 210 W/cm²
- 270 W/cm²
- 300 W/cm²
CASE 1: PICA & MSL

SLA Shear Testing for MSL

• Arc jet testing in shear environments yielded catastrophic material failures
  - Recession rate was 20+ times predicted values
  - Filler material seemed to disintegrate and evacuate the cells
  - Not a melt-fail; not correlated to shear force

![Image of material failure at different times: t = 14 sec, t = 16 sec, t = 18 sec]

• Material failure reproducible at certain conditions
**CASE 1: PICA & MSL**

**Program Decision**

- **Failure identified** in Sep 2007 after Critical Design Review and ~23 months before launch

<table>
<thead>
<tr>
<th>Option A</th>
<th>Option B</th>
</tr>
</thead>
<tbody>
<tr>
<td>Re-design mission to within heritage heat fluxes / pressures</td>
<td>Flight qualify alternate heat shield TPS material</td>
</tr>
<tr>
<td>Limits landing sites</td>
<td>PICA best candidate</td>
</tr>
<tr>
<td>Impact on science objectives?</td>
<td>Tiled ablator design never flown</td>
</tr>
<tr>
<td>Require more propellant</td>
<td>Leverages Orion PICA development</td>
</tr>
<tr>
<td>Adversely affect entry guidance robustness</td>
<td>MSL cost &amp; schedule at risk if any major technical issues arise</td>
</tr>
</tbody>
</table>

- MSL went with **Option B**, selecting PICA material
  - Leveraged past and ongoing PICA development by the CEV Orion project
  - MSL PICA testing would also expand Orion's PICA database
CASE 1: PICA & MSL

PICA consists of carbon substrate* impregnated with phenolic resin

High surface area resin morphology yields desirable thermal performance

*Fiberform™

Low phenolic loading matrix uniformly distributed throughout the substrate material

Carbon Fibers Pre-Impregnation
low density, randomly arranged

Carbon Fibers Post-Processing
connected via 'fluffy' phenolic

Impregnation
Curing
CASE 1: PICA & MSL

Go-Forward Plan

• Design, develop, test, build, and qualify a PICA heat shield for an April 2009 delivery ( < 18 months from start!)

• Fortunately, to date Orion had conducted 125 arc jet tests of PICA
  - Tested to more severe environments (heating, pressure, shear)
  - Various gap filler designs
  - Material characterization (material property tests) performed
  - High fidelity model developed for in-depth thermal and recession response

• MSL could simplify design because the aeroshell structure was composite (vs metallic for Orion)
  - CTE agreement was better
  - Lower deflections in MSL enabled direct bonding to structure and filled gaps
CASE 1: PICA & MSL

Not much time!

• MSL PICA design worked in parallel with PICA manufacturing
  - Maximum allowable gap size originally based on Orion tests
  - Gap size then refined via thermal/structural analysis; verified through tests

• TPS sizing selected at 1.25" (3.175 cm) without detailed testing or analysis
  - Conservative over-design
  - 1.25" based on maximum mass allowed by spacecraft mass budget

• Symmetric heat shield selected to minimize aero-torques

• Tiled architecture driven by
  - PICA processing limitations
  - Aerothermal environments
  - Thermal-mechanical requirements
Entry Systems & Technology Division

PICA Stagnation Testing

• Gap-filled specimens simulated cruise-to-entry effects
  - Low and high heat fluxes
  - With and without pre-cooling

• Tests using in-depth instrumentation verified PICA thermal response model

• Predicted recession rates within 20% of measured values from arc jet tests
  - MSL-relevant conditions
  - Predictions not as good at low heat rates
  - TITAN: 2D thermal response model
CASE 1: PICA & MSL

**PICA Shear Testing**

- Shear tests conducted at Ames and AEDC with wedges, swept cylinders
  - Comparison of tested PICA to thermal response model predictions
  - Effects of fiber direction
  - Gap filler response
  - Damaged or flawed acreage / gaps
  - Repair methods
  - Coating behavior

- Long gaps tested in Panel Test Facility (PTF), Turbulent Flow Duct (TFD)
Extensive PICA arc jet test series utilized 100+ test articles

PICA material robust at all tested conditions including those where SLA-561V experienced failures

RTV-560 filled gaps performed well

Recession rates varied from model predictions, but could be modeled and bounded conservatively

Heat Shield thickness
- Up front, program decision was to set it at 1.25"
- Analysis and margining process yielded a thickness of 0.94"
- So, as built vehicle had 0.31” extra thermal protection material / margin
CASE 1: PICA & MSL

MSL PICA Heat Shield

19 PICA lots manufactured for testing, development, production
⇒ 114 PICA billets ⇒ 113 PICA tiles (with 27 different tile geometries)
CASE 1: PICA & MSL

MSL Team Accomplishment

- Developed, designed, tested, built and qualified a 4.5-m tiled ablative heatshield in 18 months

- NASA’s first tiled, ablative (flight hardware) heat shield
**MSL Mission Success**

- MSL launched on 26 Nov 2011
- **6 Aug 2012**: successfully entered Mars atmosphere @ 5.8 km/s
- **Curiosity safely landed in Gale Crater**, within 3 km of the target after a 563,000,000 km journey
- **Curiosity has been producing valuable science on the surface of Mars for 1000+ days**

Top View of the MSL Heat Shield image taken by Curiosity 3 sec (50 ft) after separation from the descent Capsule
Arc Jet Testing: TPS Case Studies

Outline

Case 1: PICA & MSL
Testing identifies material issue

Case 2: Advanced TUFROC*
Test article or material?

Case 3: Conformal PICA
Testing guides material development

* Toughened Uni-piece Fibrous Reinforced Oxidation Resistant Composite
While the Space Shuttle was a technical marvel, there remains a national need for low cost, reliable access to and from Earth orbit.

- DoD Missions
- Space Station support
- Commercial access (satellite servicing, tourism, manufacturing)

**Major technical gap:** low cost, reusable TPS for high temp surfaces
CASE 2: Advanced TUFROC

Standard TUFROC History

• In 1998, NASA established **Future-X Pathfinder** program to develop 2\textsuperscript{nd} generation reusable launch systems

• In 1999, MSFC led **X-37** project was established with Boeing as the prime

• Parallel research and development of the **TUFROC** concept started in 1998

• Leadership **transitioned to DARPA in 2004** to support a U.S. Air Force vehicle – **X-37b**

• In 2003, a focused 18 month activity took **TUFROC** from research TPS to flight ready

⇒ Standard TUFROC
CASE 2: Advanced TUFROC

Flight Proven Standard TUFROC

TUFROC spans USAF X-37b wing leading edge
- NASA developed Standard TUFROC and transferred it to X-37b Prime - Boeing
- Enabling technology for critical USAF Program
- 3 successful missions, 4th mission in progress

Reusability of Standard TUFROC? ⇒ Advanced
CASE 2: Advanced TUFROC

Standard TUFROC

2 Piece Approach

*Re-radiate enough heat so that conduction through*
- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

**ROCCI Carbonaceous Cap**
- Silicon-oxycarbide phase slows oxidation
- HETC, treatment near surface slows oxidation and keeps emissivity high ($\varepsilon \sim 0.9$)
- Coated with borosilicate reaction cured glass (RCG) for oxidation resistance

**AETB Silica Insulating Base**
- Solved thermo-structural issues by adding boron oxide ($B_2O_3$) and alumino-borosilicate fibers, which also improved mechanical strength
- Increased temp capability to 2500+ °F by adding alumina ($Al_2O_3$) fiber

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**Graph:**
- Re-radiation $\propto \varepsilon T^4$
- ROCCI Cap maintains outer mold line max temp: 3000 °F
- AETB Insulating Base significantly reduces heat conducted to the vehicle max temp: 2600 °F

**Table:**
<table>
<thead>
<tr>
<th>Max Temp (°F)</th>
<th>Vehicle Structure</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>
CASE 2: Advanced TUFROC

**Advanced TUFROC**

**2 Piece Approach**

*Re-radiate enough heat so that conduction through*

- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

**ROCCI Carbonaceous Cap**

- Silicon-oxycarbide phase slows oxidation
- High temp HETC surface treatments that helps mitigate ROCCI – RCG CTE issues
- Improved, higher viscosity RCG to handle repeated cycles at higher temperatures

**AETB Silica Insulating Base**

- Solved thermo-structural issues by adding boron oxide ($B_2O_3$) and alumino-borosilicate fibers, which also improved mechanical strength
- Increased temp capability to 2500+ °F by adding alumina ($Al_2O_3$) fiber
Series of Arc jet tests conducted to evaluate modified HETC, RCG. Blunt cone provides uniform temps across stagnation region of the model (more useful for evaluating different surface treatments / coatings than blunt wedges)

**AHF T-257** (Jul 2007) Blunt cones at 0.04 atm and 78 W/cm²

<table>
<thead>
<tr>
<th>Model</th>
<th>Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1025</td>
<td>3080 °F</td>
</tr>
<tr>
<td>Model 1028</td>
<td>3070 °F</td>
</tr>
<tr>
<td>Model 1030</td>
<td>3095 °F</td>
</tr>
</tbody>
</table>

1st Exposure 5 min

Total exposure = 600 sec
CASSE 2: Advanced TUFROC

Sphere cone provides a heat flux distribution more similar to WLE flight conditions

AHF Test Series: T-284, March 2009

Sphere Cone Pre-Test Model

1st Exposure
5 min

Test Conditions
\( H_{eo} = 17.3 \text{ MJ/kg} \)
\( P_O = 0.02 \text{ atm} \)
\( q_{HW} = 61 \text{ W/cm}^2 \)

Model 1044
3120 °F

Model 1043
3000 °F

2nd Exposure
5 min
(same conditions)
Total exposure = 600 sec

Model during arc jet exposure
CASE 2: Advanced TUFROC

Arc jet test exposed corner issue with the sphere cone model

AHF Arc-Jet Exposure on Test Article 1043 (Mod IV)

\[ T_w = 3,000^\circ F \quad H_{e0} = 17.5 \text{ MJ/kg} \quad P_0 = 0.02 \text{ atm} \]

Unfiltered Test Image  Filtered Test Image  Post Test Article

Test article issue or a material issue relevant to flight hardware?

- \( T_w \) - wall temperature
- \( H_{e0} \) - enthalpy at the boundary layer edge
- \( P_0 \) - pressure at the stagnation point
CASE 2: Advanced TUFROC

Aerothermal & Thermal-Mechanical Analysis

**Heating Distribution* over Test Article**

**Surface Heat Flux**

- **Stagnation Region**
- **Shoulder**

**Thermal stresses** caused by velocity gradient near sonic line at shoulder

**Silica insulating base**

**Stresses concentrated by mechanical attachment**

- (interlocking tab)

⇒ Test article design issue
Not representative of flight hardware. Not a material issue.

**Surface heating for 5 min with a 10 min cool-down**

- **312 kPa, 17.67 MJ/kg**
- **393 kPa, 18.60 MJ/kg**

*DPLR solution from Gokcen; **FEM analysis from Squire*
CASE 2: Advanced TUFROC

Original Interlocking Tab Mechanical Attachment
CASE 2: Advanced TUFROC

Re-designed Interlocking Tab Mechanical Attachment
CASE 2: Advanced TUFROC

AHF Test Series: T-284 & T-290
Single 5 min exposures

Original interlocking tab attachment

Test Series: T-284
March 2009

Ames Model 1043
3000 °F

$H_{eo} = 17.5 \text{ MJ/kg}$
$P_{O} = 0.02 \text{ atm}$
$q_{HW} = 70 \text{ W/cm}^2$

Re-designed interlocking tab attachment

Test Series: T-290
Feb 2010

Ames Model 1048
3175 °F

$H_{eo} = 22.8 \text{ MJ/kg}$
$P_{O} = 0.034 \text{ atm}$
$q_{HW} = 85 \text{ W/cm}^2$

⇒ arc jet results confirmed no issue with material
CASE 2: Advanced TUFROC

Corner issue resolved, modified HETC & RCG testing continued

AHF T-293
Nov 2010

Pre-Test

Model 1056

1st Exposure
8 min

Test Conditions

$H_{eo} = 19.1 \text{ MJ/kg}$
$P_O = 0.03 \text{ atm}$
$q_{HW} = 70 \text{ W/cm}^2$

3000 °F

Model 1056

AHF T-301
May 2012

2nd Exposure
8 min

Test Conditions

$H_{eo} = 16.7 \text{ MJ/kg}$
$P_O = 0.03 \text{ atm}$
$q_{HW} = 61 \text{ W/cm}^2$

2900 °F

Model 1056

3rd Exposure
8 min

Test Conditions

$H_{eo} = 16.7 \text{ MJ/kg}$
$P_O = 0.03 \text{ atm}$
$q_{HW} = 61 \text{ W/cm}^2$

Total Exposure = 24 minutes

2900 °F
AHF Test Series: T-301 May 2012 (24 minutes, total exposure time)

1st 8 min Exposure 2900 °F

$H_{eo} = 19 \text{ MJ/kg}$
$P_O = 0.02 \text{ atm}$
$q_{HW} = 62 \text{ W/cm}^2$

2nd 8 min Exposure 3000 °F

$H_{eo} = 20 \text{ MJ/kg}$
$P_O = 0.025 \text{ atm}$
$q_{HW} = 70 \text{ W/cm}^2$

3rd 8 min Exposure 3000 °F

$H_{eo} = 20 \text{ MJ/kg}$
$P_O = 0.025 \text{ atm}$
$q_{HW} = 70 \text{ W/cm}^2$
CASE 2: Advanced TUFROC

TUFROC R&D Success!

• Repeatable arc jet testing of the modified TUFROC demonstrated a multiple use capability

• Modified TUFROC material and processing specification frozen and branded as Advanced TUFROC

• Technology transfer of Advanced TUFROC has started with Boeing and Sierra Nevada Corporation

Standard TUFROC performed better than expected as demonstrated by a successful re-flight of X-37b wing leading edge tiles

X-37b, April 2015 credit USAF
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  Test article or material?

- Case 3: Conformal PICA
  Testing guides material development
CASE 3: Conformal PICA

Motivation

• TPS integration is hard and expensive

• Current heat shield types all have issues / limitations
  - Monolithic: limited by size (< 1 m diameter)
  - Tile: complex with gap and seam issues
  - Honeycomb: complex with gore and curing issues
  - Compatibility with sub-structure (strain, CTE, etc.)

Tiled SpaceX Dragon & Heat Shield (PICA-X)
5 m diameter. 4 successful 8 km/s Earth re-entries 2010-13.

Honeycomb Orion Heat Shield (Avcoat)
5 m diameter. Successful Flight Test (EFT-1) Dec 2014

Monolithic Stardust Capsule
0.8 m diameter PICA Heat Shield
CASE 3: Conformal PICA

Conformal TPS

• Offers a promising solution to a number of challenges faced by traditional rigid (low strain-to-failure) TPS materials

• Compliant (high strain to failure) nature simplifies TPS integration on a wide range of aeroshell structures

• Also enables configuration of over large areas, thus reducing
  - part count
  - number of seams
  - installation complexity ⇒ time and cost
CASE 3: Conformal PICA

Initial Development

• Developed using commercially available low density rayon-based carbon felt from Morgan

• Demonstrated uniform fabrication of a sample 12-inch square and demonstrated conformability of the system over 3-inch radius
Initial Testing

- Initial formulation of Conformal TPS tested at:
  - Heat Flux: 1000 W/cm²
  - Pressure: 0.85 atm
- Conformal 1 appeared to recede 2x faster than PICA
- Testing identified erosive failure of material
- Work begun to reduce the recession difference between PICA and Conformal TPS
Redevelopment - Conformal PICA

- Work on Conformal 1 culminated in the development of Conformal PICA (CPICA)
  - Increased phenolic content and incorporated additives to increase char strength
  - CPICA recession still > PICA, but not 2x
  - Too much resin content causes delamination due to shrinkage stresses from resin cure
  - Higher density felt resolves this issue

![Image showing Conformal PICA sample with delamination issue marked]
CASE 3: Conformal PICA

Approach – Advanced Conformal TPS

• Investigated felt substrate density vs. effect on TPS ablation performance

• Used commercial needling to increase felt density and increase substrate toughness

• Areas of exploration
  - Required strength in the felt substrate?
  - Possible thickness?
  - Desired thickness?
  - Resin impregnation in denser felts?
  - Felt densification vs structural integrity?
CASE 3: Conformal PICA

Advanced Conformal TPS – Accomplishment

- Advanced CPICA substrate density increased substantially from previous generation of felt
- Arcjet tested 0.14 g/cm$^3$ felt infused with phenolic at 1850 W/cm$^2$ heat flux, 1.4 atm
- Recession of Advanced CPICA now less than both PICA and previous CPICA
Arc Jet Testing: TPS Case Studies

Acknowledgements

MSL Program & Helen Hwang*, Robin Beck*

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* NASA Ames Research Center
Arc Jet Testing: TPS Case Studies

Acronyms not identified in the charts

RCG       Reaction Cured Glass
AETB      Alumina Enhanced Thermal Barrier
HETC      High Efficiency Tantalum-based Composite
ROCCI     Refractory Oxidation-resistant Ceramic Carbon Insulation