Mars Sample Return: Grand Challenge for EDL

Ethiraj Venkatapathy

An abstract for the 10th Annual Ablation Workshop

A year ago, I gave a talk in anticipation of a Mars Sample Return effort at the 9th Ablation Workshop. Since then a lot has happened.

"April of this year, after a year of study phase, NASA and ESA signed Statement of Intent (SOI) to jointly develop a Mars Sample Return plan to be submitted to their respective authorities by the end of 2019. This signing is historic, as it signals the desire, the readiness, and the willingness to work together to execute this inspiring mission, we all have the opportunity to tackle this grand challenge. We have the scientific and engineering maturity to identify the critical technologies ready to be applied, and with discipline this campaign can be executed affordably," Jim Watzin, Mars Program Executive, NASA. NASA Centers with JPL leading the charge is in the midst of a pre-formulation phase for executing a Mars Sample Return before the end of next decade.

The proposed talk builds on the previous year talk. In light of the agreement between NASA and ESA, NASA has assumed the responsibilities for developing the earth entry vehicle (EEV) that will fly along with a European Spacecraft and return with the sample from Mars. EEV will be deployed for entry into earth. The EEV design, development, testing and certification have to result in a highly reliable sample return system. The entire architecture has to be demonstrated to meet the planetary protection requirement. NASA is considering two distinctly different earth entry vehicle architectures and with each choice, many different ablative TPS candidates. As a result of the NASA-ESA on-going studies, some of the key entry conditions and design requirements are better understood today and more are being scoped out.

The heat-shield ablative TPS choice need to be done with a good understanding as it plays a very significant role in determining the robustness of the EEV. Knowledge about how materials and system perform, and how the features could become flaws and how flaws lead to failure, etc. need to be clearly understood and the knowledge then need to be used to down select the TPS.

This proposed talk will provide greater insight into the progress being made and the challenges that need to be tackled.

Mars Sample Return:
Grand Challenge for EDL

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NASA Ames Research Center
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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)

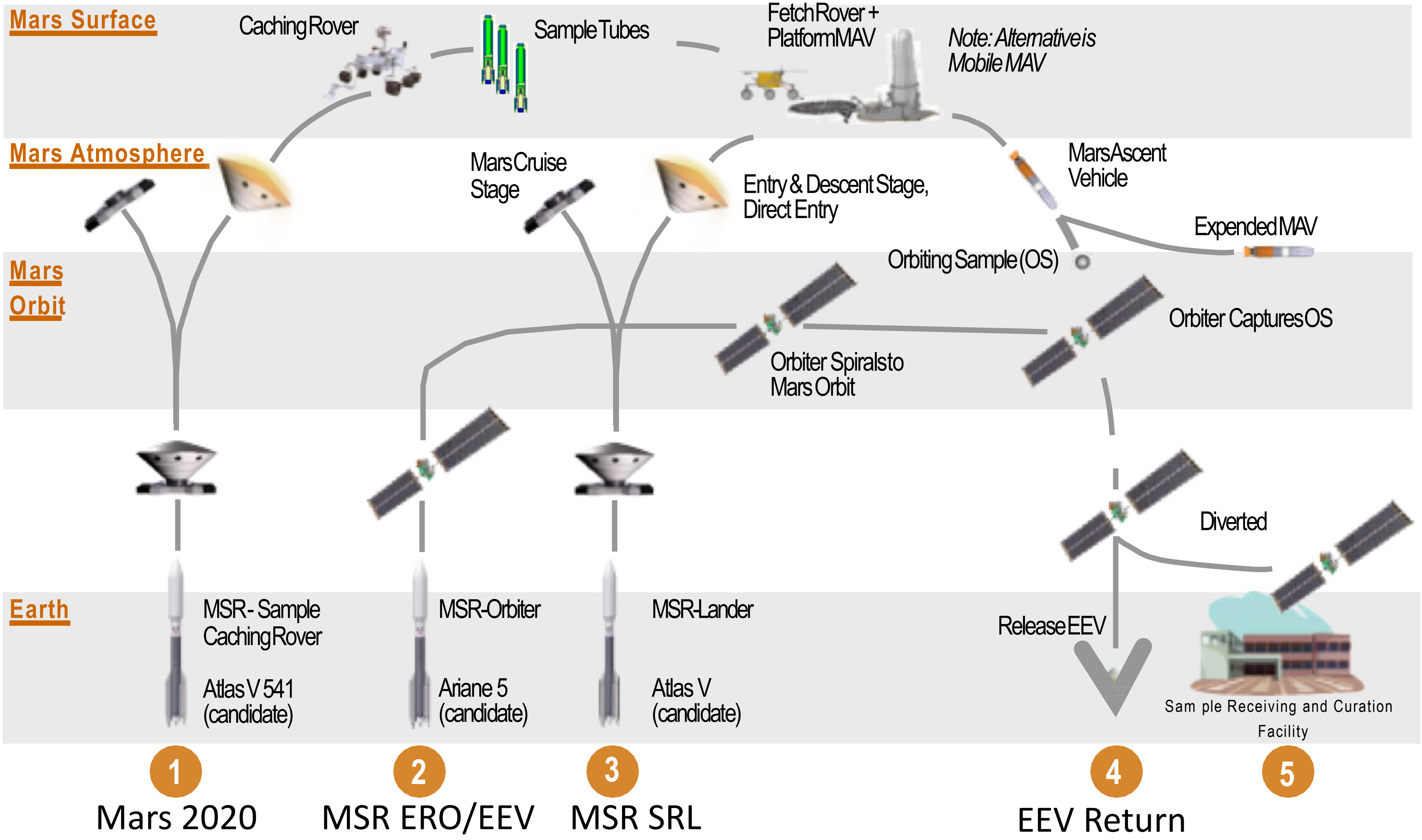
MSR Earth Entry Vehicle (and the TPS) need to be extremely robust against all possible failure modes

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



Mars Surface

Caching Rover

Sample Tubes

Fetch Rover +
Platform MAV

Note: Alternative is
Mobile MAV

Mars Atmosphere

Mars Cruise
Stage

Entry & Descent Stage,
Direct Entry

Mars Ascent
Vehicle

Expended MAV

Orbiting Sample (OS)

Mars
Orbit

Orbiter Spirals to
Mars Orbit

Orbiter Captures OS

Diverted

Earth

MSR - Sample
Caching Rover

Atlas V 541
(candidate)

MSR-Orbiter

Ariane 5
(candidate)

MSR-Lander

Atlas V
(candidate)

Release EEV

Sample Receiving and Curation
Facility

1 Mars 2020

2 MSR ERO/EEV

3 MSR SRL

4 EEV Return

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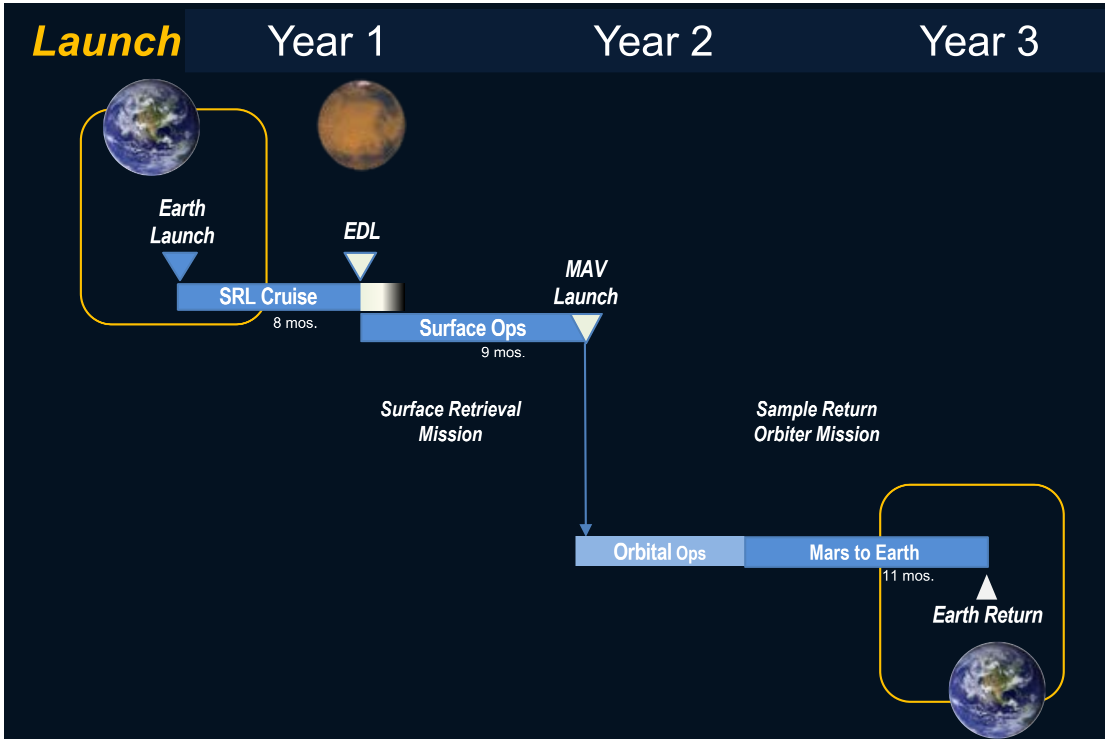
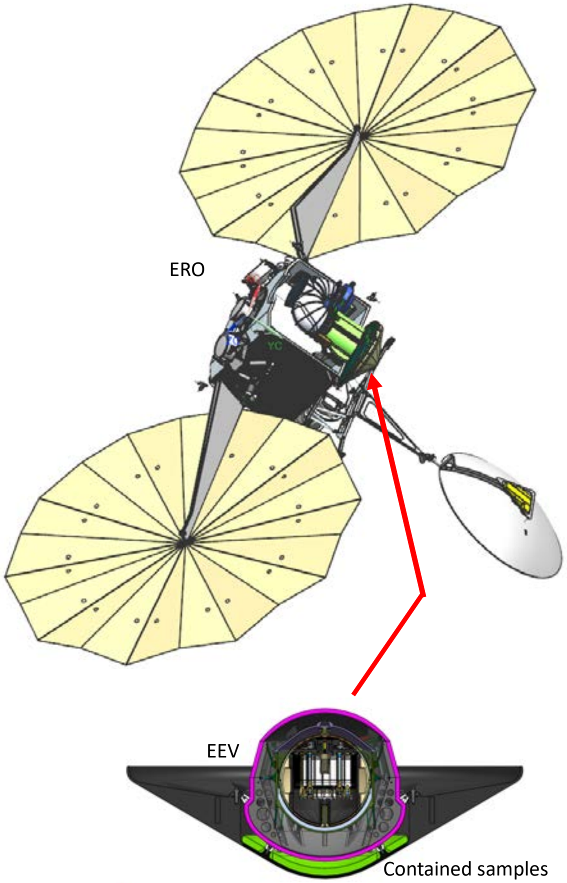
Taken from the IPPW -2018 presentation Marcus Lobia et al.

MSR EEV Campaign and Mission Design Challenges

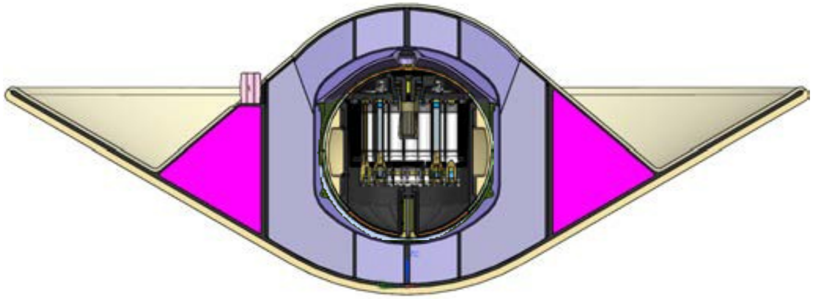




- Launch in 2026 - SRL and (ERO with EEV) missions
- ESA-NASA collaboration
- Mission Architecture and design(s) need to be technically **robust.**
  - Need to be tolerant to programmatic, schedule and budget constraints.
- This is what makes MSR - EEV a grand challenge and an opprotunity.

Current MSR EEV Concepts Under Consideration

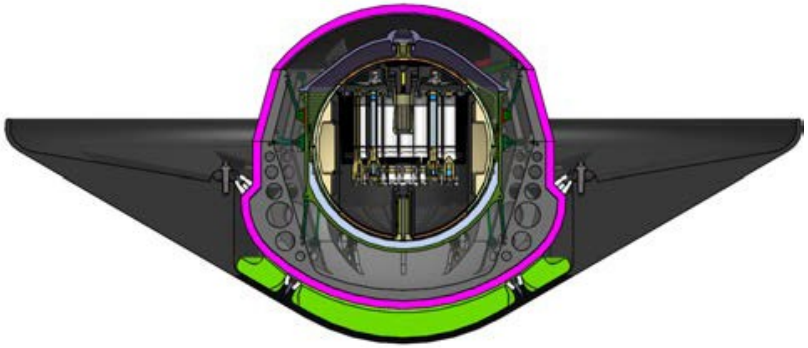
Cold Structure EEV Concept



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 < $1.0\text{x}10^{-6}$)***
  - ***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*

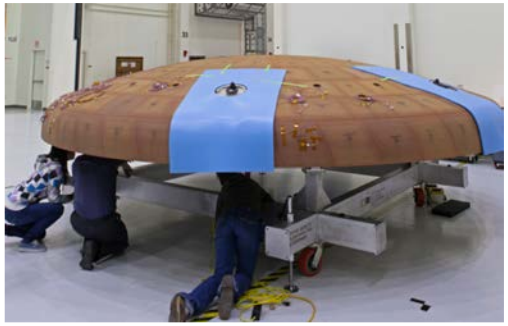
Must be Augmented Via Test

- 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

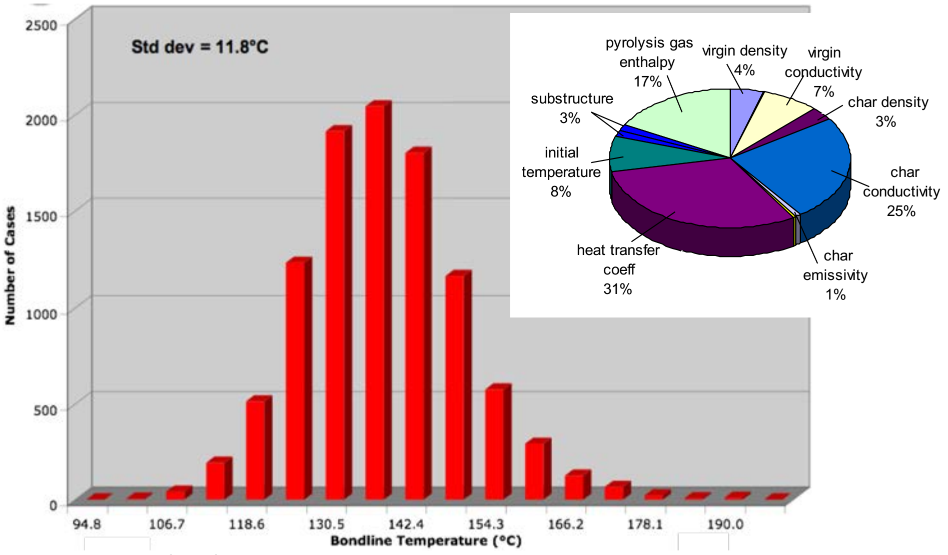
Integration

Flight Certification

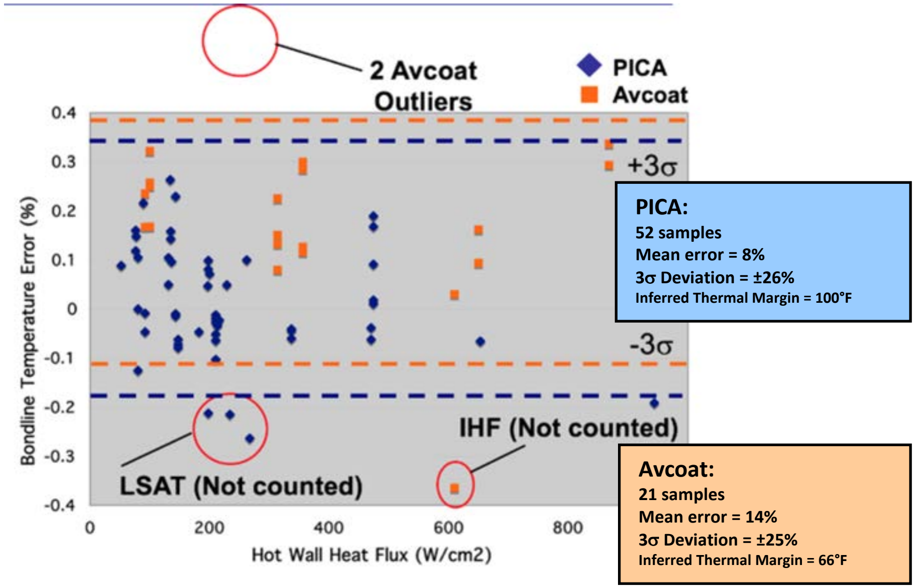
8/30/17

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

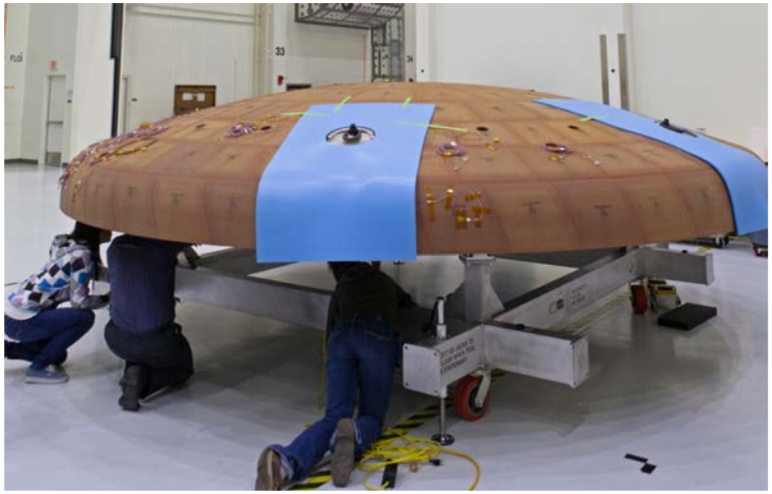


PICA:
52 samples
Mean error = 8%
3σ Deviation = ±26%
Inferred Thermal Margin = 100°F

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)

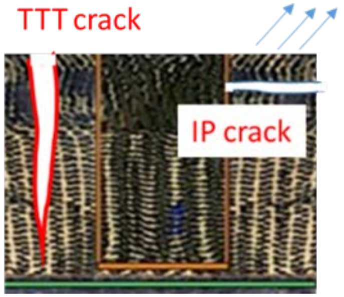
MSR EEV ?
Larger than Stardust
(smaller than Orion)
entry at (~ 13.5 km/s)
Ballistic entry
MMOD Impact
Chuteless
Impact Landing

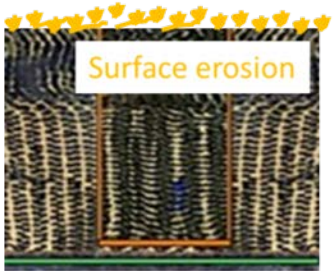
Stardust single piece, seamless heatshield

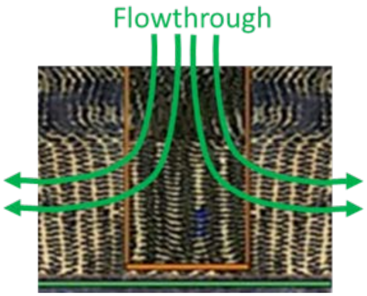
Needed: Characterization of TPS - Features, Flaws and Failure

- **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

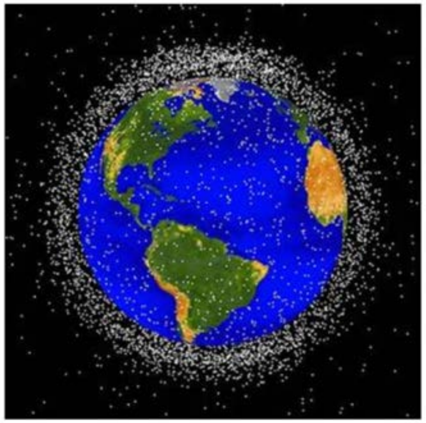


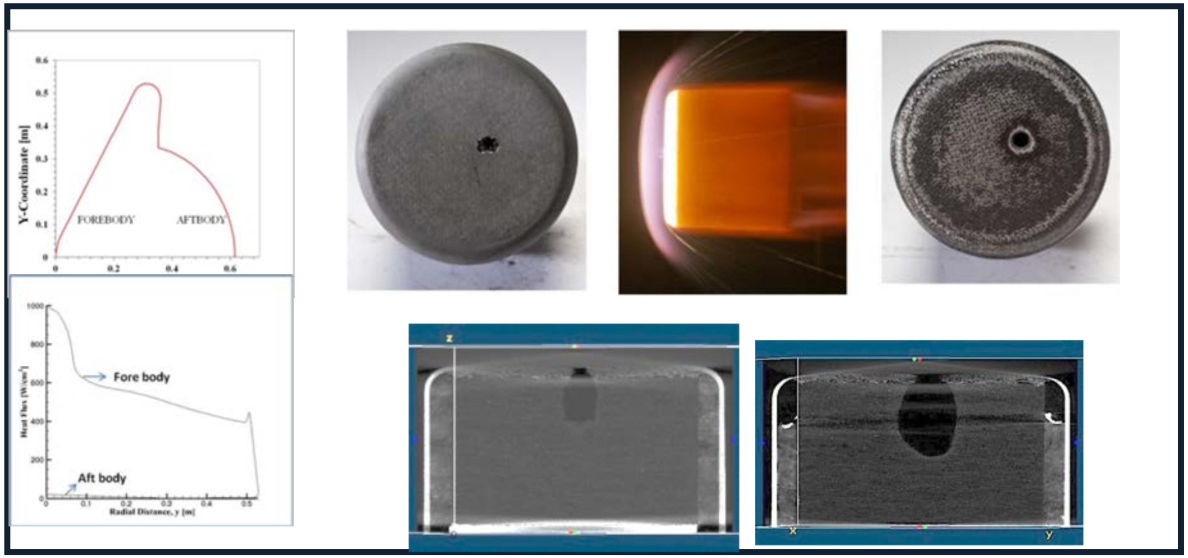




Missions and Induced Features and Flaws

- 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

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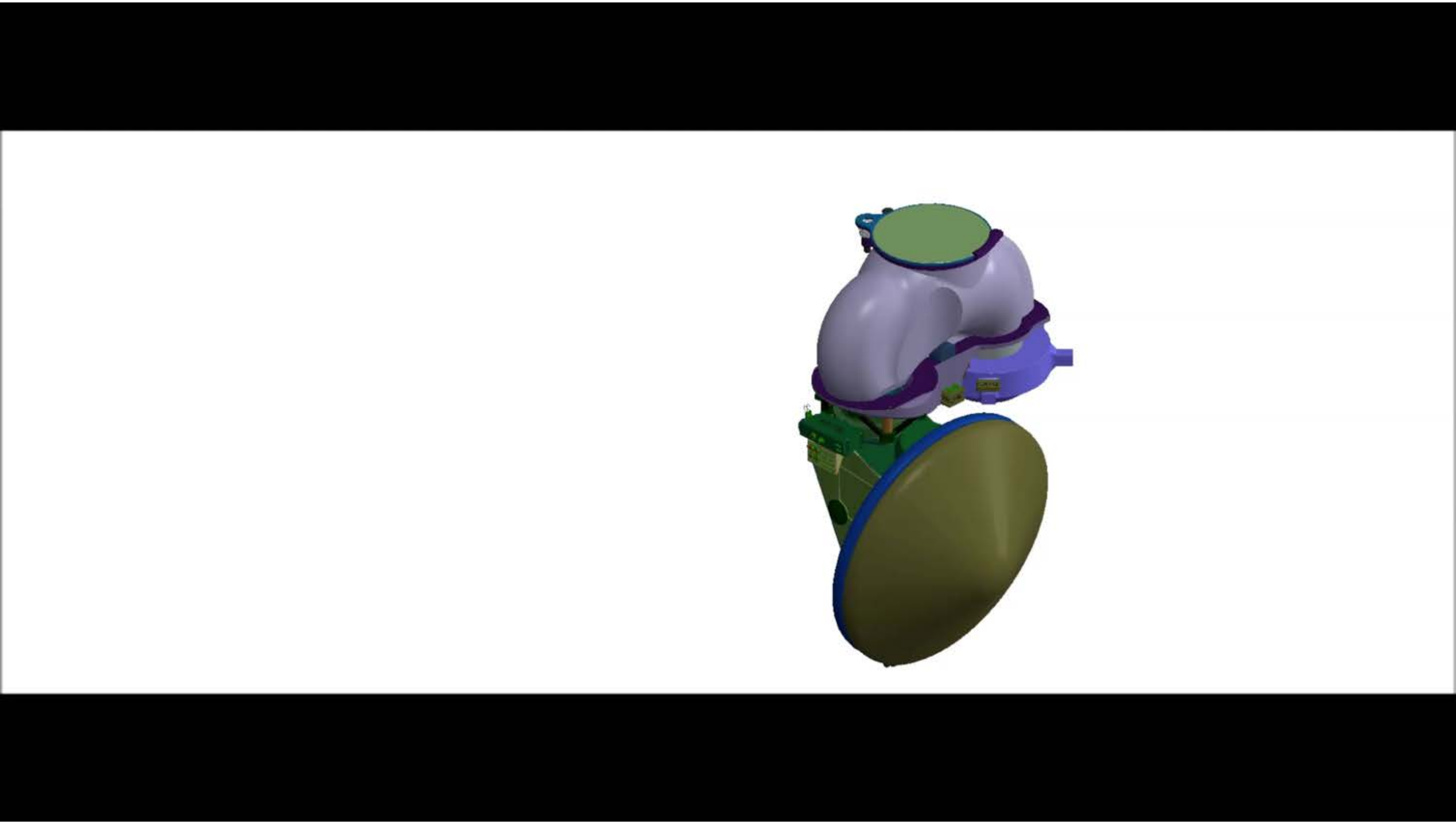
2. “A new era and a new trade space: Evaluating Earth entry vehicle concepts for a potential 2026 Mars sample return,” Scott Perino, et al., IPPW-2018, Boulder, Colorado.
3. “Hot-structure Earth entry vehicle concept for robotic Mars sample return,” -- Marcus Lobbia, et al., IPPW-2018, Boulder, Colorado.
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,

ROCS CONOPS - Animation



Questions?

GRANT SNIDER *is a cartoonist and illustrator, and the author, most recently, of "The Shape of Ideas."*

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