Thermal Protection for Mars Sample Return Earth Entry Vehicle: *A Grand Challenge for Design Methodology and Reliability Verification*

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Motivation

Grand Challenge for ablative material modeling:

- TPS certification for high reliability
  - Need to
    - Understand failure modes and failure propagation,
    - Assess features that lead may become flaws and then on to failure
    - Design - eliminate features that lead to failure and add that lead to robustness
    - Guide strategies for robust margin development,
    - Enable reliability prediction and
    - Provide evidence supporting certification of as built hardware
- NOT development of new material systems
    - May tailor available TPS architectures, particularly 3D woven concepts

Outline

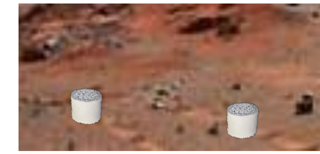
- Mars Sample Return Mission
- State of the Art
  - MSR Earth Entry Vehicle
  - TPS Reliability
  - TPS Modeling
- What is Needed
  - System Studies
  - TPS Capability Characterization
- Concluding Remarks

Mars Sample Return

as discussed in Visions & Voyages 2011 **Decadal Survey**

Sample Caching Rover

Launch from Earth/Land on Mars → Select Samples → Acquire/Cache Samples



Sample Canisters On Mars Surface

"Highest-priority flagship mission"

Mars Sample Return Lander

Retrieve/Package Samples on Mars → Launch Samples to Mars Orbit

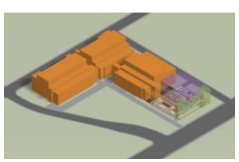
Orbiting Sample in Mars Orbit

"Important to make significant technology investments"

Mars Sample Return Orbiter

Capture and Isolate Sample Container → **Return to Earth** → **Land on Earth**

Orbiting Sample on Earth



Sample Handling Facility

Retrieve/Quarantine and Preserve Samples on Earth → Assess Hazards → Sample Science

Sample Science

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Background on Planetary Protection Requirements and the Grand Challenge

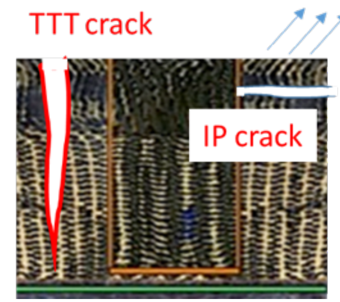
- NASA Policy Directive 8020.7G requires compliance with 1967 UN Treaty on Outer Space Article IX, which states:
  - NASA Procedural Requirement 8020.12 (Planetary Protection Provisions for Robotic Extraterrestrial Missions) is derived from Committee on Space Research (COSPAR) Planetary Protection Policy
  - 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 recent past:
  - JPL D-31974: "***probability that sample containment not assured (CNA) < 1 e-6***
  - Planetary Protection for Mars Sample Return (Conley, Kminek, 2011) "***Guidance: Probability of uncontained release of particle larger than 10 nanometers into Earth environment < 1e-6***
- Reliability allocation to subsystems is function of mission architecture
  - **EEV failure during correctly targeted entry < 4.0×10^{-7} (Gershman, 2005)**

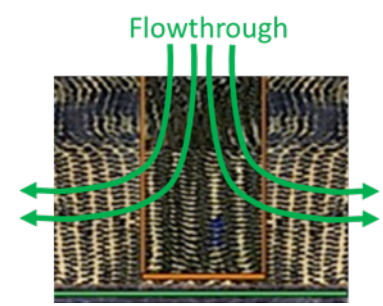
EEV (and TPS) need to be extremely robust against all possible failure modes

Features, Flaws and Failure

Structural Aero/Material

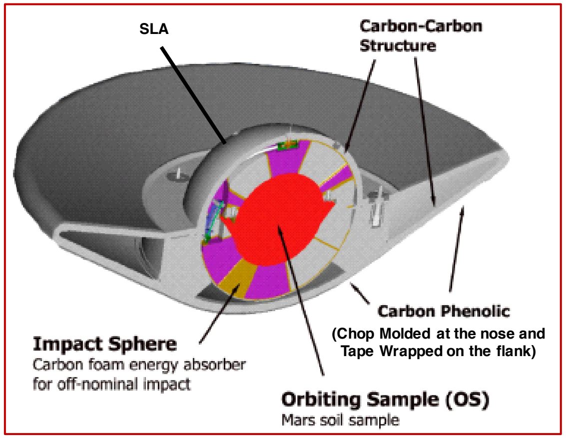
- **Acreage**
  - ➢ Through Thickness cracks causing “heat leaks”
  - ➢ In plane cracks causing reduced thickness
  - ➢ Surface erosion
    - Mechanical failure causing spallation or accelerated layer loss
    - Melt flow
  - ➢ Flow through (permeability permits interior flow)
- **Loss of attachment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

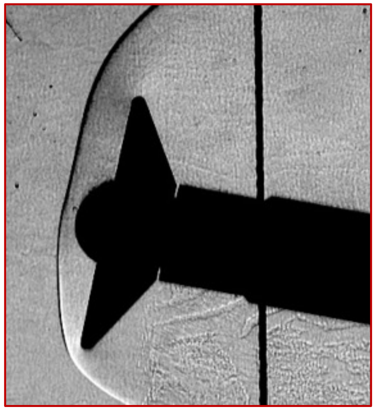




State of the Art: MSR EEV Design

- MSR EEV Design Baseline (1998-2003)
  - Assumption: passive is reliable
    - Self-righting, mono-stable entry shape
    - Chute-less Design => Direct Impact
  - TPS : Carbon-Phenolic and SLA
- Micro-Meteorite and Orbital-Debris Impact
  - MMOD impact analysis performed in 2010 showed both Carbon Phenolic and SLA are susceptible to failure due to MMOD impact.
- Reliability requirement on heat-shield and backshell
  - Failure allocation to entry system < $\mathbf{4.0x10^{-7}}$





State of the Art: 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 bondline overtemperature ~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 < 1.0×10^{-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 Modeling

Reliable As Primary Design Input

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

Must be Augmented Via Test

- Tiled systems / gap performance
- Thermostructural performance
- Margin assessment

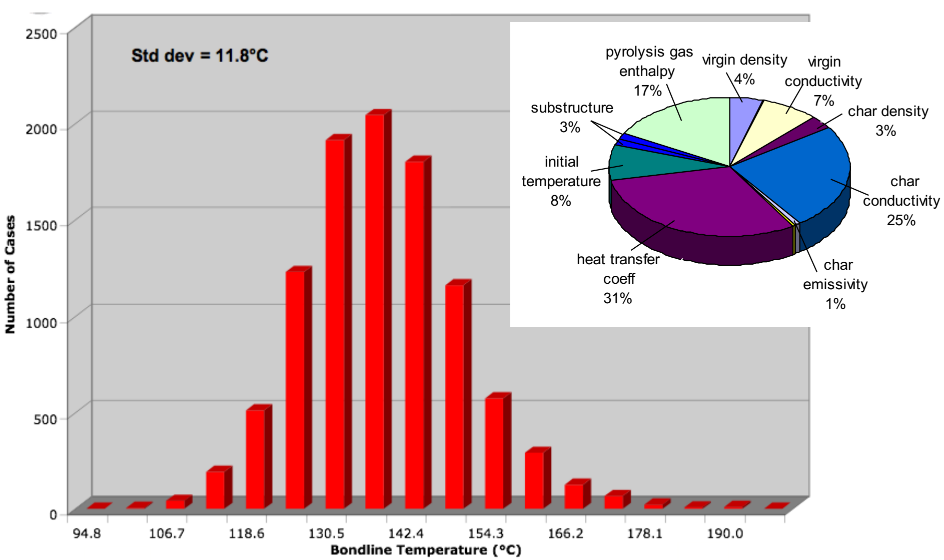
Must be Obtained Via Test

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

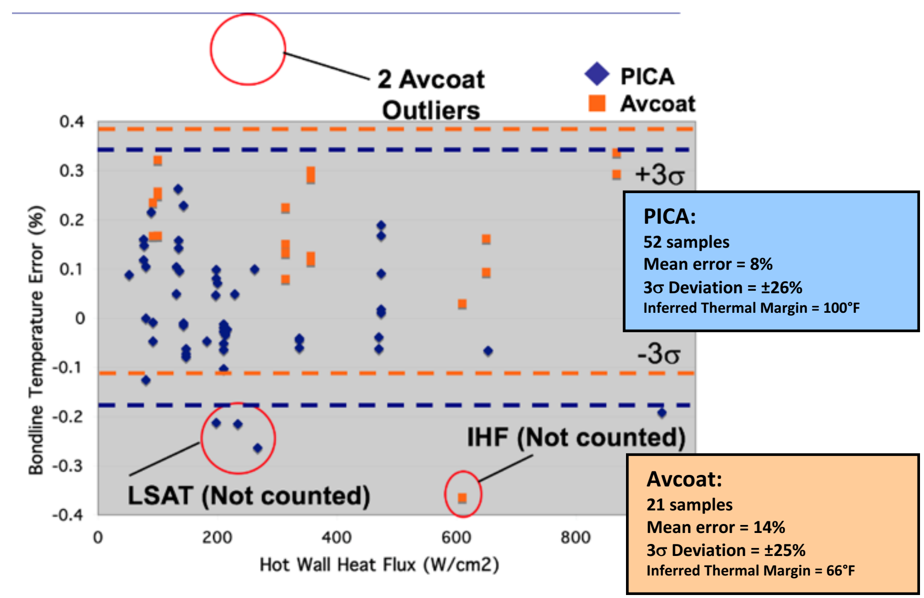
*once models have been calibrated with arc jet data for conditions and materials of relevance

We know how to do (thermal) margin !

- **A TPS system is designed (margined) 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 (AJ testing)



MC Analysis of thermal margin



Statistical analysis of Arc Jet data

State of The Art: Testing
Design, Development, Flight Qualification / Certification

Low(er) cost Mars Scout/Discovery/ New Frontiers Class

Flagship

Test Type	Mars Pathfinder	Phoenix	InSight	Stardust SRC	O-Rex SRC	Mars Exploration Rovers	MSL	M2020
Screening	X						X	
Development/ Design Verification: *Ablative & Thermal Response Development/Verification*	X	X		X	X	X	X	
Development/ Design Verification: *Design Features (gaps, repairs, defects, damage, etc)*	X	X	X	X		X	X	
Development/ Design Verification: *Singularities (e.g. hardware penetrations and special features)*	X	X		X		X	X	
Qualification*	X	X	X	X	X	X	X	
Flight Lot Workmanship Verification	X	X	X	X	X	X	X	X

We don't " Test as we Fly" nor we "Fly as we Test" and we don't have a choice. Testing alone is insufficient for certification of high reliability.

Qualification sometimes combined with flight lot workmanship verification arc jet testing

Credit: Szalai (JPL)

State of the Art: MMOD Risk to TPS

"Micrometeoroid and Orbital Debris Threat Assessment: Mars Sample Return Earth Entry Vehicle," E. Christiansen, J. L. Hyde, M.D. Bjorkman, K. D. Hoffman, et al. NASA TM 2013-217381, 2013

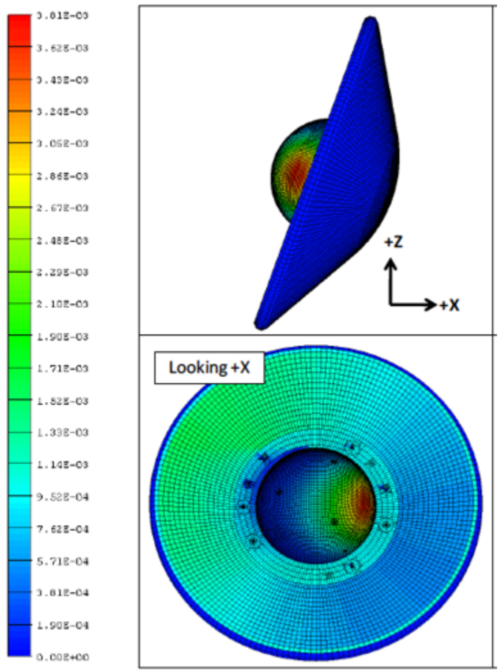
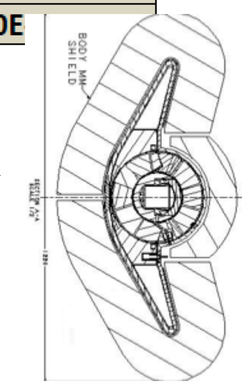


Table 5-7. MSR EEV Probability of TPS Failure Due to MMOD Impact

MSR EEV TPS Failure by MMOD Impact			
	Probability of TPS Failure		
Missions Phase	**Forward**	**Aft**	**Total**
Launch-LEO (not analyzed)	...	...	...
Earth to Mars Transit	1.32E-06	5.53E-04	5.54E-04
Mars Aerobraking	2.05E-07	8.90E-05	8.92E-05
Mars Orbit	1.33E-06	5.78E-04	5.79E-04
Mars to Earth Insert	2.74E-09	1.19E-06	1.19E-06
Mars to Earth Transit	1.20E-06	5.01E-04	5.03E-04
EEV Entry (OD only)	1.15E-06	4.09E-06	5.14E-06
"worst" case attitude			**2.80E-03**
Total	**5.21E-06**	**1.73E-03**	**1.73E-03**
"best" case attitude			**6.33E-04**
Requirement	**---**	**---**	**4.00E**

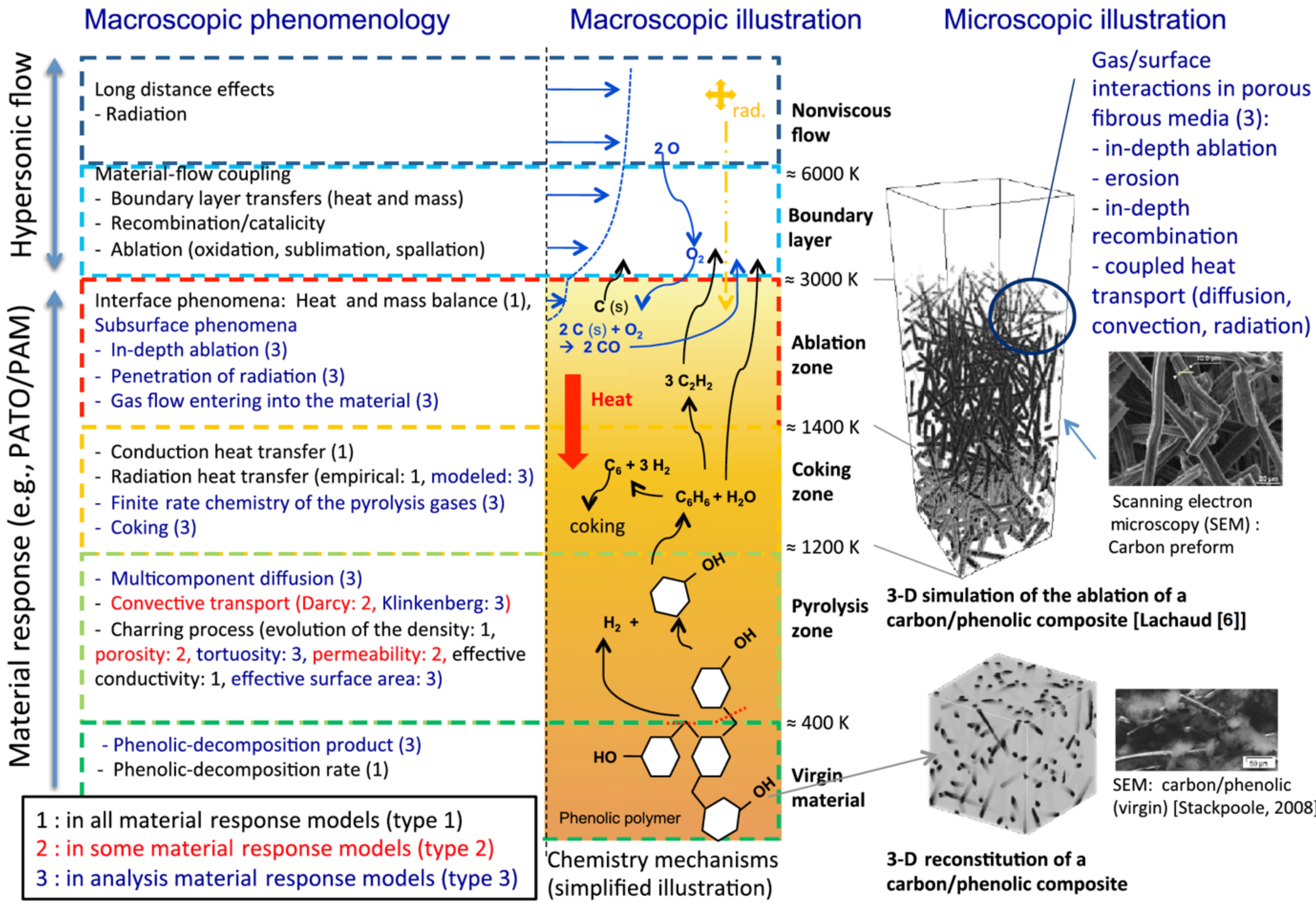
- Risk from Orbital Debris alone exceeds entire TPS allocation
  - MMOD "garage" on spacecraft does not adequately address MMOD risk
  - Dedicated MMOD shield carried to Entry Interface must separate reliably

Need TPS material that is more robust to MMOD



Alternate MMOD protection

Modeling of Material Flaws and Failure is Grand Challenge



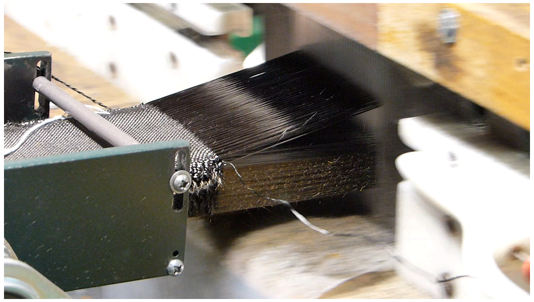
Needed: System Studies

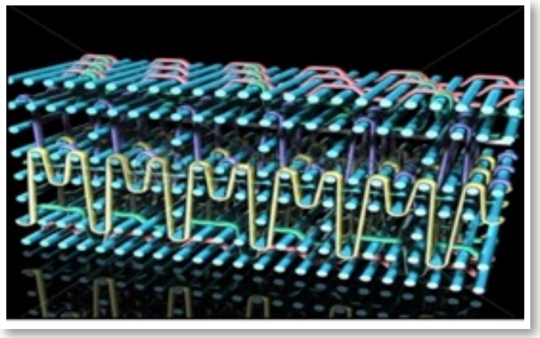
- Reliability requirements for MSR demand a new approach for campaign design
  - *Risk-based design, accounting also for common cause/mode failures, drives redundancy and diversity of system design [1]*
  - *Perform studies with reliability as primary metric*
    - *Allocation of functions to subsystems*
      - *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*

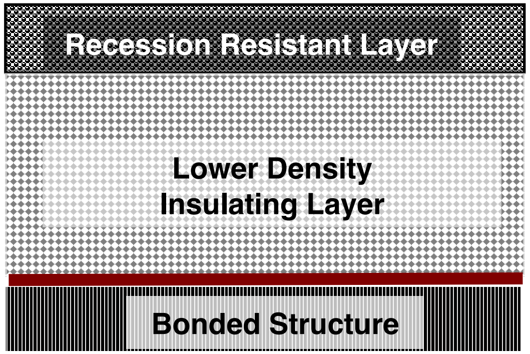
[1] Conley, Catharine A., and Gerhard Kminek, "Planetary Protection for Mars Sample Return." ESA/NASA, April 29 (2013).

Needed: TPS Robust Against All Failure Modes
(3-D Woven TPS)

- Manufacturing approach
  - ➢ 3-D weaving that allows precise placement of fibers and resin infusion
- Applications:
  - ➢ 3-D MAT – Multi-functional material for Orion Compression Pad
  - ➢ Heat-shield for Extreme Entry Environment Technology (HEEET)
    - HEEET addresses both material and system
      - Dual layer for performance and robustness
      - Seams required
    - Tech maturation (FY'14 – FY'18)
      - Targeted towards extreme entry missions
- Can 3-D woven TPS provide a robust solution to MSR EEV?



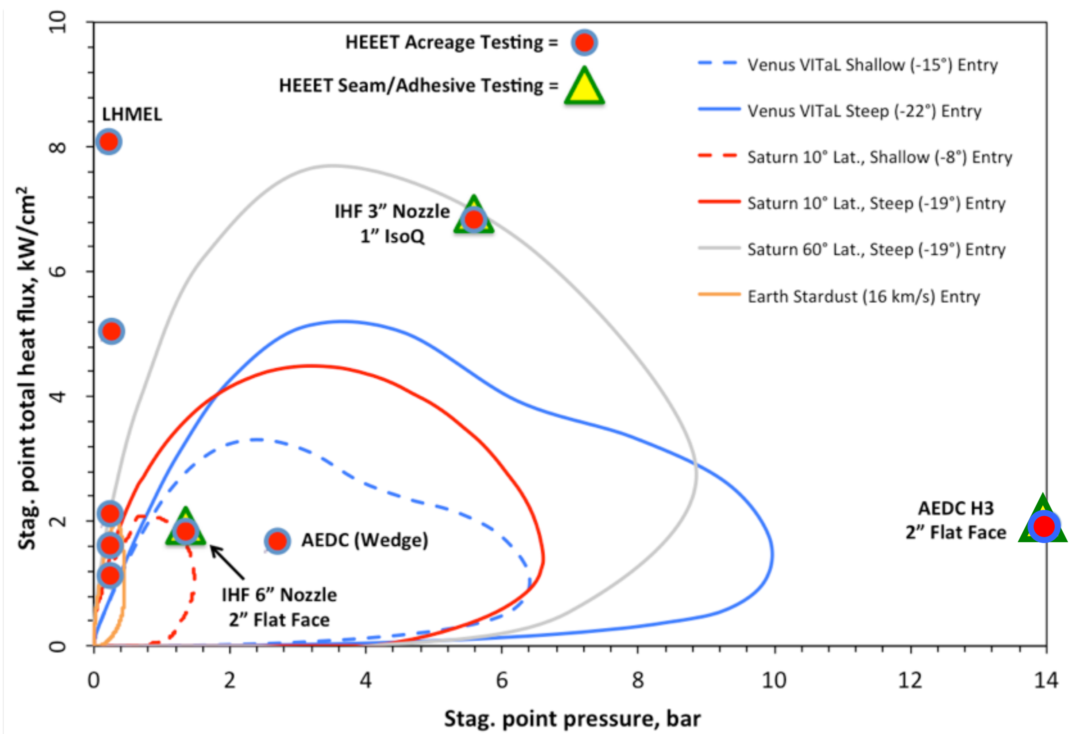




Needed: Characterization of Aerothermal Capability

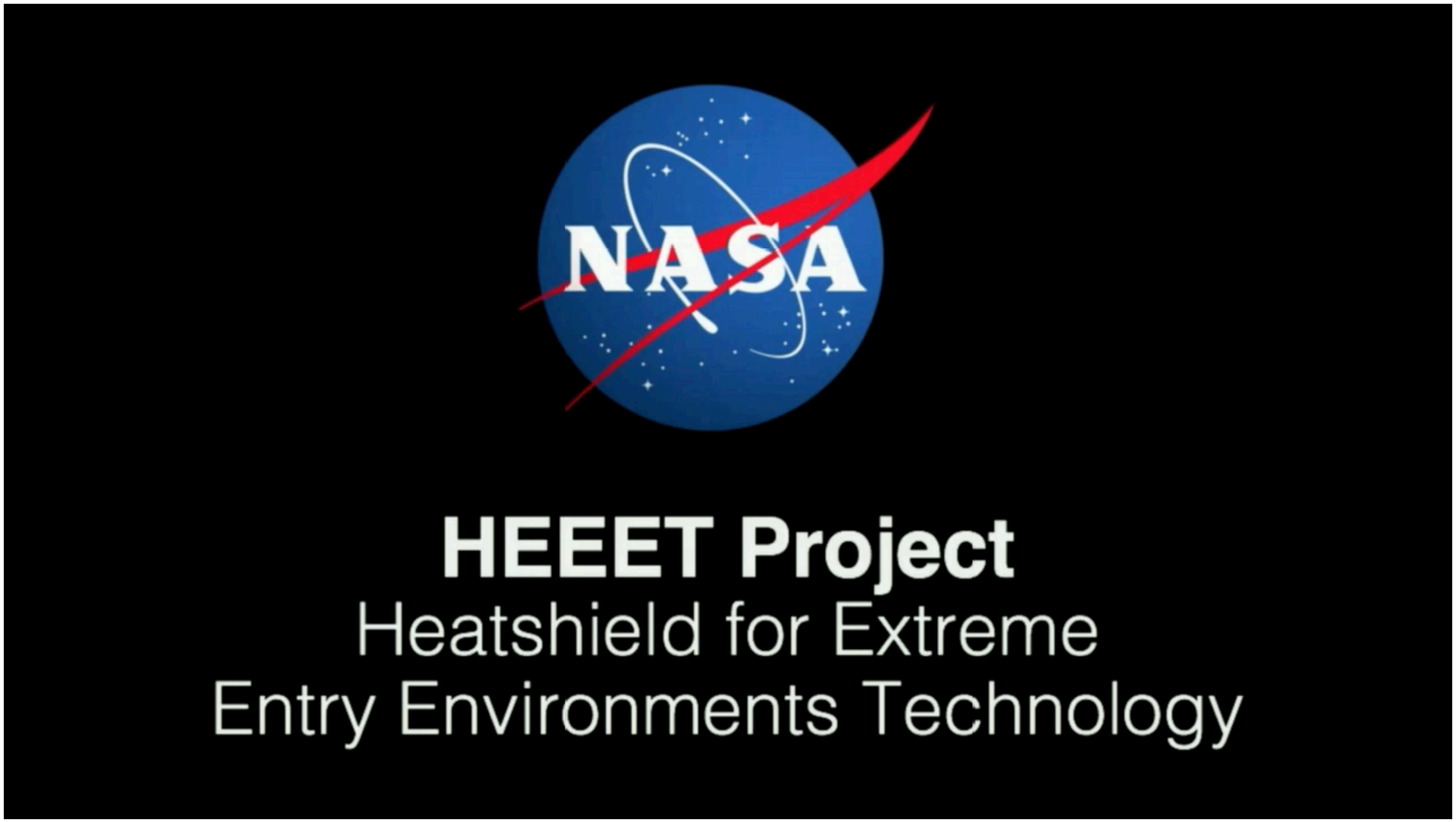
No ground test facility is fully capable of combined thermo-structural testing at extreme entry conditions

- The reference mission for the 1m diameter ETU is a 38 km/sec entry into Saturn at a -24° EFPA
- Stagnation point environments from Venus, Saturn and Earth entry missions



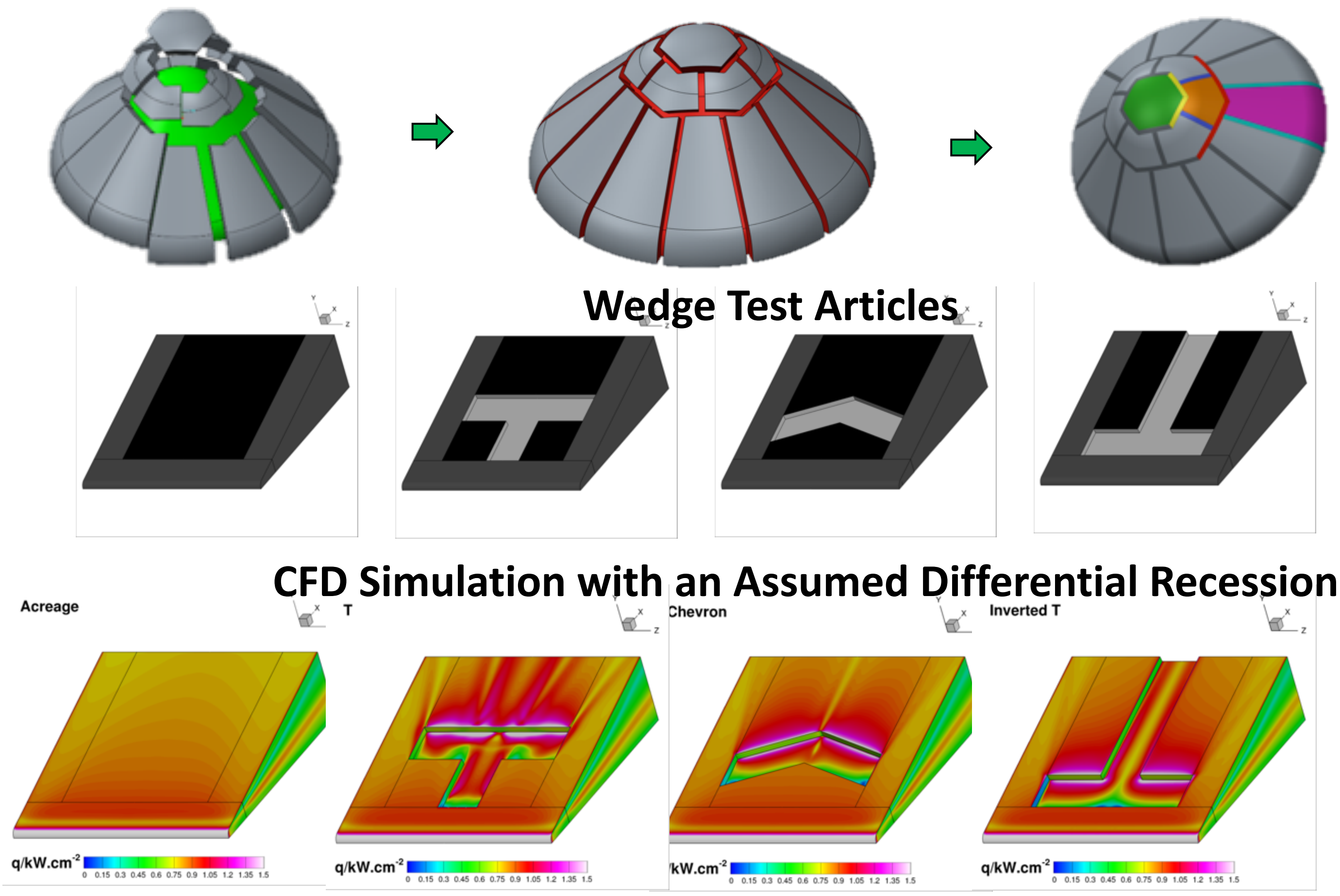
Comparison of Saturn, Venus and Sample Return Flight Environments

HEEET Development Status:
Highlights from the Arc jet Test Campaigns



- Can HEEET be robust enough to be MSR EEV heat-shield?
- How about MMOD performance?

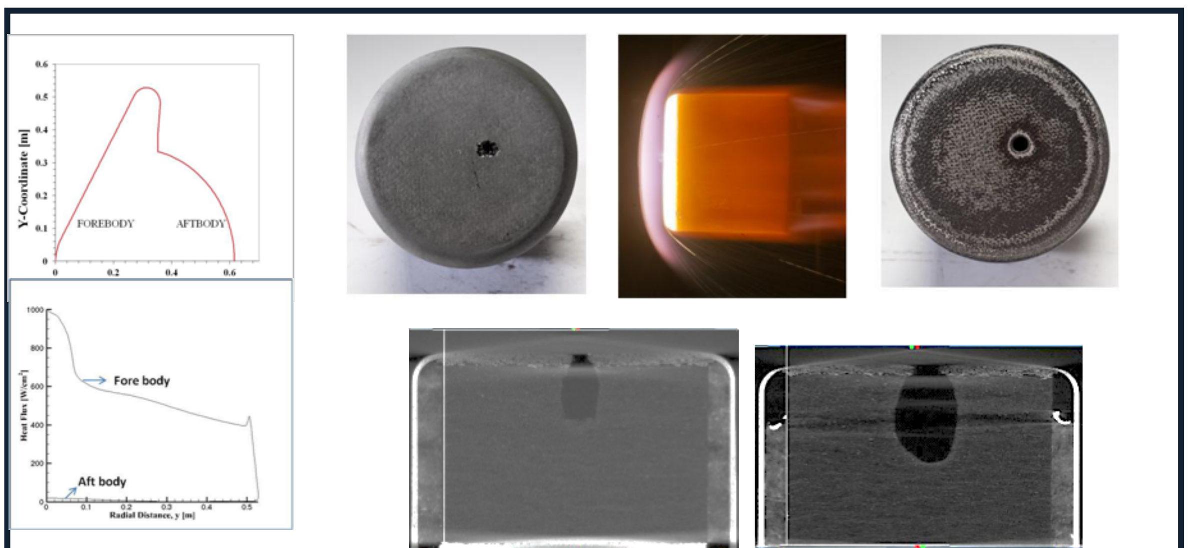
Needed: Characterization of Local Features



A single piece heat-shield would eliminate the complexity due to seam feature.
Validated modeling of seam response would provide broad configuration design options.

Needed: Characterization of MMOD Tolerance

- MMOD impact tolerant design:
  - Evaluate material behavior via testing by MMOD testing followed by arc jet testing for hole growth
  - Shuttle Orbiter and Orion TPS followed this route
  - Physics-based impact and hole growth tools needed to assess the MMOD risk



From: "Arcjet Testing of Micro-Meteoroid Impacted Thermal Protection Materials,"P. Agrawal, M. Munk and L.Glabb, AIAA Paper 2013-2903, presented at the 44th AIAA Thermosphysics Conference, June 24-27, San Diego, CA.

MSR - A Grand Challenge for the Nation
MSR TPS - Grand Challenge for the Modeling Community

- We need to be able to address:
  - What features become flaws?
  - What flaws lead to failure?
    - Char failure due to mechanical loads
    - Low density regions permitting interior flow
    - MMOD hole growth
- Testing alone is insufficient for establishing reliability
  - Cannot test in fully-relevant environments
  - Cannot perform number of tests needed for adequate failure statistics
- Multi-scale, multi-dimensional models needed
  - Must be validated against tests at range of partially-relevant environments
  - Must address material response and failure physics for all failure modes
- Mars Sample Return mission needs innovation in and application of new modeling capabilities

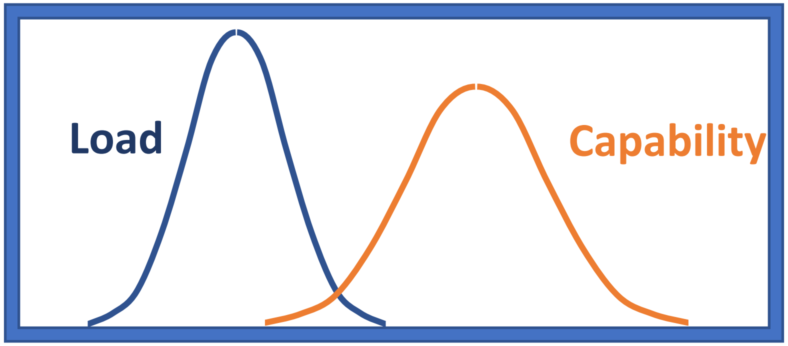
Backup

Outline

- Mars Sample Return Mission
  - Mission Description
  - Reliability Challenge
    - Need to address all failure modes
- State of the Art
  - MSR Earth Entry Vehicle
  - TPS Reliability
  - TPS Modeling
- What is Needed
  - System Studies
    - Reliability through redundancy and robustness
  - TPS Capability Characterization
    - Physics-based modeling validated against ground tests
      - Features
      - Thermo-structural Response
      - Flaw to Failure Propagation
- Concluding Remarks

Risk of TPS Failure

- **Risk is intentional interaction with uncertainty**
  - Load in new environment is uncertain
  - System capability at time of loading is uncertain
    - May be in degraded state
  - NASA Policy on Mission Assurance [2] is to **accept residual risk**
    - Remaining risk that exists after all mitigation actions have been implemented or exhausted in accordance with the risk management process
    - **As Safe As Reasonably Possible**
- **System fails when it no longer performs its function**
  - TPS no longer protects structure and payload from over-temperature



  - There is a (large) family of (thermal) load and (protection) capability curves for the TPS system

Motivation

- NASA's missions are few and far between
  - Investment in new materials and technology does not happen often
    - 3- D Woven TPS / HEEET would not have been developed if Carbon Phenolic TPS were available.
- Need an ablative TPS that can meet the Requirements for Mars Sample Return Mission in the next decade
  - The Challenge is leveraging existing/emerging TPS, design a robust aero-shell and **prove it can meet the requirements.**
- Ablation Modelling
  - Advances are focused on improving fundamental physics
    - Flight TPS design presents challenges and opportunity
- Future developments to address grand challenge of MSR TPS