Mars Sample Return:
Grand Challenge for EDL

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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 present here and elsewhere are acknowledged

Test as we Fly nor Fly as we Test ?

" '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 his presentation on "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)

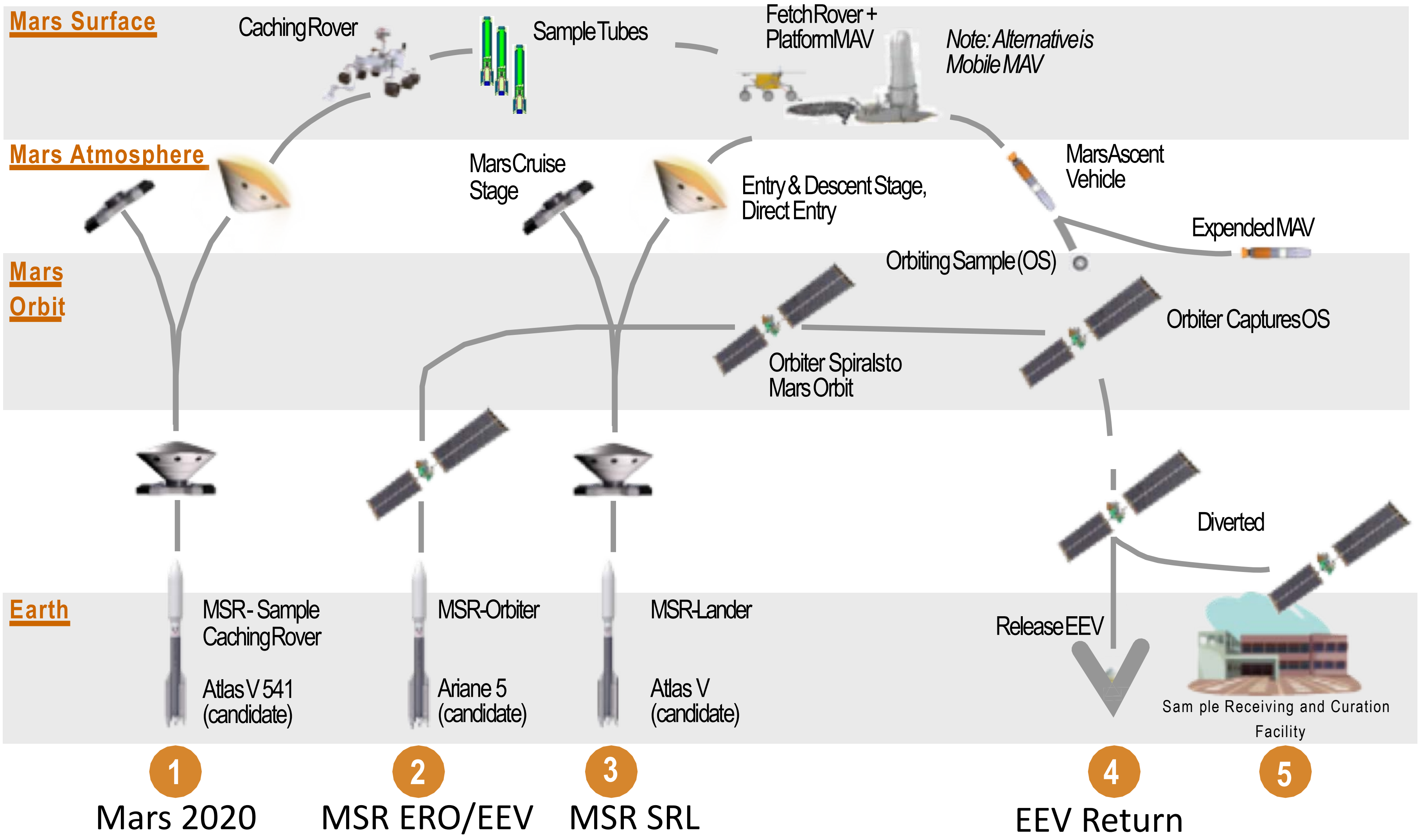
MSR Earth Entry Vehicle (and the TPS) need to be extremely robust against all possible failure modes

MSR Demands a New Approach

- 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*

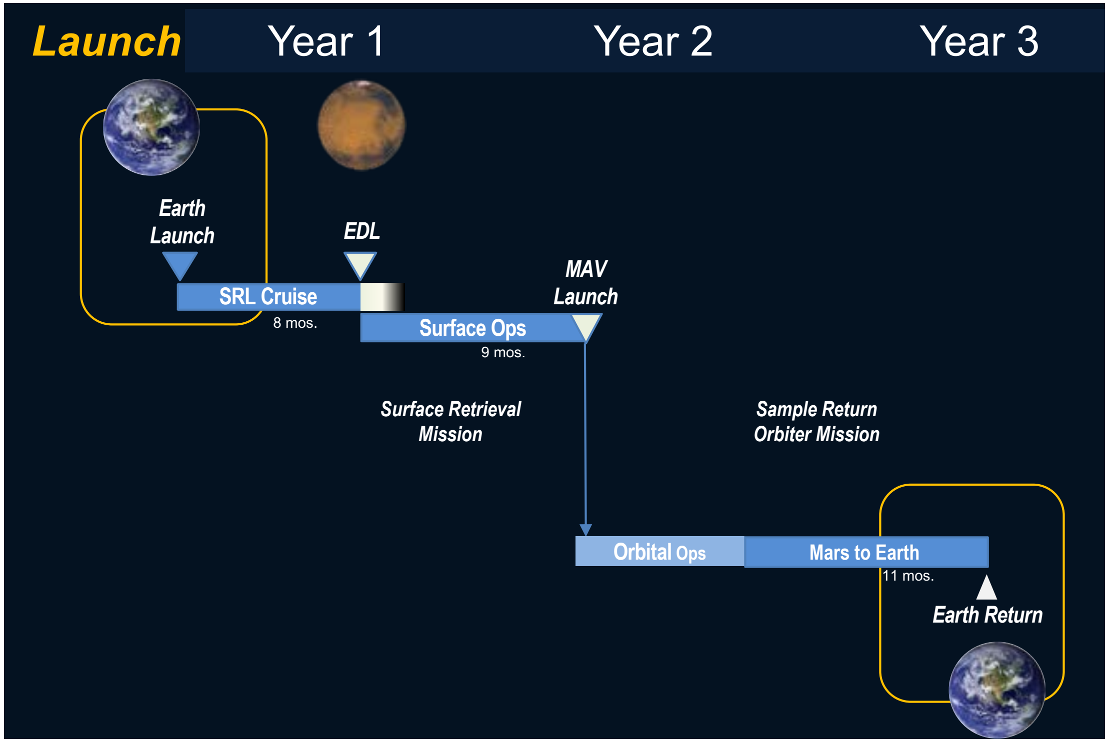
[1] Conley, Catharine A., and Gerhard Kminek, "Planetary Protection for Mars Sample Return." ESA/NASA, April 29 (2013).

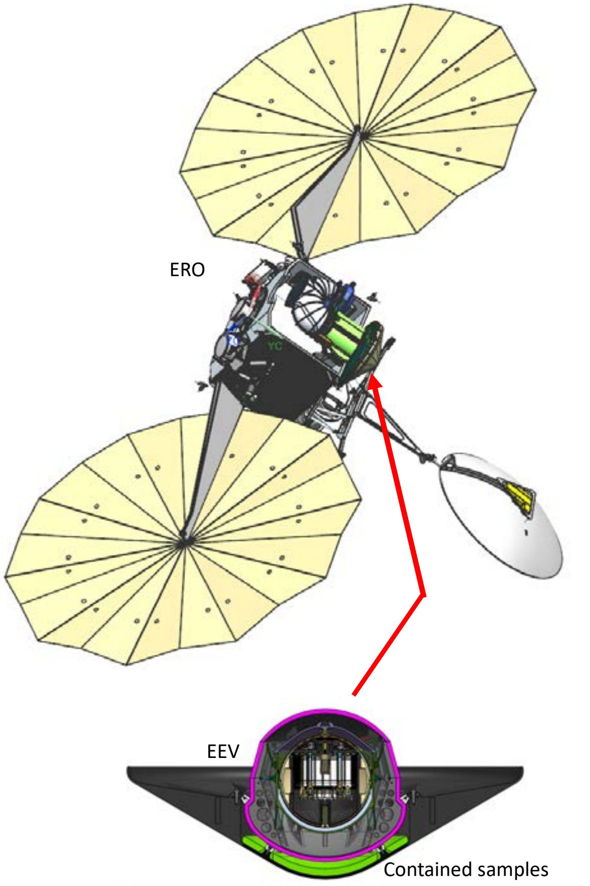
Potential Mars Sample Return – Notional Architecture



Taken from the IPPW -2018 presentation Marcus Lobia et al.

MSR EEV Campaign and Mission Design Challenges

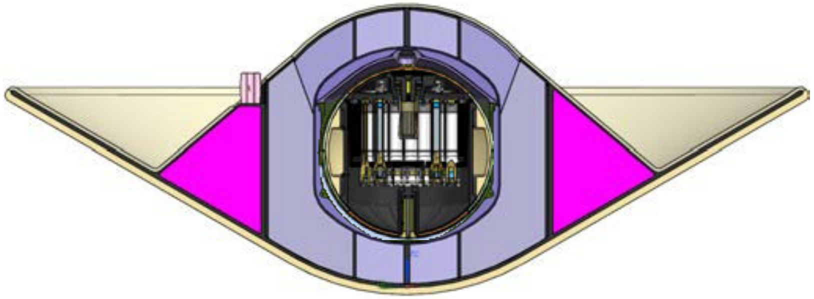




- Launch in 2026 - SRL and (ERO with EEV) missions
- ESA-NASA collaboration
- Mission Architecture and design(s) need to be technically **robust.**
  - Need to be tolerant to programmatic, schedule and budget constraints.
- This is what makes MSR - EEV a grand challenge and an opprotunity.

Current MSR EEV Concepts Under Consideration

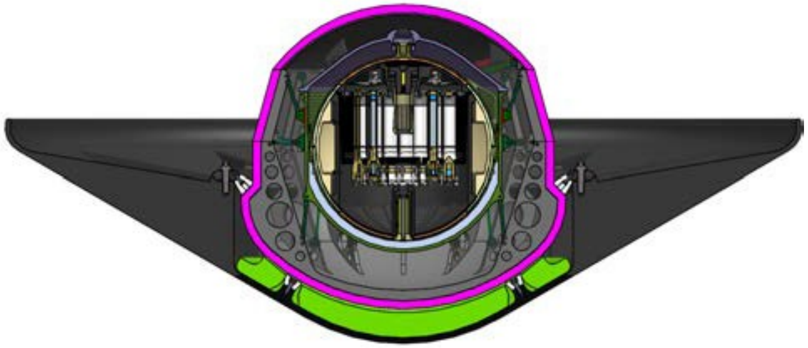
Cold Structure EEV Concept



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 ~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 and Thermo-Structural Modeling

Reliable As Primary Design Input

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

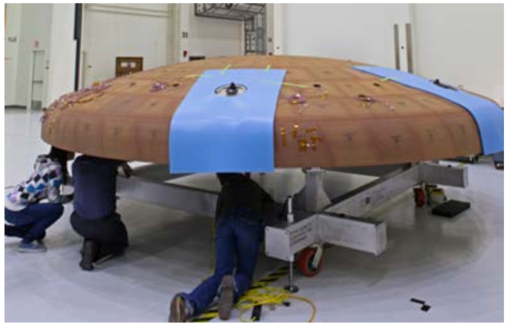
Must be Augmented Via Test

- 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

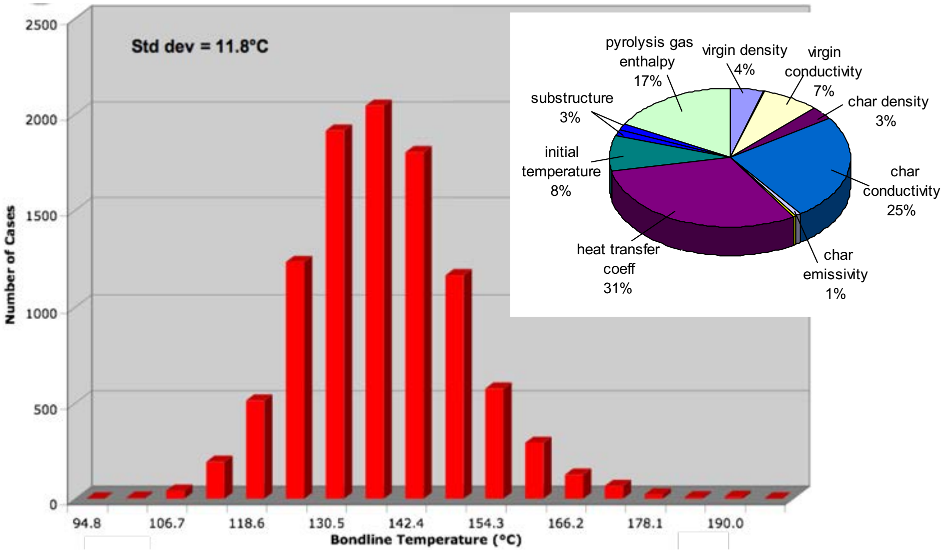


Design | Development | Testing | Manufacturing | Integration | Flight Certification

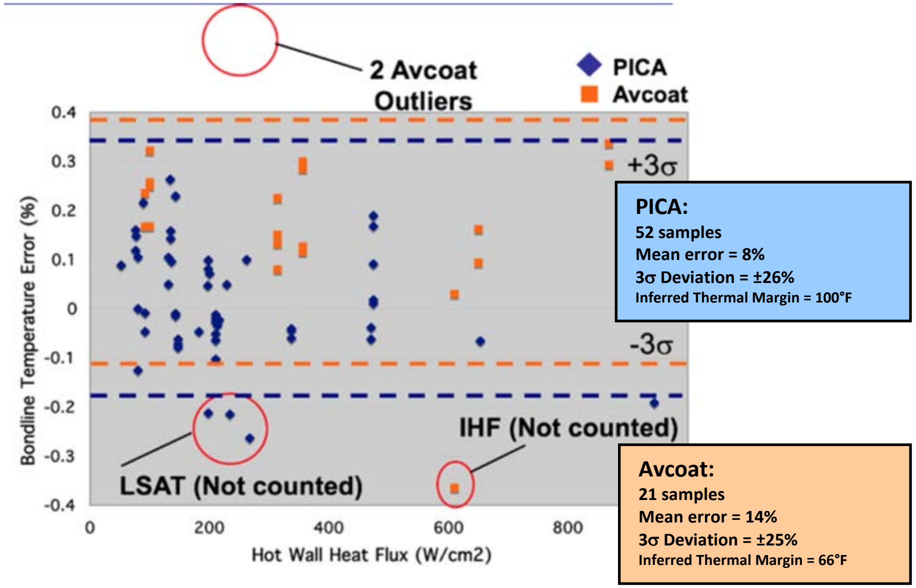
8/30/17

Do 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 (Arc Jet testing)



MC Analysis of thermal margin

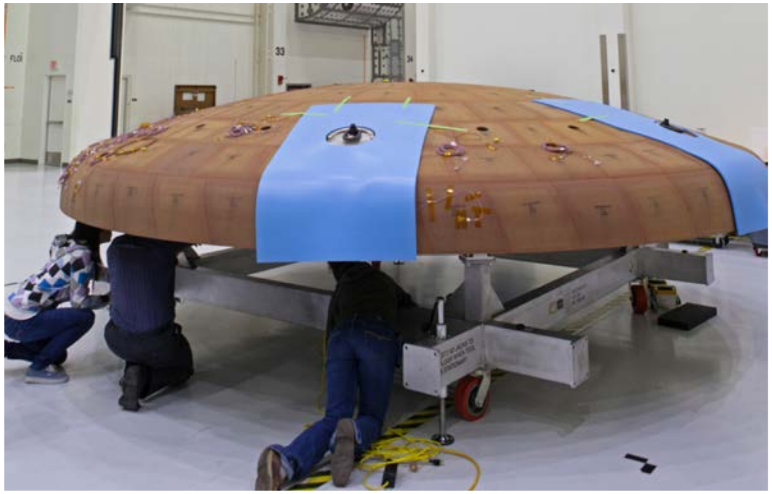


PICA:
52 samples
Mean error = 8%
3σ Deviation = ±26%
Inferred Thermal Margin = 100°F

Avcoat:
21 samples
Mean error = 14%
3σ Deviation = ±25%
Inferred Thermal Margin = 66°F

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)

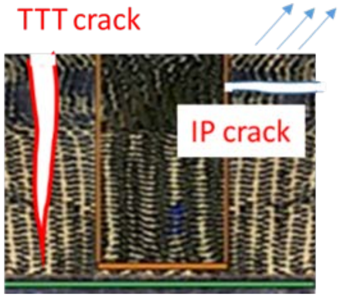
MSR EEV ?
Larger than Stardust
(smaller than Orion)
entry at (~ 13.5 km/s)
Ballistic entry
MMOD Impact
Chuteless
Impact Landing

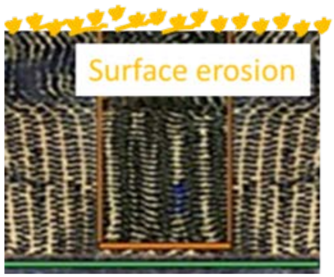
Stardust single piece, seamless heatshield

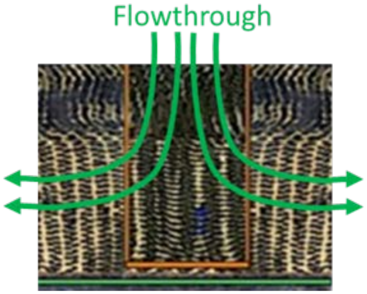
Needed: Characterization of TPS - Features, Flaws and Failure

- **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

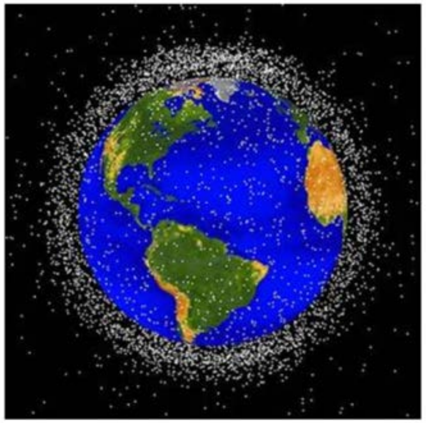
Structural Aero/Material



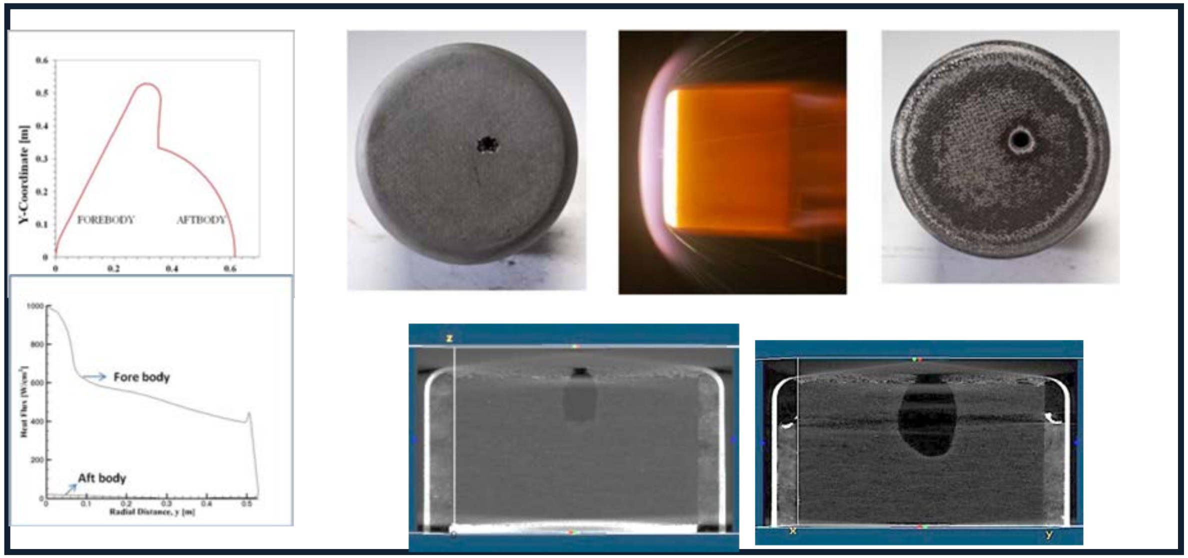




Missions and Induced Features and Flaws



- 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 the opportunity

References

1. **"Thermal Protection for Mars Sample Return Earth Entry Vehicle: A Grand Challenge for Design Methodology and Reliability Verification," E. Venkatapathy, P. Gage and M. Wright, 9th Ablation Workshop, August, 2017, Montana State University, Bozeman, MT**
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.
3. "Hot-structure Earth entry vehicle concept for robotic Mars sample return," -- Marcus Lobbia, et al., IPPW-2018, Boulder, Colorado.
4. "Overview of heatshield for extreme entry environment technology (HEEET) project," Donald Ellerby, et al., IPPW-2018, Boulder, Colorado.
5. "Highly reliable 3-dimensional woven thermal protection system for Mars sample return," Keith Peterson, et al., IPPW-2018, Boulder, Colorado.
6. "Sizing and margin methodology for dual-layer thermal protection systems," Milad Mahzari, et al., IPPW-2018, Boulder, Colorado.
7. 'More Honoured in the Breach?' Test-as-you-fly Environments for Planetary In-Situ Missions -- Ralph Lorenz,

Questions?