

Different Classes of TPS Architectures and the Influence of Material and Architecture on Failure Mode Evolution

Don Ellerby

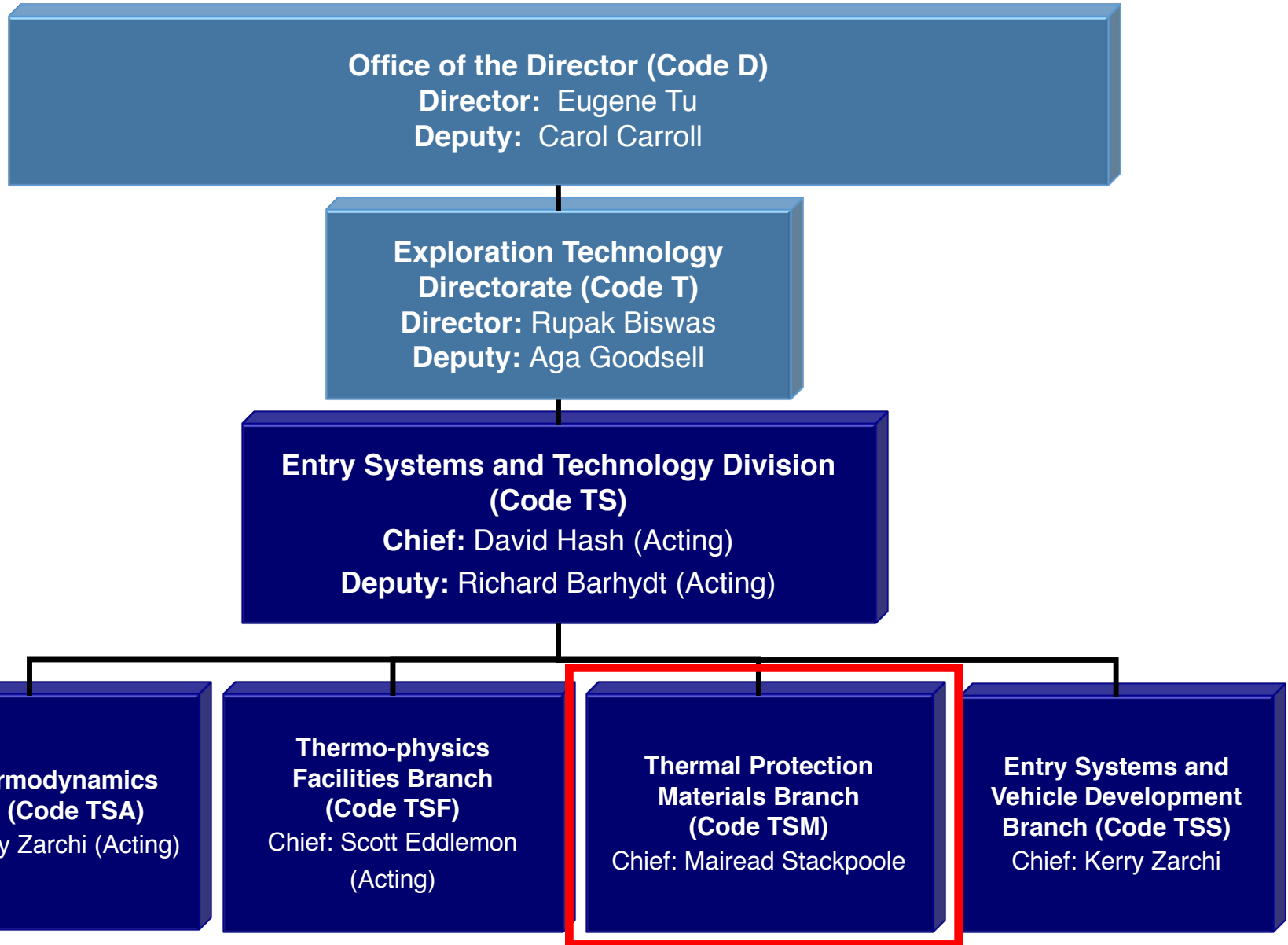
9/06/18

Presented to Ariane Group, Bordeaux.

This presentation will be given at the The 10th Ablation Workshop, Burlington, VT Sept 2018

It was presented by Mairead Stackpoole

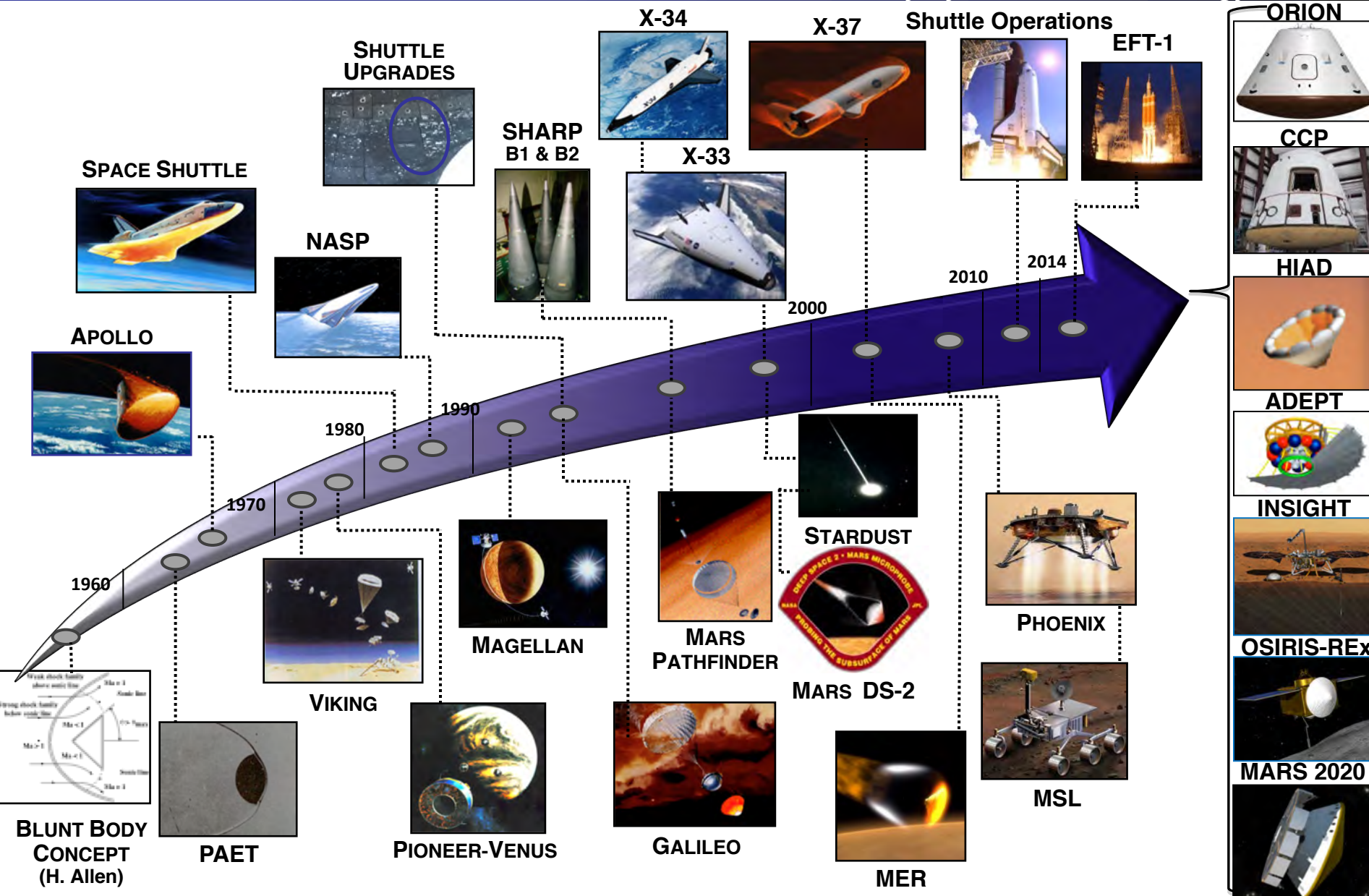
NASA Ames Research Center



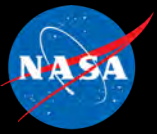


NASA Entry Vehicles / Missions Supported by Ames

Entry Systems and Technology Division



Thermal Protection Materials Development



Vision: Apply materials science and engineering in a complete process including basic research, material development, fabrication, analytical predictions and application, to support NASA mission goals.

- **TPS Materials Development**

- Ablative TPS
 - PICA and SIRCA
 - Conformal PICA
 - 3D Woven TPS (HEEET and 3D MAT)
- Reusable acreage insulation
 - Advanced ceramic tile – AETB (Alumina Enhanced Thermal Barrier)
 - Advanced coatings – TUF1 (Toughened Uni-Piece Fibrous Insulation)
- High-temperature reusable materials
 - TUFROC (Toughened Uni-piece Fibrous Reinforced Oxidation- resistant Composite)



- **TPS Materials Characterization and Testing**

- Material property testing
- Composition testing
- Arc-jet testing (unique)

- **Flight Hardware**

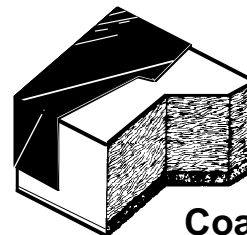
- SIRCA for MER (Mars Exploration Rover)
- Orion Developmental Flight Instrumentation (DFI)
 - EFT-1, EM-1
- EDL Instrumentation: MSL/Mars 2020

- **TPS modeling, databases**

- Thermal/mechanical finite element modeling
- Computational Materials Modeling
- TPSX material properties database
- Aerothermal Materials Response Modelling (TPS Sizing)



PICA tiles



Coatings

NASA ARC TPS Materials Roles/SME/Expertise

- Materials Development:
 - Low TRL through Mission Infusion and Sustainment
 - Current Development:
 - HEEET - **STMD**
 - CA-TPS - **STMD**
 - ADEPT Carbon Fabric - **STMD**
 - PICA Sustainability - **SMD**
 - Mission Infusion:
 - PICA: Stardust, MSL, OSIRIS-Rex, Mars 2020
 - SIRCA: MER
 - 3D-MAT: ORION EM-1
 - TUFROC: X-37, various COTS
 - TUFU Coating/AETB Tile: Orion Backshell
 - Technology Transfer:
 - PICA: Fiber Materials Inc. (FMI)
 - TUFROC: Boeing
 - Sustainment
 - PICA
 - Carbon Phenolic
- Material Response Model Development
 - Ablative TPS Sizing (thickness)
 - Tool development (FIAT, TITAN, 3D-FIAT, Icarus...)
 - Models for Specific Materials (PICA, 3D-MAT, SLA, etc...)
- Mission Support (SMD and HEOMD):
 - SMD: Flagship, New Frontiers, Discovery
 - Proposal Development through Flight
 - TPS Material SME's [MSL, Mars 2020, OSIRIS-Rex, In-Sight]
 - Orion:
 - TPS Deputy Subsystem Manager. Backshell Lead
 - TPS Material Sizing
 - TPS Material Testing: Arcjet testing, etc...
- EDL Instrumentation:
 - Orion DFI:
 - EFT-1, EM-1
 - SMD:
 - MSL (MEDLI), Mars 2020 (MEDLI-2)
 - Support to meet Future Engineering Science Instrumentation Requirements for Missions with an Entry Phase
 - Collaboration with ESA on COMARS backshell instrumentation suite

A Perspective On Failure Mode Evolution in Ablators



- From Raj – “Feature to Flaw to Failure”
- TPS failure is strongly influenced by the class of TPS material and corresponding architecture
- Failure mode is dependent on the TPS architecture
- Hopefully this overview will inform on the generic types of TPS architectures and help guide failure mode evolution modeling effort

Ablator Material Architectures

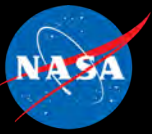


- **Honeycomb Materials**
 - Avcoat, SLA, SRAMs, Phencarbs, BLA, BPA, etc...
 - NASA does not have a H/C ablator in our TPS portfolio
- **Resin Infiltrated Preforms**
 - Silicone Impregnated Refractory Ceramic Ablator(SIRCA: NASA ARC),
 - Phenolic Impregnated Carbon Ablator (PICA: NASA ARC, Fiber Materials Inc (FMI))
- **Dual Layer Materials (not integrally woven)**
 - Carbon/Carbon-FiberForm (Genesis: LM)
 - 3-Dimensional Quartz Phenolic HD/LD (3DQP: Textron)
- **Continuous Fiber Composite Materials (laminated)**
 - Uncoated Carbon/Carbon, Carbon/Phenolic (Tape Wrapped), Silica/Phenolic (Tape Wrapped)
- **Monolithic Plastics**
 - Teflon, etc...
- **3-D Wovens**
 - Ablative and structural (ortho weave like 3D-MAT)
 - Single to Multi layer integrally woven layers (HEEET)
 - 3-D C-C
- **Others:**
 - Chop Molded Carbon/Phenolic
 - Sprayable SLA
 - Syntactic foams (Acusil)

Honeycomb Materials

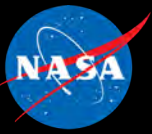


- Honeycomb Benefits
 - Stabilizes the char, preventing/reducing char spallation
 - Monolithic approach
 - Provides a method to verify bond to carrier structure
- Resins
 - Phenolic Resins: Higher Heat Fluxes
 - PhenCarbs(ARA), Boeing Phenolic Ablator(BPA)
 - Epoxy / phenolic Resins: Higher Heat Fluxes
 - Avcoat (Textron: Apollo)
 - Silicone Resins: Lower Heat Fluxes
 - Super Lightweight Ablator(SLA: LM)), SRAMs(ARA), Boeing Lightweight Ablator(BLA)
- Features leading to flaws (potentially)
 - Touch labor leading to density variability
 - Separation at ablator to H/C interface

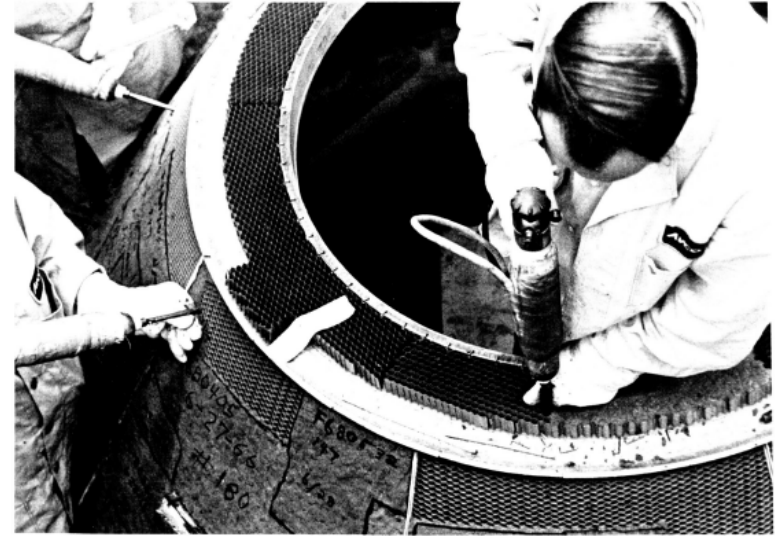


- Fillers:
 - Microballoons:
 - Silica/Glass and Phenolic
 - Fibers:
 - Silica/Glass, Ceramic and Carbon
 - Others:
 - Cork, etc...
- Constituent Pre-Treatments
 - Thermal
 - Chemical
 - Improve adhesion with honeycomb
 - Improve adhesion between fillers and resin
 - Remove sizings, remove contaminants, etc...

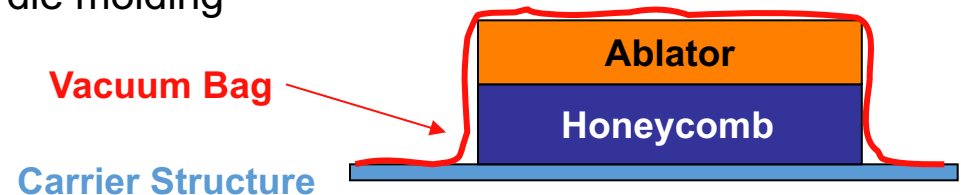
Honeycomb Materials



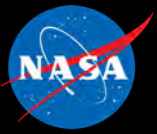
- Honeycomb:
 - Composition:
 - Silica/Ph, Glass/Ph, Carbon/Ph...
 - Cell Shape:
 - Hexagonal, Flexcore,...
 - Cell Size
 - Cell Wall Thickness
- Manufacturing Techniques:
 - Hand Packing
 - Hand Injecting (Avcoat)
 - Caulking gun
 - Press Ablator Preform into Honeycomb (or vice versa)
 - Vacuum bagging or closed die molding



AVCO technicians injecting ablator into honeycomb
(Apollo command module had 300,000 cells)



Compositions of SLA-561 and BLA



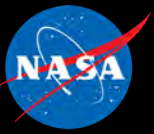
Material	Composition (Mass Fractions %)	Composition (Volume Fractions %)	Density (g/cc)
SLA-561 (LM, US Patent 4,031,059)	25 Silicone Resin 3 Silica Fibers 2 Carbon Fibers 35 Silica Microballoons 6 Phenolic Microballoons 29 Cork	5.5 Silicone Resin 0.3 Silica Fibers 0.3 Carbon Fibers 43.9 Silica Microballoons 14.4 Phenolic Microballoons 35.6 Cork	0.225
BLA (Boeing Lightweight Ablator, US Patent 6,627,697)	42 Silicone Resin 38 Silica Microballoons 4 Catalyst 16 Thinning Fluid		0.32



SLA



Resin Infiltrated Preforms (Low Density)



- Begin with a porous preform (open porosity)
 - PICA: Carbon Furnace Insulation (FiberForm)
 - SIRCA: Ceramic Shuttle Tile
 - Have some control over preform starting density and composition
- Infiltrate with a resin
 - PICA: Phenolic
 - SIRCA: Silicone
 - Resin is diluted in a solvent
 - Have ability to control resin to solvent ratio to control amount of resin in final product

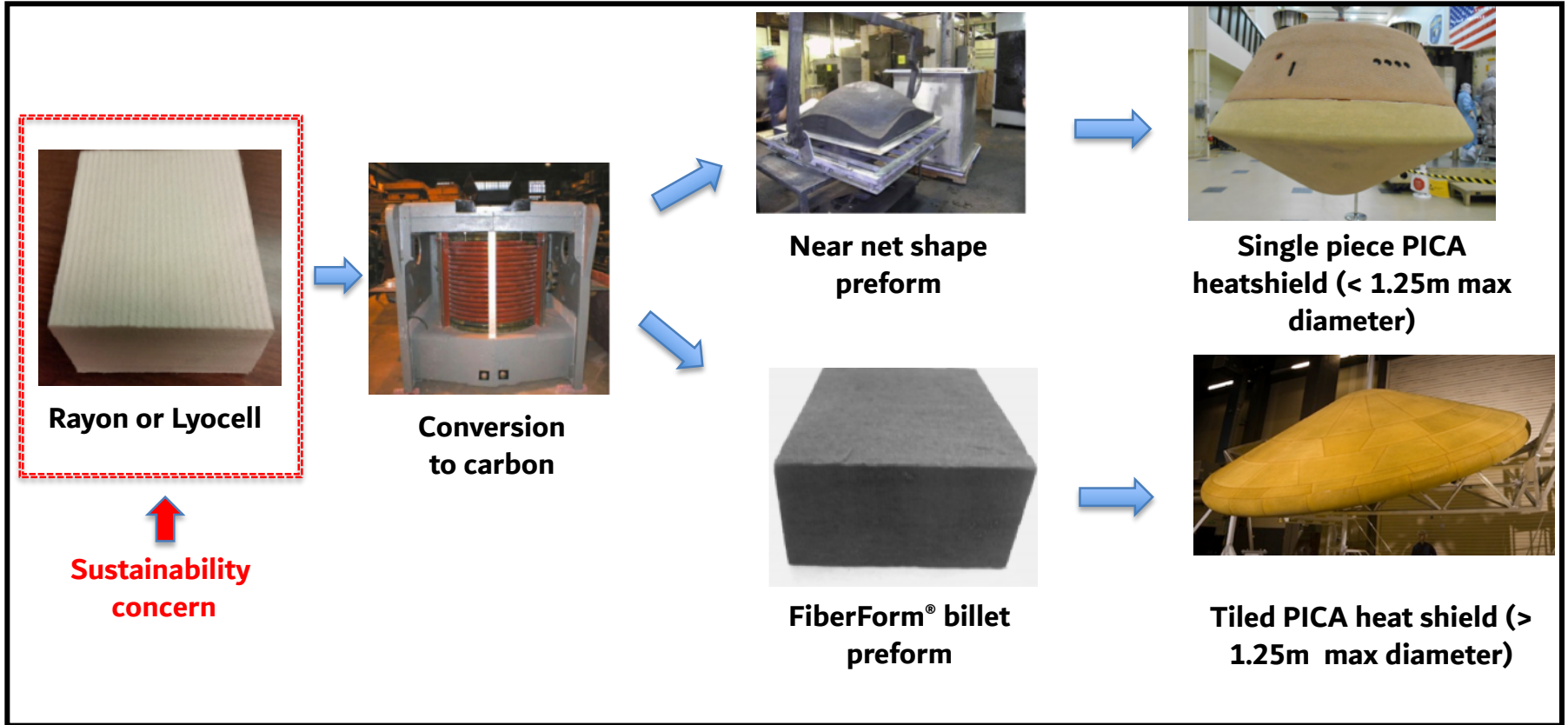
Resin Infiltrated Preforms (Low Density)



- Pros: Flexibility
 - Parameters that can be tailored:
 - Starting preform density
 - Preform to resin ratio
 - Can locally densify material with secondary application of resins
 - Resin Composition
 - Grade the resin composition within the preform from one resin composition to another
 - Phenolic at surface, lower conductivity silicone at bondline
- Cons: Limited Part Size
 - Starting PICA Block Size Limit: ~24" x ~42"
 - Single piece demonstrated to 0.87m max diameter
 - Requires gaps between parts with development of proper gap design, gap fillers etc...
 - Verification of bond between tile and carrier structure is challenging

PICA Manufacturing Overview

Role of Rayon/Lyocell in PICA Manufacturing

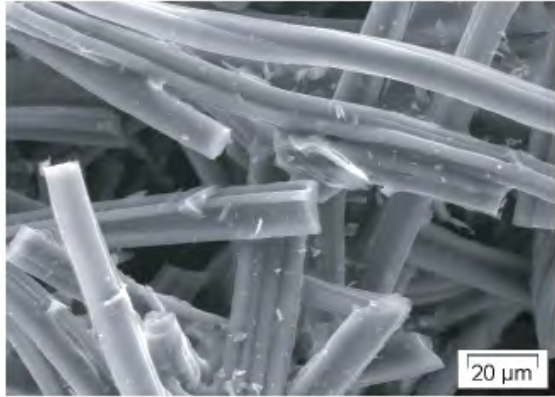


- Chopped, graphitized rayon or Lyocell - based carbon fiber slurry-cast into either block (billet) or single piece heatshield preforms
- Single piece cast heatshields have fiber oriented to optimize through-thickness thermal conductivity
- Lightweight phenolic sol-gel matrix is infiltrated into preform

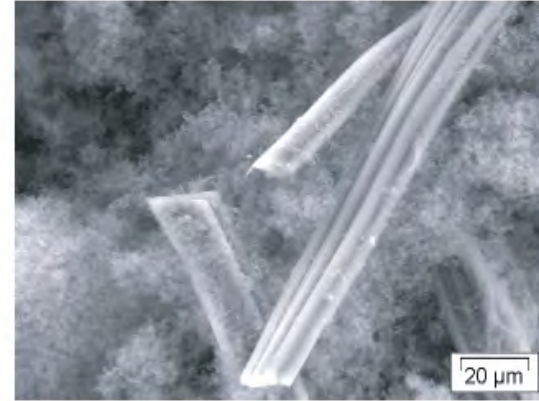
Importance of PICA Microstructure / Gap Filler



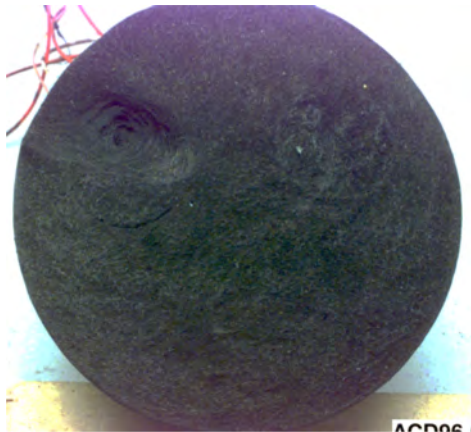
Fiberform before impregnation



PICA with phenolic resin impregnated



What happens when the phenolic resin is not present in PICA



Tunneling failure mode



Gap filler compatibility is critical

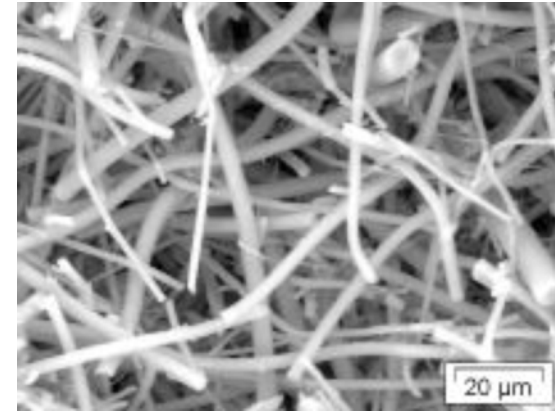


Silicone Impregnated Refractory Ceramic Ablator: SIRCA

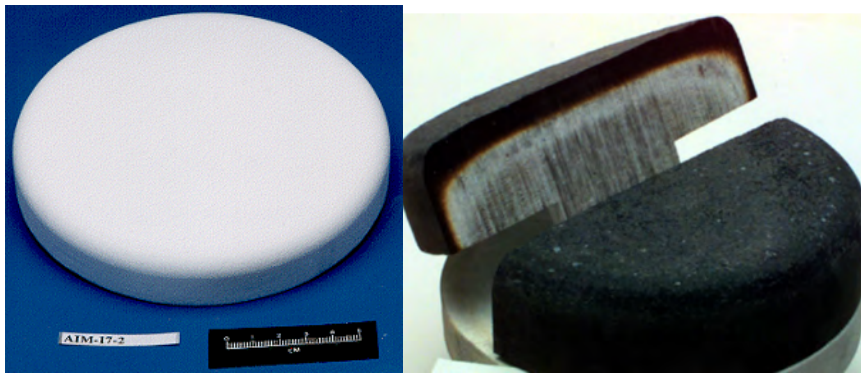
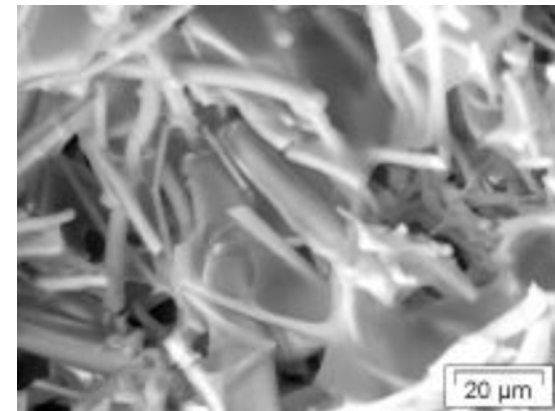


- Ceramic substrate provides good structural integrity
 - Fibrous Refractory Ceramic Insulation (FRCI-12) used
- Simple, uniform polymer infiltration process
- Low density ($0.264 \text{ g/cc} \pm 0.024 \text{ g/cc}$ or $16.5 \text{ lb/ft}^3 \pm 1.5 \text{ lb/ft}^3$)
- Easily machined to any shape and compatible with Computer Aided Machining (CAM)

Uninfiltrated LI-2200



Infiltrated LI-2200: SIRCA

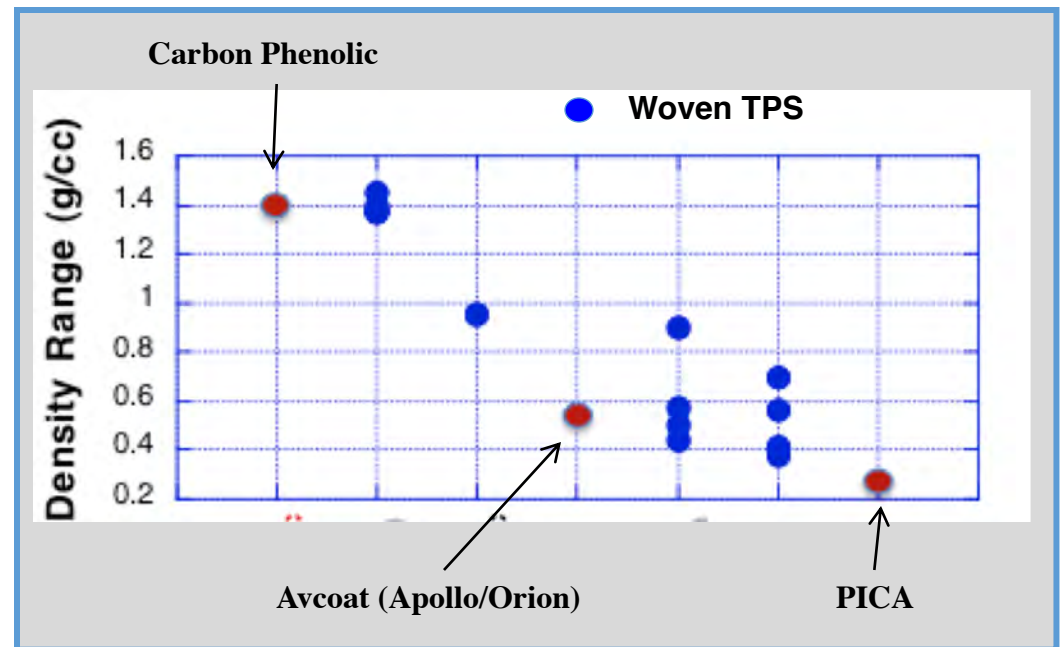
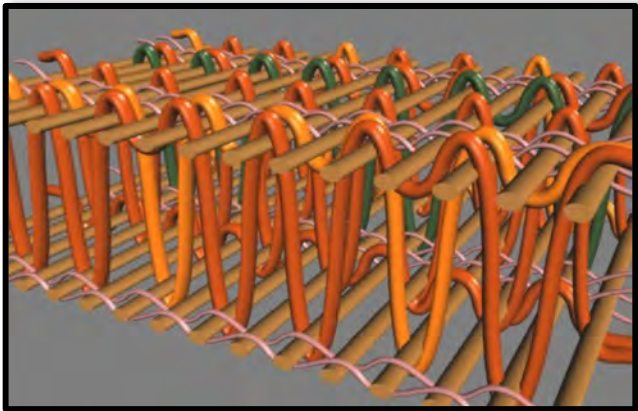


Woven TPS: What is it?



Woven TPS:

- Advanced weaving techniques either alone or with resin infusion used in manufacturing a family of ablative TPS.
- Current SOA in weaving allows for 3-D weaving of multi-layers with varying compositions and density.



Woven TPS

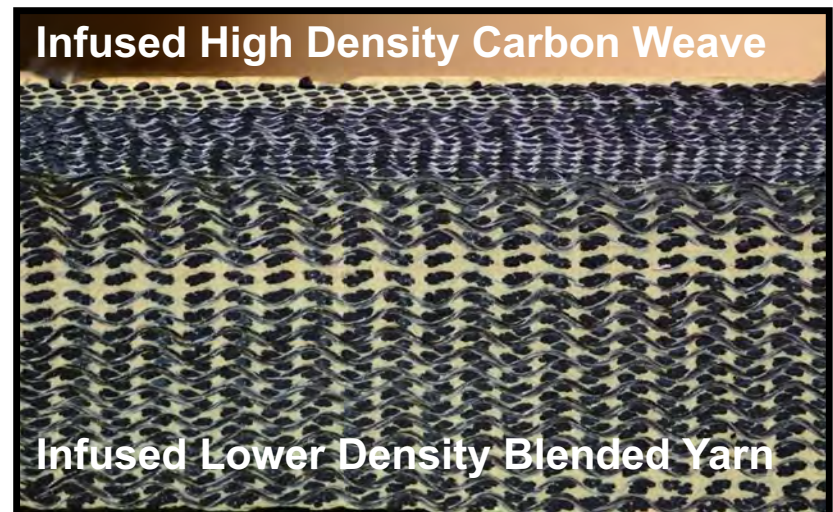
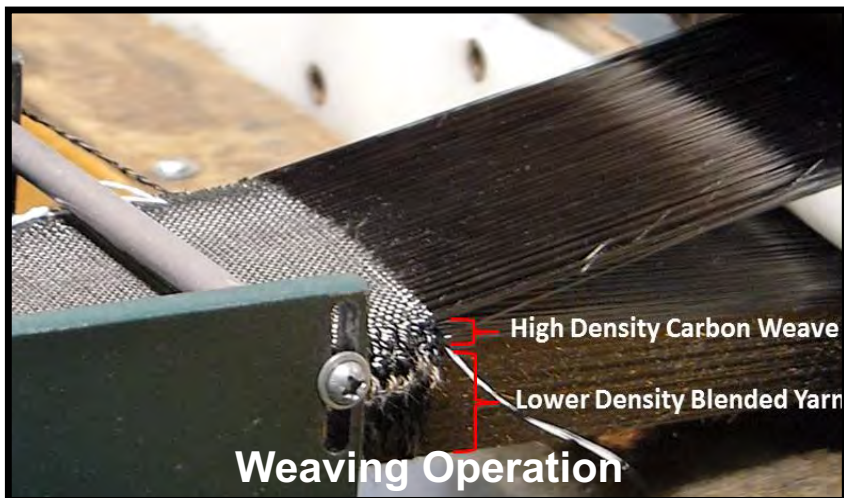


- Begin with a porous woven preform (open porosity)
 - 3D-MAT: Quartz preform
 - HEEET: Carbon or carbon/phenolic preform
 - Have control over preform starting density, number of layers and composition
- Infiltrate with a resin
 - 3D-MAT: CE – fully dense
 - HEEET: phenolic – high surface area matrix
 - Resin is diluted in a solvent
 - Have ability to control resin to solvent ratio to control amount of resin in final product
- Features leading to flaws (potentially)
 - Fiber denier
 - Interstitial spacings

- Pros: Flexibility
 - Parameters that can be tailored:
 - Starting preform density
 - Preform to resin ratio
 - Resin Composition
- Cons: Limited Part Size
 - Weaving width limitation drives need for a tiled system
 - Single piece demonstrated to 24" width (HEEET type weave)
 - Requires gaps between parts with development of proper gap design, gap fillers etc...
 - Verification of bond between tile and carrier structure is challenging
 - Need for NDE

Woven TPS - HEEET Weaving: Bally Ribbon Mills

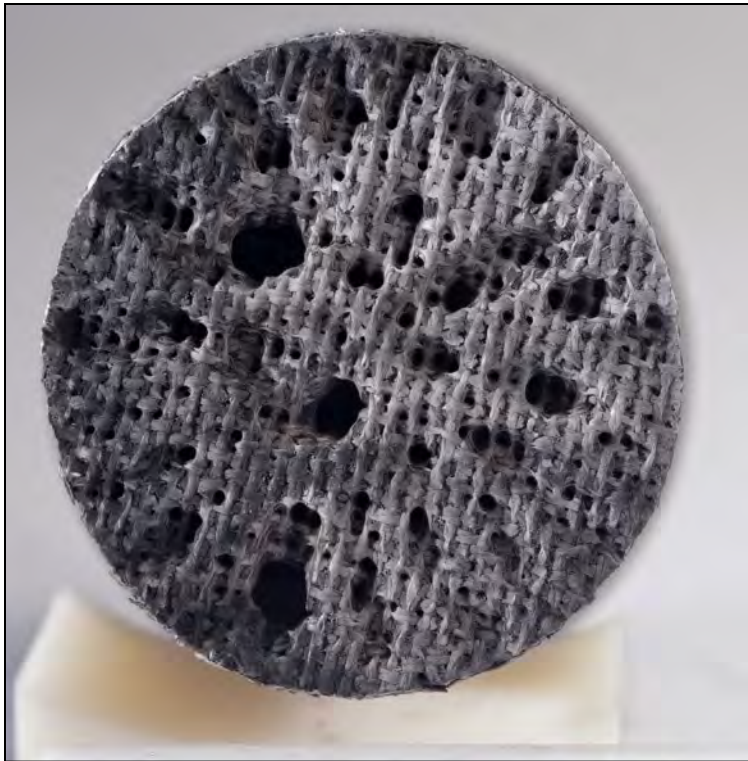
- **Dual-Layer 3-D woven material infused with low density phenolic resin matrix**
 - ◆ Recession layer
 - Layer-to-layer weave using fine carbon fiber - high density for recession performance
 - ◆ Insulating layer
 - Layer-to-layer weave: blended yarn - lower density/lower conductivity for insulative performance
- **Material Thickness:**
 - ◆ 2in (5.3 cm) thick material [0.6in (1.5cm) recession layer, 1.4in (3.8cm) insulating layer)]
- **Material Width:**
 - ◆ Initial weave capability was 6in width x 1in thickness
 - ◆ Completed weaving 13in (33cm) wide material
 - ◆ Currently weaving 24in (61cm) wide material
 - ◆ **Weaving width limitation drives need for a tiled system**
 - **Gap filler approach required**



Weave Features

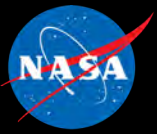


- Interstitial size drives flaw/failure
 - Permeability / scale of porosity

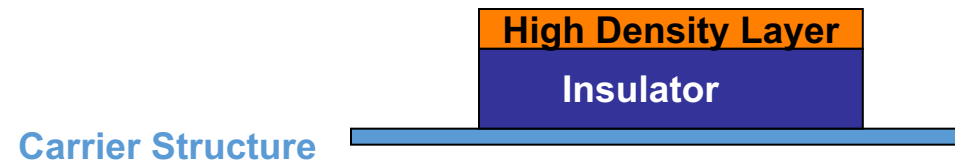


Tunneling in very low density woven material with large interstitial spaces

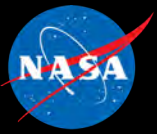
Other Dual Layer Materials (3DQP, Genesis)



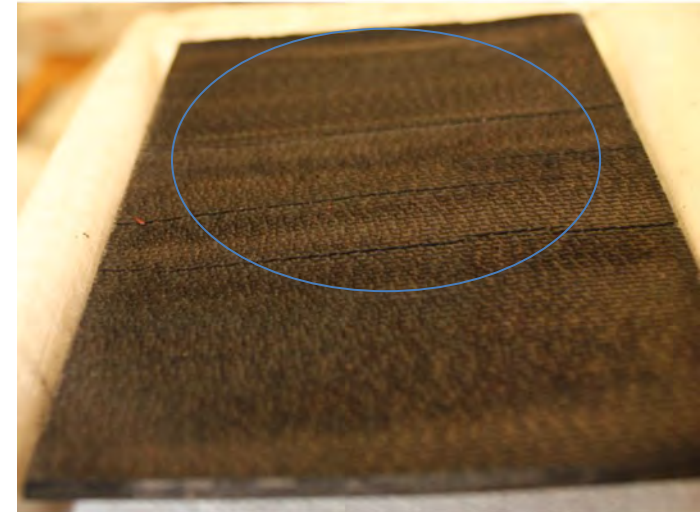
- High Density Surface Layer
 - Low recession
 - Examples:
 - C/C for LM Genesis heat shield concept
 - Si/Ph for Textron 3DQP Dual Layer
- Insulating Second Layer
 - Low thermal conductivity
 - Low density
 - Chemically and/or mechanically attach/bond layers together
 - Examples:
 - FiberForm for LM Genesis heat shield concept
 - Mod 58 Phenolic Syntactic Foam for Textron 3DQP
- Bond between surface layer and insulating layer



2-D Continuous Fiber Composites

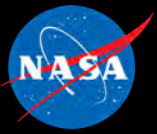


- Used in most extreme reentry environments
- Higher Density
- Lower Recession
- Higher Thermal Conductivity
- Long Heritage
- Manufacturing:
 - Tape Wrapped
 - Chop Molded
 - Compression Molding
- Examples:
 - C/C
 - High Density Layer on Genesis Heat Shield
 - BRV Nostetips
 - C/Ph
 - Galileo Heat Shield
 - Pioneer Venus
 - DoD Reentry Vehicles
 - Rocket Nozzles



Prone to delamination failure

Factors That Influence TPS Design



- Aerothermal Environment
 - Peak conditions (heat flux, shear, pressure) maybe used to screen suitability of a given material
 - Total heat load will be used to size the thickness and therefore total mass of the heat shield
- Strength/Stiffness (Airloads/Vibroacoustic)
 - Limits of ablator material will drive things such as carrier structure design(stiffness) and block layout for segmented approaches
- Outgassing
- Space Environment
 - LEO: Atomic Oxygen
 - UV
 - Long Term Space Exposure
- Damage Tolerance/Impact Resistance
- Repairability
- Refurbishment
- ***Reliability requirements***

Things to Consider when Developing Ablative Materials



- Target Mission Reentry Environment:
 - Heat Flux
 - Pressure
 - Shear
 - Enthalpy
 - Heat Load
- From a Thermal/Ablation Perspective:
 - Low Density
 - Low Thermal Conductivity
 - High Emittance (Virgin and Char)
 - Char Yield
 - May want high char yield for
 - Blowing
 - Molecular weight of species (low)
 - At what temp does decomposition begin
 - Good mechanical integrity of char (resistant to spallation and shear)
 - Glassy material may have challenges in high shear

Materials Characteristics to Consider when Developing Ablative Materials



- From a design/system/manufacturing perspective:
 - Low total mass
 - Monolithic heat shield
 - No gaps/seams
 - CTE similar to carrier structure
 - Reasonable cost
 - Ease of manufacturing
 - Manufacturing robustness
 - Long Pot Life
 - Insensitive to ambient environments in green state
 - Reproducible / automated
 - Sustainable
 - Scalability of process from lab to production
 - Strength and Stiffness

Other Considerations

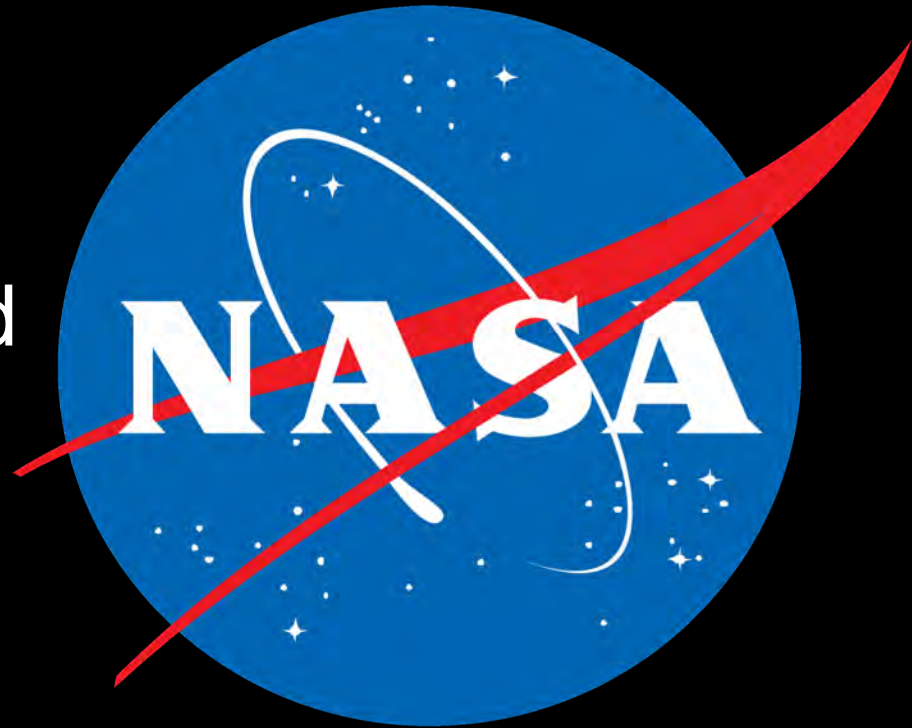


- Gap Design in Segment Approaches
 - Aerothermal Testing
 - Structural Testing
 - Ease of integration
- Transparency of material to shock layer radiation
 - Currently no ground based facility that combines convective and radiative heating
- Impact resistance to Micro Meteoroid and Orbital Debris (MMOD)
 - So concepts will be inherently more impact resistant
- Bond Verification
 - Ability to verify good bond between ablator and carrier structure
- Non-Destructive Evaluation (NDE)
 - Ability to find critical defects within material
- Waterproofing
 - Is waterproofing required and if so finding a compatible waterproofing agent.
- Atomic Oxygen
 - Is material susceptible to oxidation by atomic oxygen and if so finding a compatible coating.



Questions?

National Aeronautics and
Space Administration



Ames Research Center
Entry Systems and Technology Division

Mars Sample Return: Grand Challenge for EDL



Ethiraj Venkatapathy

Senior Technologist, Entry Systems
Exploration Technology Directorate
NASA Ames Research Center

Presented to the Ariane Group, Bordeaux

September 6th, 2018

This presentation will be given at the The 10th Ablation Workshop, Burlington, VT Sept 2018
and it has been approved for public release

The key elements of this talk have been presented and discussed in many forums including
the last Ablator Workshop in Bozeman, MT .

Contributions by number of folks at NASA Ames and elsewhere is acknowledged



Test as we Fly?

“ ‘Test as you fly’ is a worthy goal. But if not quite a myth, it is at least ‘a custom more honoured in the breach...’ “

“ Better to do many imperfect tests early and understand, than to attempt a ‘perfect’ test, as it never actually will be so. “

..... by Ralph Lorenz.

(From the presentation: “Test-as-you-fly” environments for planetary missions, IPPW-2018)

Can advances in multi-scale modelling and physics based simulation redefine “test” as we fly?

Background on Planetary Protection Requirements and the Grand Challenge



- NASA Policy Directive 8020.7G requires compliance with 1967 UN Treaty on Outer Space Article IX, which states:
 - Sample return from Mars and other water worlds: **Category V**
 - **“Restricted Earth Return”**
 - Highest degree of concern is expressed by the **“Absolute prohibition of destructive impact upon return, the need for containment throughout the return phase ...”**
 - Both ESA and NASA have defined design guidelines for mission studies in the past and these guidelines are evolving.
 - Score card for less restrictive Sample Return Missions:
 - 2 successful (Stardust and Hayabusa) and 1 unsuccessful (Genesis)

MSR Earth Entry Vehicle (and the TPS) need to be extremely robust against all possible failure modes

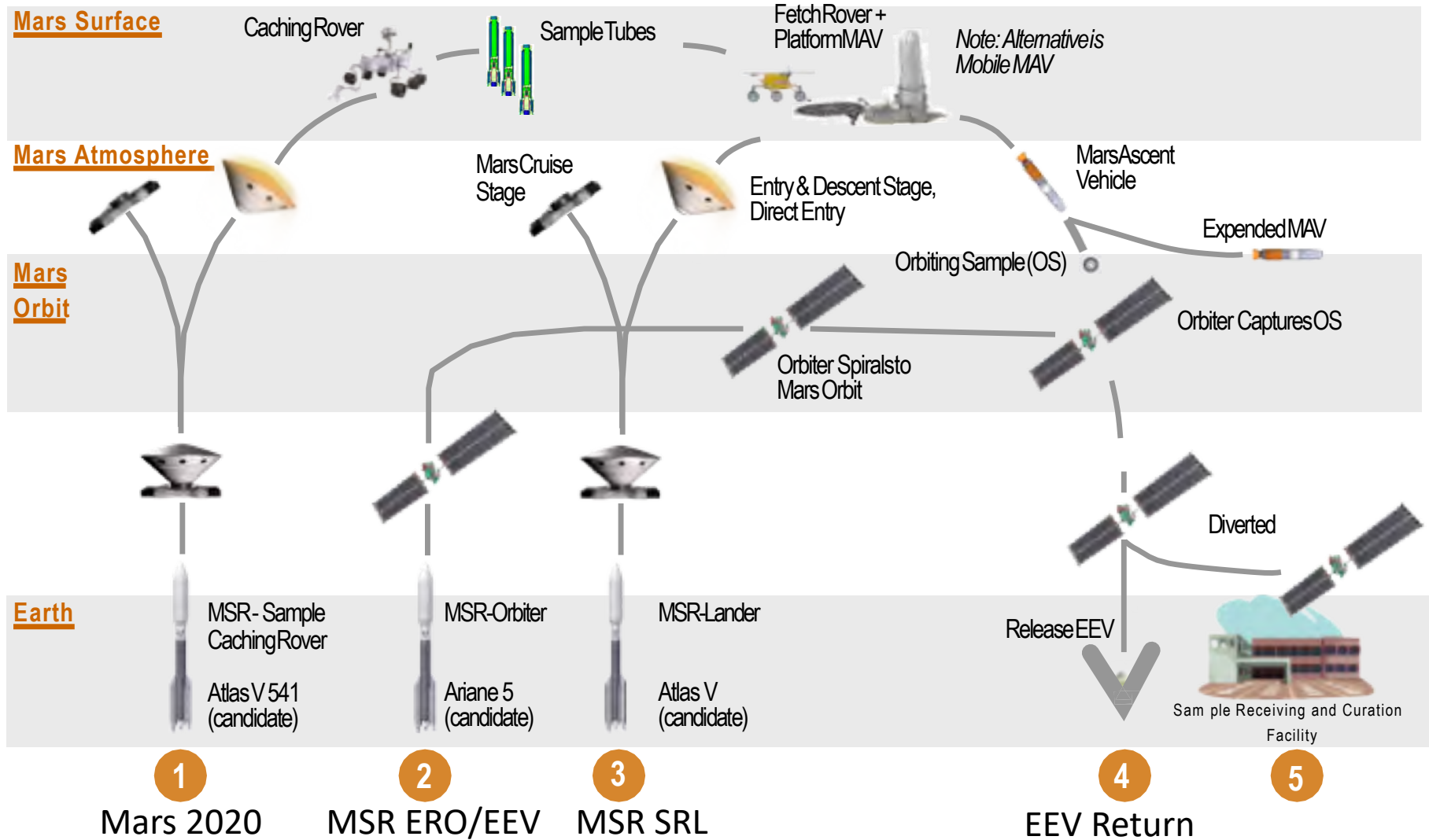
A New Approach to MSR



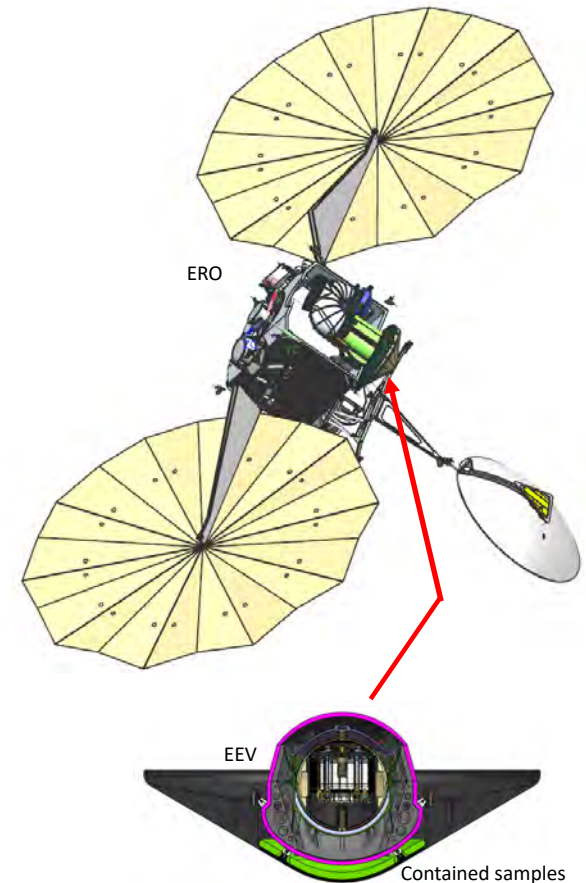
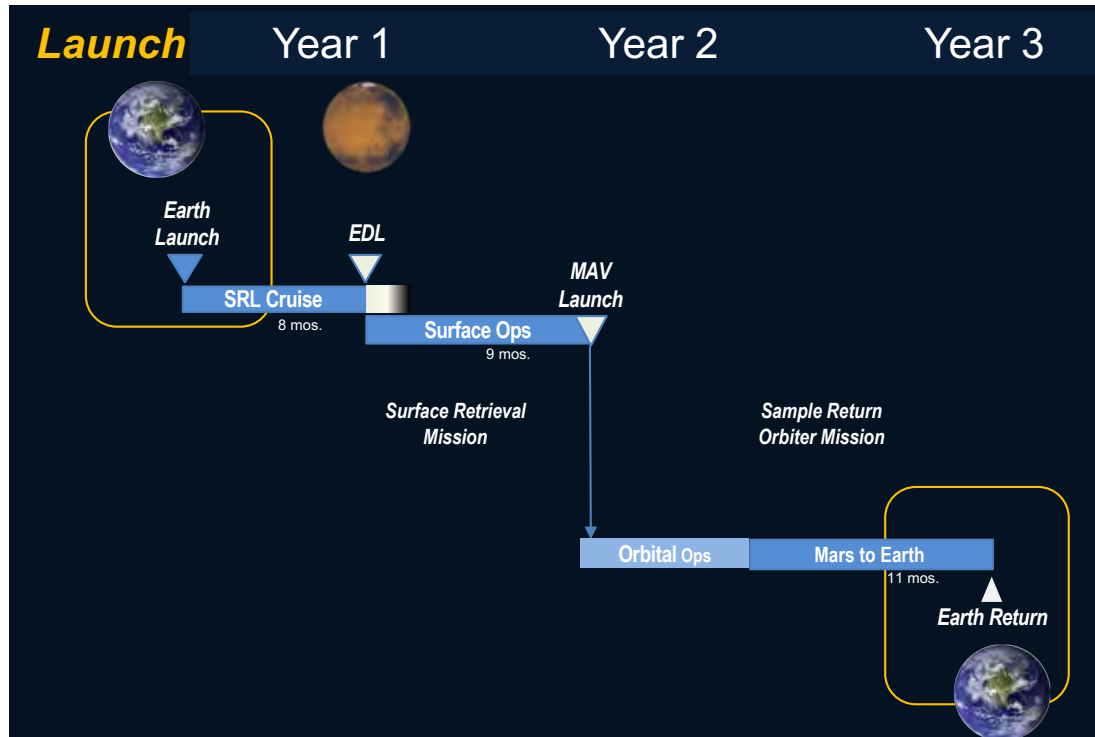
- Reliability requirements for MSR demand a new approach
 - *Risk-based design, accounting also for common cause/mode failures, drives redundancy and diversity of system design [1]*
 - *Perform studies with reliability as primary metric*
 - *Allocation of functions to subsystems*
 - *TPS role in MMOD protection and landing impact attenuation*
 - *Dissimilar redundant capability*
 - *TPS typically exempted from redundancy requirements:*
 - *Design for Minimum Risk*
 - *Re-visit creative options for secondary TPS*
 - *Account for consequence of primary failure on secondary load environment*
 - *Safety features*
 - *Detect incipient failure*
 - *Sacrifice some science return to assure planetary protection*

[1] Conley, Catharine A., and Gerhard Kminek, "Planetary Protection for Mars Sample Return." ESA/NASA, April 29 (2013).

Potential Mars Sample Return – Notional Architecture



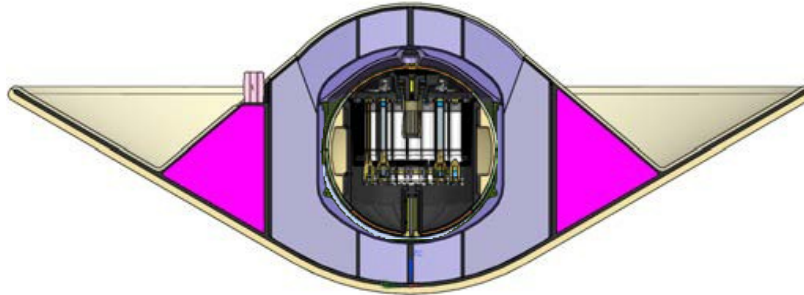
MSR EEV Campaign and Mission Design Challenges



- Launch in 2026 - SRL and (ERO with EEV) missions
- ESA-NASA collaboration
- Mission Architecture and design(s) need to be technically **robust**.
 - Need to be tolerant to programmatic, schedule and budget constraints.
- This is what makes MSR - EEV a grand challenge and an opportunity.

Current MSR EEV Concepts Under Consideration

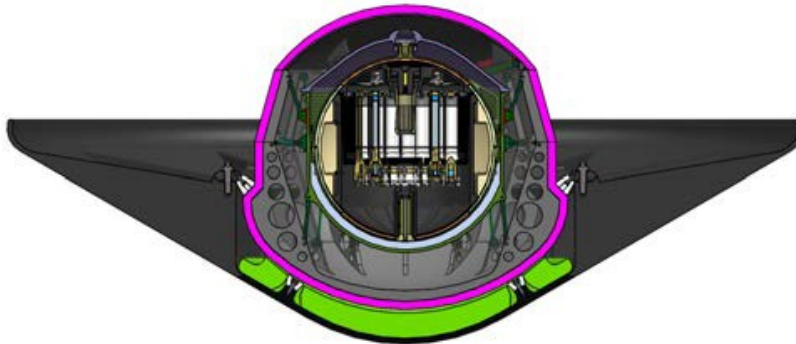
Cold Structure EEV Concept



PICA and 3-D Woven (HEEET and Variants)

- PICA will need to be single piece (like Stardust but much bigger)
- HEEET – Tiled with seams
 - Tested at much higher conditions
- Other 3-D Woven could be single piece
 - Need further development

C/C EEV Concept



2-D and 3-D Carbon-Carbon

- Many different forms of Carbon-Carbons
 - 2-D and 3-D or combination
 - Single or multi-piece
 - DoD experience base (+ and -)
- Hot-structure construct
 - Design, Manufacturing, integration and certification challenges

Design concepts have to be robust against MMOD, entry and ground impact and be mass efficient

State of the Art: System and TPS Reliability



- **Waiver required for EFT-1 test flight**, due to negative structural margins against cracking of Avcoat ablator (Vander Kam, Gage)
 - PRA estimate for structural failure due to TPS bond-line over temperature $\sim 1/160,000$ ($6.25e-6$)

Orion Crew Vehicle Reliability allocations

Orion Post- PDR	ISS	Lunar
Requirement: Loss of Crew	1/290	1/200
TPS Allocation	1/5600	1/2100

From: (AIAA 2011-422)

- **Shuttle** *Analysis of data from successful flights (did not include consideration of off-nominal TPS states) estimated TPS reliability of 0.999999 (or failure $< 1.0 \times 10^{-6}$)*
 - *Columbia accident highlighted need for consideration of damage due to debris impact*
- **Robotic missions (No known mission failures due to TPS failure) (most not instrumented)**
 - Recession data for Galileo indicated near failure at shoulder
 - MSL identified shear-induced failure mode for SLA during ground test campaign – switch to PICA
 - Root cause of Mars DS2 failure unknown, but entry failure deemed unlikely

- **Need comprehensive hazard analysis**
 - Assess likelihood and consequence for each hazard
- **Need robust performance margins for all failure modes**
 - Ground test to failure to establish performance limits

State of the Art: TPS and Thermo-Structural Modeling



Reliable As Primary Design Input

- 1D thermal sizing*
- Multi-dimensional conduction*

Must be Augmented Via Test

- Tiled systems / gap performance
- Thermo-structural performance
- Margin assessment

Must be Obtained Via Test

- Singularities (e.g. cut-outs, windows, closeouts, seals)
- Failure modes
- Off-nominal performance (damage)
- Reliability assessment
- Materials design

*once models have been calibrated with arc jet data for conditions and materials of relevance



Design

Development

Testing

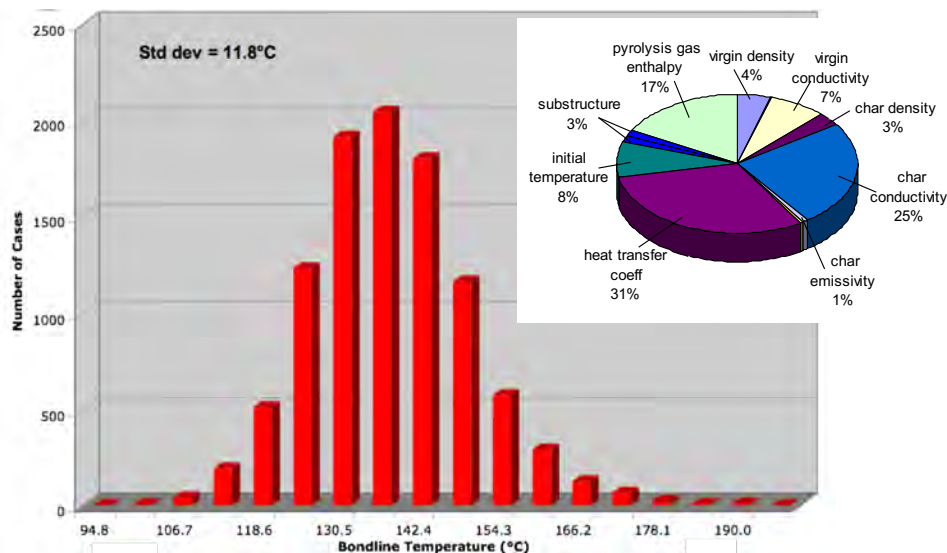
Manufacturing

Integration

Flight Certification

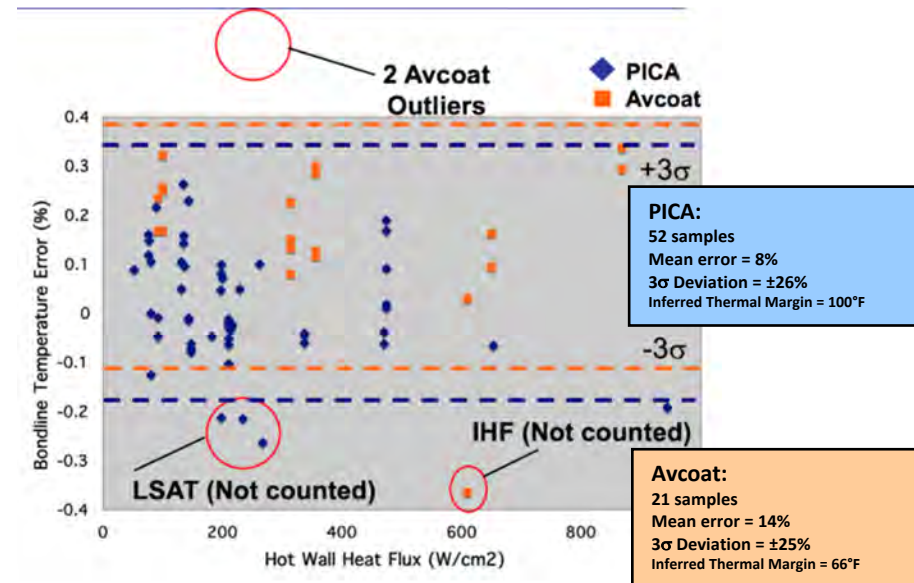
Do we know how to do (thermal) margin?

- **A TPS system is designed (margin) to a given reliability**
 - In other words, it must be robust to off-nominal conditions
 - **Thickness margin is typically applied as one reliability factor**
- **Thickness margin is evaluated by evaluating uncertainties in environments and material performance and tracking their influence on design metrics of interest (e.g. bondline temperature)**
 - Goal is a full Monte-Carlo process, but we are not there yet
 - Margin assessment is currently reliant on statistical performance data (Arc Jet testing)



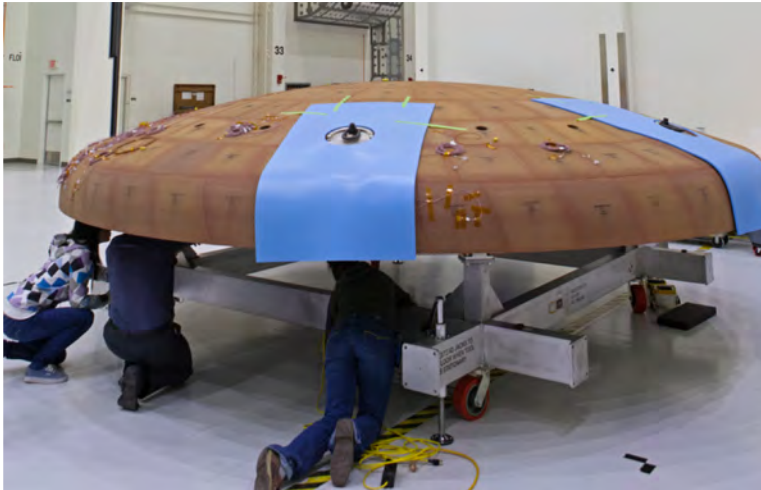
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MC Analysis of thermal margin



Statistical analysis of Arc Jet data

Understanding the Features: From TPS Material to Integrated System



Orion EM1 5.0 m Heat-shield (block Avcoat, RTV gap filler, Compression Pad, Instrumented Plugs)



HEEET 1m Engineering Test Unit (ETU)

MSR EEV ?

Larger than Stardust
(smaller than Orion)
entry at (~ 13.5 km/s)

- Ballistic entry
- MMOD Impact
- Chute-less
- Impact Landing



Stardust single piece, seamless heatshield

Needed: Characterization of TPS - Features, Flaws and Failure



Structural Aero/Material

▪ Acreage

- Through Thickness cracks causing “heat leaks”
- In plane cracks causing reduced thickness
- Surface erosion
 - Mechanical failure causing spallation or accelerated layer loss
 - Melt flow
- Flow through (permeability permits interior flow)

▪ Loss of attachment of tiles or gap fillers, causing complete loss of thermal material over a large area

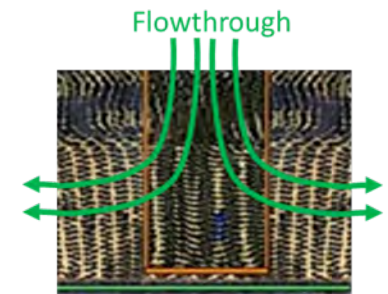
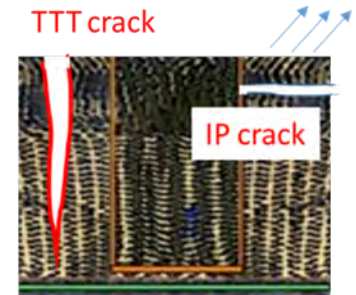
- Adhesive mechanical failure
 - Substrate failure adjacent to adhesive
- Adhesive thermal failure

▪ Cracking and opening of seams, permitting a “heat leak” in the gaps between tiles

- Adhesive mechanical failure
 - Tile failure adjacent to adhesive
- Adhesive char and erosion

▪ Material response prediction error

- Recession rate error
 - **Differential recession at seam**
- Conduction

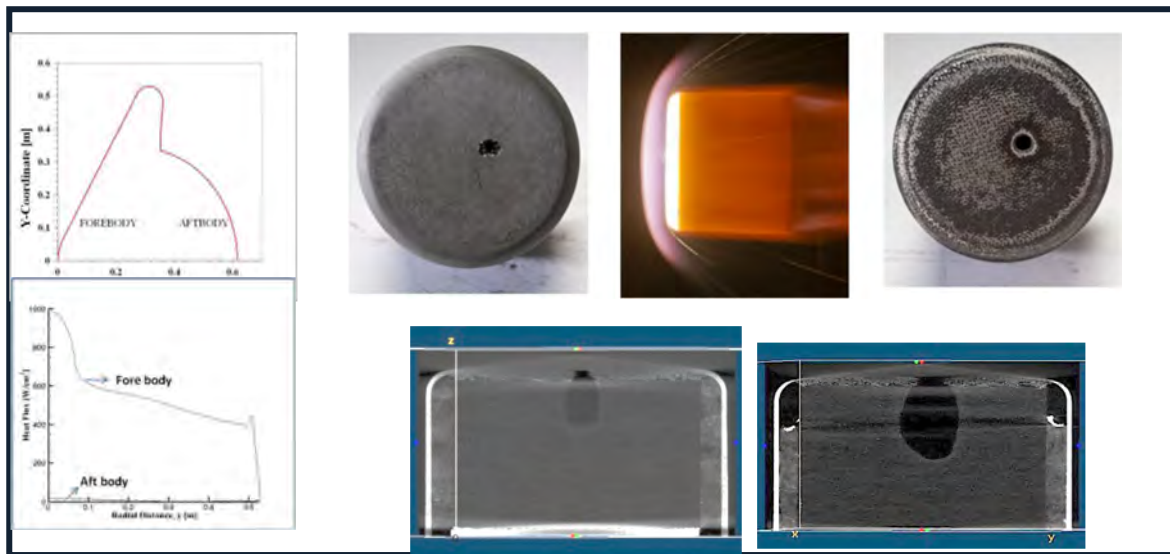


Mission: Induced Features and Flaws



■ Launch to Landing

- Launch,
- deep space cold soak,
- micro-meteor and orbital debris,
- entry and
- landing



Physics-based impact and hole growth tools needed to assess the MMOD risk



Unique Challenge for MSR EEV

- Human missions certification is via ground and flight tests (Orion as well as Commercial Crew) combined with simulation
- MSR EEV demands a different approach
 - Robustness requirement is more stringent than human missions
 - Launch by 2026 time-line does not allow for flight test

Rethinking our approach –

- Design from the perspective of certification
 - Will require understanding features that become flaws and flaws that lead to failure. Can we design these features that lead to failure? Can we introduce features that prevent failure?
- **Certification through modeling and simulation anchored to tailored tests**
 - **Physics based multi-scale modeling and simulation tools anchored to relevant test data.**
- **A great opportunity for Multi-scale integrated modeling approach**

TPS certification will be the biggest challenge as well as opportunity



References

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2. [“A new era and a new trade space: Evaluating Earth entry vehicle concepts for a potential 2026 Mars sample return,”](#) Scott Perino, et al., IPPW-2018, Boulder, Colorado.
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7. [‘More Honoured in the Breach?’ Test-as-you-fly Environments for Planetary In-Situ Missions](#) -- Ralph Lorenz,

Questions?

