Thermal Protection for Mars Sample Return

Earth Entry Vehicle: A Grand Challenge for Design Methodology and Reliability Verification

Ethiraj Venkatapathy\(^1\), Peter Gage\(^2\) and Michael Wright\(^1\)

\(^1\)Entry System and Technology Division,
NASA Ames Research Center, Moffett Field, CA.

\(^2\)Neerim Corp., NASA Research Park, Moffett Field, CA

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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

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

“Highest-priority flagship mission”

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

“Important to make significant technology investments”

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

Retrieve/Quarantine and Preserve Samples on Earth → Assess Hazards → Sample Science
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 < 4.0x10^-7 (Gershman, 2005)

EEV (and TPS) need to be extremely robust against all possible failure modes
Features, Flaws and Failure

- **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

**Structural Aero/Material**

- TTT crack
- IP crack
- Surface erosion
- Seam opening
- Attachment Loss
- Flowthrough
State of the Art: MSR EEV Design

  - 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 $< 4.0 \times 10^{-7}$
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)

<table>
<thead>
<tr>
<th>Orion Post- PDR</th>
<th>ISS</th>
<th>Lunar</th>
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<tbody>
<tr>
<td>Requirement: Loss of Crew</td>
<td>1/290</td>
<td>1/200</td>
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<tr>
<td>TPS Allocation</td>
<td>1/5600</td>
<td>1/2100</td>
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</tbody>
</table>

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 < 1.0x10^-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)

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**MC Analysis of thermal margin**

**Statistical analysis of Arc Jet data**

**PICA:**
- 52 samples
- Mean error = 8%
- $3\sigma$ Deviation = ±16%
- Inferred Thermal Margin = 100°F

**Avcoat:**
- 21 samples
- Mean error = 14%
- $3\sigma$ Deviation = ±25%
- Inferred Thermal Margin = 66°F
**State of The Art: Testing**
**Design, Development, Flight Qualification / Certification**

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

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Mars Pathfinder</th>
<th>Phoenix</th>
<th>InSight</th>
<th>Stardust SRC</th>
<th>O-Rex SRC</th>
<th>Mars Exploration Rovers</th>
<th>MSL</th>
<th>M2020</th>
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<td><strong>Development/ Design Verification</strong></td>
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<tr>
<td>Design Features (gaps, repairs, defects, damage, etc)</td>
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<td>Singularities (e.g. hardware penetrations and special features)</td>
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*Qualification sometimes combined with flight lot workmanship verification arc jet testing*

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.

*Credit: Szalai (JPL)*
State of the Art: MMOD Risk to TPS


- 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**
Modeling of Material Flaws and Failure is Grand Challenge

Macroscopic phenomenology

- Long distance effects
  - Radiation

- Material-flow coupling
  - Boundary layer transfers (heat and mass)
  - Recombination/catalicity
  - Ablation (oxidation, sublimation, spallation)

Interface phenomena: Heat and mass balance (1), Subsurface phenomena

- In-depth ablation (3)
- Penetration of radiation (3)
- Gas flow entering into the material (3)

- Conduction heat transfer (1)
- Radiation heat transfer (empirical: 1, modeled: 3)
- Finite rate chemistry of the pyrolysis gases (3)
- Coking (3)

- Multicomponent diffusion (3)
- Convective transport (Darcy: 2, Klinkenberg: 3)
- Charring process (evolution of the density: 1, porosity: 2, tortuosity: 3, permeability: 2, effective conductivity: 1, effective surface area: 3)

Material response (e.g., PATO/PAM)

- Phenolic-decomposition product (3)
- Phenolic-decomposition rate (1)

1: in all material response models (type 1)
2: in some material response models (type 2)
3: in analysis material response models (type 3)

Macroscopic illustration

Nonviscous flow

\[ \approx 6000 \text{ K} \]

Boundary layer

\[ \approx 3000 \text{ K} \]

Ablation zone

\[ \approx 1400 \text{ K} \]

Coking zone

\[ \approx 1200 \text{ K} \]

Pyrolysis zone

\[ \approx 400 \text{ K} \]

Chemistry mechanisms

(simplified illustration)

Microscopic illustration

Gas/surface interactions in porous fibrous media (3):

- in-depth ablation
- erosion
- in-depth recombination
- coupled heat transport (diffusion, convection, radiation)

Scanning electron microscopy (SEM): Carbon preform

3-D simulation of the ablation of a carbon/phenolic composite [Lachaud [6]]

SEM: carbon/phenolic (virgin) [Stackpoole, 2008]

3-D reconstitution of a carbon/phenolic composite
**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

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
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?
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

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