Atmospheric Entry Instrumentation in the Next Decade: A NASA Perspective

IEEE Wireless for Space and Extreme Environments (WiSEE) Conference
Passive Wireless Sensors Technology (PWST) Workshop
10-12 October 2017, Montréal, Quebec, Canada

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Presentation Outline

- **I look forward to engaging with sensor providers and innovators at the workshop this week.**
- **Outline of my talk:**

Basic need and value proposition for atmospheric entry instrumentation

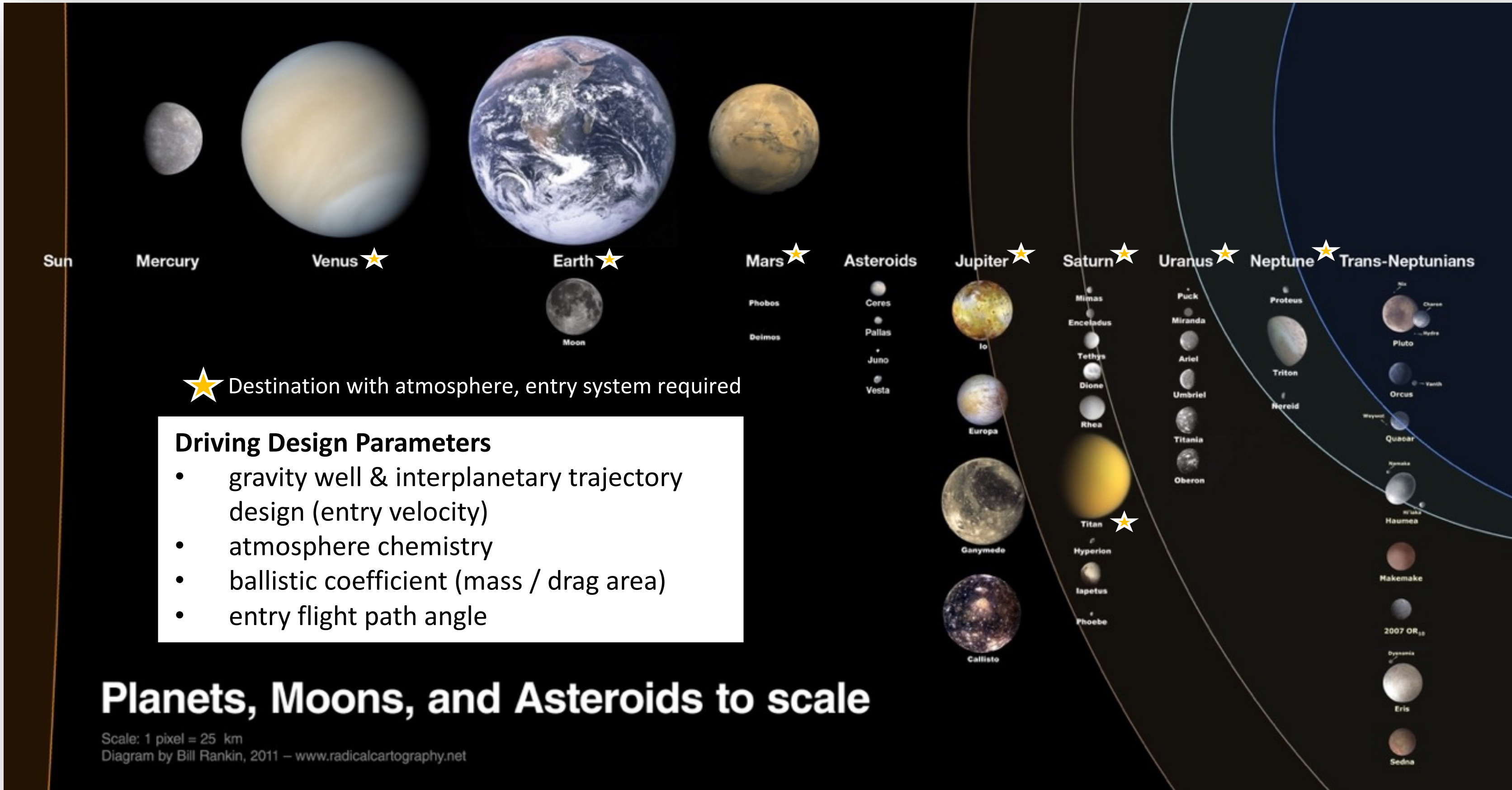
NASA's current entry instrumentation activities

Instrumentation needs from the sensor provider community

This presentation describes my own perspectives and may not represent those of NASA

Entry systems enable *in situ* exploration of the solar system

- An entry system delivers a payload from outside the atmosphere to a specified altitude-speed condition within the atmosphere
- Different destinations and mission requirements bring different challenges



Driving Design Parameters
- gravity well & interplanetary trajectory design (entry velocity)
- atmosphere chemistry
- ballistic coefficient (mass / drag area)
- entry flight path angle

Several parameters make up the atmospheric entry system design space

Physics of Planetary Entry

- Common set of physics, but certain physics will dominate depending on the mission details
- Motivation for understanding these physics is the engineering design problem
  - Can drive the mass and risk of the primary in situ science/exploration mission
- Instrumentation is required to validate and improve physical models used for design

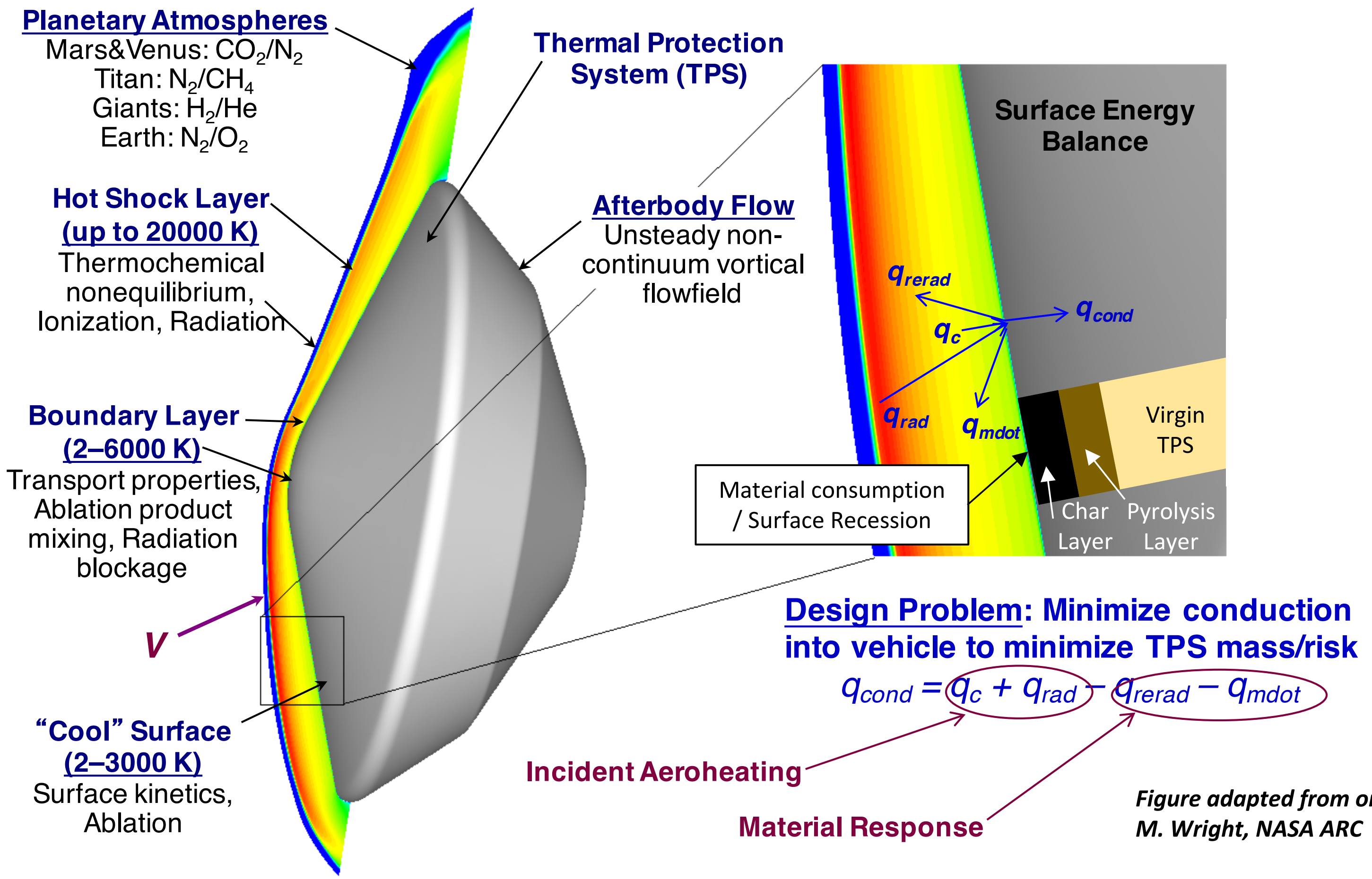
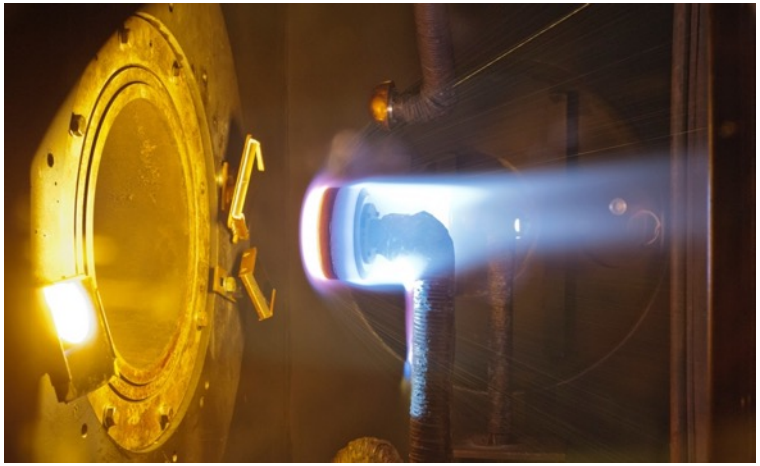


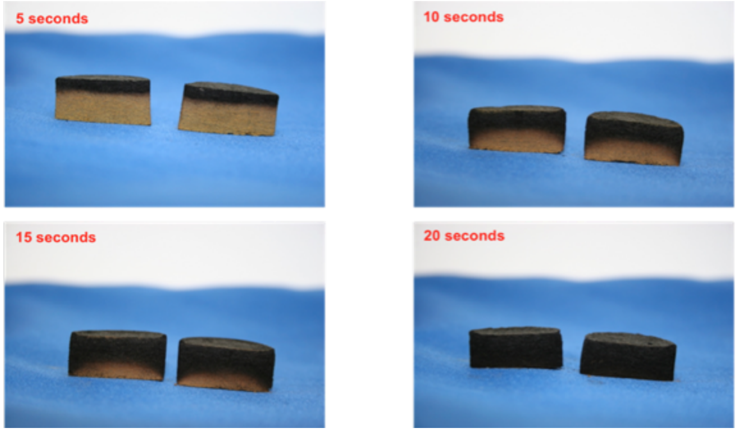
Figure adapted from original by M. Wright, NASA ARC

Instrumenting Ablative Thermal Protection Systems (TPS)

- Ablation is a thermochemical process that relies on material consumption for energy management
- Ablative TPS instrumentation must measure thermochemical parameters with high accuracy as the material is burning away
  - Instrumentation Priority 1: don't interfere with basic function of TPS (protect the payload)
    - Strictly enforced at NASA through "do-no-harm" testing and analysis
  - Instrumentation Priority 2: measure the right thing
    - Difficult to achieve in practice, even with the most simple sensors (e.g. thermocouples)
    - Requires extensive characterization in ground test facilities (arc jets)



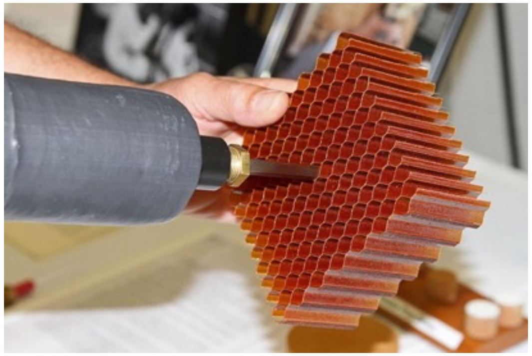
Arc jet testing of sensors in ablative TPS (Image: NASA)



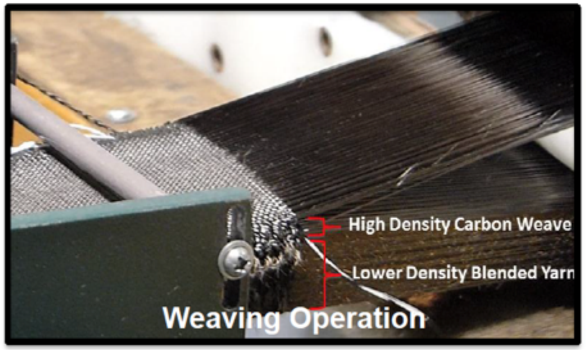
Example of of TPS ablation during entry
Time-history cross sections of PICA tested at 300 W/cm2 and 3.5 kPa in HYMETS (Szalai, 2011)

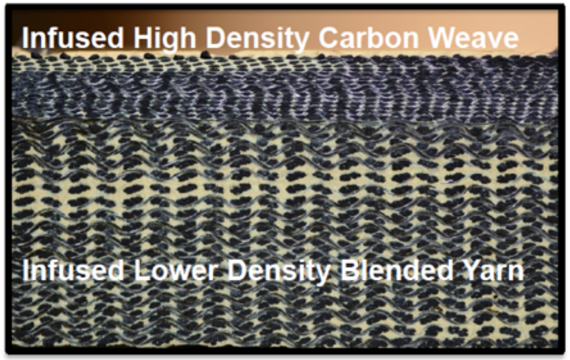
TPS Material Selection – No "one-size-fits-all" solution

- Several TPS options are available through NASA and industry, and the material selection will influence instrumentation design. Examples:



Avcoat being manufactured for Orion EFT-1 (Image: Space.com)





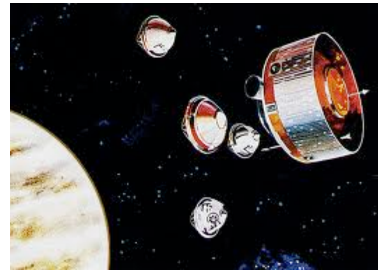
Heatshield for Extreme Entry Environment Technology (HEEET) is woven and infused with resin (Image: Ellerby 2016)

- Primary requirements for an ablative TPS material:
  1. No failure modes in the margined flight environment
  2. Predictable material response
  3. Mass-efficient when sized for maximum allowable bond line temperature
- Flight heritage also plays a large role in TPS material selection
  - "It worked last time" is a good argument, but beware of extrapolation
  - "This is enabling" is a good argument, but improved capability must justify higher risk

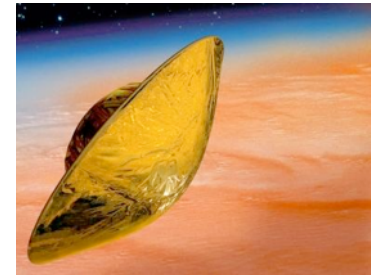
Examples of Entry Systems with Ablative TPS

Apollo

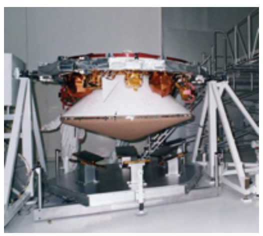
Soyuz



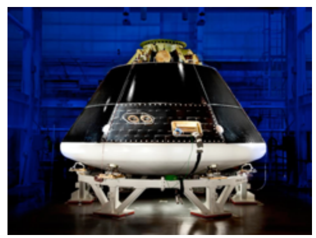
Pioneer Venus



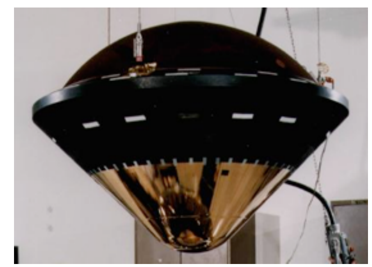
Huygens Probe



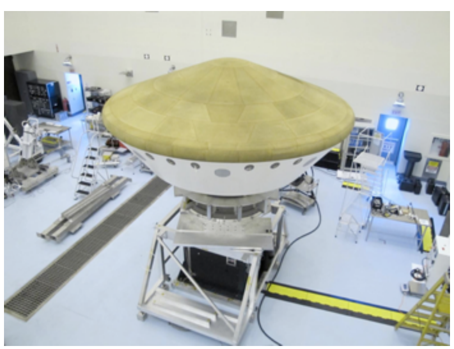
Mars Pathfinder



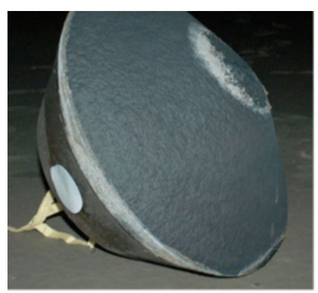
Orion MPCV



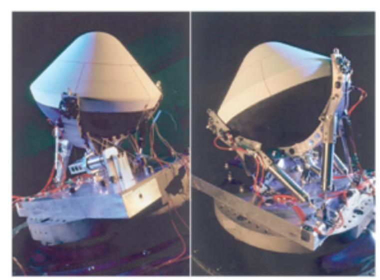
Galileo Probe



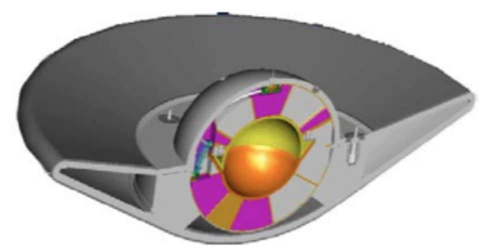
Mars Science Laboratory



Stardust SRC



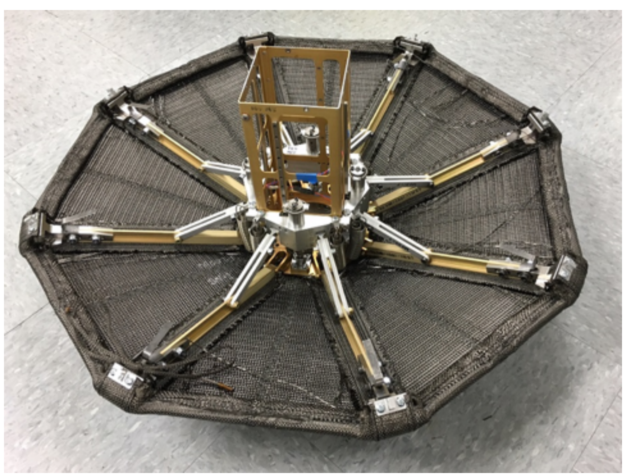
DS-2 Probes



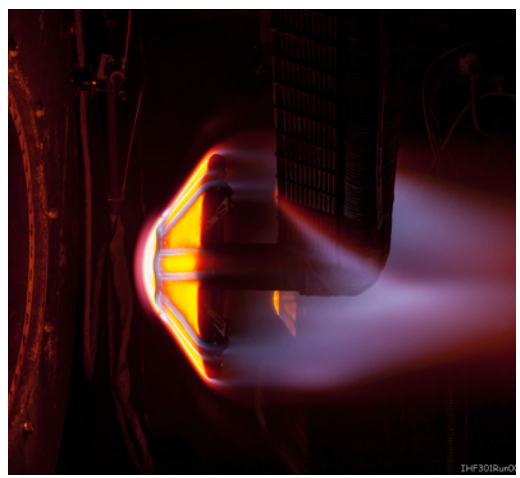
Mars Sample Return Earth Entry Vehicle

Deployable Heatshields: an Emerging Opportunity for Instrumentation Providers

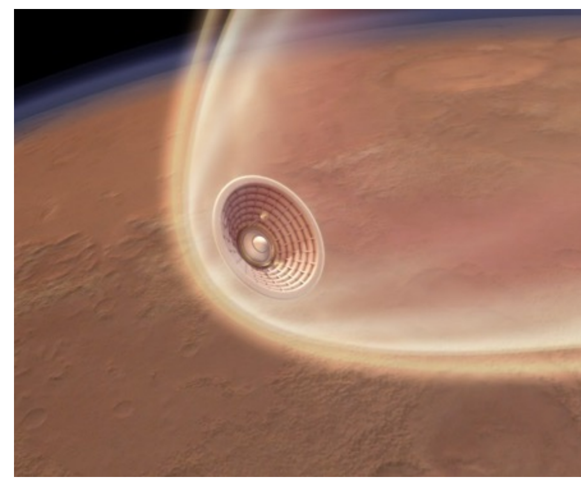
- Deployable heatshields are mission-enabling at small and large scales
  - Reason: relaxed volume constraints and/or lower heating environments than rigid aeroshell
  - Enabling for Mars human exploration-class entry vehicles
  - Enabling for nanosat-scale entry vehicles → P-Pod to ESPA-class missions
- NASA is currently developing two low ballistic coefficient systems
  - ADEPT: Adaptable Deployable Entry and Placement Technology
  - HIAD: Hypersonic Inflatable Aerodynamic Decelerator
- Deployable heatshields present unique challenges (and opportunities) for instrumentation
  - Integration with woven materials
  - High packing density prior to deployment
  - Need to measure stress-strain of flexible materials



Nano-ADEPT (3U Cubesat payload)



ADEPT testing in arc jet



HIAD Entering Mars Atmosphere

Potential Benefits of Wireless Technology (Active and Passive)

- **Wireless has benefits that are often discussed (and seldom implemented) in the entry systems community**
  - Eliminate negative effects of long harnesses
    - Mass constrained situations
    - Signal attenuation
  - Enable instrumentation of extremely small entry vehicles where volume and routing of harnesses is an issue
- **I don't think wireless solutions need to beat wired solutions on performance**
  - Wireless enables a flexible architecture
    - Allows for sensor selection later in design process
    - Flexibility on channel count
    - Potentially greater spatial resolution on heatshield than wired systems
  - Wireless power (inductive charging) could eliminate the need for a cable cutter between the heatshield data system and the primary spacecraft
  - Lower integration risk
  - Low-impact / passive sensors could be useful for forensics even if they can't provide high accuracy
- **Challenges:**
  - Wired thermocouples are easy and accurate
  - Complexity (real and perceived)
  - Electromagnetic Interference
  - Thermal and power limitations
  - Sensor interrogator distance limitations (passive wireless)

Wireless solutions must solve the *right* problems

Entry Instrumentation Value Proposition

- **A given mission has two primary "knobs" it may turn to improve entry system design**
  1. Improve fidelity of computational models that predict system response
  2. Increase system margin (e.g. pick "overkill" TPS, increase TPS thickness)

$$\text{Importance of model fidelity} \propto \frac{1}{\text{Available Margin}}$$

- **A given mission will conduct ground tests to validate a computational model for its limited need case**
  - Residual risk remains with this approach because it is impossible to simulate all aspects of the entry environment in ground testing (can't "test as you fly, fly as you test")
  - Flight data is the ultimate resource for computational model validation

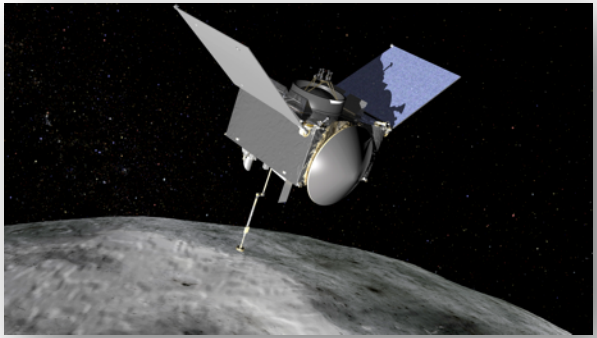
- **Entry system instrumentation provides critical forensic data for understanding anomalies**

- **NASA's approach:**
  1. Build computational models with the most impact on future missions
     - E.G.: Coupled aerothermal-material response, radiative heating, fluid-structure interaction, free-flight CFD
  2. Instrument *all* future entry vehicles (or at least consider it), regardless of the science benefit to *that* mission.
     - Pay missions extra for this (don't take it out of their baseline budget)
  3. Validate computational models with flight data
  4. Adjust margin policies for better understanding of risk
  5. Reap benefits: enabled capabilities, lower entry system mass, reduced risk / increased safety

NASA Programs and Projects Supporting Entry Instrumentation

- A NASA Technology Executive Council memo of 2014 states that NASA Mission Directorates will actively work together to assess and include EDL instrumentation *on all entry missions*.
  - This memo was intended to avoid a perceived catch-22 that flight data only benefits the *next* mission
  - Desire to avoid missed opportunities to obtain flight data: e.g. Stardust, OSIRIS-Rex

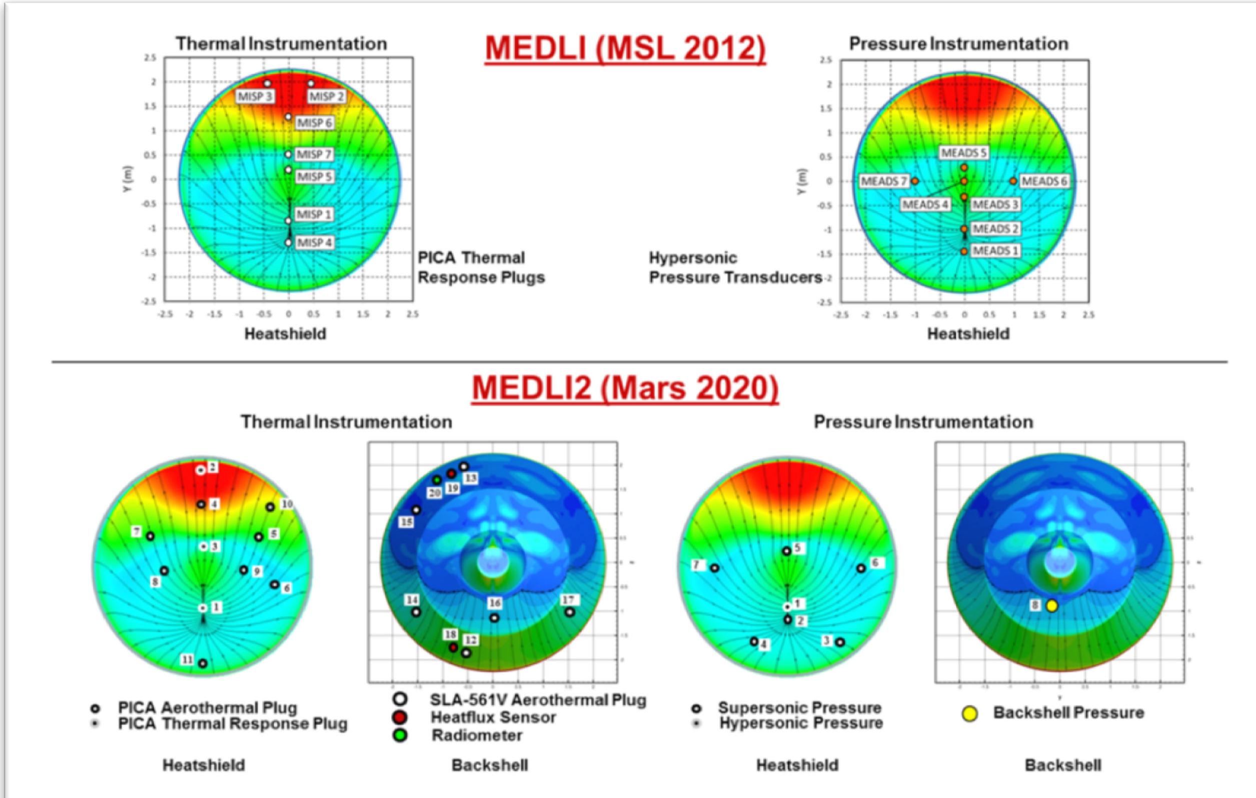
Missed Opportunity:
Stardust (Earth re-entry in 2006)
No entry instrumentation



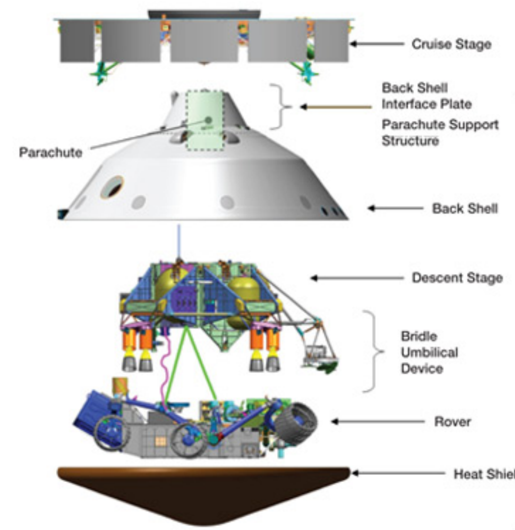
Missed Opportunity:
OSIRIS-Rex (Earth re-entry in 2023)
No entry instrumentation

- **Science Mission Directorate (SMD)** explores the solar system through three mission classes: Discovery, New Frontiers, and Flagship
  - EDL instrumentation was required for Discovery 14, and is in Announcement of Opportunity for New Frontiers 4
  - Recent flagship-class Mars missions have included instrumentation: Mars Science Laboratory (MEDLI), Mars 2020 (MEDLI2)
  - Planetary Science Deep Space SmallSat Studies (PSDS3) program
- **Human Exploration and Operations Mission Directorate (HEOMD)**
  - Orion EFT-1 heatshield contained extensive instrumentation
  - EM-1 and EM-2 heatshields will be instrumented
- **Space Technology Mission Directorate (STMD)**
  - Small Business Innovative Research (SBIR) program (TRL 1-5)
  - Space Technology Research Grants: NASA Space Technology Research Fellowships (NSTRF), Early Career Faculty, Early Stage Innovation
  - Entry Systems Modeling (ESM) project – a primary customer of flight data
- **NASA Centers (IR&D)**
  - In-house sensor development and testing
  - Nurture international collaborations

State of the Art: MEDLI, MEDLI2, and Orion



Sensor Locations for MEDLI and MEDLI2 (Hwang, AIAA 2016)

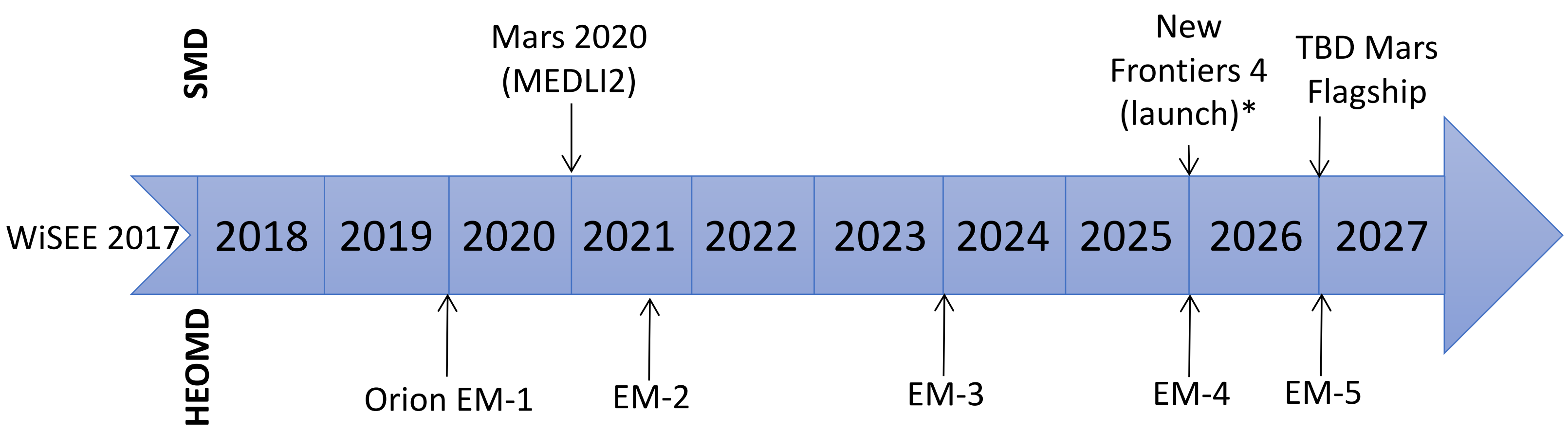


- MEDLI2 builds on MEDLI with backshell instrumentation: heat flux sensors, a radiometer, and a low pressure sensor
- Orion EFT-1 had extensive instrumentation drawing from MEDLI heritage
- **No wireless sensors on these entry systems (passive or active)**
- Good reference on past instrumentation: Wollard, B.A., Braun, R.D., Bose, D., "Aerothermodynamic and Thermal Protection System Instrumentation Reference Guide," IEEE Aerospace Conference, March 2016

Entry Instrumentation Flight Opportunities: 2018-2027

- **Ground and flight tests of new NASA entry system technologies may allow new sensor providers to get in the game. For example:**
  - HEEET (woven TPS for extreme entries)
  - ADEPT (mechanically deployable heatshield)
  - HIAD (inflatable heatshield)
- These projects are incentivized to leverage technologies from organizations with successful Phase I/II SBIRs.
- NASA is risk averse when it comes to relying on new sensor technologies for its main line of science and exploration missions (timeline below)

*Five out of six of the possible missions are expected to include atmospheric entry:
- Comet Surface Sample Return*
- Lunar South Pole-Aitken Basin Sample Return*
- Ocean Worlds (Titan* and/or Enceladus)
- Saturn Probe*
- Venus In Situ Explorer*



Emerging entry technology projects are more willing to try to things *and* are incentivized to leverage new tech

Instrumentation Needs and Accuracy Goals

" Mission concepts for this New Frontiers Opportunity that involve Entry, Descent, and Landing (EDL) into an atmosphere of a Solar System object (including the Earth) shall include an Engineering Science Investigation (ESI), to be funded outside the cost cap, to obtain diagnostic and technical data about vehicle performance and entry environments."

- **New Frontiers 4 Goals & Objectives Document (available for download on New Frontiers Program webpage)**

- Technical objectives, measurement, and accuracy goals are given for the four primary EDL phases/subsystems
- **NASA already has good technical solutions for many of these measurements**
- **Not all of these measurements have equal importance to NASA**

Technical Objectives	Quantity/Measurement	Accuracy Goal
Aerothermal Environment and Thermal Protection System (TPS)		
Aerodynamic heating	Heat Flux – Forebody	±5%
	Heat Flux – Afterbody	±10%
Reduced TPS and vehicle mass, reduced subsystem risk for future missions	In-Depth Temperatures, as a function of time at multiple locations	±15%
	Recession in Flight (multiple locations)	±2 mm
	Final Recession (if recovered)	±1 mm
Demonstrate adequate bonding and bondline integrity	TPS-to-structure bondline visualization (before and after flight)	±0.5 mm
Atmosphere, Aerodynamics, and Flight Dynamics		
Reconstruct EDL including atmospheric density. Increase landing accuracy.	Inertial Rates (IMU), mass properties	varies
	Static pressure on vehicle surface at stagnation point	±0.5% FS
Determine vehicle attitude in hypersonic regime	IMU, mass properties, and static pressure on vehicle surface at multiple locations	Pressure ±0.5% FS
Verify aerodynamic coefficients in hypersonic and supersonic regimes; winds in the supersonic regime	IMU, mass properties, and static pressure on vehicle surface at multiple locations	Pressure ±0.5% FS
Atmospheric Decelerator		
Enhance system capability (heavier payloads, higher altitudes, etc.), reduce mass, increase reliability and performance for future missions	Aero decelerator total angle of attack at start of inflation	±2°
	Observations of aero decelerator area oscillations	30 fps
	Aero decelerator force-time history	±2% of force @ 60 Hz
	Aero decelerator angles of attack and sideslip vs. time	±1° @ 30 Hz
	Aero decelerator drag coefficient vs. time and Mach number	±4% @ 60 Hz
Vehicle Structure		
Reduce mass, increase reliability and performance for future missions	Entry Loads	±10%
	Landing Loads	±10%

List of Technical Objective for the ESI

Measurement Priorities

Measurement Objective	Earth Entry	Venus Entry	Saturn Entry	Titan Entry	Relevant Sensors/Instrumentation/Data
Aerothermal/TPS					
Aerothermal Environment	M	H	H	H	Near-surface thermocouples, heat flux sensors
TPS Response	M	H	H	H	In-depth thermocouples
TPS Recession/Mass Loss	L	M*	H	L*	Recession sensors
Gas-cap Radiation	H	H	M	L	Radiometers, airborne observation for Earth return
Pre-Flight Vehicle Investigation	H	n/a	n/a	n/a	CT-Scan, laser scan, bond verification, etc.
Post-Flight Vehicle Investigation	H	n/a	n/a	n/a	CT-Scan, laser scan, TPS cores, bond verification, etc.
Airborne Observation	H	n/a	n/a	n/a	Infrared Imaging, TPS seeding sensors
Atmosphere, Aerodynamics, Flight Dynamics					
Atmospheric Density, Dynamic Pressure	L	M	M	M	IMU, high-speed surface stagnation pressure transducer
Winds	L	L	L	L	IMU, low-speed surface stagnation pressure transducer
Vehicle Attitude, Aerodynamic Coefficients	L	M	L	M	IMU, multiple surface pressure transducers
Atmospheric Decelerator					
Parachute/Decelerator Performance	L	M	M	M	IMU, surface pressure transducers, camera(s)
Vehicle Structure					
Entry Loads	M	M	M	M	IMU, load cells

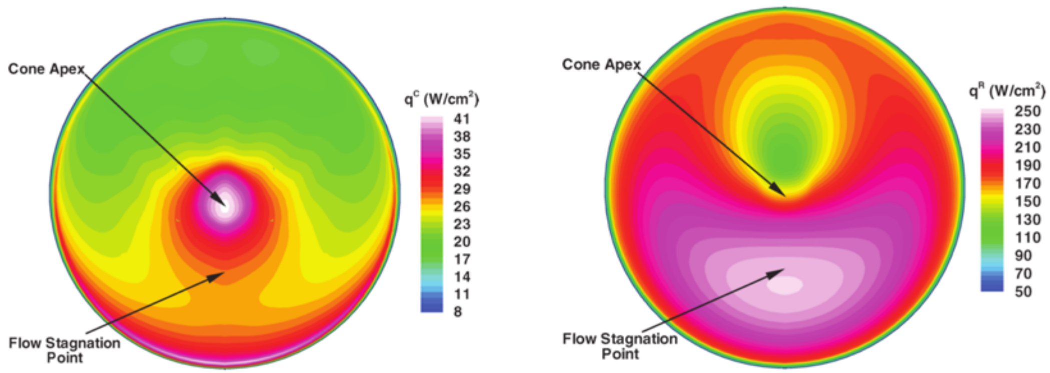
H = High Priority, M = Medium Priority, L = Low Priority
*** = Depending on material, entry speed**

Measurement Priorities with Destination and Vehicle Type

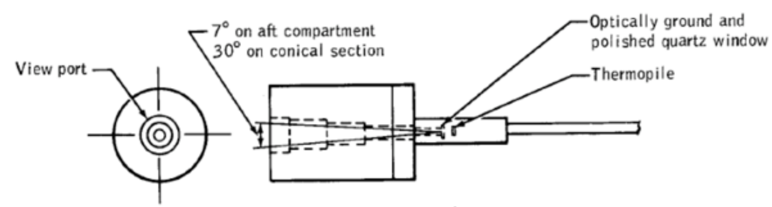
- **Where should you focus?**
    - Parameters that drive atmospheric entry vehicle design
    - State-of-the-art sensor technologies that insufficient accuracy and reliability
    - Computational models that would be validated by these measurements and contain high uncertainty
- I encourage sensor developers to focus on **TPS Recession / Mass Loss** and **Gas-Cap Radiation**

Critical Measurement: Radiative Heat Flux

- Heat flux on an entry vehicle is caused by convection (air friction) and radiation (incident light from the shock)
- Computational models for predicting radiative heat flux can carry more uncertainty than those for predicting convective heat flux
  - Radiative heating predictions carry largest uncertainties in our discipline (up to 300%)
  - Leads to entry vehicle designs with large margins (and reduced science payload capability)
- Example: Titan aerocapture
  - Convective heating is relatively low by atmospheric entry standards
    - Entry velocity of 6.5 km/s
    - Produces 40-45 W/cm^2 max stagnation point convective heating
  - Radiative heating from cyanogen (CN) at the stagnation point could be as high as 300 W/cm^2 (7X convective component)
    - Titan atmosphere consists primarily of nitrogen with small amounts of argon and methane (3%)
    - Methane dissociates in the shock layer and forms CN, a strong radiator
  - Post-flight analysis of Huygens probe data showed far lower heating than predicted. Lower model uncertainty could led to reduced margins.
- Radiative heating increases as entry vehicle gets larger (both forebody and backshell)



Convective (left) and radiative (right) heating for example Titan aerocapture entry vehicle (Ref: Wright et al, 2005)



Apollo 4 and 6 radiometer schematic (Lee and Goodrich, 1972)

Critical Measurement: Recession

- Predictions of material recession (loss) carry high uncertainty and are an important factor in TPS design
- Example: Galileo Probe
    - Mass loss of 79 kg during entry (23% of probe entry mass)
    - Higher recession on frustum than expected as measured by ARAD sensor
- Recession sensors have had mixed success and there is room for innovation
- Potential upcoming missions with high recession are in need of a sensor solution
    - Venus In Situ Explorer
    - Saturn Probe
- Its critical for developers to work with actual TPS materials due to highly-integrated nature of most recession sensors
- Wireless solutions have shown potential in this area, but accuracy will be a challenge

Dark Universe, AMNH

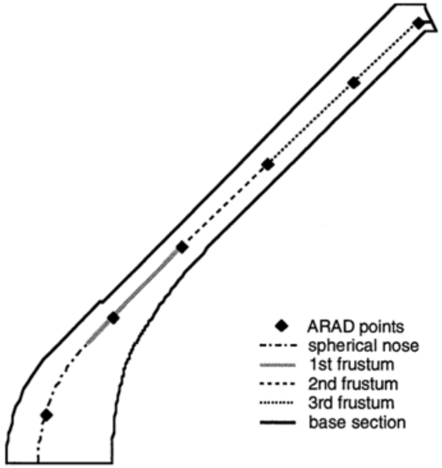


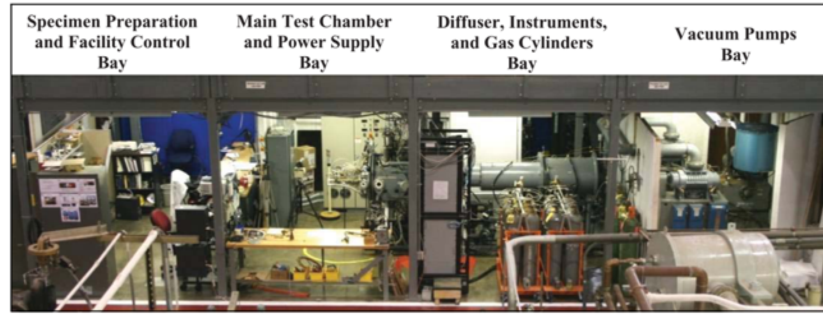
Fig. 5 Reconstruction of heatshield final shape (to scale with initial centerline thickness of 14.6 cm).

(Milos et al., 1999)

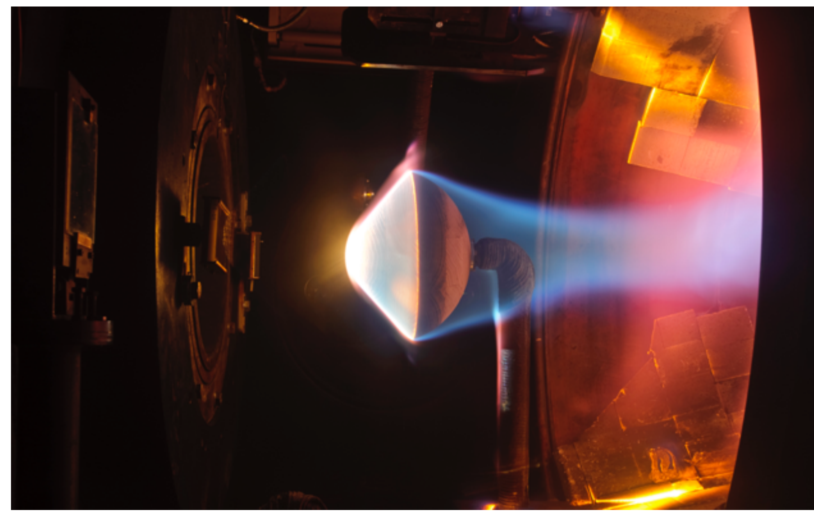
Testing new sensors

- Several facilities are available world-wide with widely varying test condition capabilities (and costs)
  - See Chazot 2014 for a list of global facilities and their capabilities
  - The HyMETS facility at NASA LaRC is a lower cost facility that is excellent for early screening of sensor technologies (See Splinter 2011)
    - Costs are generally within reach of Phase II SBIR projects
  - NASA Ames is home to the Agency's workhorse high-enthalpy test facilities for TPS material and sensor development (See references for link to test planning guide)

- Wireless technology has potential applications in high enthalpy facilities
  - The time needed to connectorize, install, and verify wired sensor connections in arc jet test articles is a bottleneck.
  - Being able to connect facility data systems to arc jet models without wires would speed model installation and improve testing throughput



NASA LaRC Hypersonic Materials Environmental Test System (HyMETS)



Probe test at NASA Ames Aerodynamic Heating Facility (AHF)

Characterizing sensor performance in high-enthalpy flow facilities is a critical prerequisite to mission adoption

Recommendations

- Focus on **new entry system technologies** in order to mature **new sensor technologies**

- Instead of competing with wired technologies, focus on the unique capabilities of wireless. For example:
  - Low-impact / passive sensors could be useful for forensics even if they can't provide high accuracy
  - Wireless enables a flexible architecture
  - Wireless power (inductive charging) could eliminate the need for a cable cutter between the heatshield data system and the primary spacecraft
  - Lower integration risk

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Acknowledgements

- Ed Martinez
- Helen Hwang
- Michelle Munk
- Ethiraj Venkatapathy
- George Raiche
- Todd White
- Don Ellerby
- Milad Mahzari
- Gregory Swanson
- Jeremy Vander Kam
- Kathy McGuire
- Christine Szalai

Thank you for your attention!