Arc Jet Testing
of
Thermal Protection Materials:
3 Case Studies

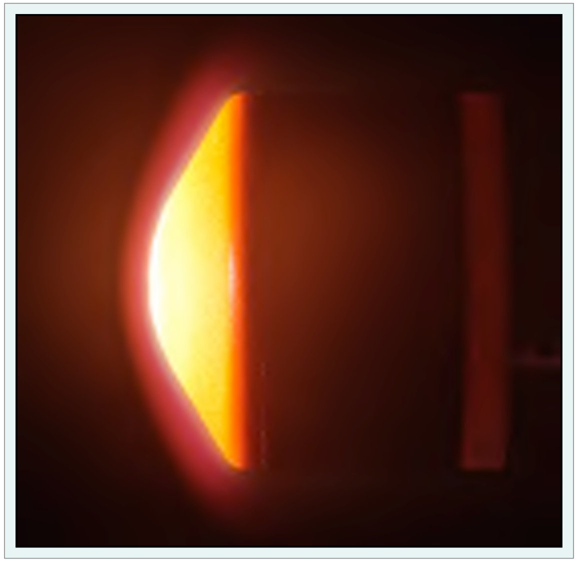
NSMMS
22 June 2015

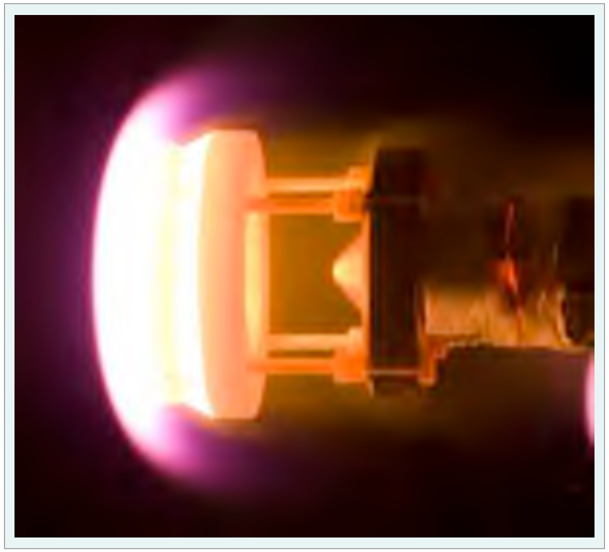
Sylvia Johnson, Chief Materials Technologist
Joe Conley, Chief, Thermal Protection Materials Branch
NASA Ames Research Center

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.

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

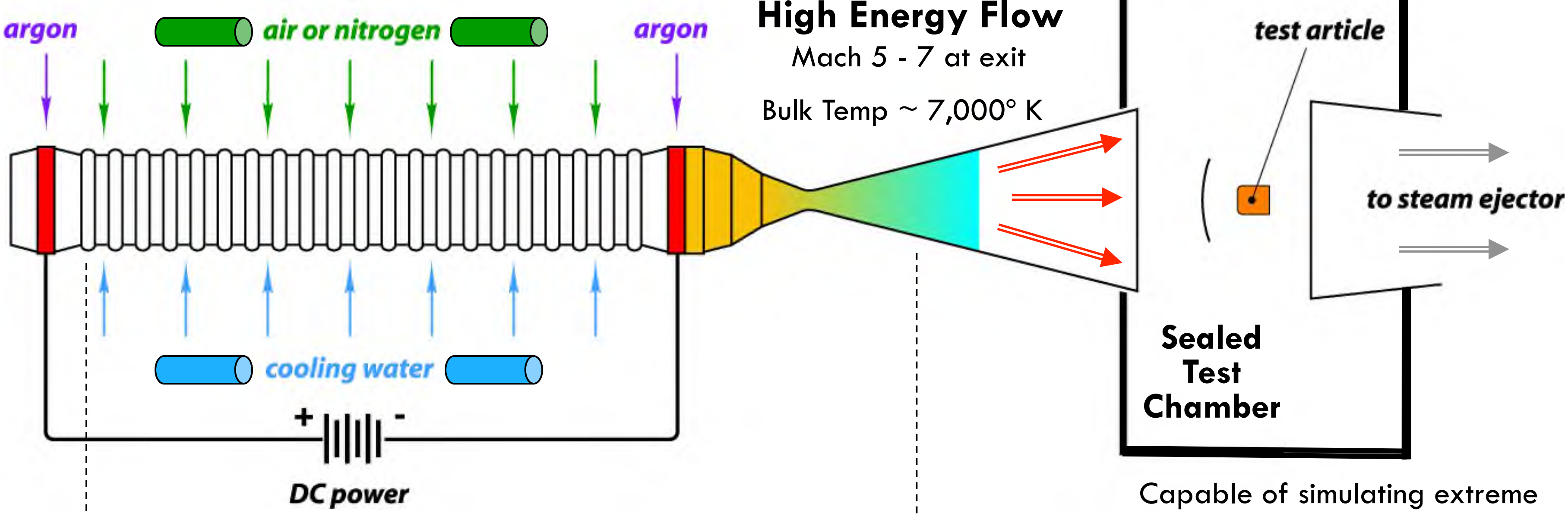
Test article or material?

Case 3: Conformal PICA

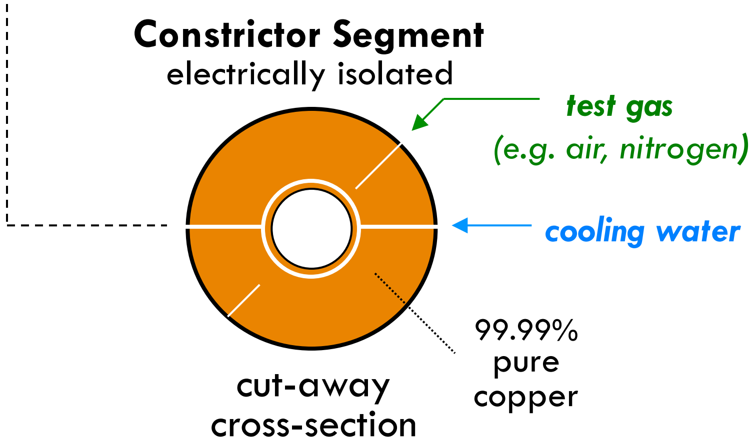
Testing guides material development

Arc Jet Testing: TPS Case Studies

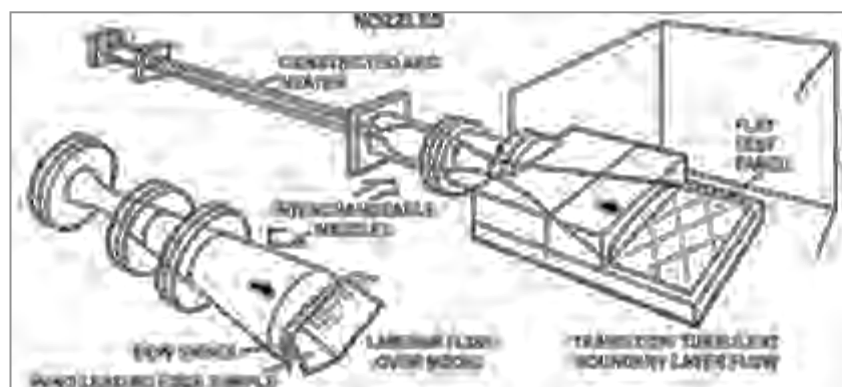
ArcJet Basics



Capable of simulating extreme upper atmosphere (1 - 5 Torr)



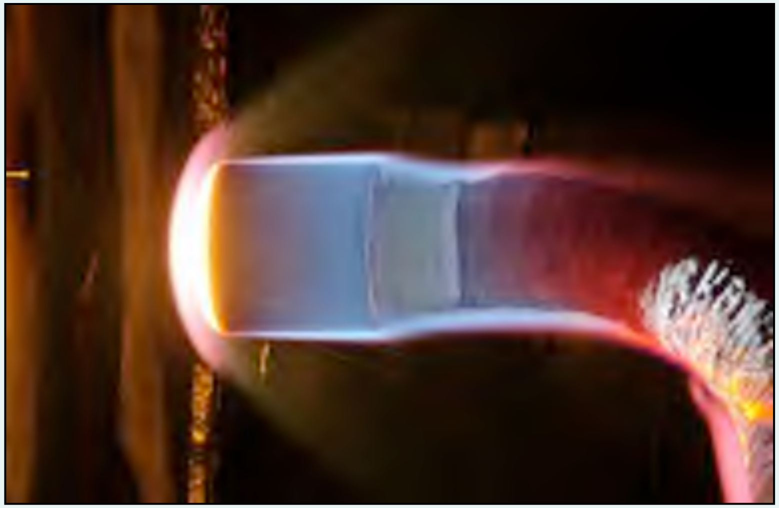
Interchangeable Nozzles



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

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

* Phenolic Impregnated Carbon Ablator

** Mars Science Laboratory

CASE 1: PICA & MSL

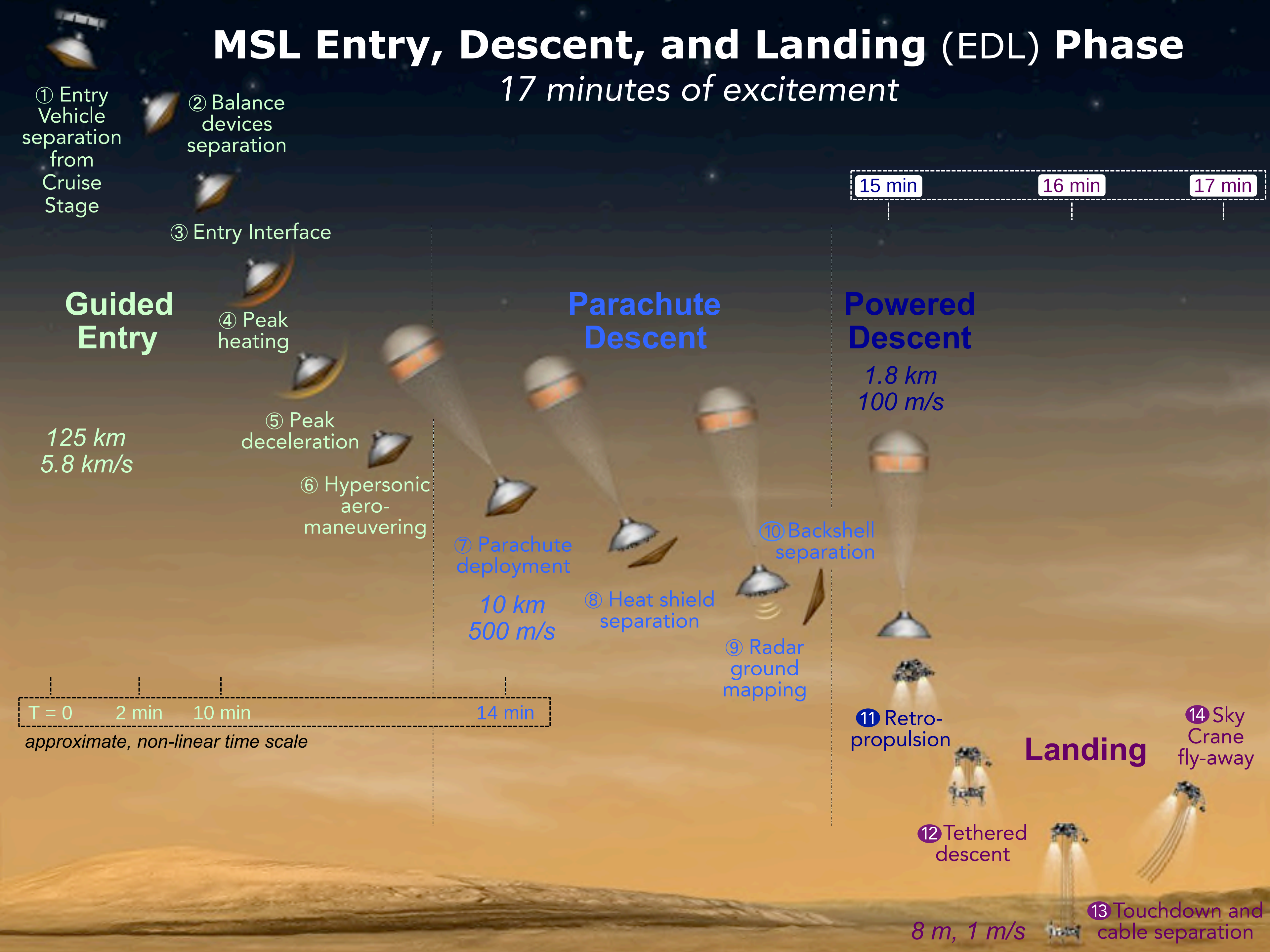
Objective of NASA's Mars Science Laboratory (MSL) **program was to place an SUV size rover** (Curiosity) **safely on the surface of Mars**

Sky Crane with Rover

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

Curiosity rover

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
Guided Entry
125 km
5.8 km/s
Parachute Descent
⑦ Parachute deployment
10 km
500 m/s
⑧ Heat shield separation
⑨ Radar ground mapping
⑩ Backshell separation
Powered Descent
1.8 km
100 m/s
⑪ Retro-propulsion
⑫ Tethered descent
Landing
⑬ Touchdown and cable separation
⑭ Sky Crane fly-away
8 m, 1 m/s
15 min
16 min
17 min
T = 0
2 min
10 min
14 min
approximate, non-linear time scale

CASE 1: PICA & MSL

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.**

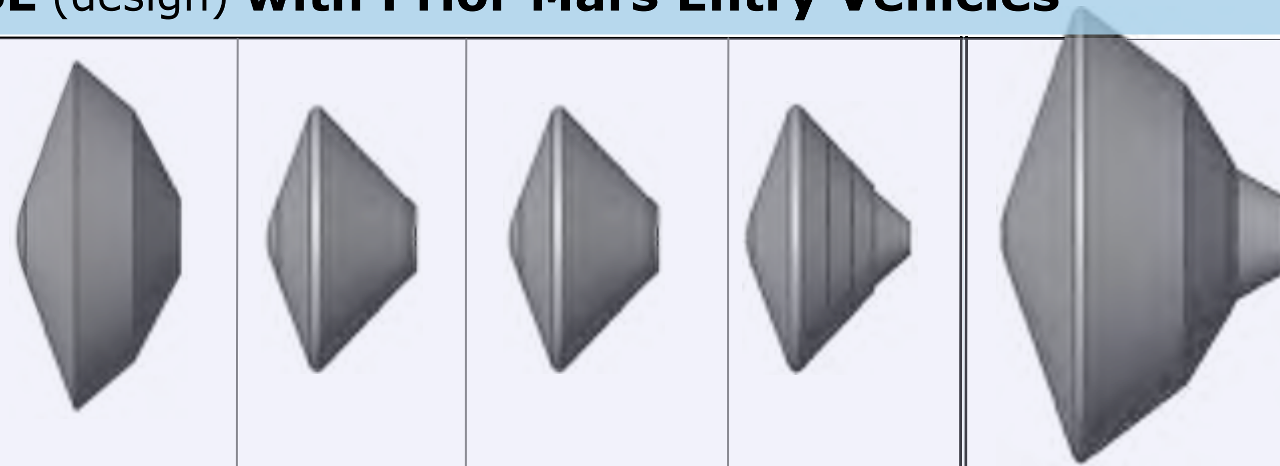
Curiosity rover ~ 5 times the mass of MER Spirit / Opportunity rovers.

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



U.S. Mars Missions Entry Vehicles	Viking 1 & 2	Pathfinder	MER A & B*	Phoenix	MSL (*design*)
Entry year	**1976**	**1997**	**2004**	**2008**	
Entry mass (kg)	980	585	840	570	*3,380*
Entry speed (km/s)	4.5	7.6	5.5	5.5	5.6
Heat shield diameter (m)	3.5	2.65	2.65	2.65	*4.5*
Heat shield (TPS) **material**	SLA-561V	SLA-561V	SLA-561V	SLA-561V	*SLA-561V*
TPS thickness (cm)	1.3	1.9	1.6	1.4	*TBD*
Peak heat flux (W/cm^2)	20	120	50	55	*200*
Turbulent (at peak heat flux)?	No	No	No	No	*Yes*
Peak pressure (atm)	0.1	0.2	0.1	0.08	*0.37*

KEY *denotes MSL not in class with prior Missions*

*Spirit & Opportunity

CASE 1: PICA & MSL

SLA Stagnation Testing for MSL

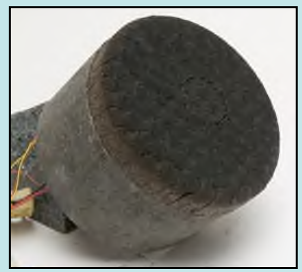
- **MSL baselined SLA-561V**, which performed well in stagnation arc jet testing and was heatshield material for all previous Mars missions

- Glass vaporization allowed material to withstand **heat fluxes > 300 W/cm^2**

- **No failures observed**

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

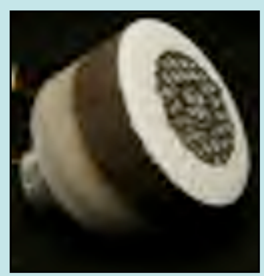
MSL Stagnation Test Articles (SLA-561V)



30 W/cm^2

90 W/cm^2

150 W/cm^2



210 W/cm^2

270 W/cm^2

300 W/cm^2

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

t = 14 sec

t = 16 sec

t = 18 sec

- **Material failure reproducible** at certain conditions

CASE 1: PICA & MSL

Program Decision

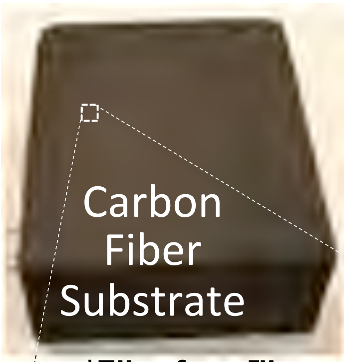
- **Failure identified** in Sep 2007 after Critical Design Review and **~ 23 months before launch**

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

- 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

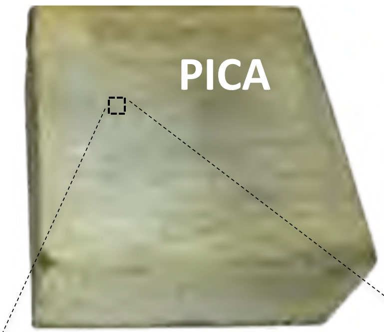


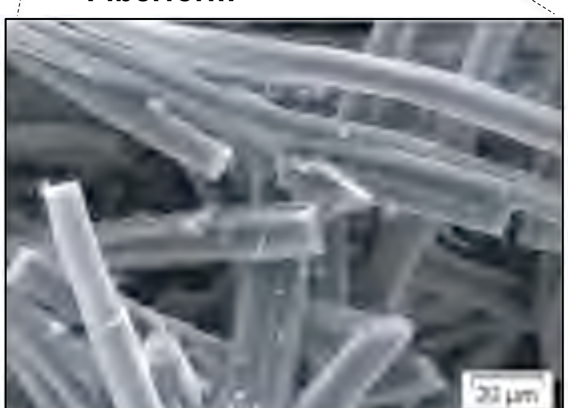
*Fiberform™

+

impregnation

curing





Carbon Fibers Pre-Impregnation
low density, randomly arranged

Low phenolic loading matrix uniformly distributed throughout the substrate material

Carbon Fibers Post-Processing
connected via 'fluffy' phenolic

High surface area resin morphology yields desirable thermal performance

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!)

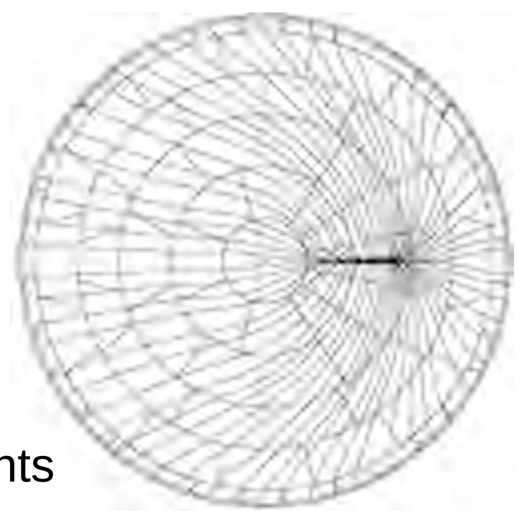
- **Fortunately, to date Orion had conducted 125 arc jet tests of PICA**
  - Tested to more severe environments (heating, pressure, shear)
  - Various gap filler designs
  - Material characterization (material property tests) performed
  - High fidelity model developed for in-depth thermal and recession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



CASE 1: PICA & MSL

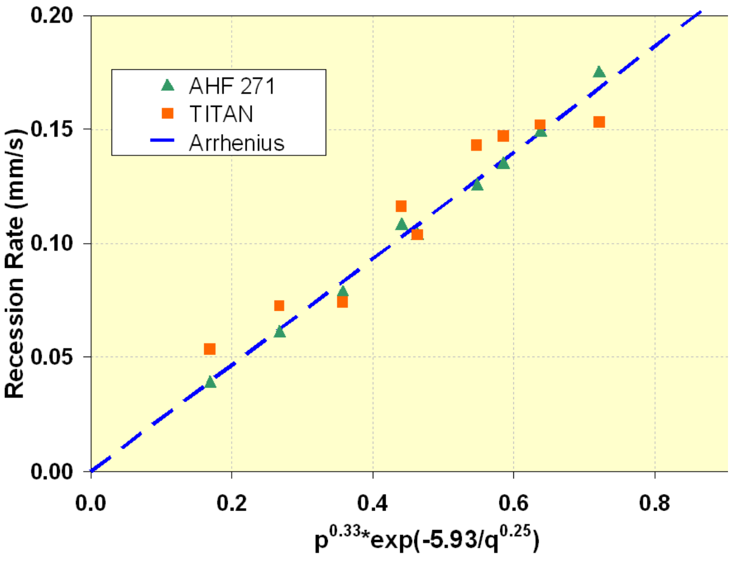
Entry Systems & Technology Division

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)

CASE 1: PICA & MSL

PICA Test Results

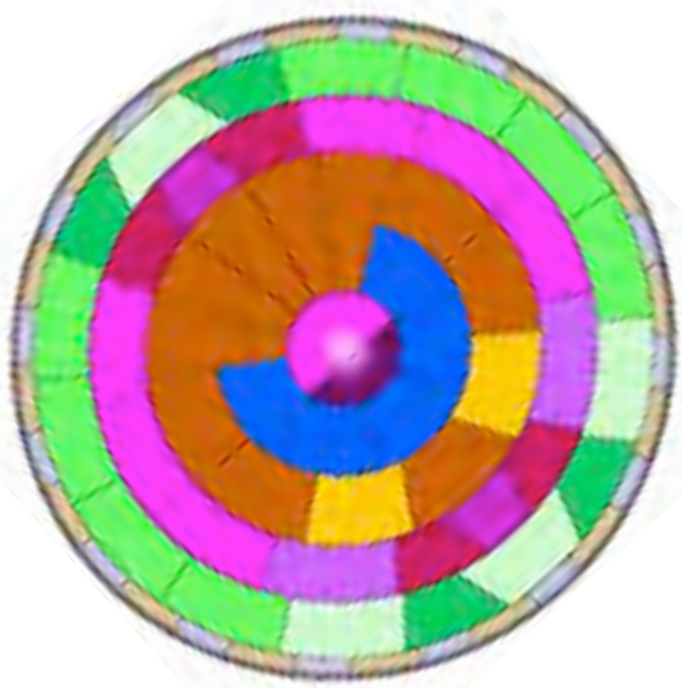
- **Extensive PICA arc jet test series utilized 100+ test articles**
- **PICA material robust at all tested conditions including those where SLA-561V experienced failures**
- **RTV-560 filled gaps performed well**
- **Recession rates varied from model predictions, but could be modeled and bounded conservatively**
- **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)



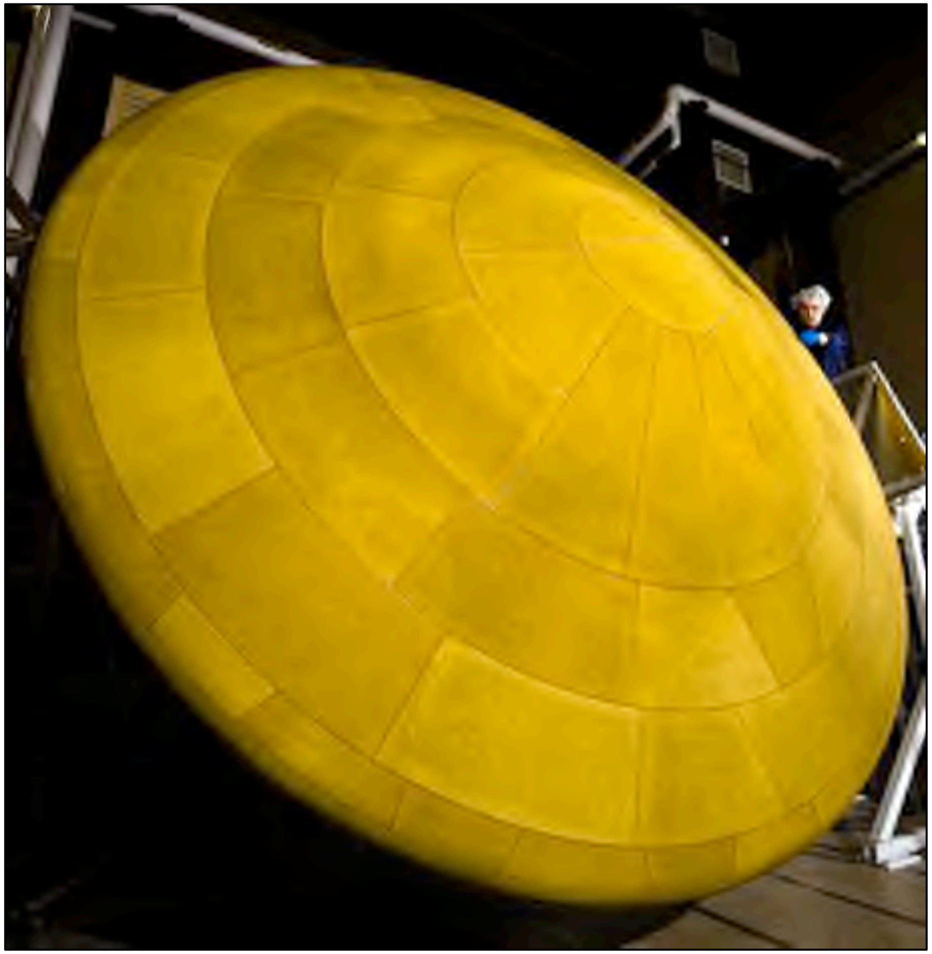
PICA Heat Shield Tile Layout

4.5 meter diameter PICA Heat Shield

CASE 1: PICA & MSL

MSL Team Accomplishment

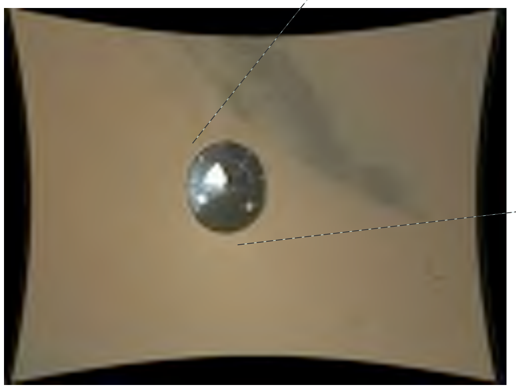
- **Developed, designed, tested, built and qualified a 4.5-m tiled ablative heatshield in 18 months**
- **NASA's first tiled, ablative** (flight hardware) **heat shield**



CASE 1: PICA & MSL

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

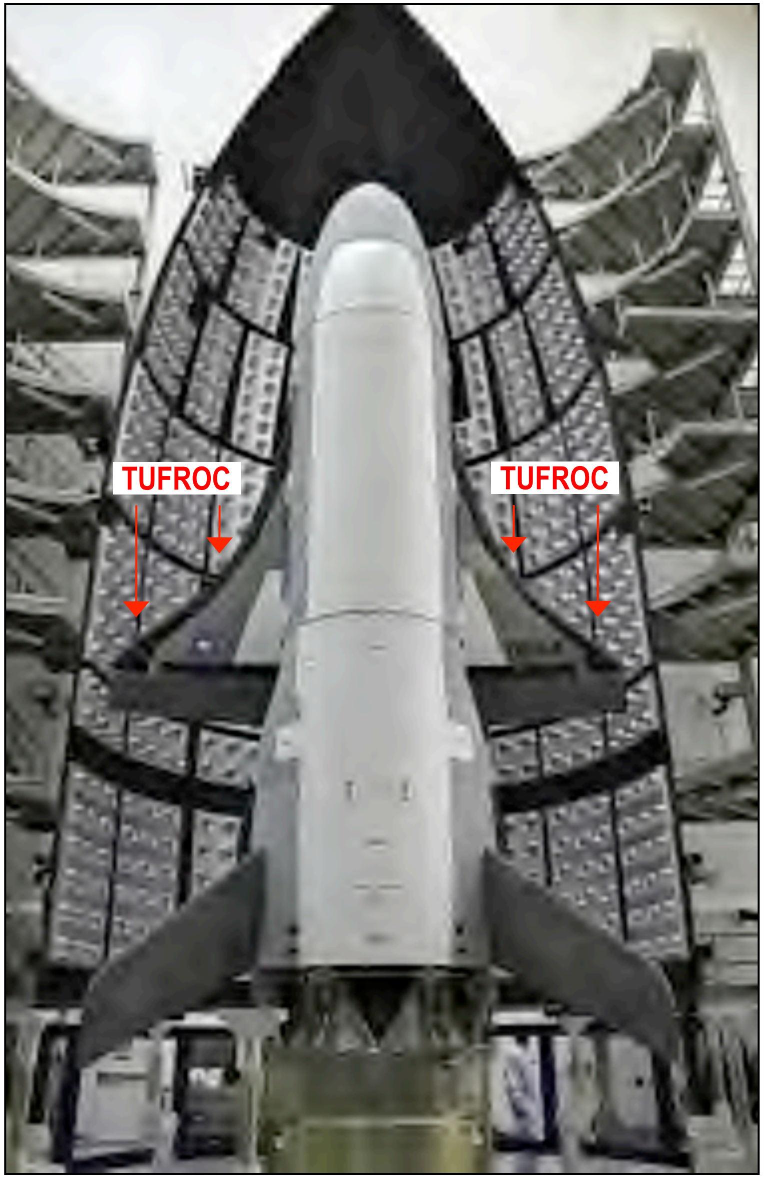
Standard TUFROC History

- In 1998, NASA established **Future-X Pathfinder** program to develop 2nd 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



X-37b Preparing for 1st launch, Apr 2010

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

X-37b after 224 days (90 million miles) **in orbit, Dec 2010**

CASE 2: Advanced TUFROC

Standard TUFROC

2 Piece Approach

Re-radiate enough heat so that conduction through

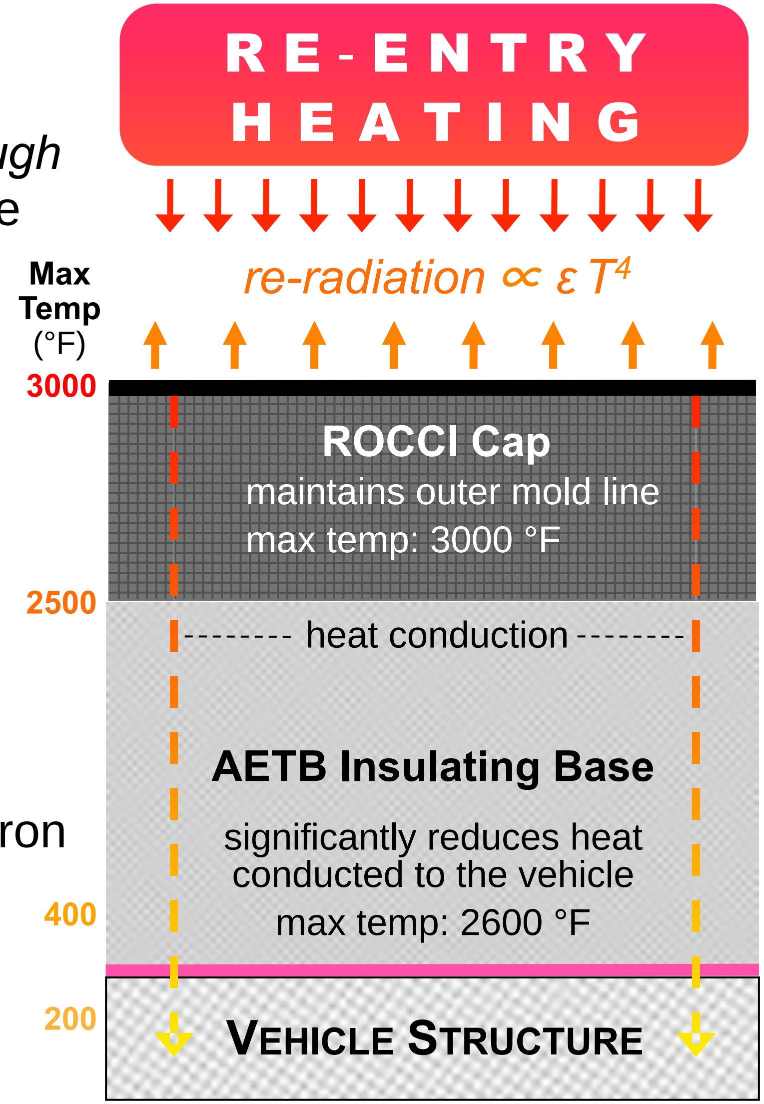
- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

ROCCI Carbonaceous Cap

- Silicon-oxycarbide phase slows oxidation
- HETC, treatment near surface slows oxidation and keeps emissivity high (ε ~ 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



CASE 2: Advanced TUFROC

Advanced TUFROC

2 Piece Approach

Re-radiate enough heat so that conduction through

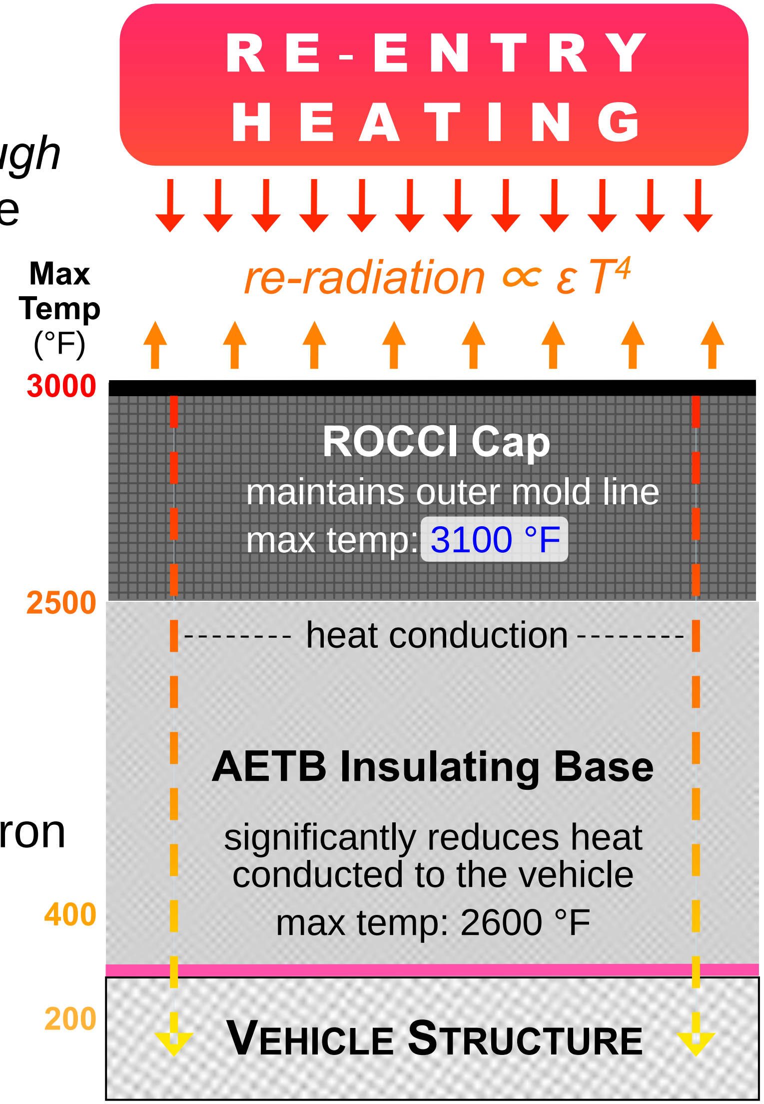
- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

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



CASE 2: Advanced TUFROC

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/cm^2

1st Exposure
5 min

2nd Exposure
5 min

Total exposure = 600 sec

Model 1025

3080 °F

3100 °F

Model 1028

3070 °F

3090 °F

Model 1030

3095 °F

3060 °F

CASE 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

Model during arc jet exposure

1st Exposure
5 min

Test Conditions

H_{eo} = 17.3 MJ/kg
P_O = 0.02 atm
q_{HW} = 61 W/cm^2

Model 1044

3120 °F

2nd Exposure
5 min
(same conditions)

Total exposure = 600 sec

Model 1043

3000 °F

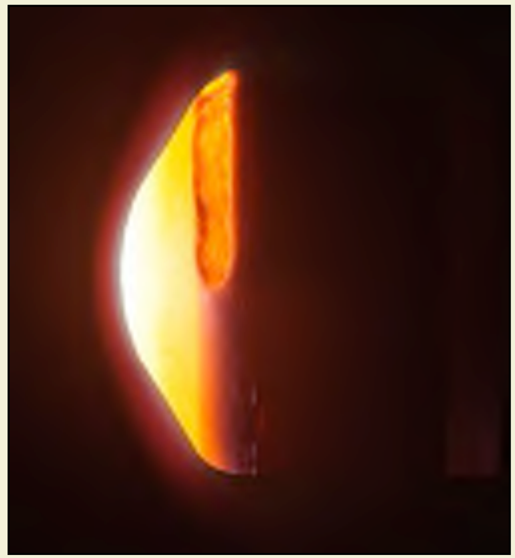
CASE 2: Advanced TUFROC

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° F H_{e0} = 17.5 MJ/kg P_0 = 0.02 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

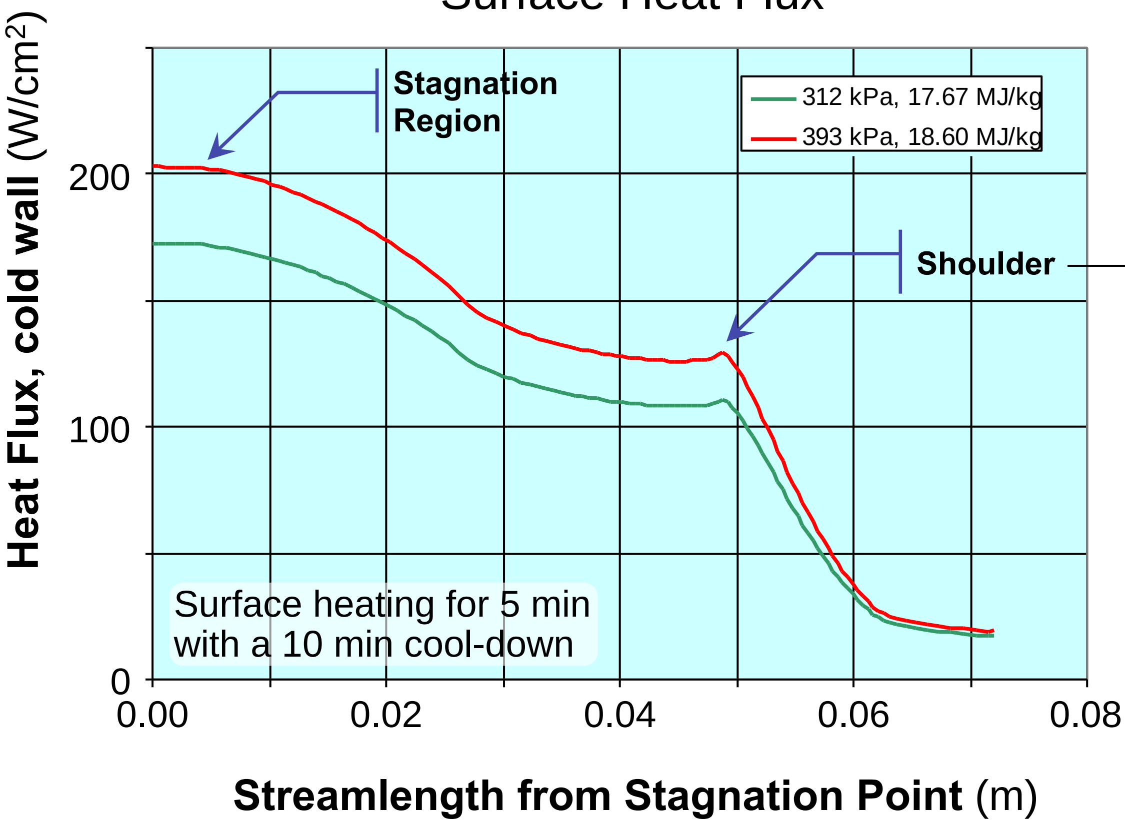
CASE 2: Advanced TUFROC

Entry Systems & Technology Division

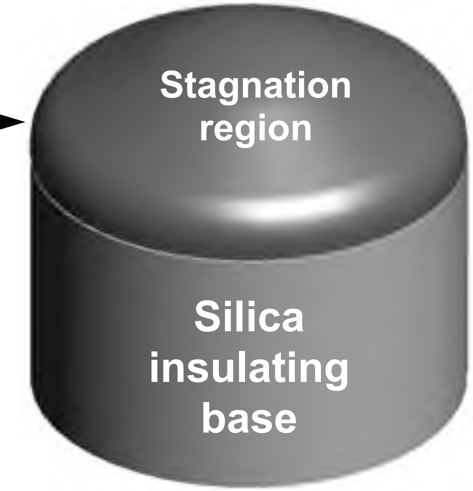
Aerothermal & Thermal-Mechanical Analysis

Heating Distribution* over Test Article

Surface Heat Flux



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

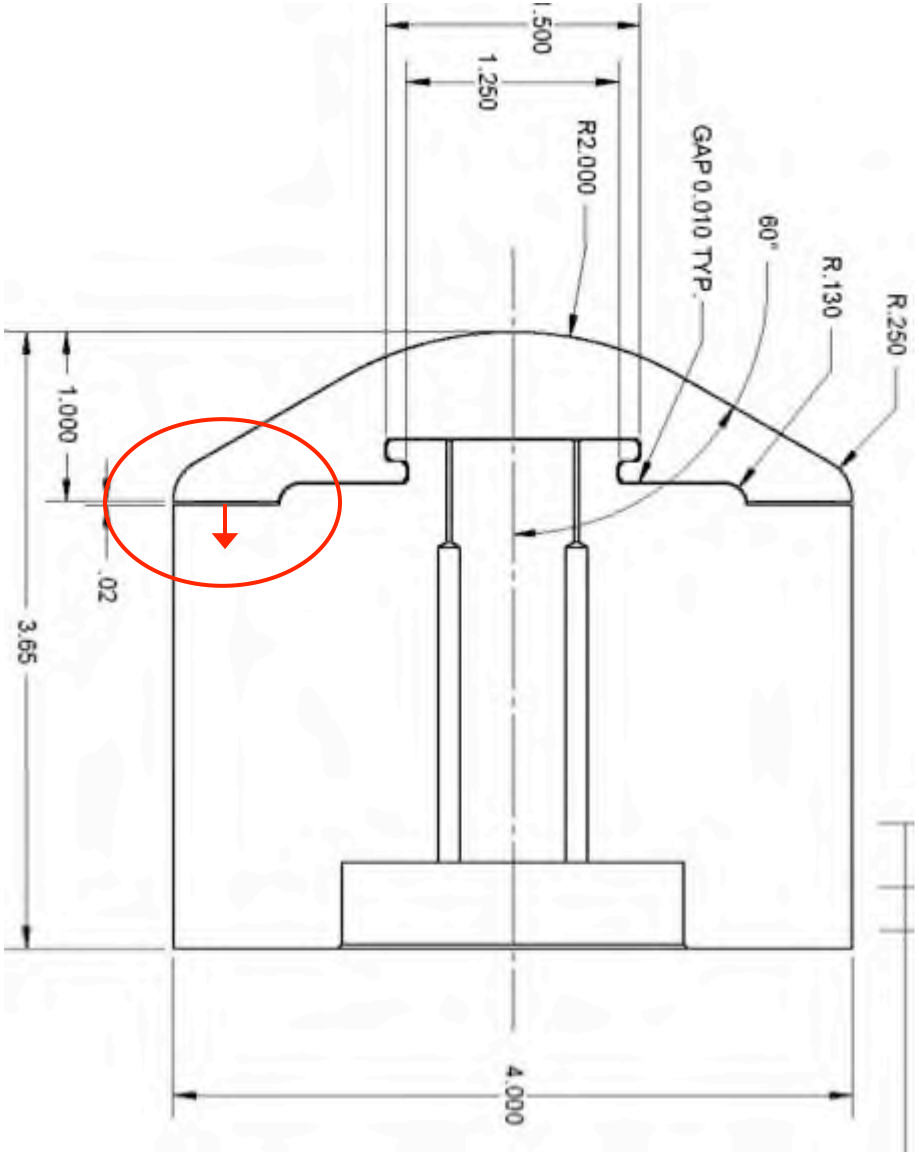


Stresses concentrated by mechanical attachment (interlocking tab)

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

*DPLR solution from Gokcen; **FEM analysis from Squire

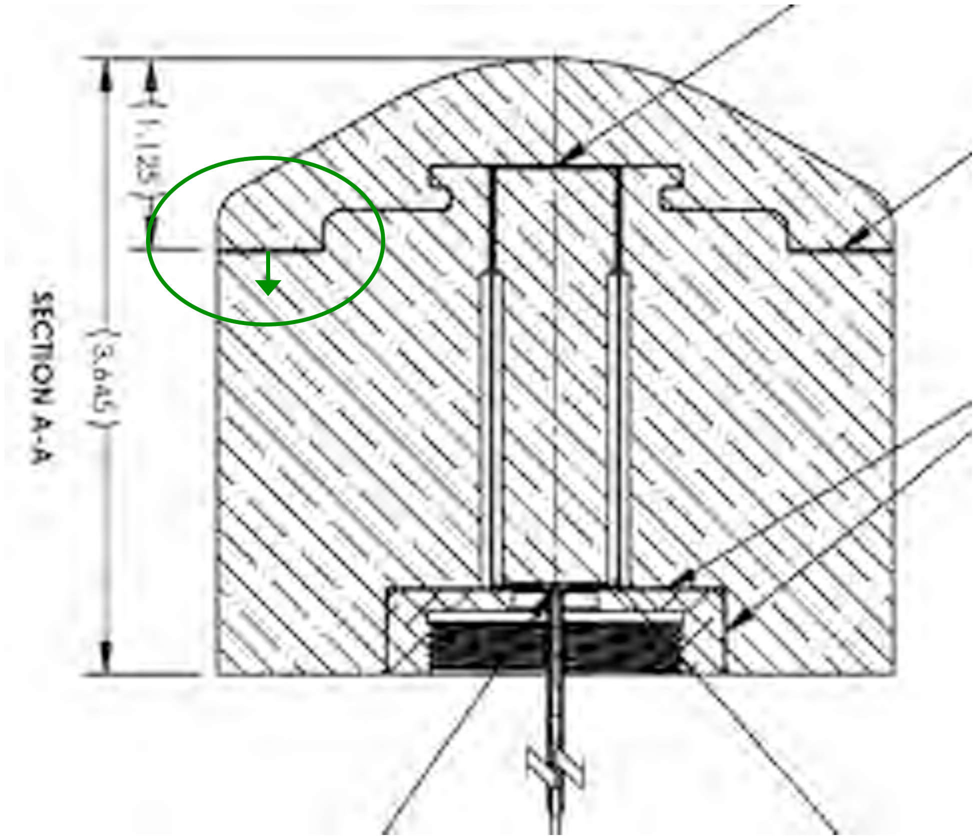
Original Interlocking Tab Mechanical Attachment



CASE 2: Advanced TUFROC

Entry Systems & Technology Division

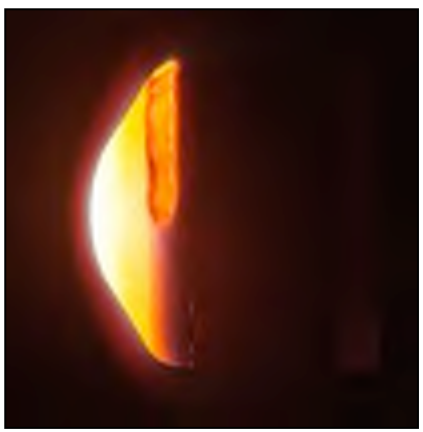
Re-designed Interlocking Tab Mechanical Attachment



CASE 2: Advanced TUFROC

Sphere-cone
arc jet test model

pre-test



AHF exposure

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 MJ/kg
P_O = 0.02 atm
q_{HW} = 70 W/cm^2

Re-designed interlocking tab attachment

Test Series: T-290
Feb 2010

Ames Model 1048

3175 °F

H_{eo} = 22.8 MJ/kg
P_O = 0.034 atm
q_{HW} = 85 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 MJ/kg
P_O = 0.03 atm
q_{HW} = 70 W/cm^2

Model 1056

3000 °F

AHF T-301
May 2012

2nd Exposure
8 min

Test Conditions
H_{eo} = 16.7 MJ/kg
P_O = 0.03 atm
q_{HW} = 61 W/cm^2

Model 1056

2900 °F

3rd Exposure
8 min

Test Conditions
H_{eo} = 16.7 MJ/kg
P_O = 0.03 atm
q_{HW} = 61 W/cm^2

Total Exposure = 24 minutes

2900 °F

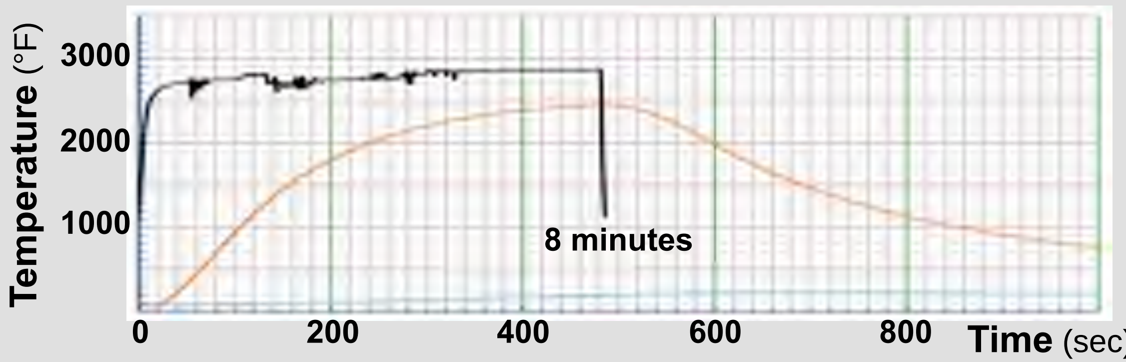
CASE 2: Advanced TUFROC

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

Model H-1087

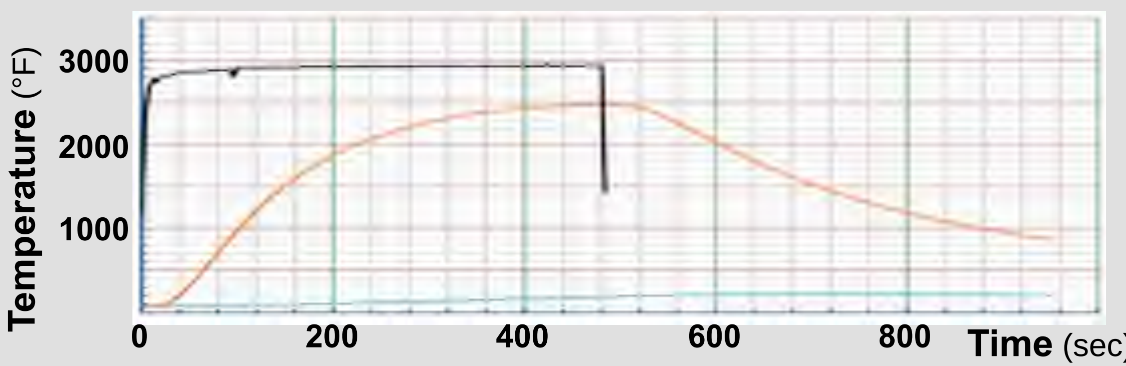
1st 8 min Exposure 2900 °F

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



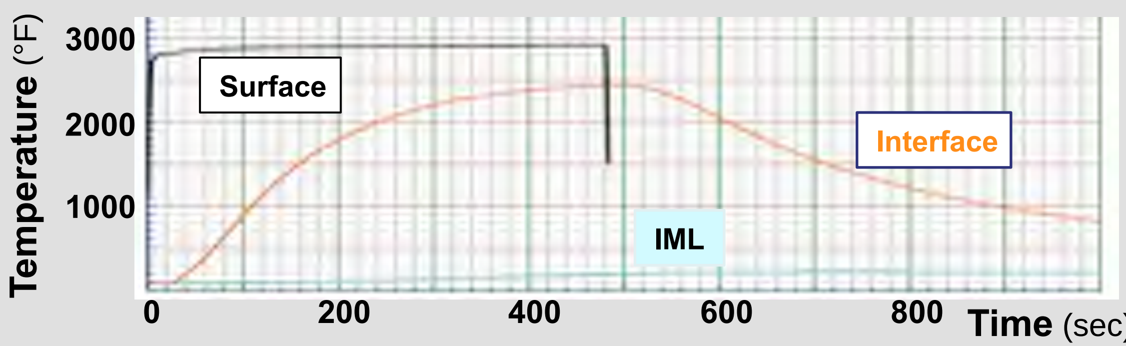
2nd 8 min Exposure 3000 °F

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



3rd 8 min Exposure 3000 °F

H_{eo} = 20 MJ/kg
P_O = 0.025 atm
q_{HW} = 70 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

credit USAF

X-37b, April 2015

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

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.)

Monolithic Stardust Capsule
0.8 m diameter PICA Heat Shield

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

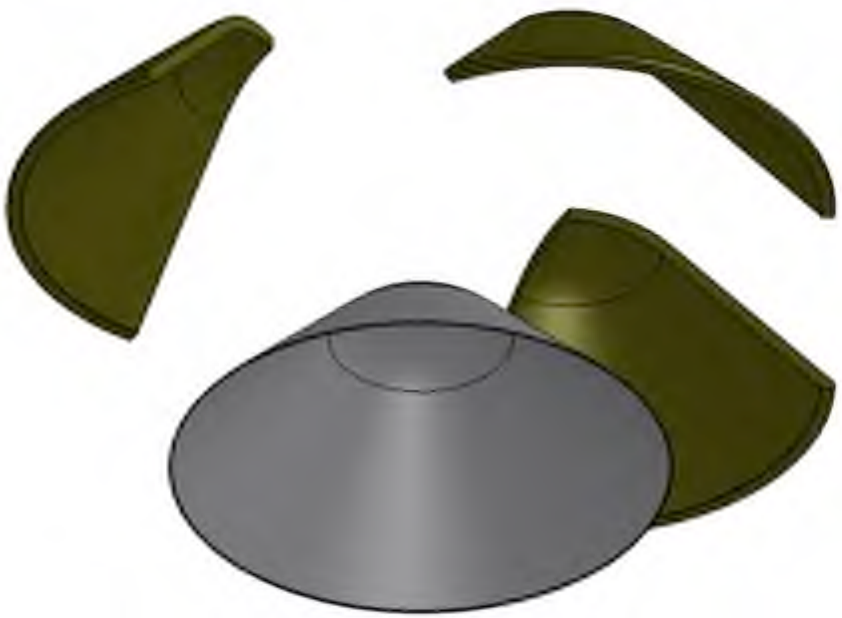
CASE 3: Conformal PICA

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**

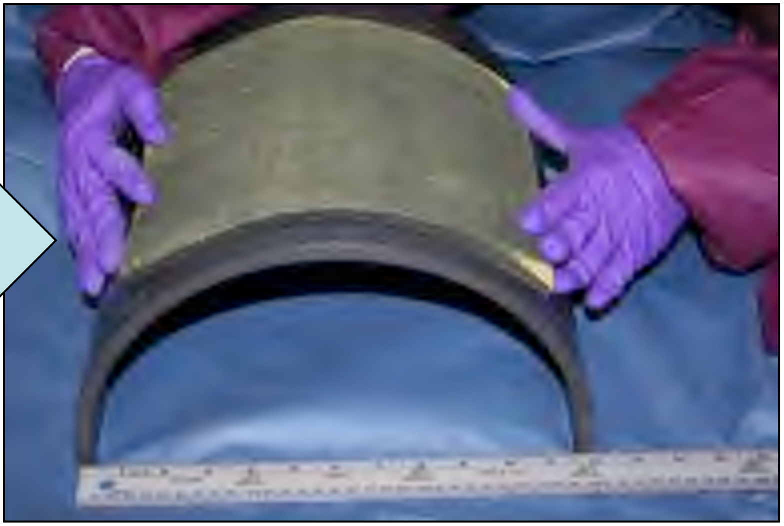
- **Also enables configuration of over large areas, thus reducing**
  - part count
  - number of seams
  - installation complexity ⇒ time and cost



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**



CASE 3: Conformal PICA

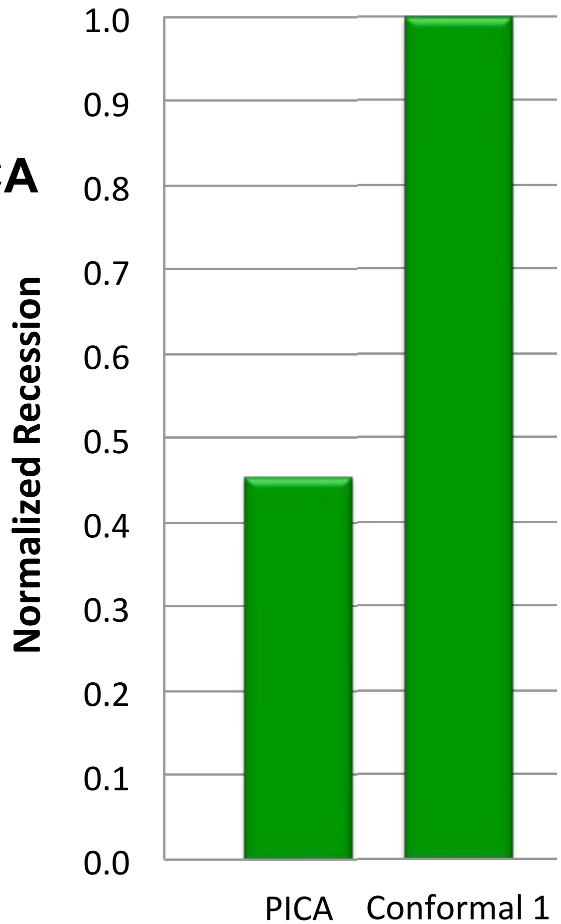
Initial Testing

- **Initial formulation of Conformal TPS tested at:**

  Heat Flux: 1000 W/cm^2

  Pressure: 0.85 atm

- **Conformal 1 appeared to recede 2x faster than PICA**



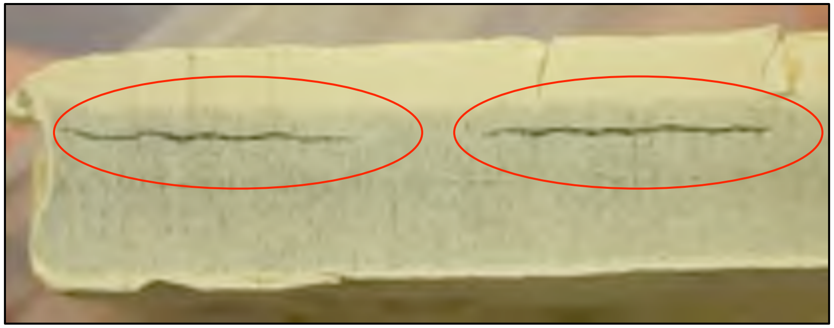
- **Testing identified erosive failure of material**

- **Work begun to reduce the recession difference between PICA and Conformal TPS**

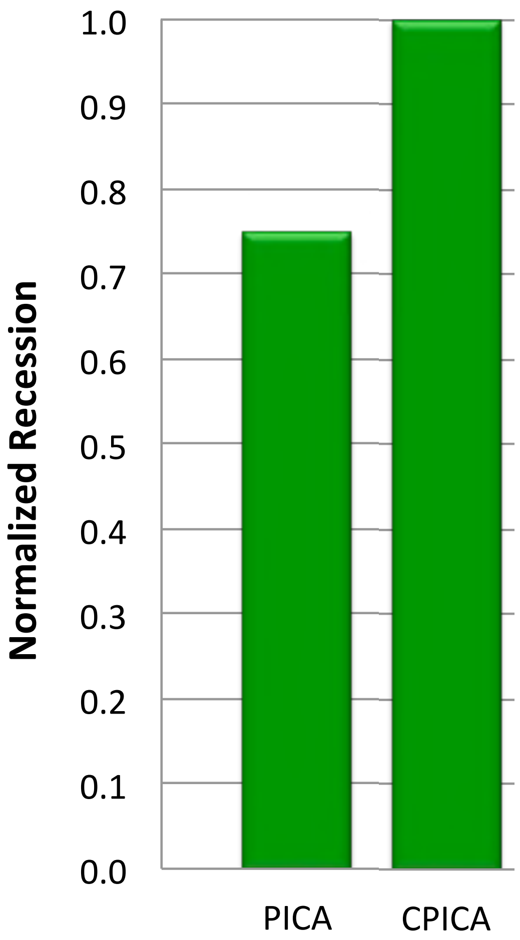
CASE 3: Conformal PICA

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



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?

Conformal-1 and CPICA Substrate

	Density	Thickness	Description
Morgan VDG (Rayon Based)	0.09 g/cm^3	1-inch	CPICA Baseline

Advanced Conformal Substrate Options

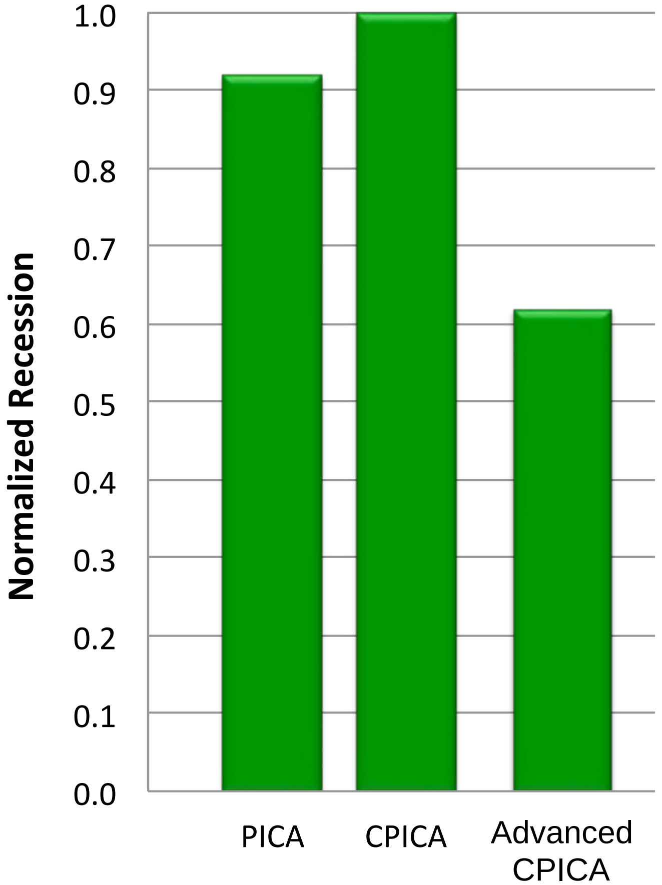
	Density	Thickness	Description
Pan-Based	0.14 g/cm^3	1-inch	PAN 1 - P1
	0.17 g/cm^3	2-inch	PAN 2 - P2
	0.17 g/cm^3	3-inch	PAN 3 - P3
	0.45 g/cm^3	1-inch	PAN 4 - P4
Rayon-Based	**Density**	**Thickness**	**Description**
	0.14 g/cm^3	3-inch	Rayon 1 – R1
	0.16 g/cm^3	1/2-inch	Rayon 2 - R2
	0.19 g/cm^3	3/8-inch	Rayon 3 - R3
	0.20 g/cm^3	1/2-inch	Rayon 4 – R4

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**

Advanced CPICA



- **Recession of Advanced CPICA now less than both PICA and previous CPICA**

Acknowledgements

MSL Program & Helen Hwang, Robin Beck**

*STMD Conformal Flexible Ablators Project & Matt Gasch**

Tom Squire, Mike Wright*, Tahir Gocken**

* NASA Ames Research Center

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