Earth Entry Requirements for Mars, Europa and Enceladus Sample Return Missions: A Thermal Protection System Perspective

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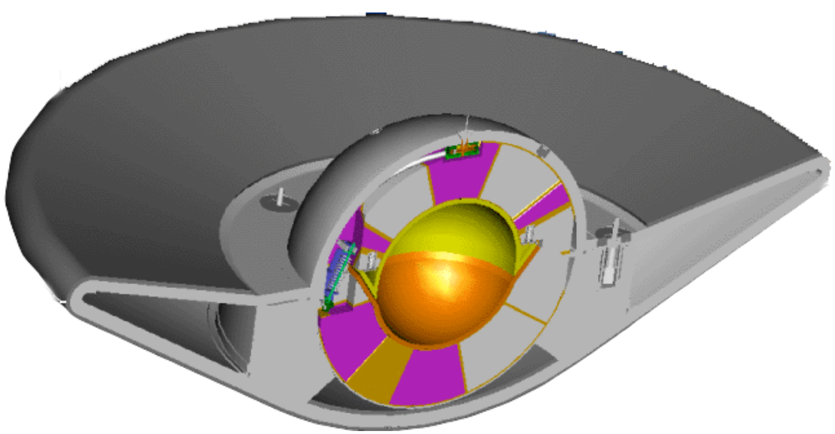
Introduction

- **Background on Planetary Protection**
  - Derived requirement for Thermal Protection System (TPS) reliability
  - Context on TPS reliability for other human and robotic missions
- **Brief Review of Mars Sample Return Studies**
  - Drivers for TPS reliability
  - Opportunities for reliability improvement
- **Emerging new TPS technologies**
  - Impact on reliability
- **Conclusions**



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** …."
  - No numeric reliability allocations are provided
  - 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)**
    - **TPS for single string EEV < 2.5×10^{-7} (Preliminary PRA, Fragola 2003)**

EEV and TPS need to be extremely robust against all possible failure modes in the mission architecture

TPS Reliability for other NASA missions

- **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 0f 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

Mars Sample Return and EEV – Past, Present and Future

- **MSR is a Campaign (3- phase reference architecture)**
  - Mars 2020 (first leg is to cache sample)
  - Next two legs neither fully defined or committed by NASA
    - Direct entry with EEV, or
    - Integrated Human and Robotic Mars Campaign is an option
      - Lunar sortie using Orion (Human assisted MSR) (Gershman, 2015)
  - Mission reliability may be improved with redundancy and active failure mitigation
    - Other avenues - robotic sortie from earth-lunar orbit?

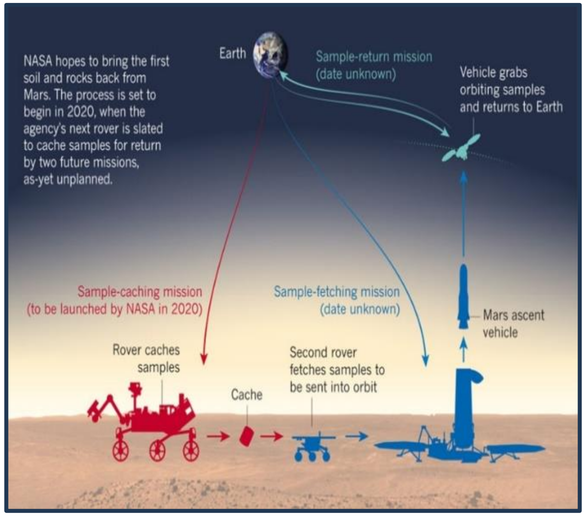
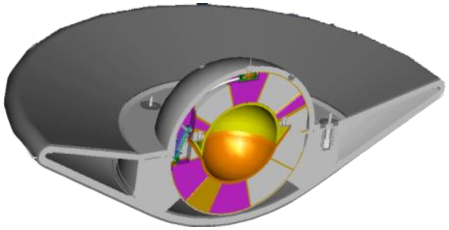


Figure Credit: Scientific American

- **EEV design (2005) assumption that passive subsystems maximize reliability**
  - EEV design is monostable, chuteless and impact tolerant
  - Carbon phenolic (CP) for the heat-shield
    - DoD flight rate success for CP use in ballistic missiles
  - Micro-meteor and Orbital Debris impact – Recognized but not addressed

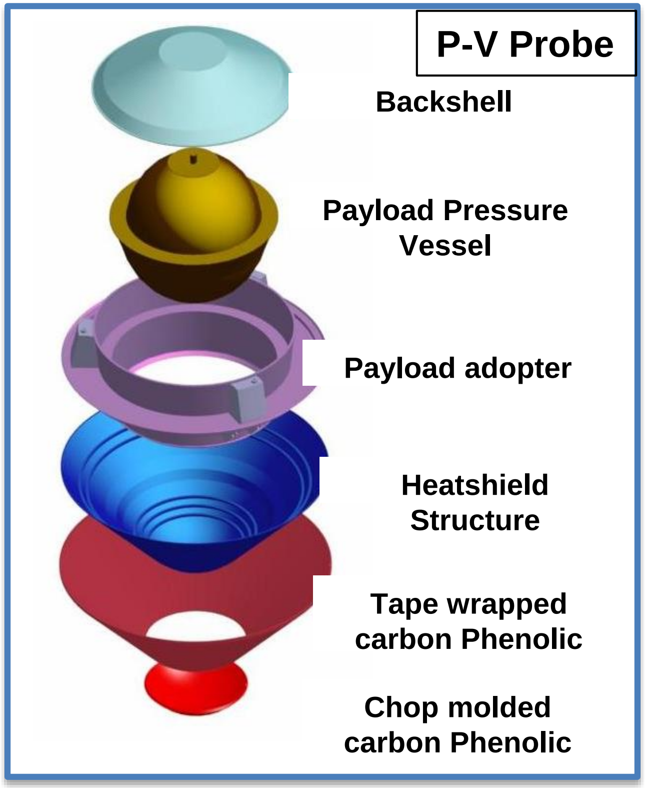


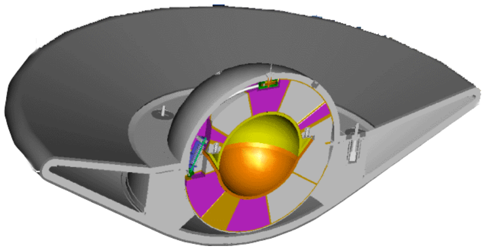
Mission options for MSR likely applicable for Enceladus/Europa SR in the longer term.
- **EEV design, once proven for MSR, will be adopted for other Sample return missions**

Carbon Phenolic

MSR EEV carbon phenolic reliability argument is based on DoD's use on ballistic missiles

- Design is based on Pioneer-Venus and Galileo Probes
- Two types of CP needed for blunt body
  - Chop Molded and Tape Wrapped
  - Manufacturing and failure modes are different for the two
  - DoD uses only tape wrapped on slender body missiles
- Chop-molded is the weakest link
  - Four Venus and 1 Galileo probes
    - Flight data from Galileo
    - Not enough ground or flight data to establish reliability estimates
  - Tape-wrap manufacturing and use for DoD
- Precursor Rayon and the processing of heritage have atrophied
  - NASA obtained and processed the heritage rayon for MSR ~(2003 -2006)
  - Challenge is how to establish reliability for CP for MSR with limited quantity of carbonized rayon in hand
    - Capability including failure modes vs flight environment





MMOD Risk Evaluation (2013)

"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

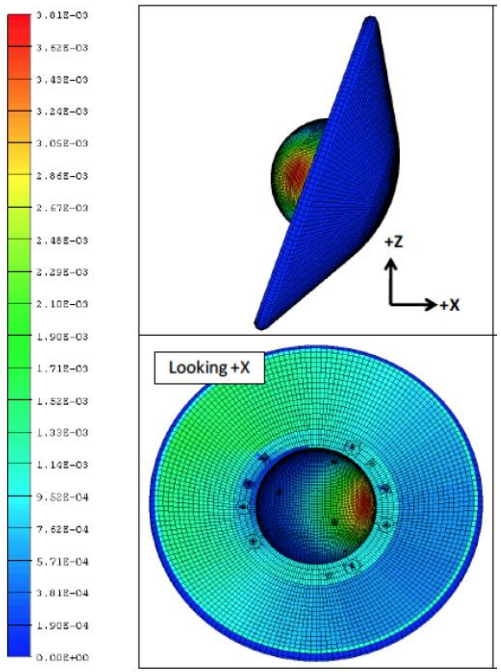
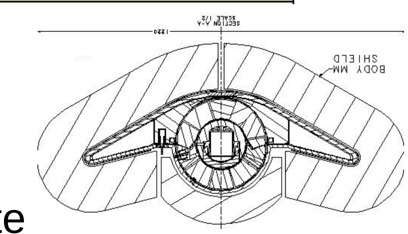


Table 5-7. MSR EEV Probability of TPS Failure Due to MMOD Impact

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-07**

- 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
  - **TPS material that is more robust to MMOD is needed**

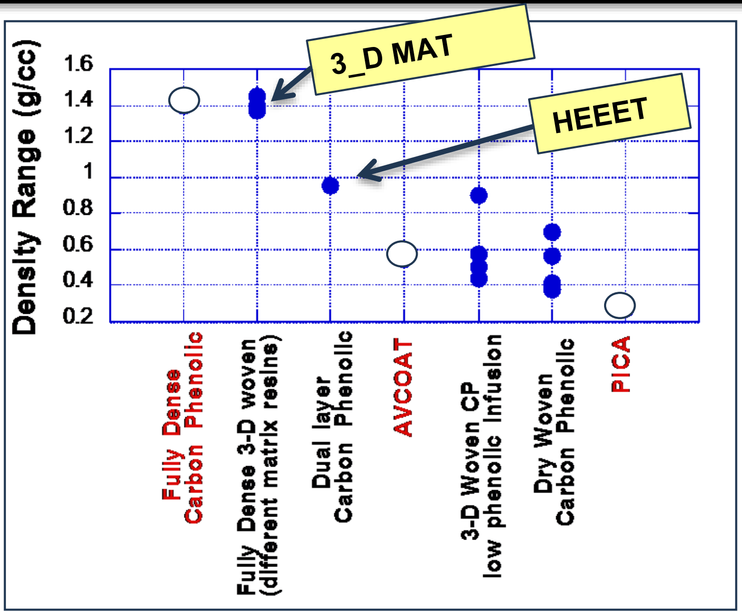


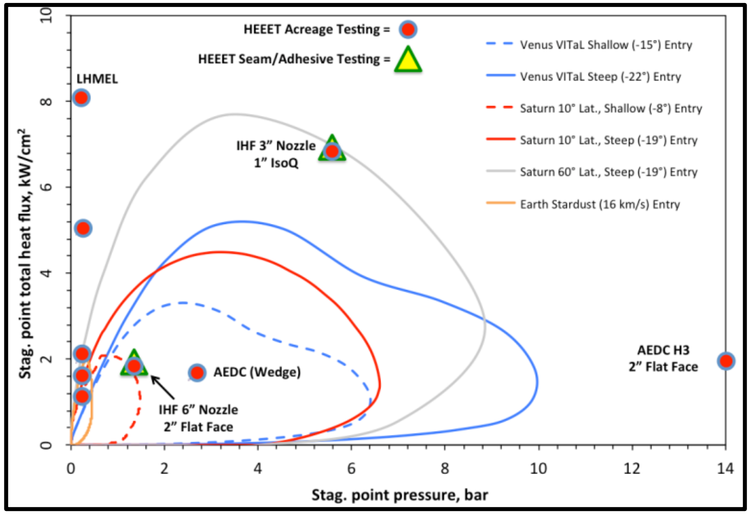
Alternate to Garage (Corillis)

Emerging New Technologies, Materials and Capabilities

Emerging TPS Technology Capability: 3-D WOVEN TPS

- **3-D Woven TPS is a family and not a single TPS.**
  - Automated processes – better quality control
  - weaving/resin infusion allows multi-layer and multi-functional material development (3-D MAT & HEEET)
- **HEEET is targeting Venus and Saturn**
  - very efficient compared to CP (~50% of the mass)
- **Acreage panels of HEEET**
  - very robust at extreme conditions
  - no failures observed in testing across the board
  - Tested at (8000 W/cm2 laser testing, combined 7000 W/cm2 and 6 atm pressure, 2000 W/cm2 and 20 atm. Arc jet testing) compared with MSR EEV peak conditions (< 2000 W/cm2 and < 0.5 atm)
- **HEEET acreage and carbon phenolics have been tested side-by-side at where CP exhibits spallation and other known failure modes**
- **3-D Woven could be**
  - Optimized for heatshield and backshell
  - Can achieve both efficiency and robustness
  - more tolerant of MMOD (not tested) due to multilayer

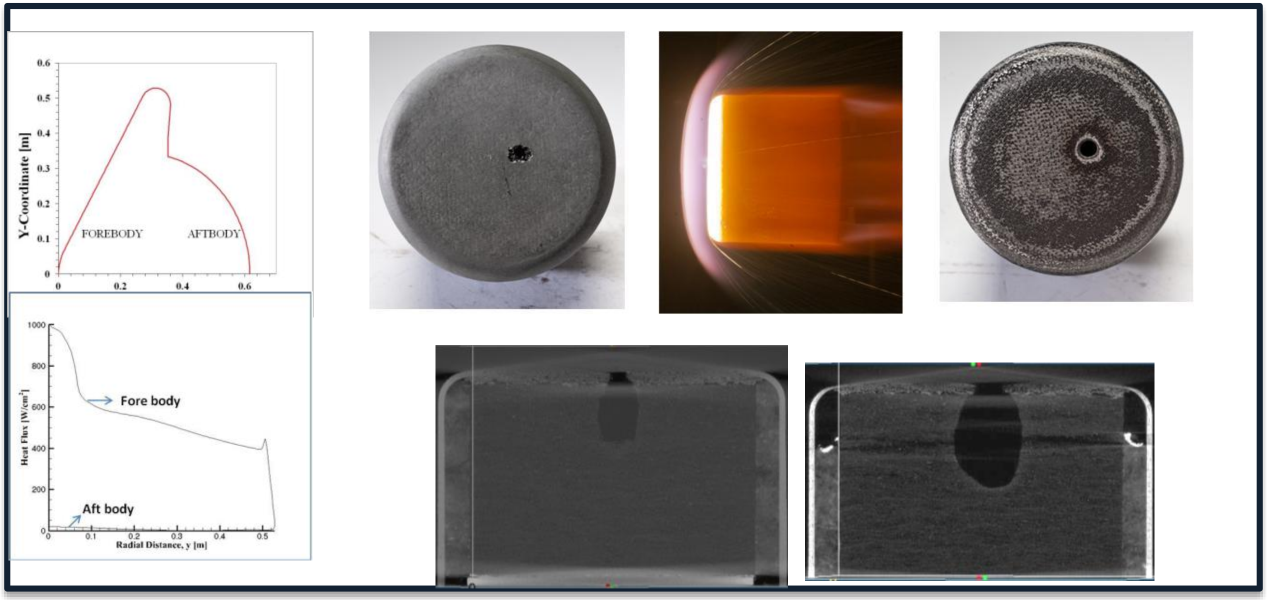




MMOD Tolerant Design - Emerging Capability

- Testing and Analysis of TPS with MMOD Impact for MMOD Impact Tolerant Design

- **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 have been validated with data have been uses to assess the MMOD risk
  - Example shown below for Carbon-Carbon



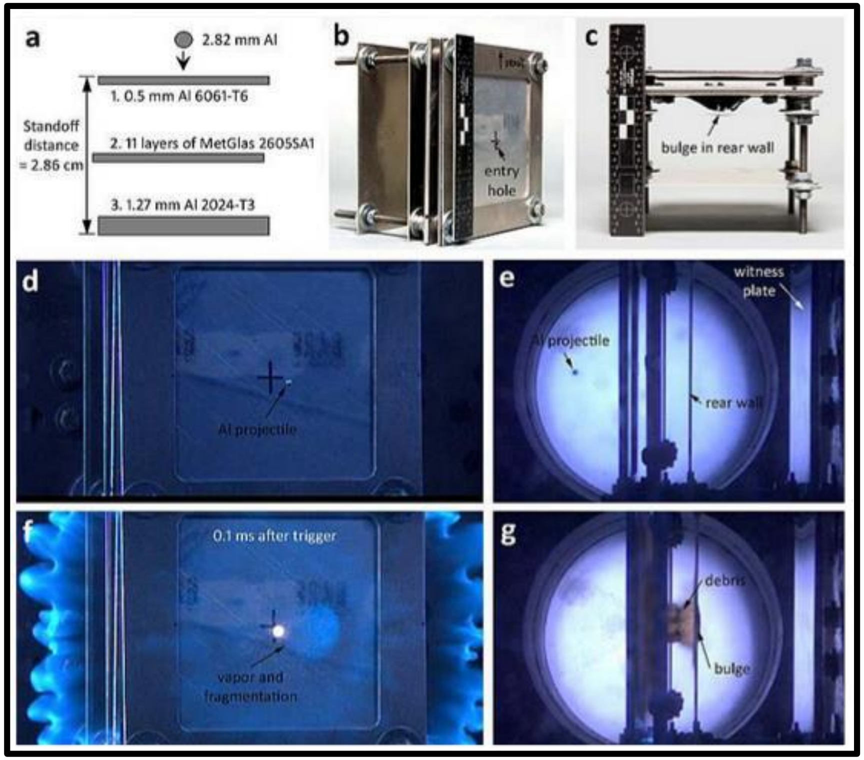
From: "Arcjet Testing of Micro-Meteoroid Impacted Thermal Protection Materials,"P. Agrawal, M. Munk and L.Glabb, AIAA Paper 2013-2903, presented at the 44th AIAA Thermosphysics Conference, June 24-27, San Diego, CA.

Emerging New Materials for MMOD Protection

Metallic-glasses:

- Offer a unique combination of high-hardness, high-strength, low-melting temperatures (for shield vaporization)
- Limited hypervelocity studies on metallic glasses as potential spacecraft shielding have provided important data about which features of these novel materials.
  – When tested under identical conditions with a baseline Whipple shield similar to what is currently used on the ISS, a shield with intermediate layers of metallic glass passed the test while the baseline sample did not.

"Hypervelocity Impact Testing of a Metallic Glass-Stuffed Whipple Shield," D.C. Hofmann, L. Hamill, E. Christianson, and S, Nutt, Adv. Engrg. Matls. (2015) 1-10 DOI *http://dx.doi.org/10.1002/adem.201400518*

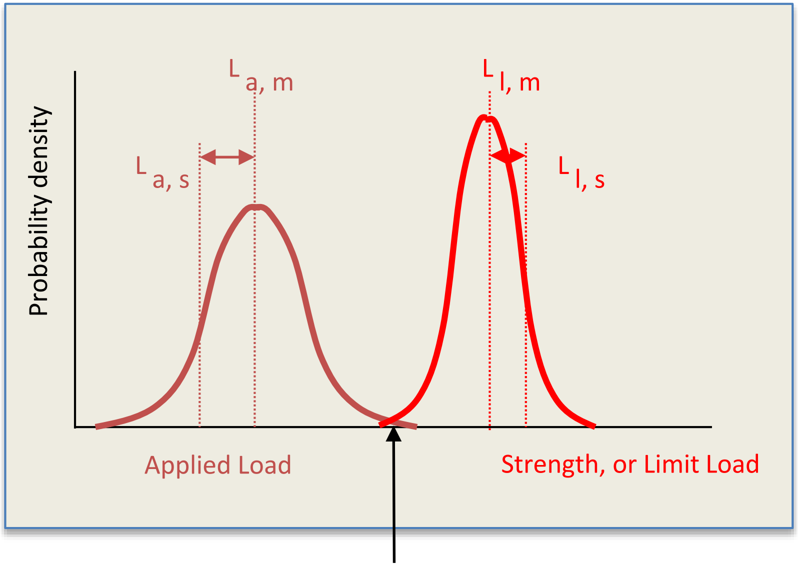


- **Iron-based bulk metallic glasses (BMG), or Amorphous steel**, new materials that are under development are affordable to manufacture, incredibly hard, but at the same time, not brittle.
- Work on the steel alloy, named SAM2X5-630, is the first to investigate how amorphous steels respond to shock

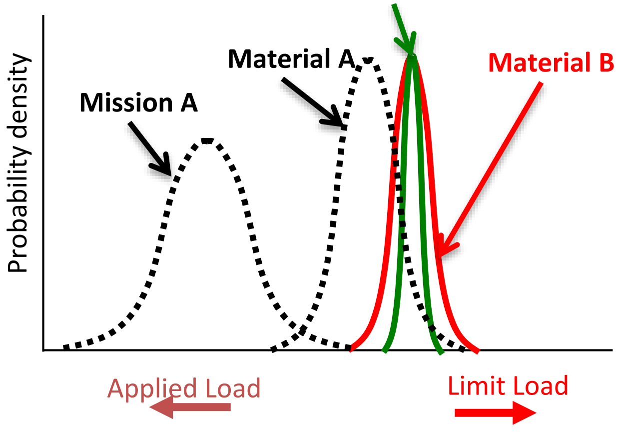
Gauri R. Khanolkar et al., "Shock Wave Response of Ironbased In Situ Metallic Glass Matrix Composites," Scientific Report (http://www.nature.com/articles/srep22568) 6, article number: 22568 (2 March 2016) (doi:10.1038/srep22568)

Reliability – "Devil is in the Tail"

- **Demonstrating Reliability /Robustness is the overlap between applied load vs limit strength – the overlap of the tail**
- **In order to define the overlap of the two tails**
  - Challenge: off-nominal design loads along with precursor events that lead to failure due to environment vs variability that lead to strength variations
  - Things such as manufactured material property variability, performance variability (both nominal and off-nominal), acceptance spec and verification for variance, etc.



Failure occurs in instances when applied load exceeds limit load. This area is given by the index of reliability.



To achieve higher reliability, increase the mean differences and/or decrease the variance

How do we tackle the grand challenge? (Earth Entry Vehicle DDT&E and Verification for Mars/Enceladus/Europa Sample Return)

From: Conley, Catharine A., and Gerhard Kminek. "Planetary Protection For Mars Sample Return" ***ESA/NASA, April*** **29 (2013). Recommended Approach:**

To meet planetary protection requirements: Risk based design, accounting also for common cause/mode failures, drives redundancy and diversity of system design.

- Usually not used for robotic missions to that extent but for man-rated system;
- *Need to go beyond man-rated systems* because consequences go beyond occupational risk potentially also affecting general public.
- Fault tree needs to become the best friend of system engineer from the very begin!

- **Demonstrating Reliability /Robustness is the overlap between applied load vs limit strength – the overlap of the tail**
- **In order to define the overlap of the two tails**
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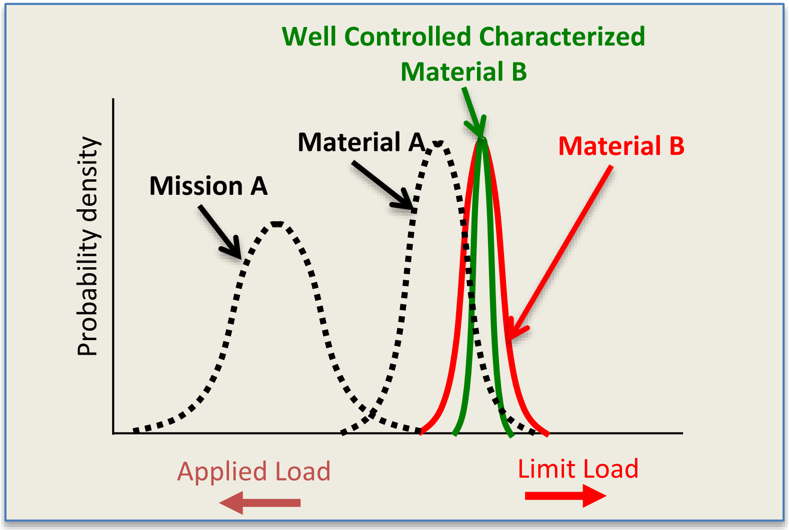

Looking to the Future

- **Emerging new technologies and materials combined with lessons learned from Orion, and progress in testing and analysis have the potential to make MSR EEV much more robust – until we actively pursue we will not know how robust?**
- **Samples Return Missions from Mars or Enceladus or Europa likely to take a decade and more**
  - This gives time for technology development in support of EEV
  - Alternate mission/campaign architecture developments
- **Two areas for investigation and investment**
  - **Emerging 3-D Woven TPS**
    - Promising for improved design - reliability and performance
      - Compositional simplicity, manufacturing quality control, inherent robustness
    - MMOD and impact tolerance characterization
      - Could provide secondary benefits
    - Failure modes and design based on robustness
      - Testing and analysis aspects, developed and in use for Orion TPS.
  - **MMOD**
    - Emerging new materials need to be assessed and integrated with EEV/Mission

References:

"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.

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"Hypervelocity Impact Phenomenon in Bulk Metallic Glasses," L. Hamill, S. Roberts, M. Davidson, W.L. Johnson, S.Nutt, D. C. Hofmann, Adv. Eng. Mater. 2013, 16, 85-˚ ©-93. DOI: 10.1002/adem.201300252

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"Planetary Protection for Mars Sample Return", Gershman, R.; Adams, M.; Mattingly, R.; Rohatgi, N.; Corliss, J.; Dillman, R.; Fragola, J.; Minarick, J.; COSPAR PTP1-0011-02,2002.

COSPAR Planetery Protection Policy (published in *Space Research Today*, COSPAR's information bulletin, Number 193, August 2015

"Overview of the Mars Sample Return Earth Entry Vehicle," Robert Dillman and James Corliss, IPPW6

Why Mars/ Enseladus/ Europa Earth Entry Vehicle is a grand challenge?

Challenge: Verification of design guideline that *"probability that sample containment not assured (CNA) < 1 e-6," and for TPS, single string system, "failure < 2.5 x 10^{-7}"*

From: Conley, Catharine A., and Gerhard Kminek. "Planetary Protection For Mars Sample Return" *ESA/NASA, April* 29 (2013)

- Critical planetary protection task for MSR at campaign level
- Orbiter System: Potential affected sub-systems to support safety critical functions, i.e., verification of biological containment system, Earth divert maneuver.
- **Earth Return Capsule: Potential affected sub-system are *heat shield* *and stability during entry*.**

Recommended Approach:

- Critical design approach to meet planetary protection requirements:
  - *Need to go beyond man-rated systems* because consequences go beyond occupational risk potentially also affecting general public.
  - Risk based design, accounting also for common cause/mode failures, drives redundancy and diversity of system design.
    - Usually not used for robotic missions to that extent but for man-rated system;
  - Fault tree needs to become the best friend of system engineer from the very begin!