Materials for Space: It's Challenging!

Sylvia M. Johnson
NASA Ames Research Center,
Moffett Field, CA, USA

High Temperature Materials Chemistry XV

March 29-April 1, 2016
Orleans, France

Sylvia.m.johnson@nasa.gov

Non-crewed Exploration of Solar System

Human Exploration on Mars

Where are we going?

Outline

- Where we're going
  - Hazards of space travel
  - Human exploration: Mars

- Materials needs and challenges for space applications
  - 5 research/technology areas

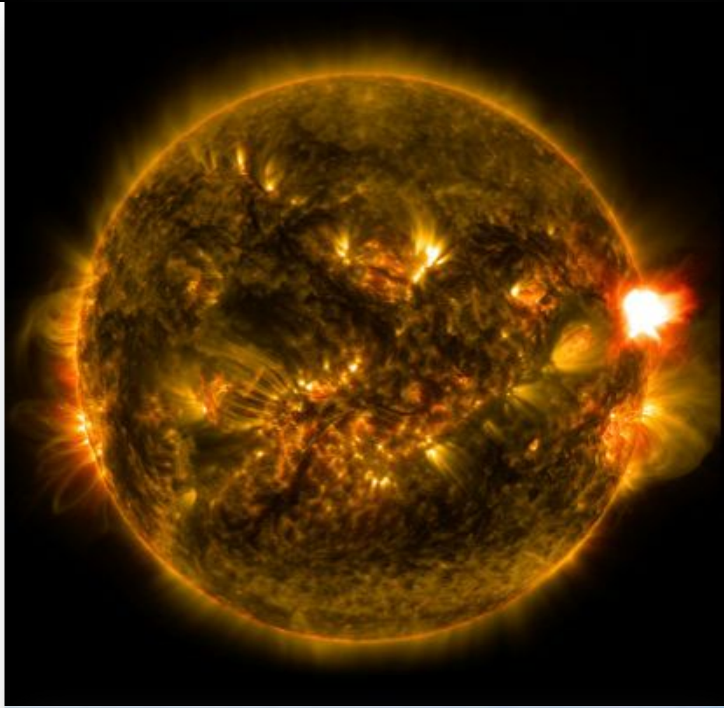
- Thermal protection systems
  - Background
  - Challenges for robotic missions to planets(Saturn, Venus)
  - Challenges for crewed missions to Mars
  - Potential solutions

New technologies are needed and,

we can't do it without materials!

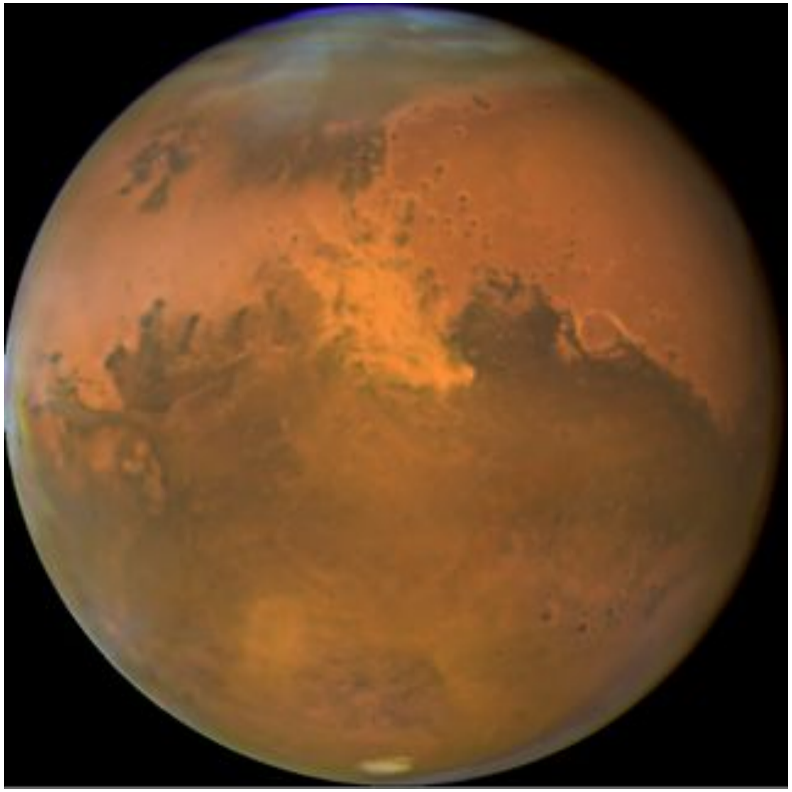
Hazards of Space Travel …and Habitation

- Time scale: Structures may be in corrosive/ high UV environment for many years before use
- Solar radiation—bad for humans, bad for electronics, bad for structures
- Cosmic radiation-very bad for humans, for electronics and structures
- Micrometeroids
- Gravity: too much or too little
- Atmosphere/environment: lack thereof, or toxic species
- Lack of life support: O_2, food, water, power
- Atmospheric entry/reentry: significant structural and thermal effects on vehicles



Humans to Mars

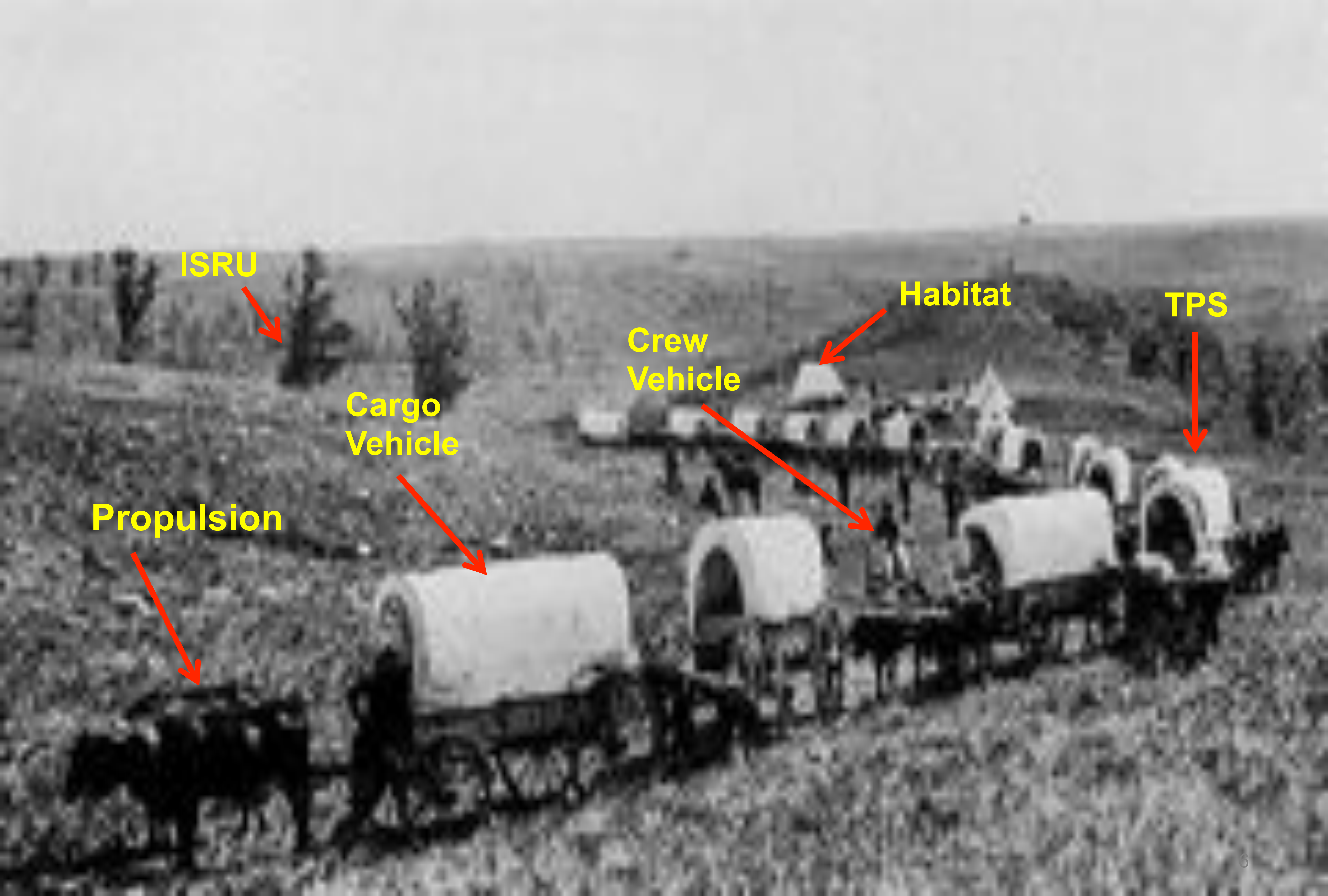
- People need a lot of equipment
- Life support
  - Habitats
  - Food
- Need equipment in place before they arrive
- May want to come home…
- Very expensive, high tech, safe expedition



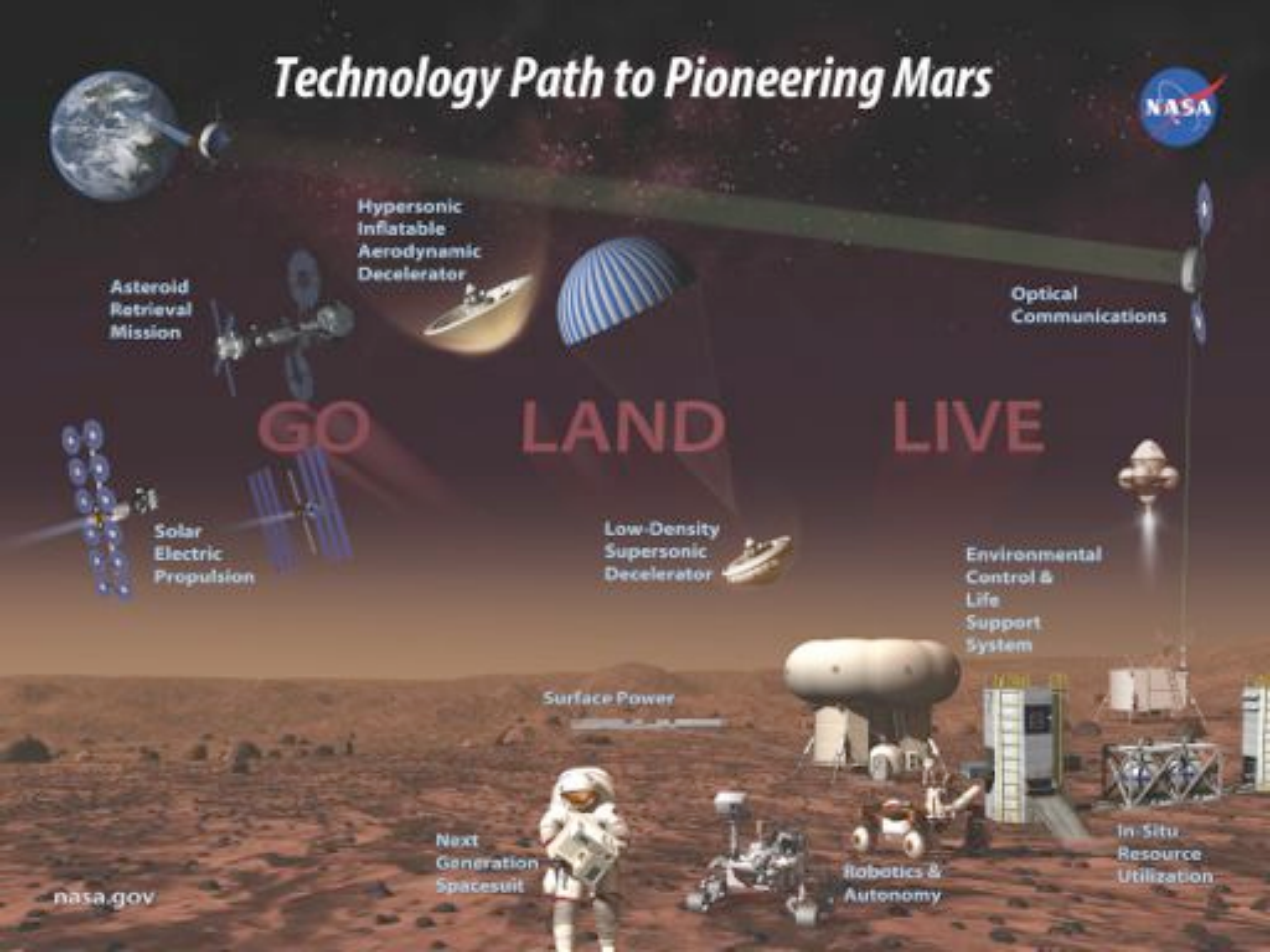
Mars in a sandstorm (2005)

NASA: Hubble Telescope

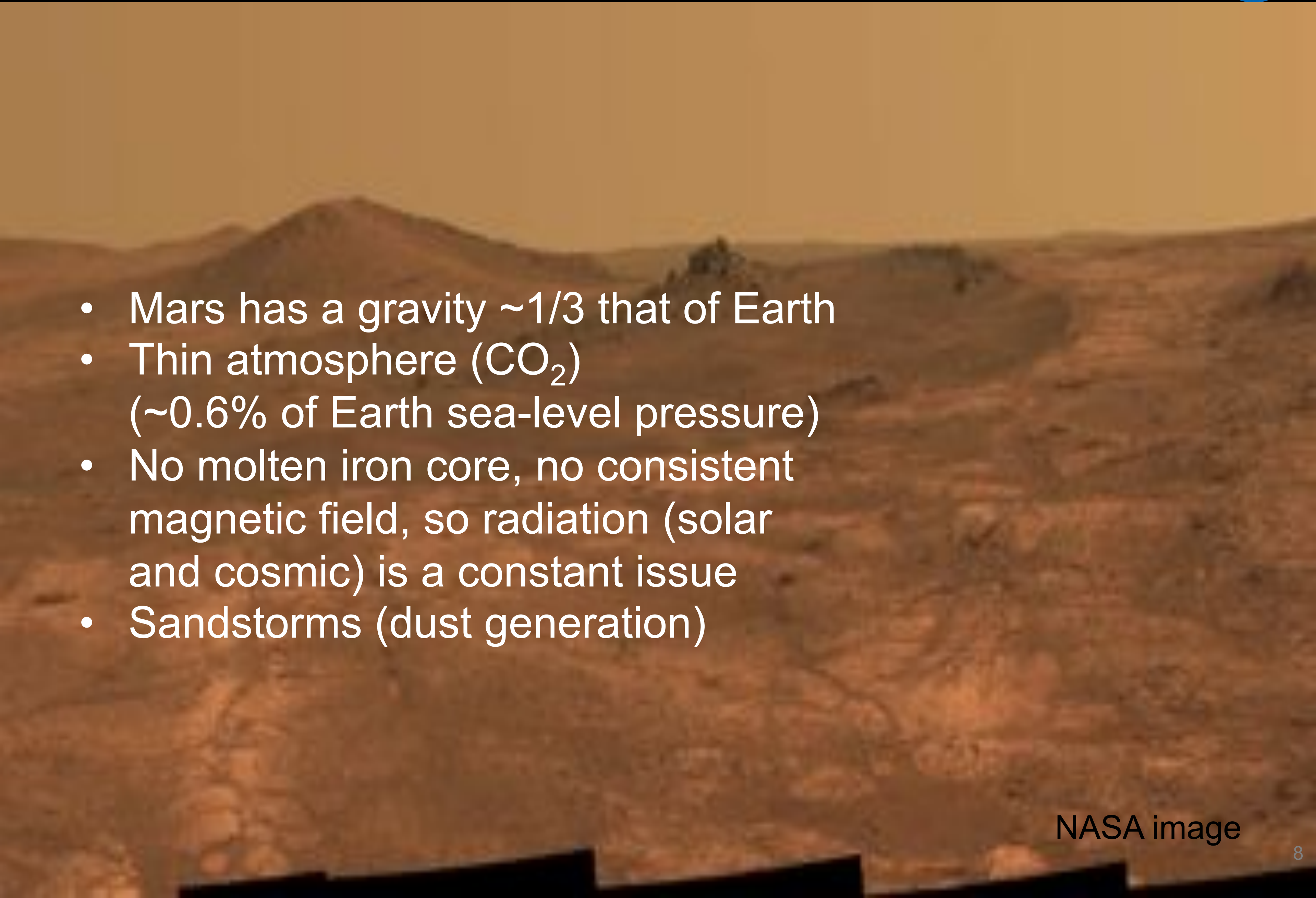
Pioneering on Earth



Technology Path to Pioneering Mars



Martian Landscape



- Mars has a gravity ~1/3 that of Earth
- Thin atmosphere (CO_2)
  (~0.6% of Earth sea-level pressure)
- No molten iron core, no consistent magnetic field, so radiation (solar and cosmic) is a constant issue
- Sandstorms (dust generation)

NASA image

Outline

- Where we're going
  - Hazards of space travel
  - Human exploration: Mars
- Materials needs and challenges for space applications
  - 5 research/technology areas
- Thermal protection systems
  - Background
  - Challenges for robotic missions to planets(Saturn, Venus)
  - Challenges for crewed missions to Mars
  - Potential solutions

New technologies are needed and
we can't do it without materials!

System Challenges and Materials Needs

- **System Challenges**
  - **Mass reduction**
  - **Radiation protection**
  - **Reliability**

- **Materials Development Needs**
  - Lightweight structural materials
  - Computationally designed materials
  - Flexible material systems
  - Materials for extreme environments
  - Special materials

Affordability: Key to extent and timing

NASA Technology Roadmaps 2015

- http://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_12_materials_structures_final.pdf

Lightweight Structural Materials --Mass and Volume Matter!

- Emphasis
  - Reduce mass of structures that leave Earth/ enter atmosphere
  - Increase useful payload
  - Lower launch cost
  - Reduce fuel needed for return
    - ~300lbs of fuel to move 1lb from Earth to Mars and back
  - Provide more benign entry conditions
- Materials: Multifunctional structural with
  - Radiation resistance
  - Thermal protection
  - Sensors
  - Repair functions (self healing)
- Composite materials, especially polymer matrix composites

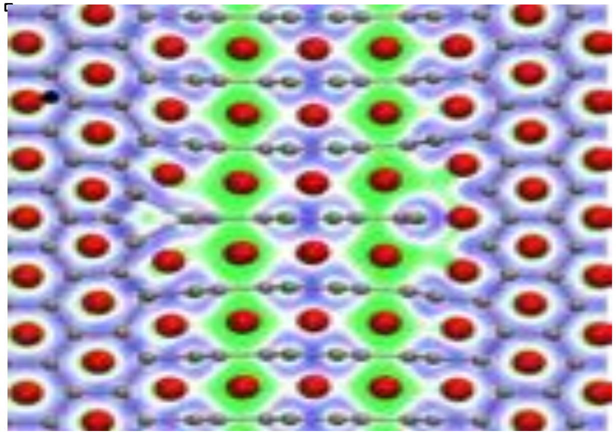
5.5m Composite Tank (MSFC)

Composite tank: saves 33% of weight and ~25% of cost

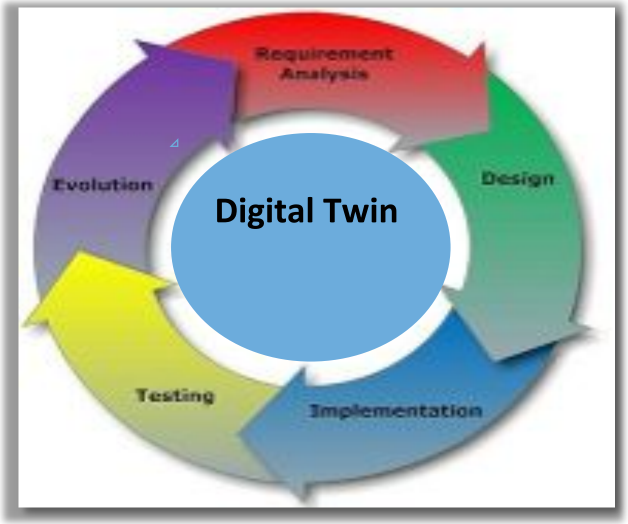
Computationally Designed Materials

Decrease development time, operational costs, improve safety

- **Emphasis**
  - Predict lifetimes—reduce testing and shorten mission insertion times
  - Design: improve/tailor properties
  - Processing: robust, reduce experiment
- Materials Design: Extension to Systems: "Virtual Digital Twin"
  - Simulation capability to manage system from concept through flight
  - Evaluate the effects of actual flight parameters



Computational model of ZrB_2 UHTC atomic structure

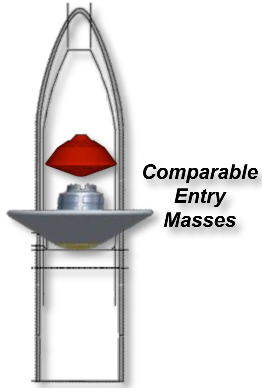


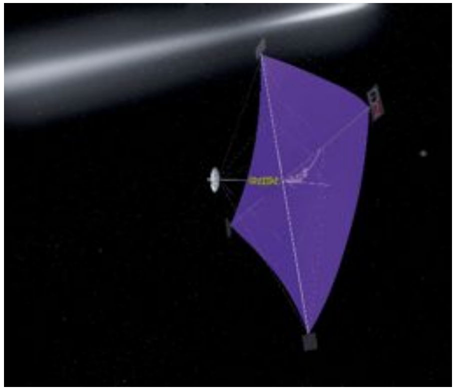
Flexible Materials

- **Emphasis:**
  - Minimize launch volume and mass and maximize use volume
- **Materials:**
  - Flexible materials for structures, (habitats), aeroshells, solar power
    - Deployed or inflated: mechanisms
    - Morphing materials: power requirements
  - Reliable life support structures : multifunctional materials.
  - Heat shields
    - Expandable aeroshells for landing large masses on Mars
- Example: Solar sails: use momentum of photons for propulsion
    - Very large, very low areal density, efficient
    - Deployment issues/stresses increase with size
    - Multilayer material
    - Goal is <2um thickness, 90,000m^2

Courtesy Inspiration Mars

Launch Vehicle Fairing Constraints



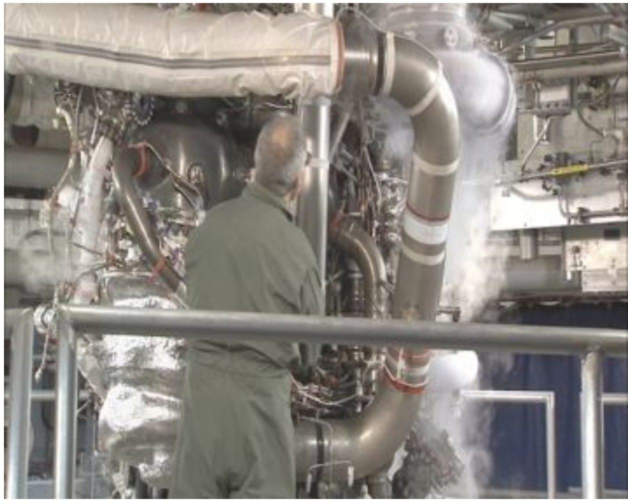


Solar sail:
0.5 km
diameter

http://www.nasa.gov/centers/marshall/images/content/152149main_9906265_1140x900.jpg

Materials For Extreme Environments

- **Emphasis**
  - Protect against extremes of temperature, pressure, corrosion, radiation and combined environments
    - Space operations
    - Planetary operations
    - Heat shields
    - Propulsion
  - Protection of electronics and people from radiation and combined environments is especially challenging
- **Materials:**
  - Ceramic matrix composites
  - Ultrahigh temperature ceramics
  - Advanced alloys
  - Coatings
  - Insulators
  - Radiation-hardened electronics
- **Example: Cryogenic insulation for fuel tanks**
  - Currently storage time is ~12 hours
  - Need: high thermal resistivity/low density
  - Enable long term storage and protection from space environments.



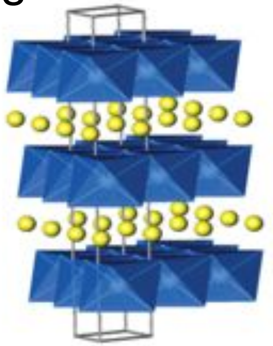
http://www.nasa.gov/sites/default/files/2014-12-11-rs-25chilltest.jpg

Special Materials

- **Emphasis**
  - Space suits for improved dexterity/lower weight
  - Optically transparent windows for habitats and instruments
  - Power generation:
    - Long life,
    - High efficiency
    - Radiation hardened
  - Energy storage
    - Low mass materials,
    - Reliable over long term in extreme environments and temperatures
    - Multifunctional batteries
- Goals:
  - Energy density: > 400Wh/kg
  - Power density: >100W/kg


[redacted]

Solar array (ESA/NASA)



Beyond Li ion batteries

http://www.nasa.gov/sites/default/files/thumbnails/image/16938569907_90b5c8a831_o.jpg

Outline

- Where we’re going
  - Hazards of space travel
  - Human exploration: Mars
- Materials needs and challenges for space applications
  - 5 research/technology areas
- Thermal protection systems
  - Background on Entry
  - Background on TPS
  - Challenges for robotic missions to planets(Saturn, Venus)
  - Challenges for crewed missions to Mars
  - Potential solutions

New technologies are needed and
we can’t do it without materials!

Entry Heating Parameters

- Reentry heating : 2 primary sources
  - **Convective heating** from both the **flow of hot gas** past the surface of the vehicle and catalytic chemical **recombination reactions** at the surface
  - **Radiation heating** from the **energetic shock layer** in front of the vehicle
- Heating depends on reentry speed (V), vehicle effective radius (R), and atmospheric density (ρ)

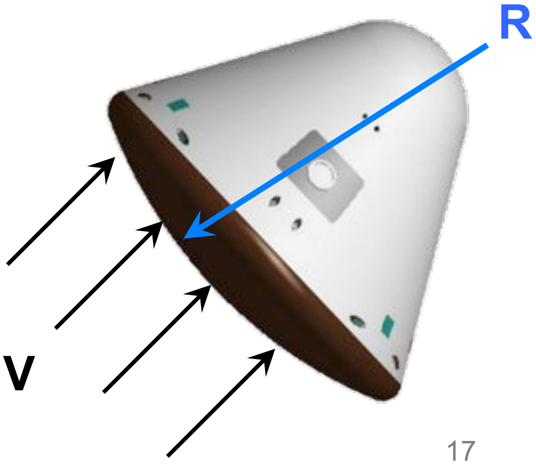
$$\dot{q}_{conv} \propto V^{3}\left(\frac{\rho}{R}\right)^{0.5}$$

Convective Heating

$$\dot{q}_{rad} \propto \boxed{V^{8}}\rho^{1.2}R^{0.5}$$

Shock Radiation Heating

- As reentry speed increases, both convective and radiation heating increase
  - Radiation heating dominates at high speeds
- As vehicle radius increases, convective heating decreases, but radiation heating increases



Thermal Protection Systems

- Protect vehicle structure and contents (people and things) from the heat of entry through an atmosphere
- Rely on material's response to environment
- Response depends on
  - Material properties
  - Configuration of the system
  - Specific conditions (heat flux, pressure, flow)
- Physical Forms: rigid, conformable, flexible

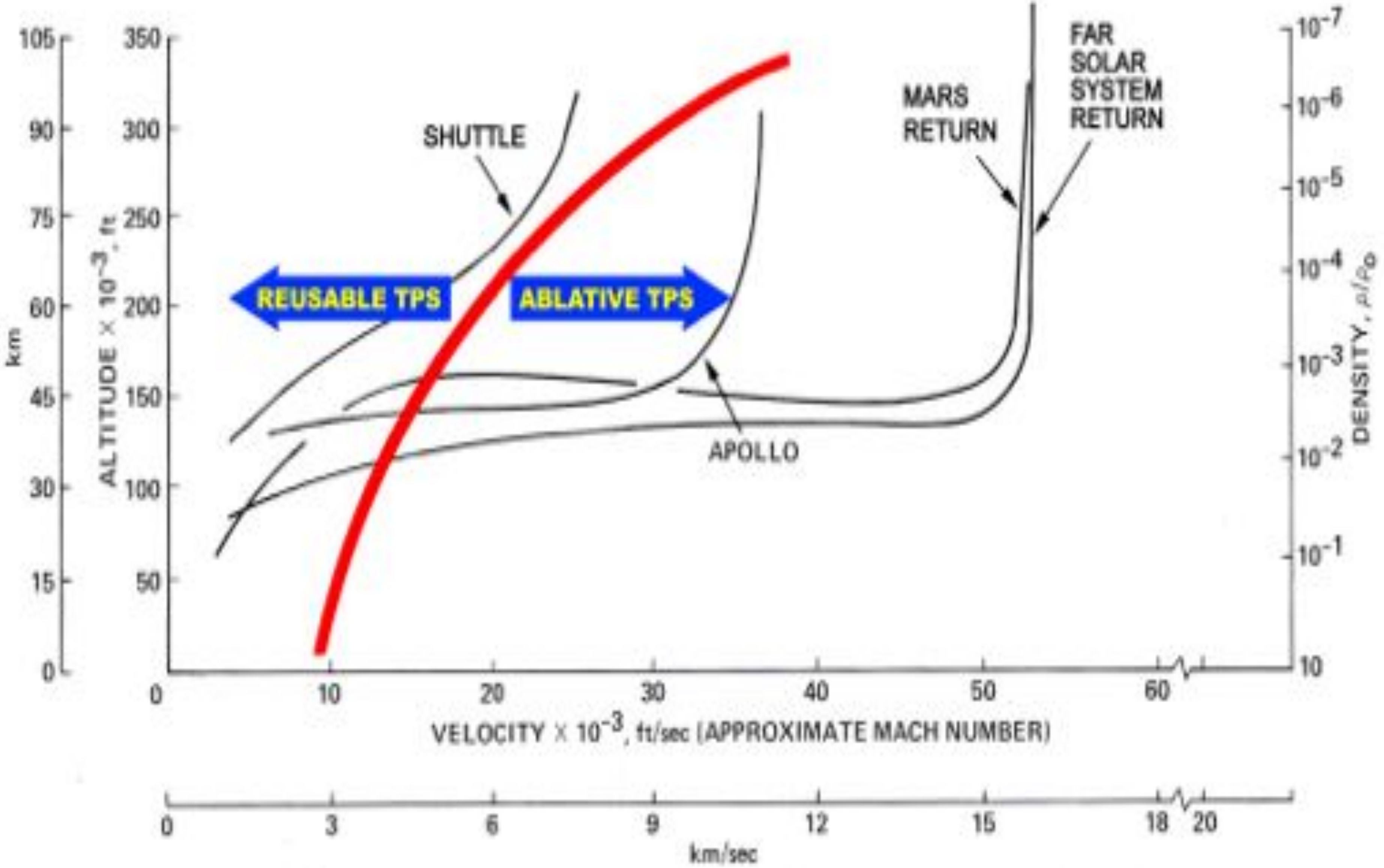
One size does not fit all!

Different TPS for different vehicles, location on vehicles, and mission conditions

Goal of all TPS is reliable and efficient performance

Specifically addresses challenges of mass reduction and reliability

Reusable vs. Ablative TPS

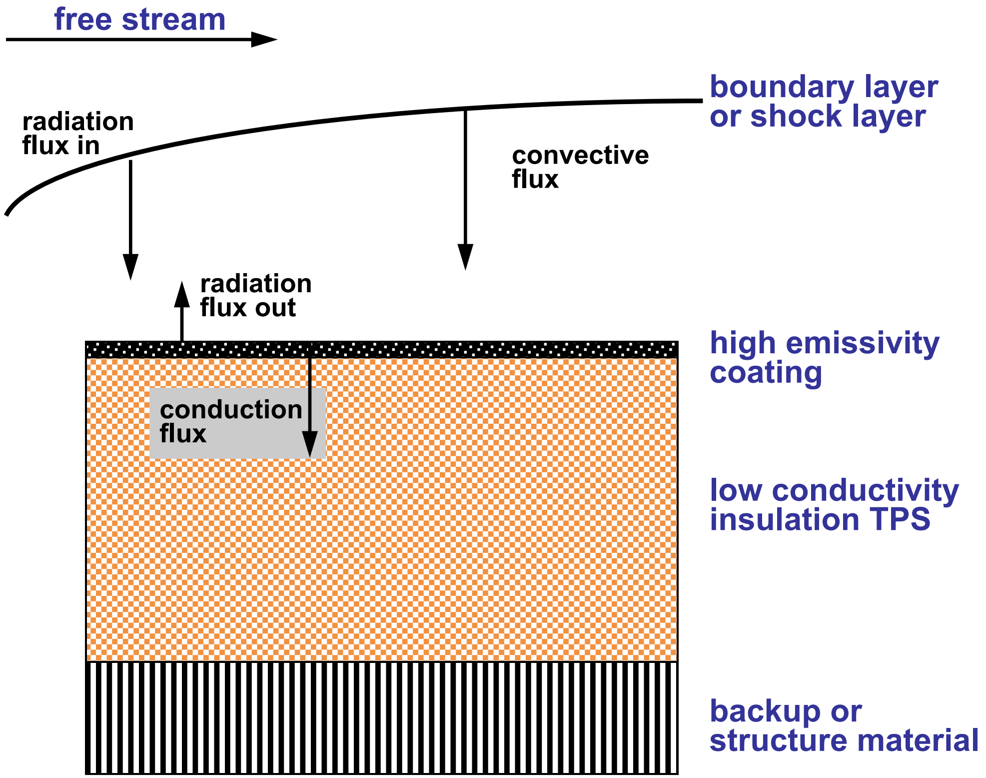


Insulative/Reusable TPS

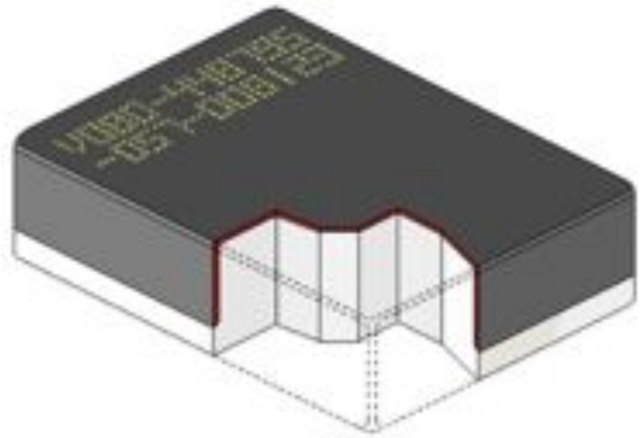
Energy management through storage and re-radiation — material unchanged

When exposed to atmospheric entry heating conditions, surface material will heat up and reject heat in the following ways:

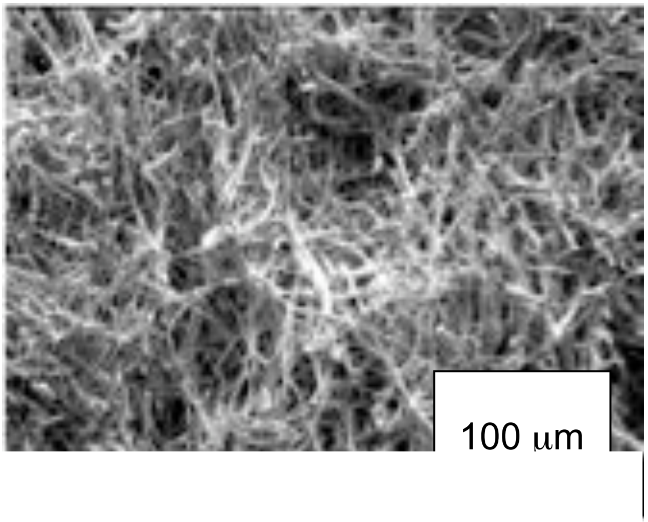
- Re-radiation from the surface and internal storage during high heating condition
- Re-radiation and convective cooling under post-flight conditions



Reusable TPS: Tiles and Coatings

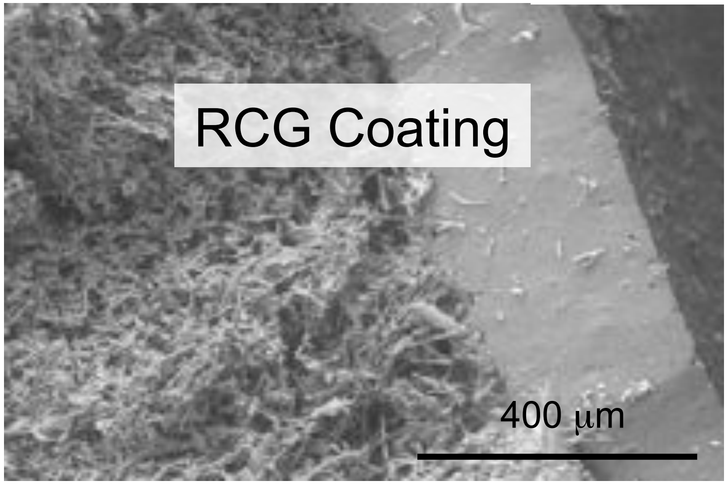


Density: 0.14 to 0.19 g/cm^3

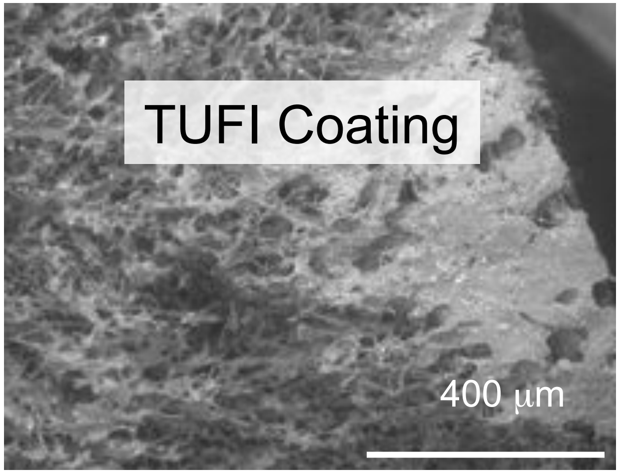


- Silica-based fibers
- Mostly empty space- >90%porosity

“Space Shuttle Tile”



- RCG is a thin dense high emittance glass coating on the surface of shuttle tiles
- Poor impact resistance



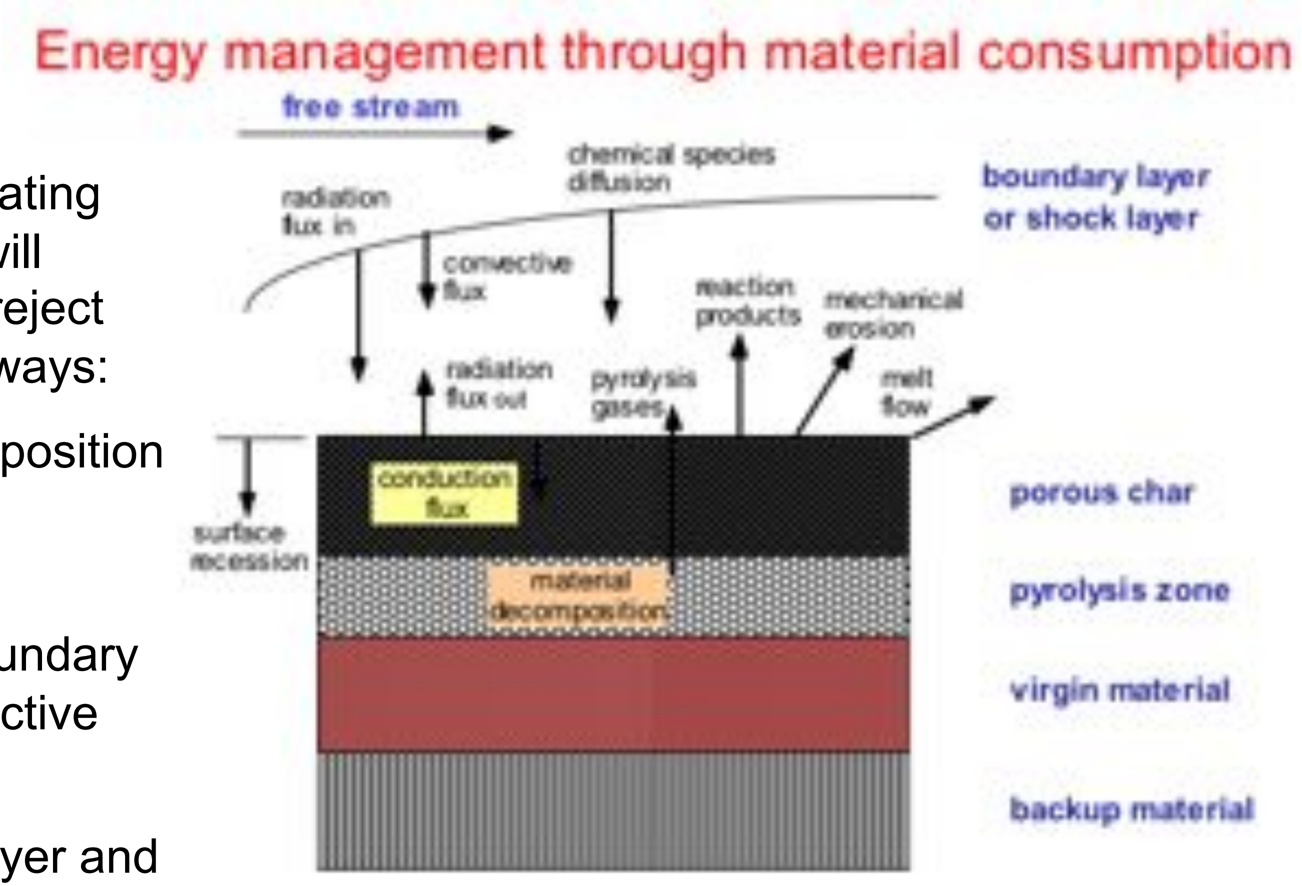
- TUFI coatings penetrate into the sample
- Porous but much more impact resistant system

Ablative TPS

Energy management through material consumption

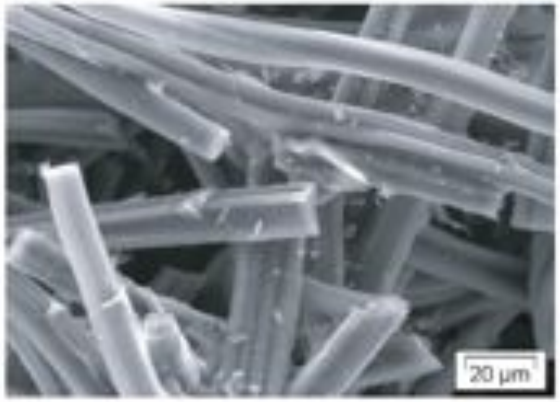
When exposed to atmospheric entry heating conditions, material will pyrolyze (char), and reject heat in the following ways:

- Endothermic decomposition of polymer
- Blowing of ablation products into the boundary layer reduces convective heating
- Formation of char layer and re-radiation

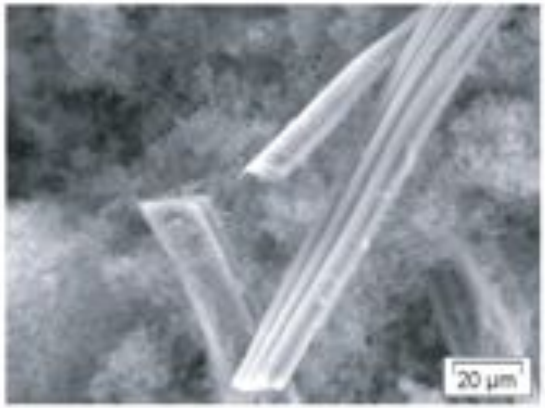


Phenolic Impregnated Carbon Ablator (PICA)

Processing Detail

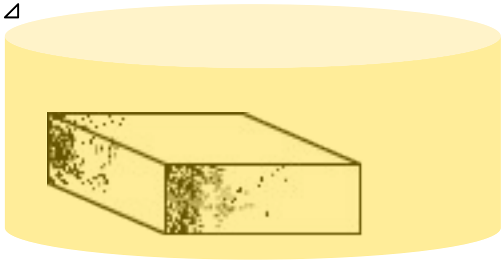


Fiberform™ before impregnation



PICA: Fiberform™ with phenolic resin

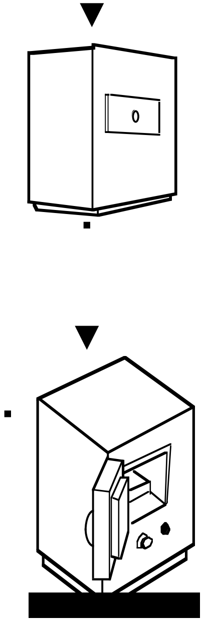
Carbon Fiberform™



Resin Impregnation

Phenolic Resin

PICA has low density (~0.27g/cm^3) and is an efficient ablator at high heat fluxes



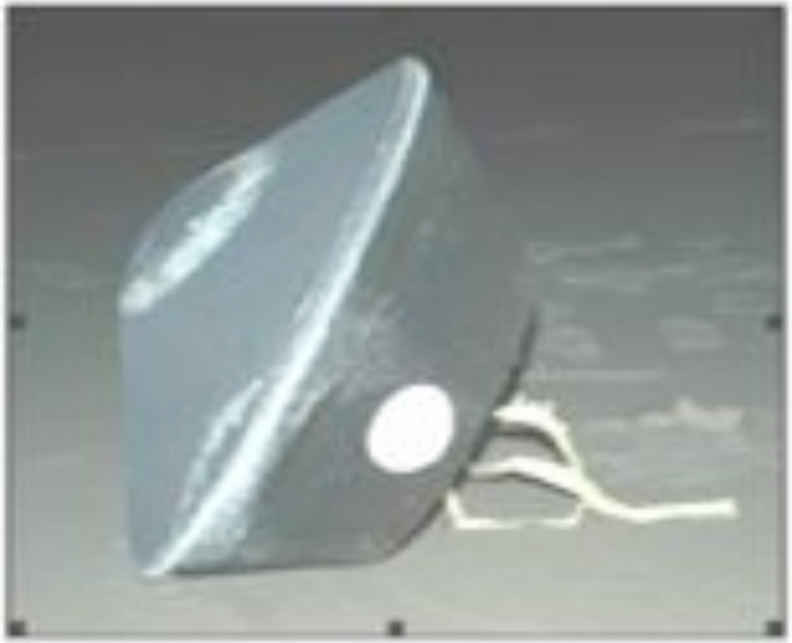
PICA Arc Jet Model

Drying Cycle

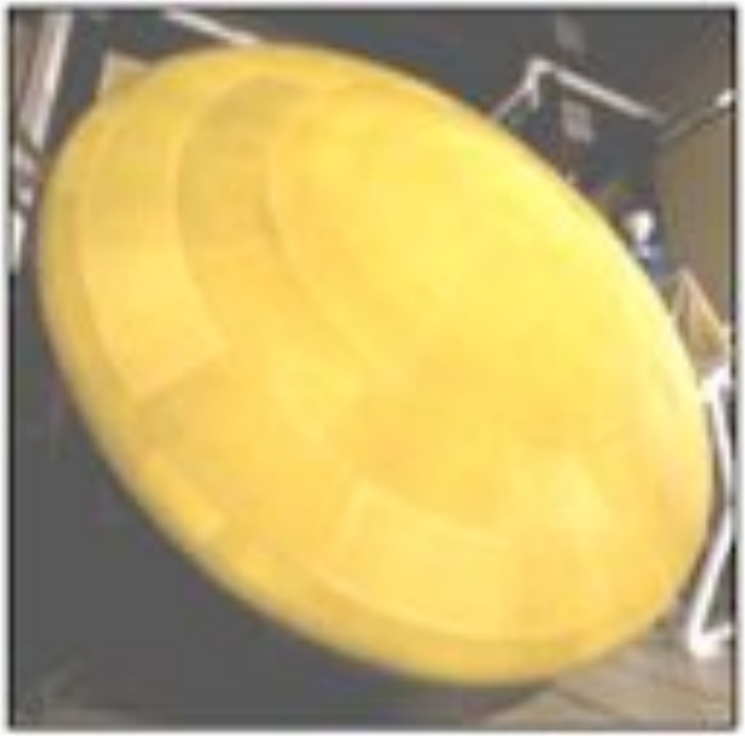
PICA Applications

PICA was the enabling TPS material for the Stardust mission where it was used ***as a single piece heatshield***

PICA was the primary heatshield for Mars Science Lab (MSL) and is used in SpaceX's Dragon cargo vehicle in a **tiled configuration**



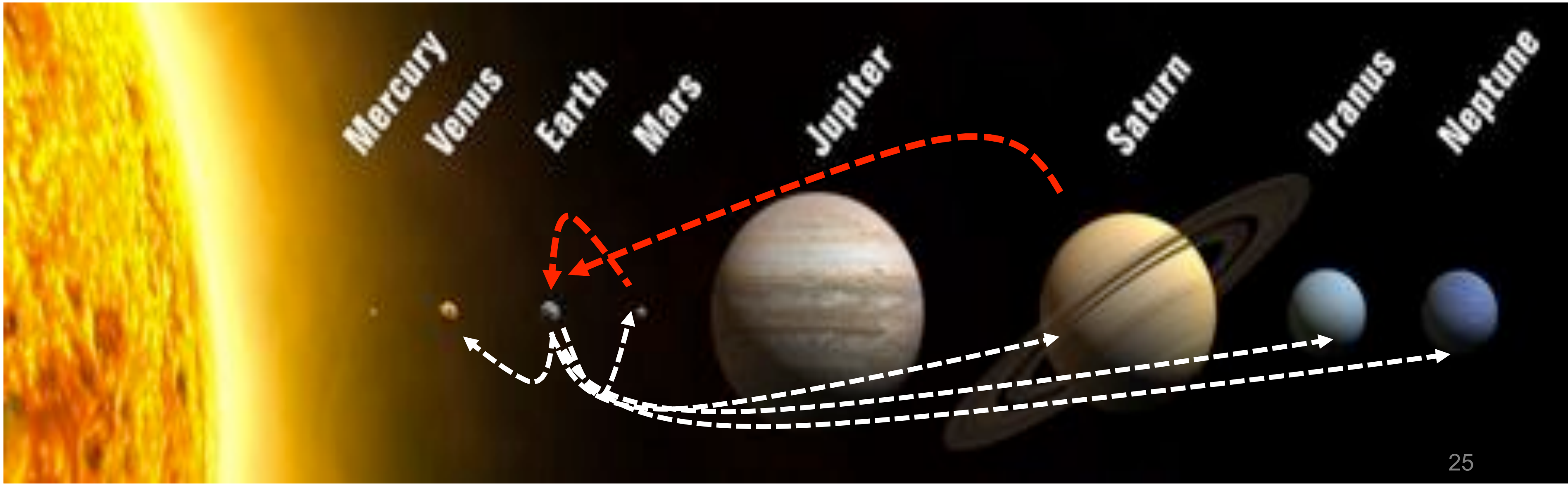
Stardust sample return capsule post flight with PICA as the forebody TPS. (0.8m diameter)



MSL Heat Shield (4.5m diameter)

Destinations and Challenges

- Saturn and Venus: robotic missions
  - Very extreme environments, especially Venus atmosphere
  - Saturn: very large, very high heating on entry
- Mars: robotic and crewed mission
  - Crew requires large amount of cargo
  - Crew to and from surface separately

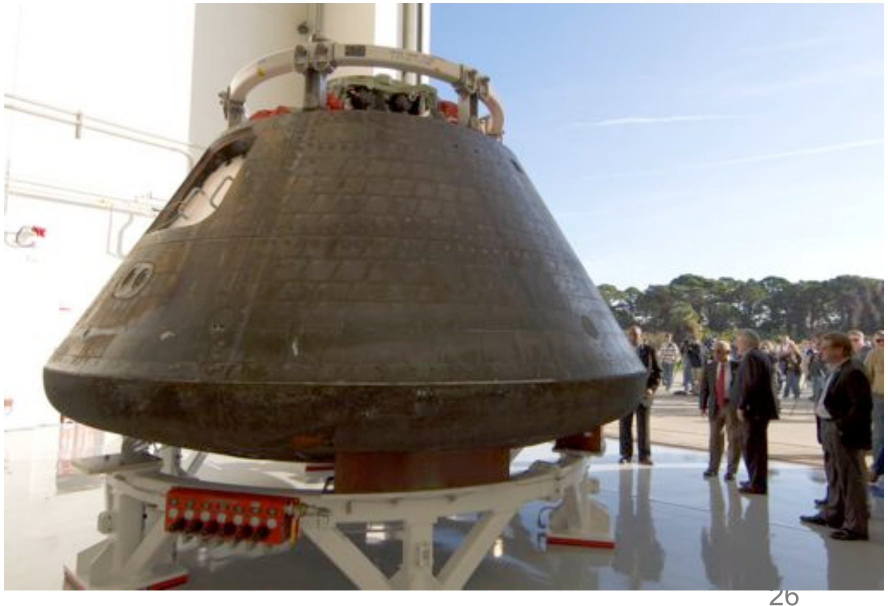


TPS Selection

- Entry into outer planets/ Venus
  - Large aeroshells for deceleration
- Entry into Mars
  - Sky crane approach of MSL/Curiosity not feasible for loads>1.5mt to Mars
  - Balloons / parachutes not very effective
  - Need large aeroshell
- High speed entry into Earth's atmosphere
  - Direct trip/ entry: entry speed> 13.5km/s
  - Orion vehicle: need more capable TPS
  - Inspiration Mars proposed very small reentry vehicle: lower heat flux, current TPS
- Scenarios have differing degrees of risk to humans—length of time in space, entry speeds, g forces, hazard of changing vehicles

Planet Mission Studies	Peak Heat Flux Range (W/cm^2)	Pressure Range (atm)	Heat Load Range (kJ/cm^2)
Venus[1]	2400 - 4900	4 - 9	11 - 12
Saturn[2]	1900 - 7700	2 - 9	80 - 272

1. Prabhu, D.K., et. al.; IEEE Aerospace Conference, Big Sky, MT, March 2-9, 2013
2. Allen, G. A. and Prabhu, D. K.; private communication



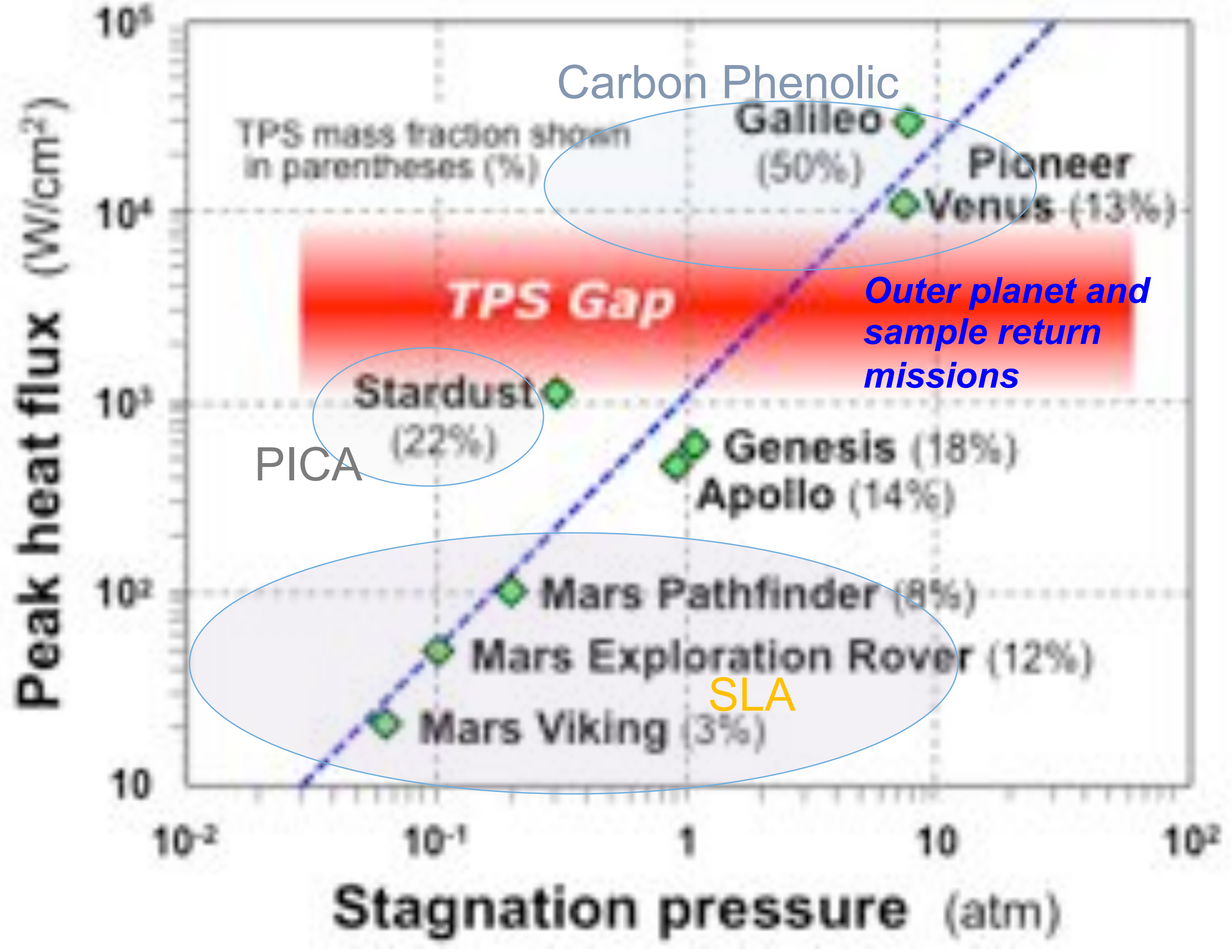
http://www.nasa.gov/exploration/systems/orion/gallery/index.html?id=341169

Future Missions: TPS Availability and “Gap”

- Carbon phenolic
  - high heat fluxes
- PICA/other ablators
  - < ~ 2,000 W/cm^2

Historical TPS Mass Fraction

by Heat Flux and Pressure

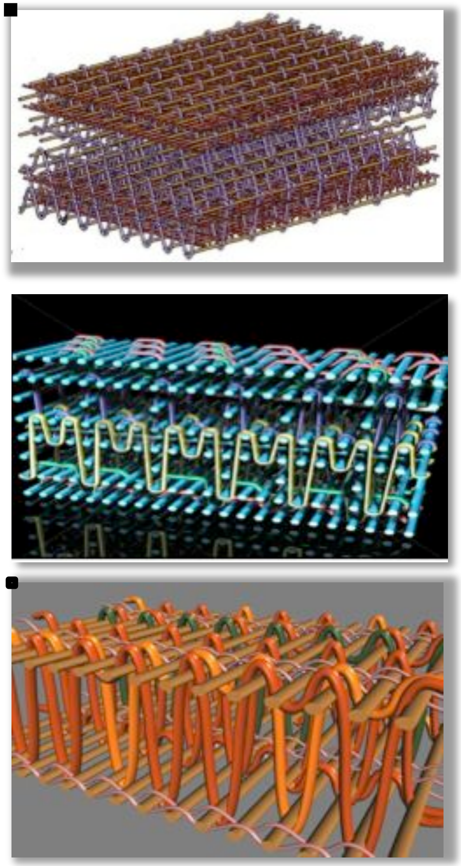


No efficient TPS for the gap from ~1000W/cm^2 to 10,000W/cm^2

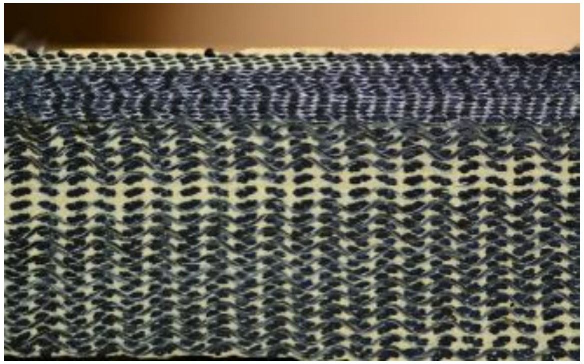
3D Woven TPS

An approach to the design and manufacturing of* ablative *TPS by the combination of weaving precise placement of fibers in an optimized 3D woven manner and then resin transfer molding when needed

- Design TPS for a specific mission
- Tailor material composition by weaving together different types of fibers and by exact placement using computer controlled, automated, 3-D weaving technology
- One-step process for making a mid-density dry woven TPS
- Ability to infiltrate woven preforms with polymeric resins for highest density TPS to meet more demanding thermal requirements

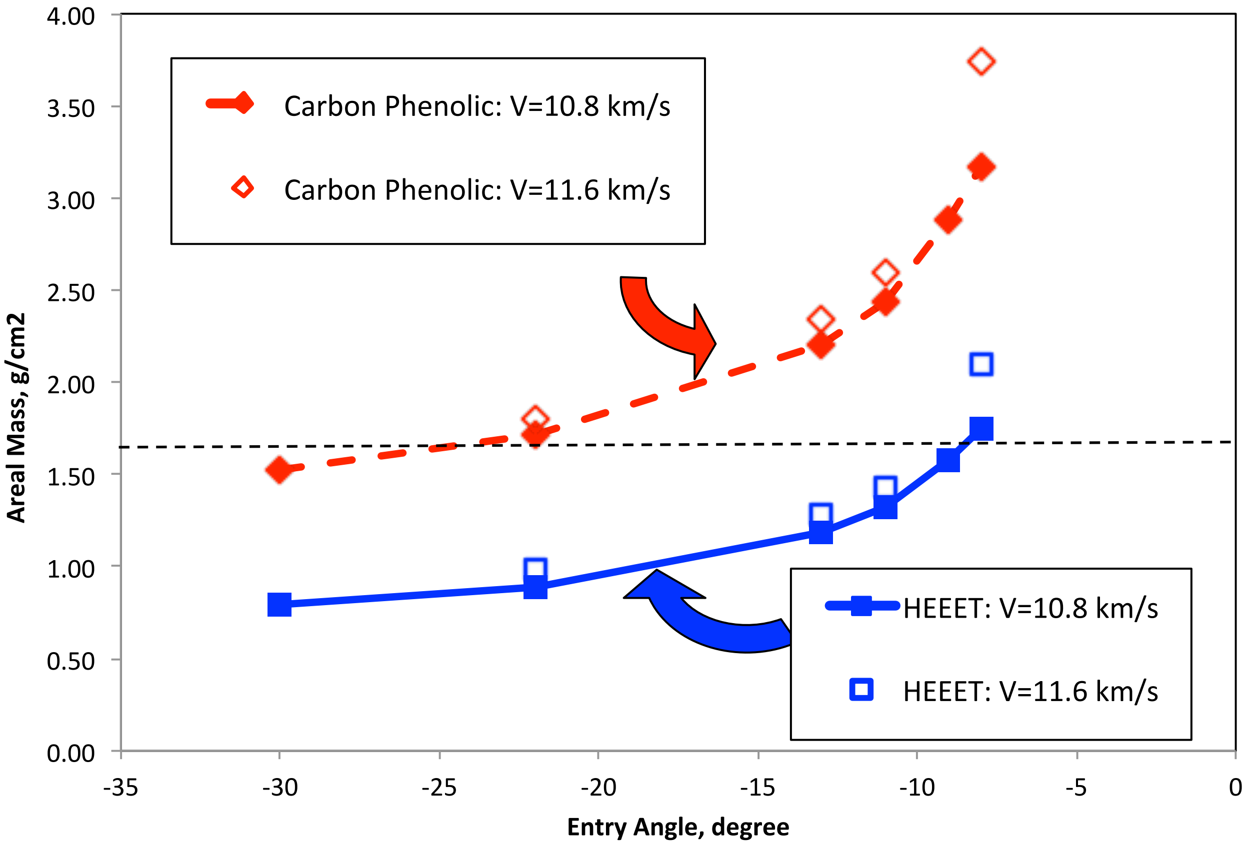


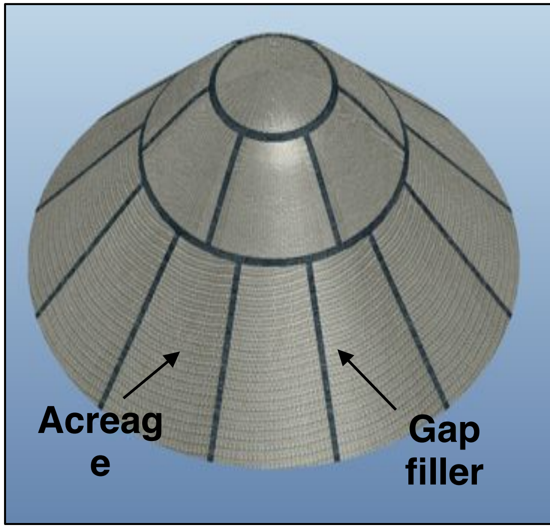
Blended Yarn



Resin infused

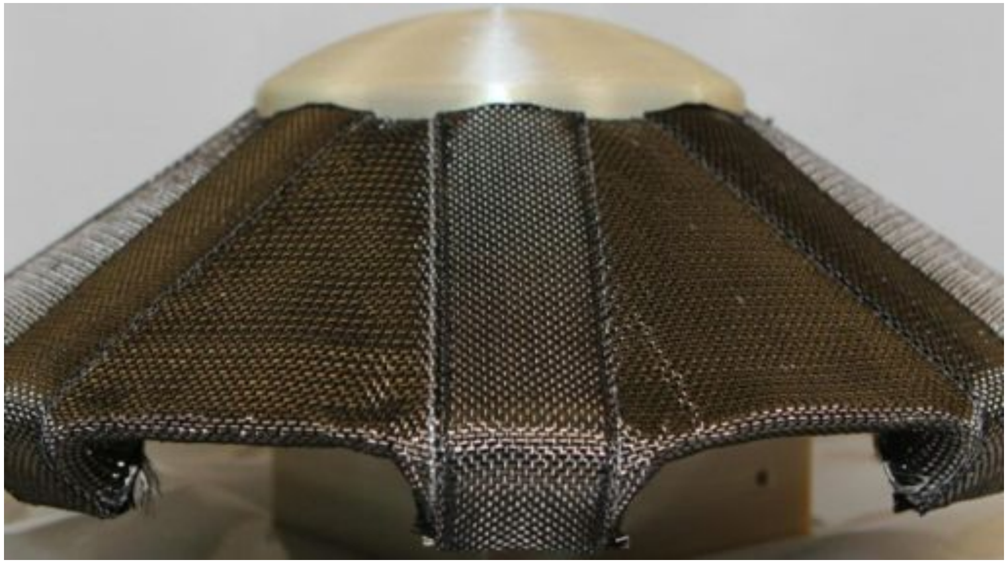
Potential Mass Savings!





- Improved mass efficiency of woven TPS material for Venus entry
  - More mass for instrumentation
  - Lower G loads

Deployable Heat Shield Concept



Test model of deployable system

TPS:

- 6 layers of carbon fiber weave (3D weave)
- Has to withstand aerodynamic and aerothermal loads.
- Medium Heat Rate Capability (250 W/cm^2)

Deployment system

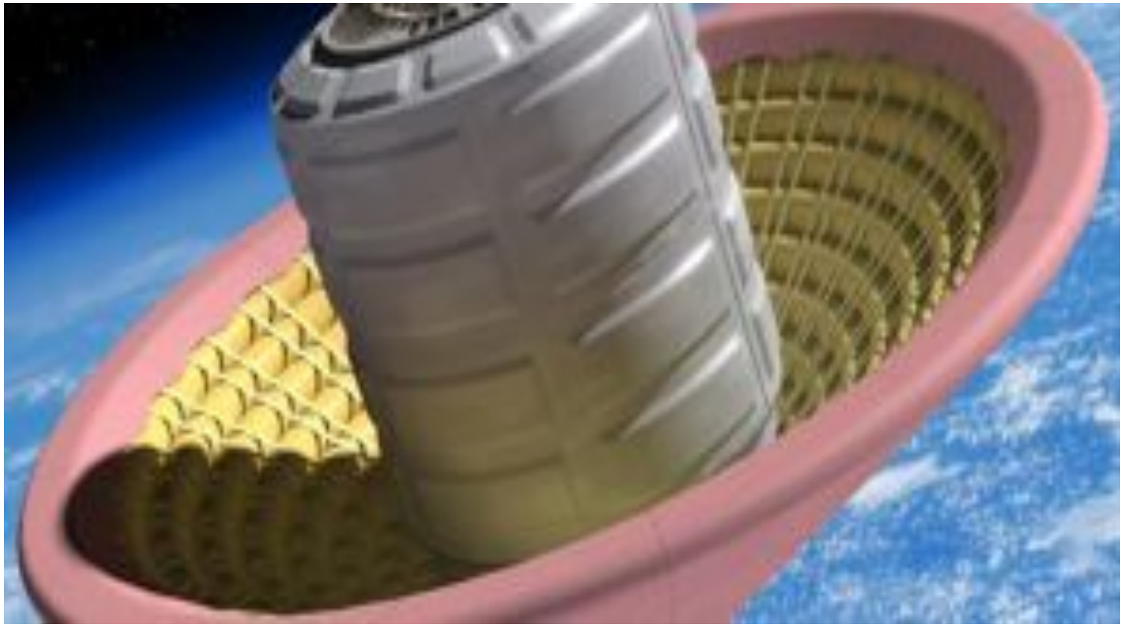
Current concepts for Venus exploration

Potential for expansion to Mars entry (~16m diameter)

Large sizes will place significant demands on structure and mechanisms

Inflatable Heatshield Concept

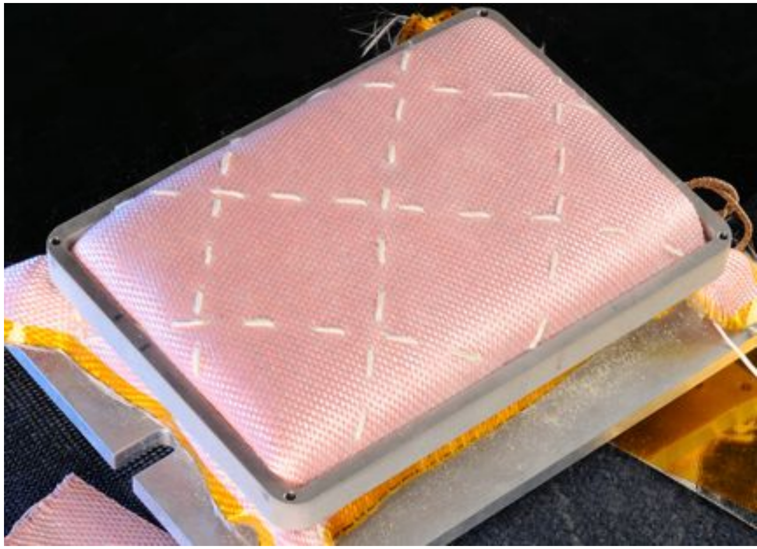
Inflatable structure with a flexible TPS



Inflatable aeroshell covered in TPS

High **E**nergy **A**tmospheric **R**eentry **T**est (HEART)

Current testing in few meter diameter range.
16-20m required for Mars entry and ~20t load.
Issue: long term leakage.



TPS
Outer heat resistant layer
Middle insulating layer
Inner non-permeable layer
Example: SiC/carbon felt layers impregnated with pyrogel

Materials for High Speed Earth Entry

- Capability is related to the density of the materials
  - Using low density materials at very high heat fluxes leads to rapid recession
- PICA/advanced PICA—capable up to 11km/sec (lunar return), probably more capable but not fully tested
  - Stardust (<1m) came in at 12.6m/s (1200W/cm^2)
  - Testing up to 2000W/cm^2 in progress
- Woven TPS: tested up to 8000W/cm^2
- Conformable PICA capable maybe up to 1000W/cm^2, but recession/shear need to be better characterized
- Need new materials and concepts that allow for
  - Tailored materials—different properties through thickness to reduce mass and improve performance
  - Handle radiative entry heating as well as convective heating:surface treatments to reflect radiation
  - Anti-catalytic coatings that prevents release of heat at the surface

Key is to balance design and materials to make efficient and reliable TPS for space exploration.

TPS Solutions Availability

- Potentially available for Venus and Saturn (3D woven TPS, deployable aeroshells)
- Potentially available for landing cargo on Mars
  - Deployable or inflatable concepts for heavy loads
- Current materials probably satisfactory for landing small human craft on Mars
  - PICA, existing ablators
  - Could also use deployable or inflatable concepts
- Returning people or samples to earth
  - Current materials not sufficient for high speed (>~13.5km/s) entry of Orion type vehicle
  - Can design mission to involve transfer or use of smaller vehicles but involves risk and complexity

Remaining TPS Needs

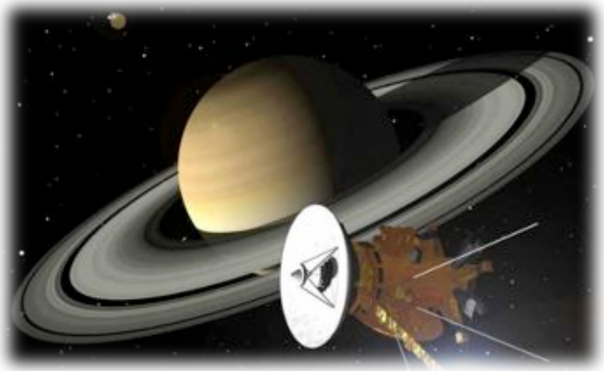
- Improve existing concepts and develop higher capability materials
- Capability to test in relevant environments and provide data for modeling
- Characterize materials to understand behavior
- Develop computational materials approaches to design, processing and lifetime prediction

Concluding Remarks

- Space exploration is exciting but not easy!
- Many systems require new technology
- Challenges are always
  - Mass reduction
  - Radiation protection
  - Reliability
- Affordability is also key to success

Materials innovations are key to success of critical integrated systems

Materials will enable much of the dream!



Acknowledgements

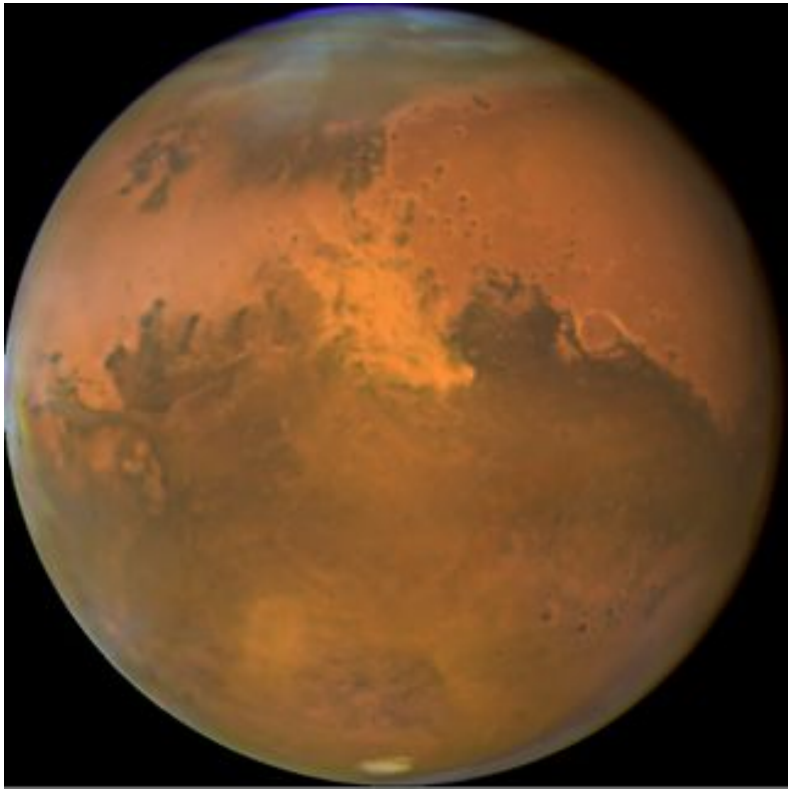
- Thomas Squire (NASA-ARC)
- Joseph Conley (NASA-ARC)
- Pete Lillehei (NASA-LaRC)
- Mairead Stackpoole (NASA-ARC)
- Alan Cassell (NASA-ARC)
- All the people who have worked on these technologies

National Aeronautics and Space Administration

Ames Research Center
Entry Systems and Technology Division

Mars: Not such a Friendly Place

- Mars has a gravity ~1/3 that of Earth
- Thin atmosphere (CO_2) (~0.6% of Earth sea-level pressure)
- No molten iron core, no consistent magnetic field, so radiation (solar and cosmic) is a constant issue
- Sandstorms (dust generation)



Mars in a sandstorm (2005)

NASA: Hubble Telescope

Image from NASA

Earth Reentry Overview

- Atmospheric reentry vehicles require thermal protection systems (TPS) because they are subjected to intense heating

- Heating is dependent on:
  - Vehicle shape
  - Entry speed and flight trajectory
  - Atmospheric composition
  - TPS material composition & surface properties

- Reentry heating comes from two primary sources
  - Convective heating from both the flow of hot gas past the surface of the vehicle and catalytic chemical recombination reactions at the surface
  - Radiation heating from the energetic shock layer in front of the vehicle

Rigid, Conformable and Flexible TPS

Physical Forms of TPS

- Rigid – fabricated in a rigid form and usually applied in a tiled configuration to a rigid substructure
- Conformable – fabricated in a flexible form and shaped to a rigid substructure; final form may be rigid or compliant
- Flexible – fabricated and used in a flexible form, where flexibility is an essential component of the heatshield, e.g., deployable systems, stowable systems
- Woven – can be any of the above

Systems Challenges & Materials Needs

Materials	Mass Reduction	Radiation Protection	Reliability
Lightweight structural materials	✓	✓	✓
Computationally designed materials	✓	✓	✓
Flexible material systems	✓	✓	✓
Materials for extreme environments	✓	✓	✓
Special materials	✓	✓	✓

Affordability: Key to extent and timing