



Thermal Protection Materials: Development, Characterization and Evaluation

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Acknowledgements

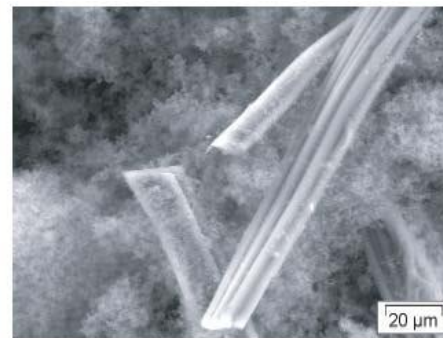
- NASA: Thomas Squire, Robin Beck, Don Ellerby, Matt Gasch, Mairead Stackpoole, Helen Hwang, Deepak Bose, Frank Milos, Joe Conley, Dan Leiser, David Stewart, Ethiraj Venkatapathy, Bernie Laub
- ERC: Jay Feldman

Everyone who works in the field of TPS.



Outline

- Introduction
- Thermal Protection Materials and Systems (TPS)
 - Reusable materials
 - Sharp leading edges (Ultra high temperature ceramics (UHTCs))
 - Ablative materials
 - New materials under development
- Characterization of TPS for Performance and Design
- A Tale of Two Heat Shields
 - Recent Uses and Development of Heat Shields and Materials Issues





Introduction

- NASA Ames focused on:
 - Qualifying and certifying TPS for current missions
 - Developing new TPS for upcoming missions
- Approaches to TPS development differ with risk — crewed vs. robotic missions:
 - Crewed
 - Loss of life must be avoided
 - What must be done to qualify and certify TPS?
 - Robotic missions
 - Can take more risk
 - But scientific knowledge can be lost too
- Goal for all TPS is efficient and reliable performance
- Need to understand materials to enable design and use



Thermal Protection Systems

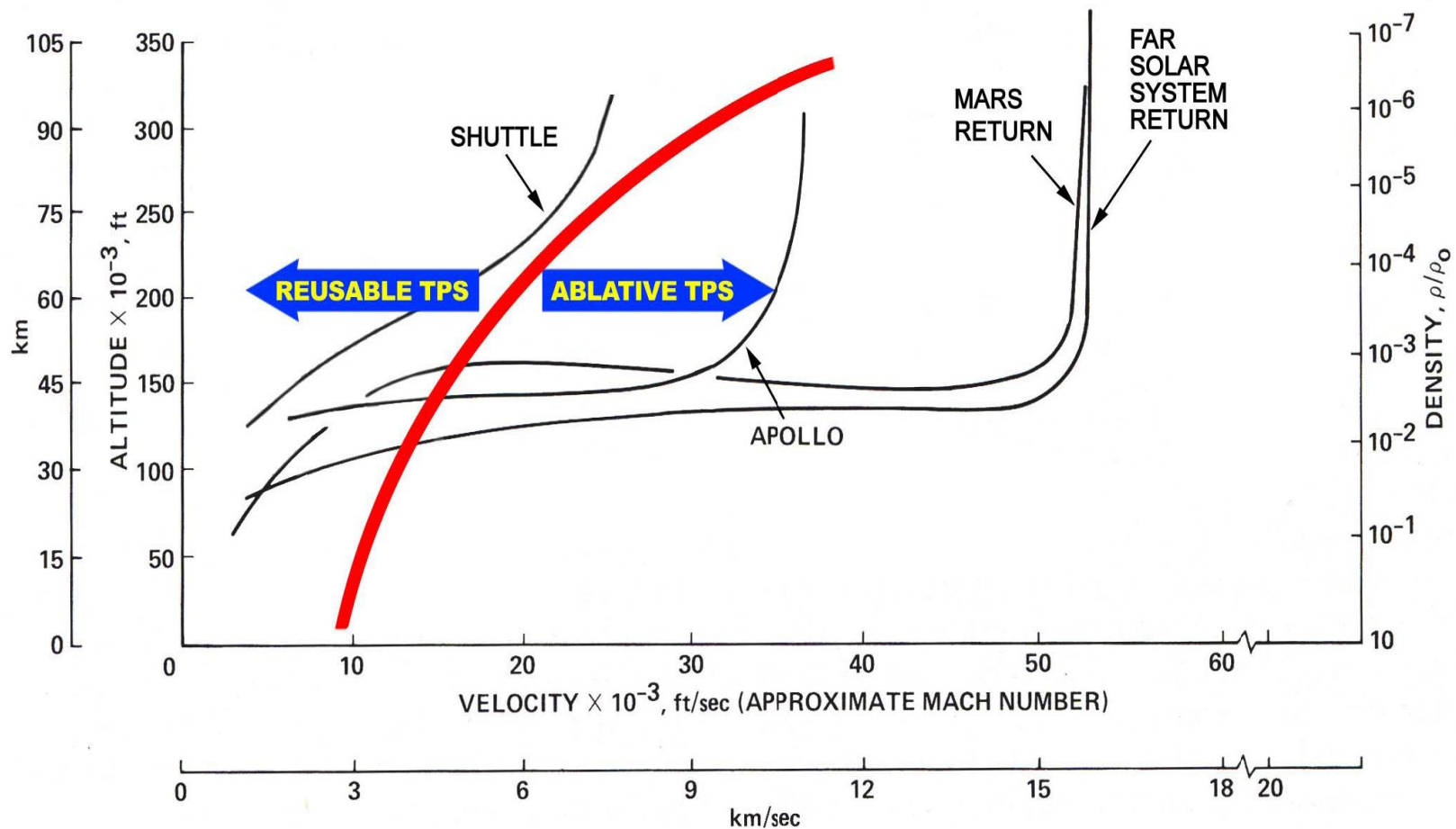
- Protect vehicle structure and contents (people and things) from the heat of entry through an atmosphere
- Rely on materials response to environment
- Response depends on
 - Material properties
 - Configuration of the system
 - Specific conditions (heat flux, pressure, flow)

One size does not fit all!

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



Reusable vs. Ablative TPS

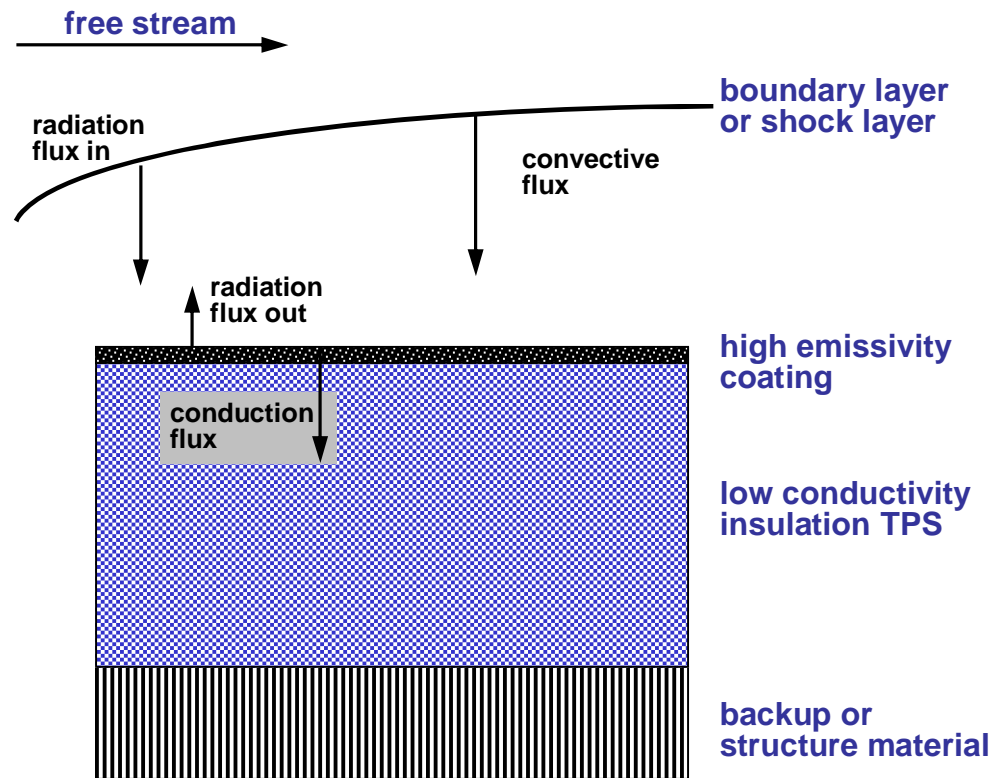


Insulative TPS

Energy management through storage and re-radiation — material unchanged

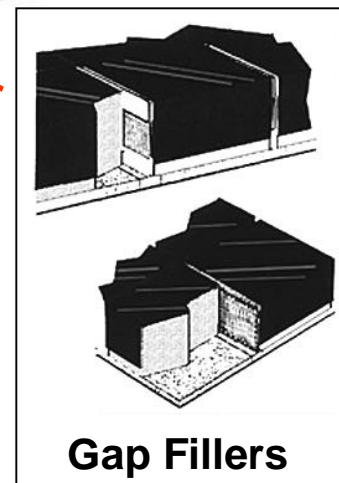
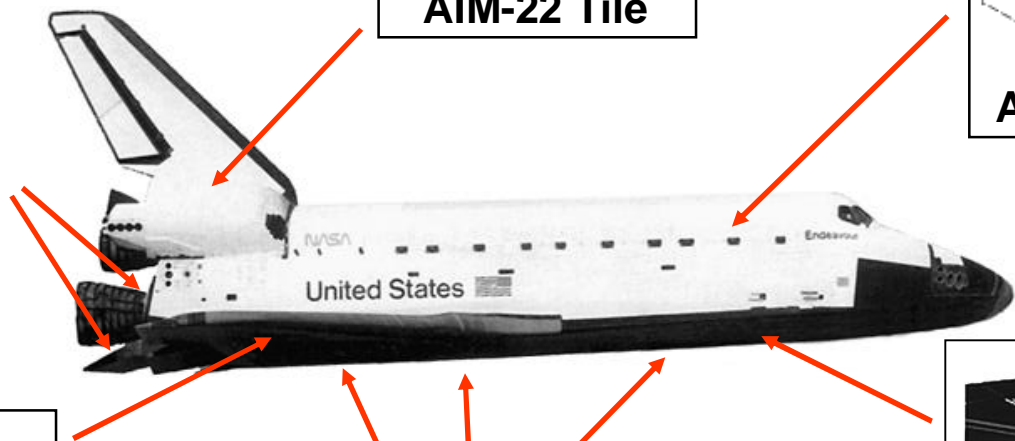
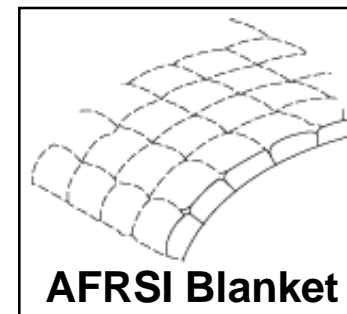
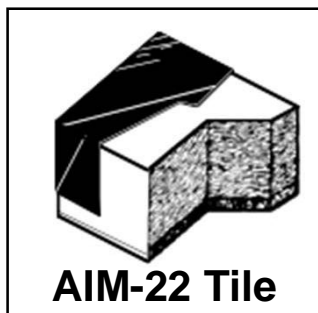
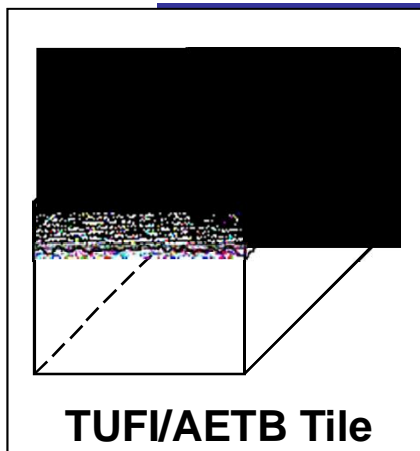
When exposed to atmospheric entry heating conditions, surface material will heat up and reject heat in the following ways:

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





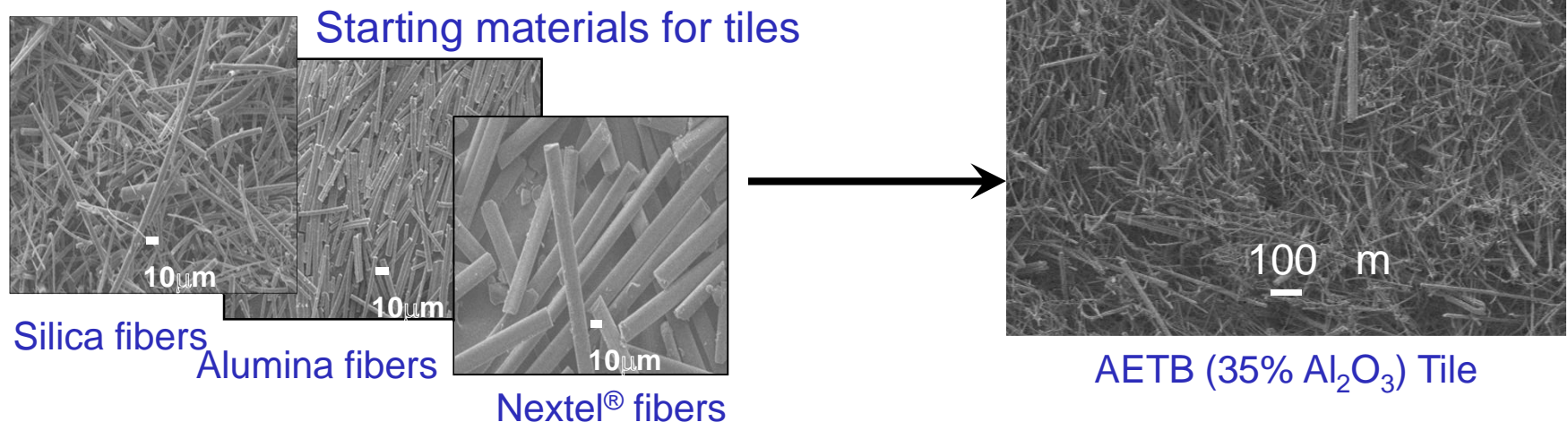
Ames-Developed Thermal Protection Materials Used on Shuttle





Reusable TPS: Tiles

- Effort started in 1970's by ARC to provide NASA with TPS materials and processing expertise
- Insulation materials used to protect the aluminum sub-structure of the shuttle.
- High purity silica, aluminoborosilicate, and alumina fibers
- LI-900, FRCI-12, AETB-8
- Open porous structure
- Used on over 100 shuttle missions

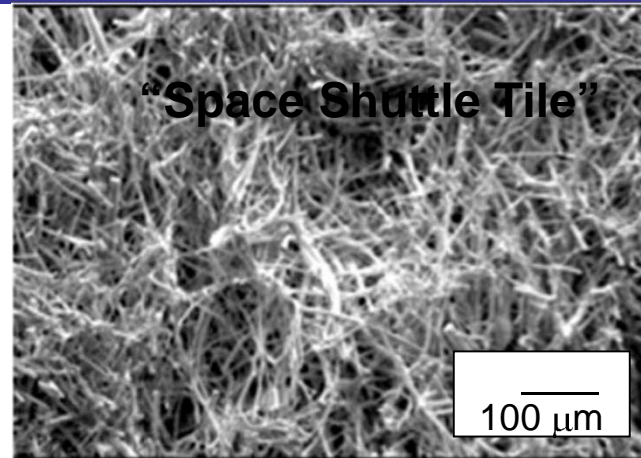


Tiles are heterogeneous with regions of low density and clumps of fibers with some nonfibrous inclusions

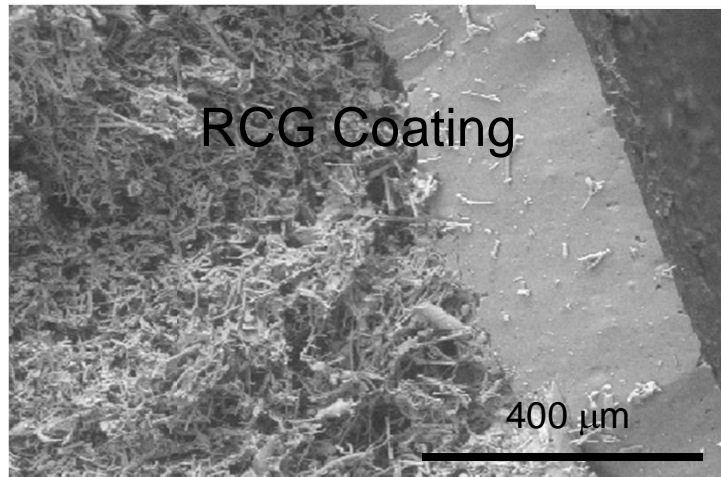


Reusable TPS: Coatings

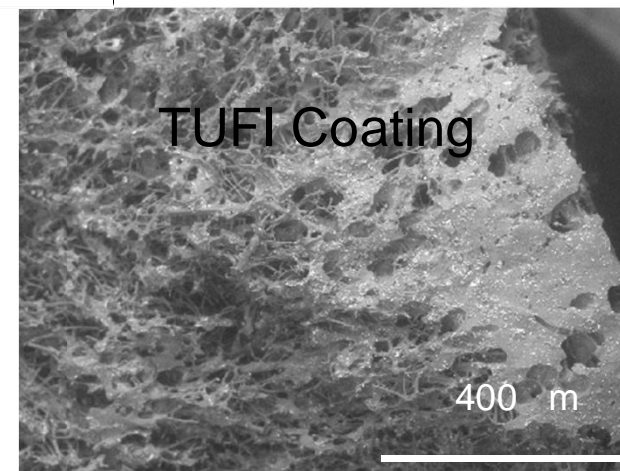
RCG: Reaction Cured Glass
TUFI: Toughened Unipiece Fibrous Insulation



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



- 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



Shuttle Flight Testing of LI-900/RCG vs AETB-8/TUFI in Base Heatshield



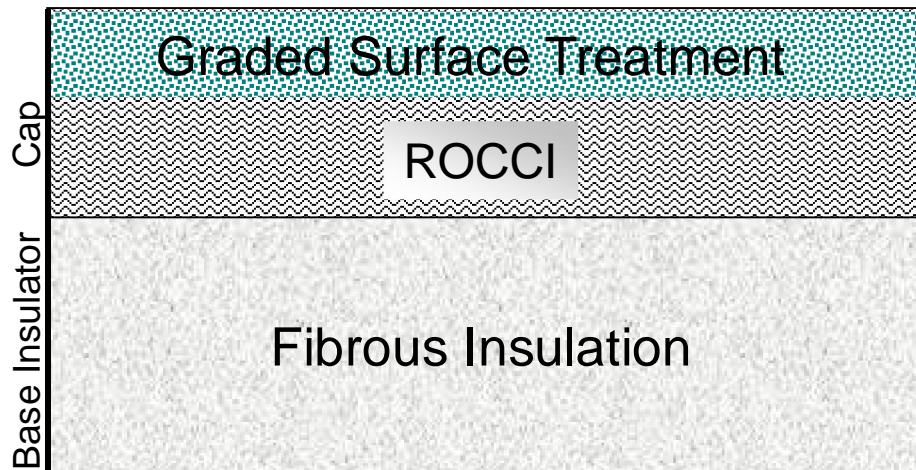
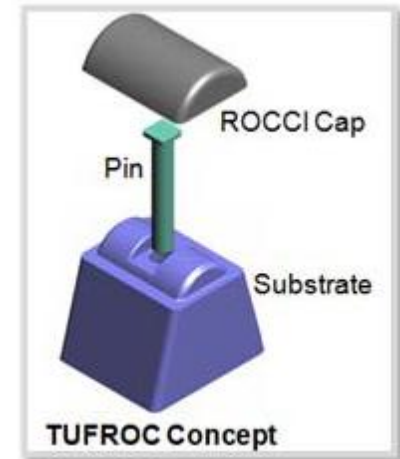
TUFI/AETB-8 Tiles Undamaged After
Three Flights



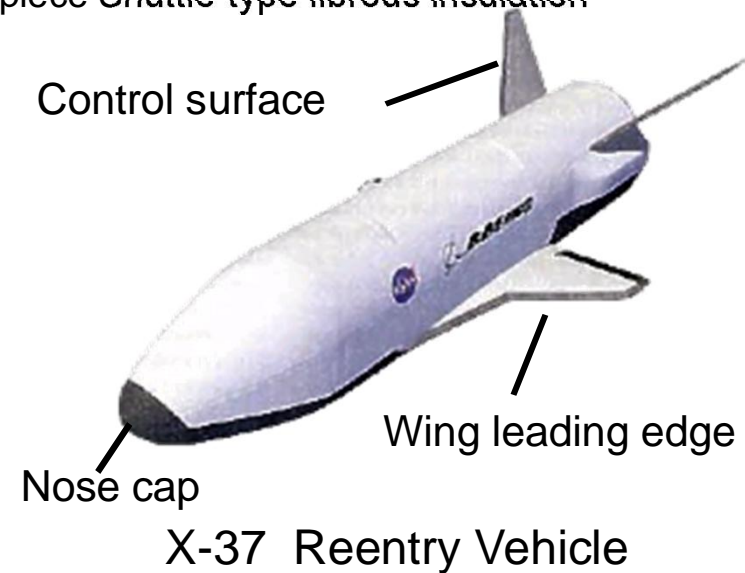
Development of Advanced TUFROC TPS

(Toughened Unipiece Fibrous Oxidation Resistant Ceramic)

- Developed TUFROC for X-37 application
- Advanced TUFROC developed recently
- Currently transferring technology to Boeing
- System parameters:
 - Lightweight (similar to LI-2200)
 - Dimensionally stable at surface temperatures up to 1922 K
 - High total hemispherical emittance (0.9)
 - Low catalytic efficiency
 - In-depth thermal response is similar to single piece Shuttle-type fibrous insulation



Schematic of TUFROC TPS



X-37 Reentry Vehicle



X-37B after Landing



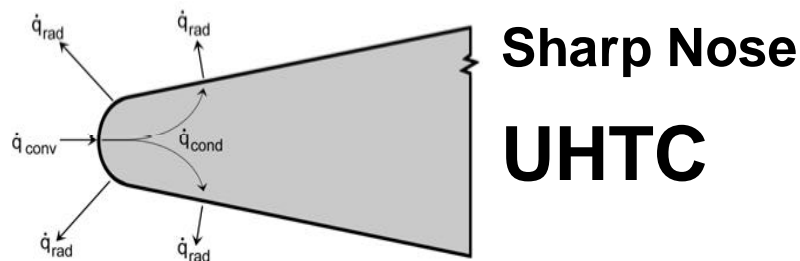
TUROC is on Leading Edges

<http://www.popsci.com/technology/article/2012-06/air-forces-mysterious-x-37b-space-plane-returns-earth-after-15-months-orbit>



Sharp Leading Edge Energy Balance

- Insulators and UHTCs manage energy in different ways:
 - Insulators store energy until it can be eliminated in the same way as it entered
 - UHTCs conduct energy through the material and reradiate it through cooler surfaces

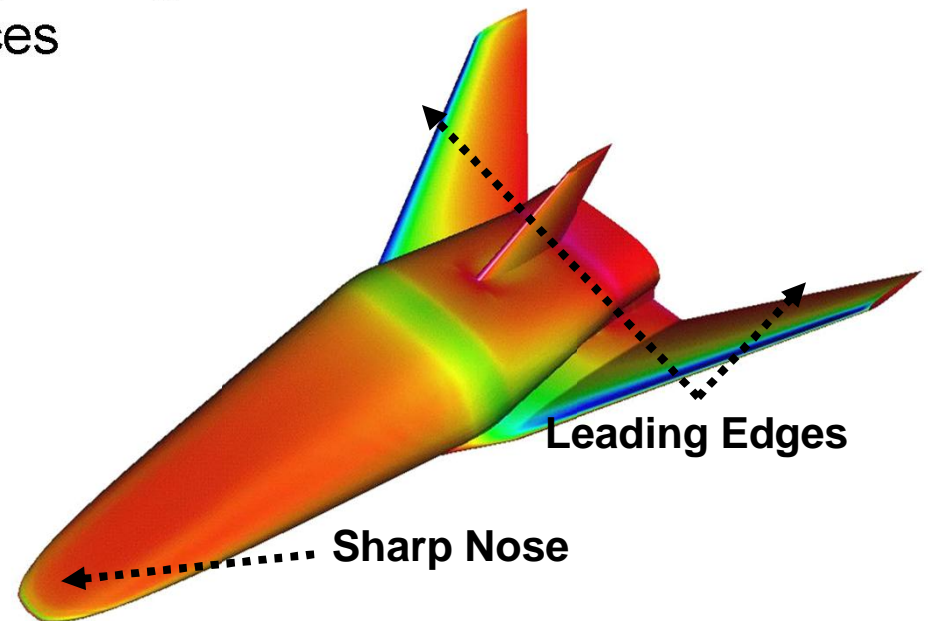


Sharp Nose

UHTC

High
Thermal

$$\dot{q}_{conv} = \dot{q}_{rad} + \dot{q}_{cond}^{activity}$$



Leading Edges

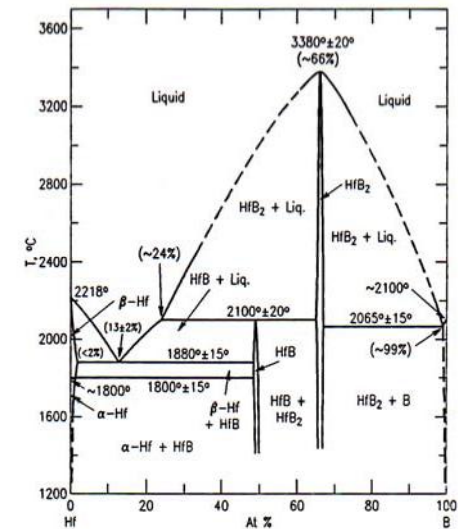
Sharp Nose

Dean Kontinos, Ken Gee and Dinesh Prabhu. "Temperature Constraints at the Sharp Leading Edge of a Crew Transfer Vehicle." AIAA 2001-2886 35th AIAA Thermophysics Conference, 11-14 June 2001, Anaheim CA

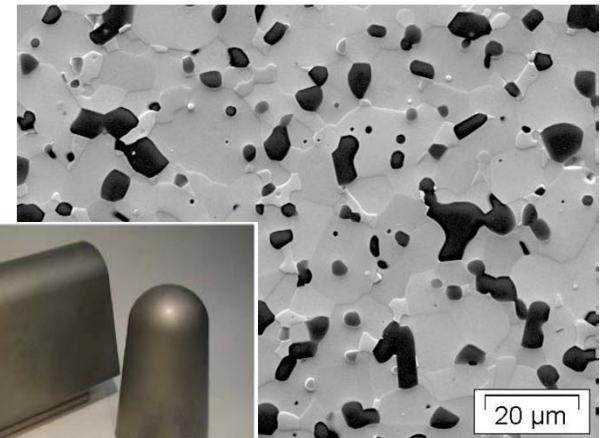


Ultra High Temperature Ceramics (UHTCs) : A Family of Materials

- Borides, carbides and nitrides of transition elements such as hafnium, zirconium, tantalum and titanium
- Some of highest known melting points
- High hardness, good wear resistance, good mechanical strength
- Good chemical and thermal stability under certain conditions
 - High thermal conductivity
 - Good thermal shock resistance
- The microstructure of UHTCs clearly shows their composite nature
 - Distribution of material phases
 - Flaw size and distribution



Hf-B Phase Diagram



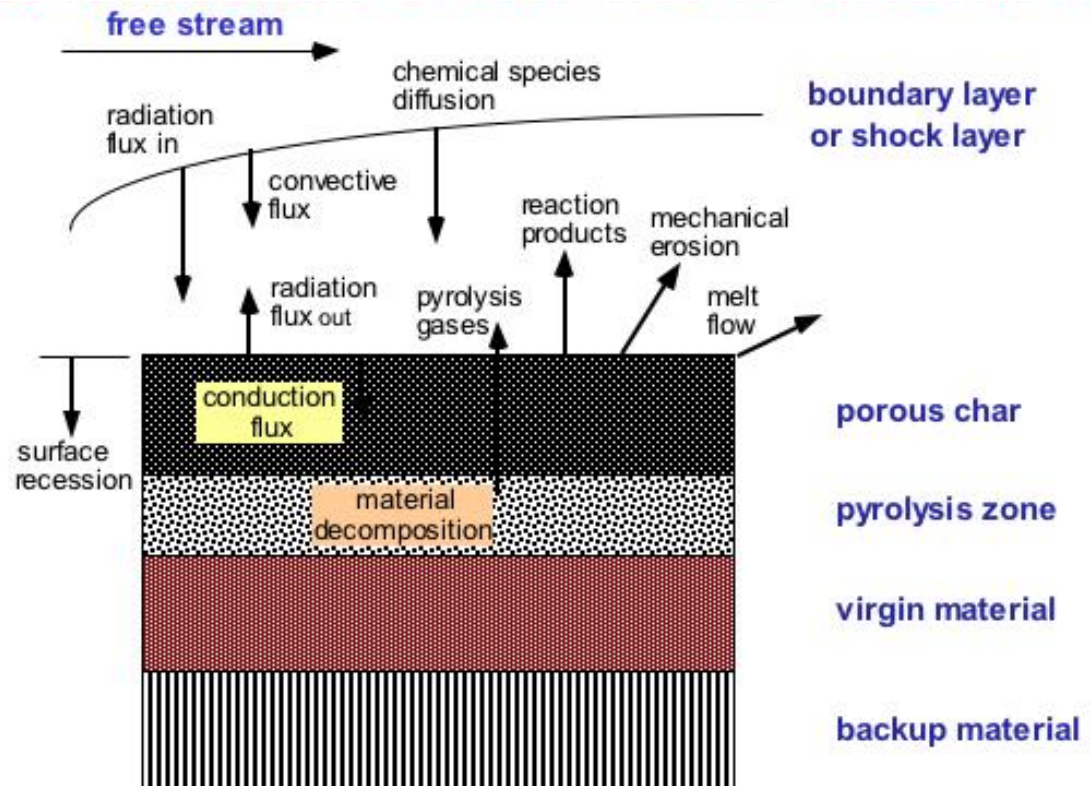


Ablative TPS

Energy management through material consumption

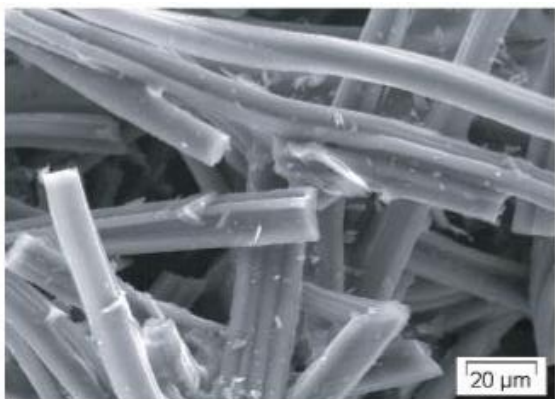
When exposed to atmospheric entry heating conditions, material will pyrolyze (char), and reject heat in the following ways:

- Pyrolysis of polymer
- Blowing in boundary layer
- Formation of char layer and re-radiation

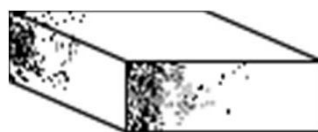




PICA Processing

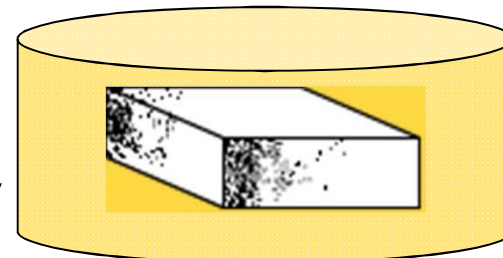


Fiberform™ before impregnation

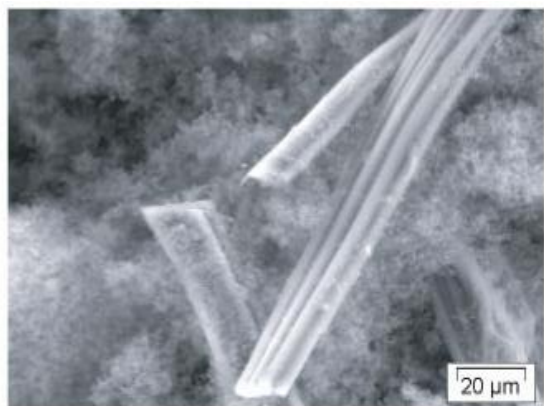


Carbon Fiberform™

Phenolic Resin



Resin Impregnation

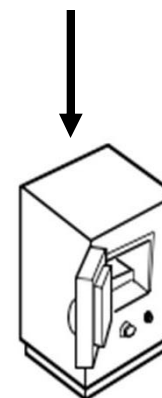


PICA: Fiberform™ with phenolic resin



PICA Arc Jet Model

Drying Cycle





PICA Background

- Phenolic Impregnated Carbon Ablator (PICA) was an enabling TPS material for the Stardust mission where it was used ***as a single piece heatshield***
- PICA has the advantages of low density ($\sim 0.27\text{g/cm}^3$) coupled with efficient ablative capability at high heat fluxes
- PICA is the primary heatshield for Mars Science Lab (MSL) and SpaceX's Dragon vehicle in ***a tiled configuration***

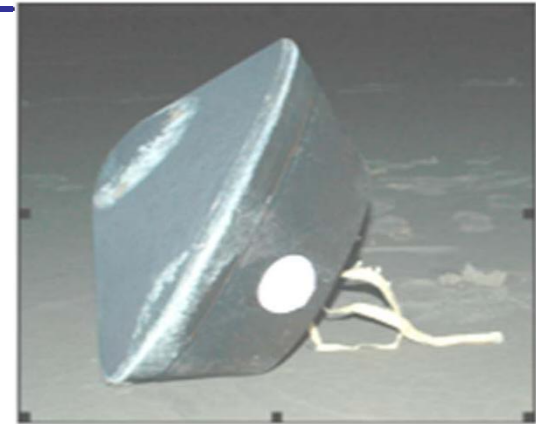
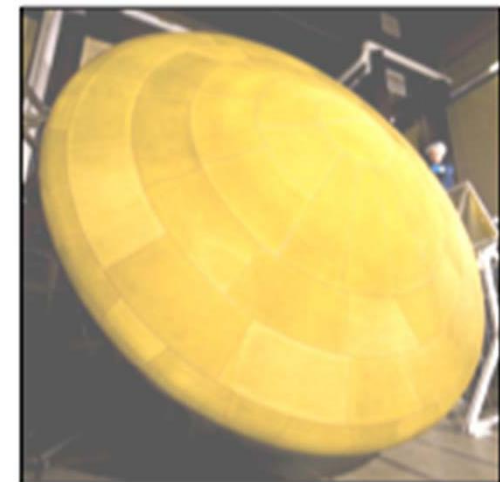


Image of the sample return capsule post flight with PICA as the forebody TPS. (0.8m diameter)

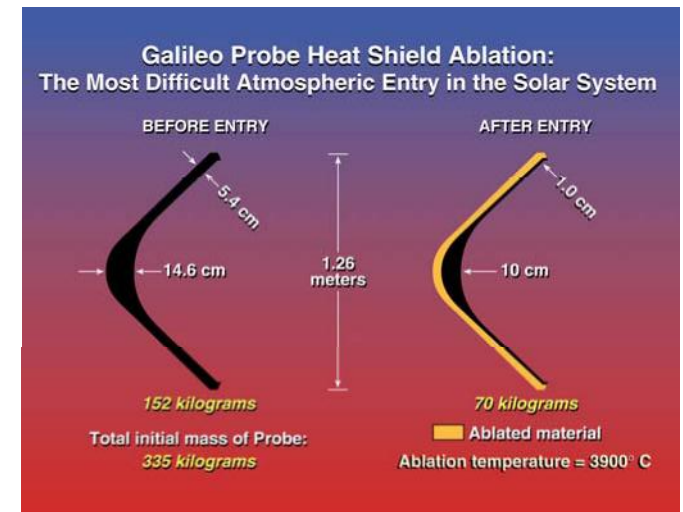


MSL Heat Shield
(4.5m diameter)



Carbon Phenolic TPS

- Carbon Phenolic TPS
 - 1960s: fully dense (1.45-1.5 g/cm³) carbon phenolics were optimized
 - only materials available for use at very high heat fluxes and high pressure conditions, yet the least favorable in terms of density
- Carbon phenolic material made from carbon fiber weaves fully infiltrated with phenolic resin
- Current effort to investigate approaches to fabricating carbon phenolic materials
 - Issues with fiber supplies
- Carbon phenolic TPS was used on Galileo heat shield for very demanding entry into Jupiter's atmosphere





What are Rigid, Conformable and Flexible Ablative Materials?

- 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



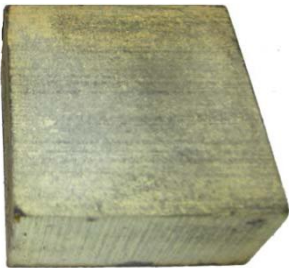
Conformable/Flexible Ablators

- Fibrous substrate, such as felt, woven cloth
- Matrix of various resins and fillers
- Flexible/conformable ablators have significant design, system integration, and performance advantages compared to rigid ablators
 - Manufacturability
 - Reduction in piece-parts
 - Ease of assembly
 - Enables larger diameter aeroshells
 - Eliminates gap and seam issues (thermo-mechanical, aero-physics phenomena)



Families of Ablators Under Development

Rigid Ablators



Advanced PICA-like ablators



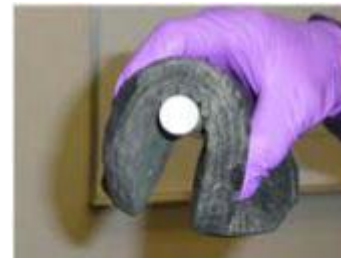
Graded Ablators

Conformable Ablators



Conformable PICA

Flexible Ablators



Flexible PICA

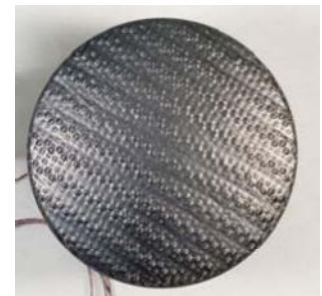


Flexible SIRCA

Woven TPS



Mid density TPS

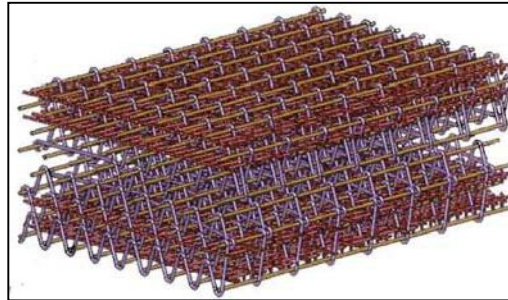
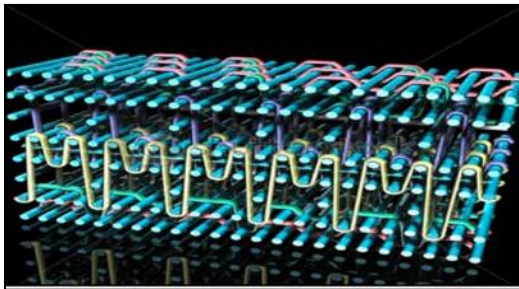


Carbon phenolic replacement



What is the 3D Woven TPS concept?

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



- Ability to design TPS for a specific mission
- Tailor material composition by weaving together different types of fibers (e.g. carbon, ceramic, glass, polymeric)
- One-step process for making a mid-density dry woven TPS
- Ability to infiltrate woven structure with a polymeric resin to meet more demanding thermal requirements



Characterization of TPS

- Why characterize materials so extensively?
 - Evaluate performance
 - Select appropriate materials
 - Verify manufacturing reliability
 - Enable modeling of behavior
 - Design system/heatshield
 - Correlate processing and properties to improve materials

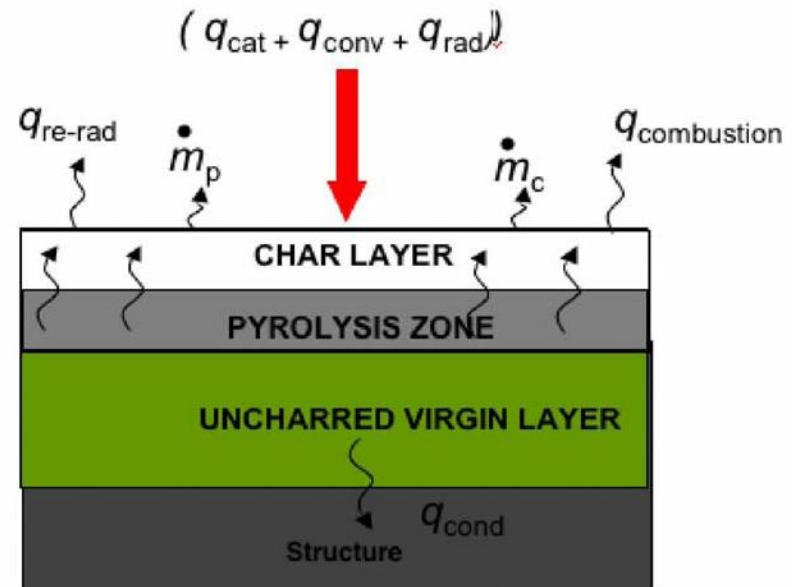


Manufacturing Variability

- Real-world manufacturing processes have inherent variability.
 - These variations can lead to scatter in the material properties.
- Necessary to quantify allowable lot-to-lot and in-lot variability of properties.
 - This may also include acceptable flaw and inclusion size.

Example: Ablator Properties

- Evaluating:
 - Virgin/char strength
 - Recession rate
 - Thermal conductivity
- Evaluating the interconnection between properties
 - Tradeoffs
 - Greater density = greater strength, but generally increased thermal conductivity



Single use (ablative) TPS



Material Properties

- Thermal properties
 - Thermal conductivity, specific heat, thermal expansion
- Physical properties
 - Density, hardness, emissivity
- Mechanical properties
 - Strength, elastic modulus, toughness
- Properties may vary with temperature and/or pressure (porous materials)
- Microstructure depends on processing and composition



Properties for Modeling and Design of Ablators

Thermal Response Model

Density (virgin/char)

Thermal Conductivity (virgin/char)

Specific Heat (virgin/char)

Emissivity & Solar Absorptivity (virgin/char)

Elemental Composition (virgin/char)

Thermal Gravimetric Analysis

Porosity & Gas Permeability

Heat of Combustion (virgin/char)

Heat of Pyrolysis

Thermal Structural Analysis

Tensile:
strength, modulus, strain to failure

Compressive:
strength, modulus, strain to failure

Shear:
strength, modulus, strain to failure

Poisson's Ratio

Thermal Expansion (virgin/char)

TPS/Carrier System Tests

Tensile strength

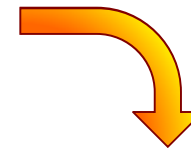
Shear strength



Process for Characterizing Ablators

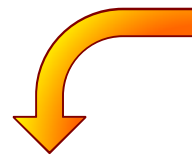
Produce Material

Flight-like production, not model material
Consider mission environments



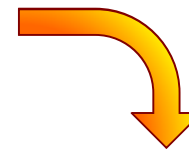
Evaluate Material's Variability

NDE recommended
Insight into construction is critical to determine likely challenges



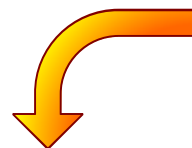
Determine Appropriate Testing Techniques

May depend on material's density and construction
4 cm honeycomb not represented by a 1 cm coupon



Determine Quantity and Sampling Scheme

Influenced by material variability & project scope



Execute Testing & Evaluate Data



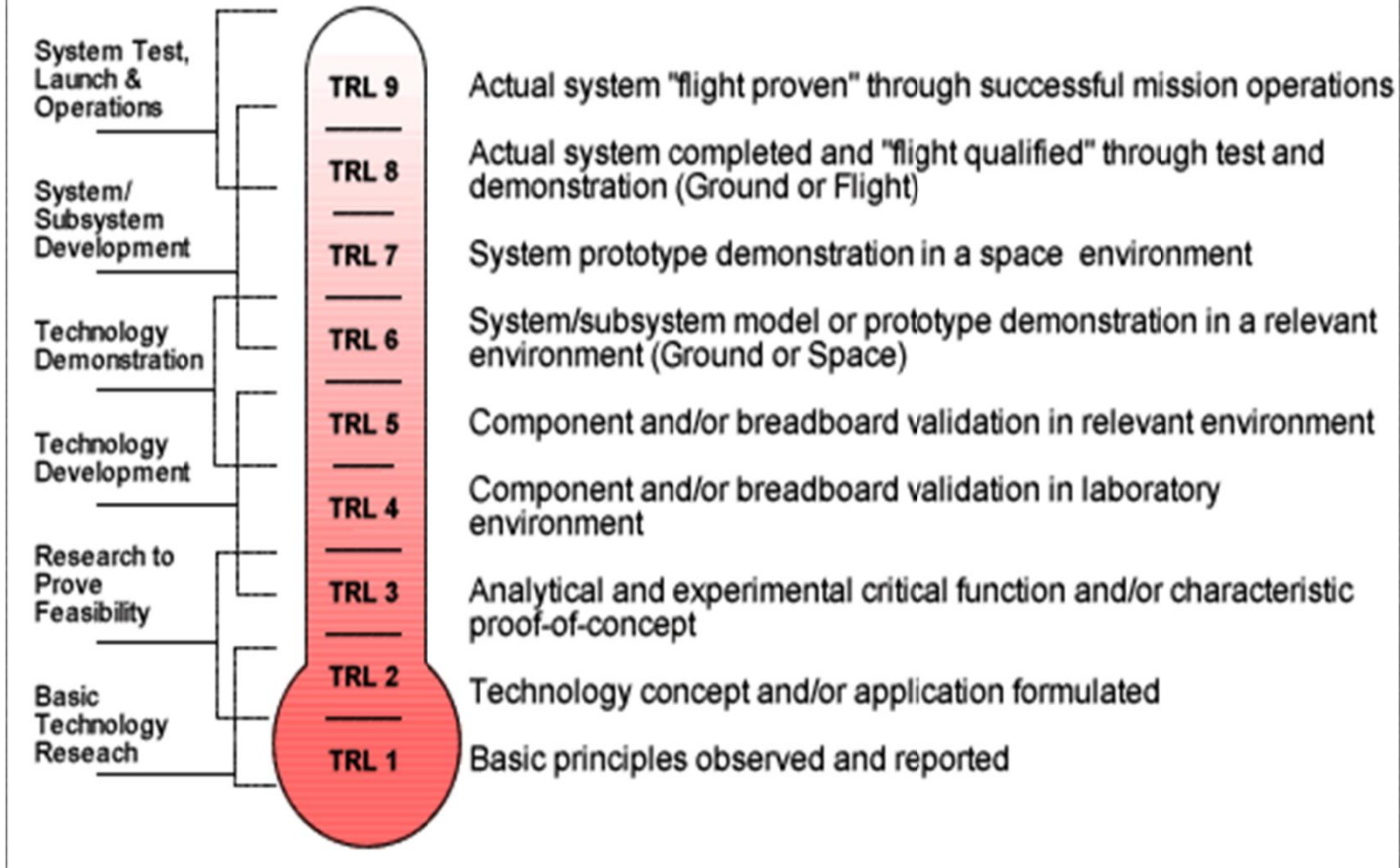
Selection of Appropriate Material

- Historical approach:
 - Use heritage materials: “It’s worked before...”
 - Risk-reduction strategy
 - Limited number of flight-qualified ablative materials
 - Different vehicle configurations and reentry conditions (need to qualify materials in relevant environments)
- As missions become more demanding, we need higher capability materials — necessary to have a robust research and development program
- *Reusable and ablative materials are both needed*
- Must test materials in relevant environments
- Provide path for insertion/use of new materials



Technology Readiness Levels

Technology Readiness Levels (TRLs)





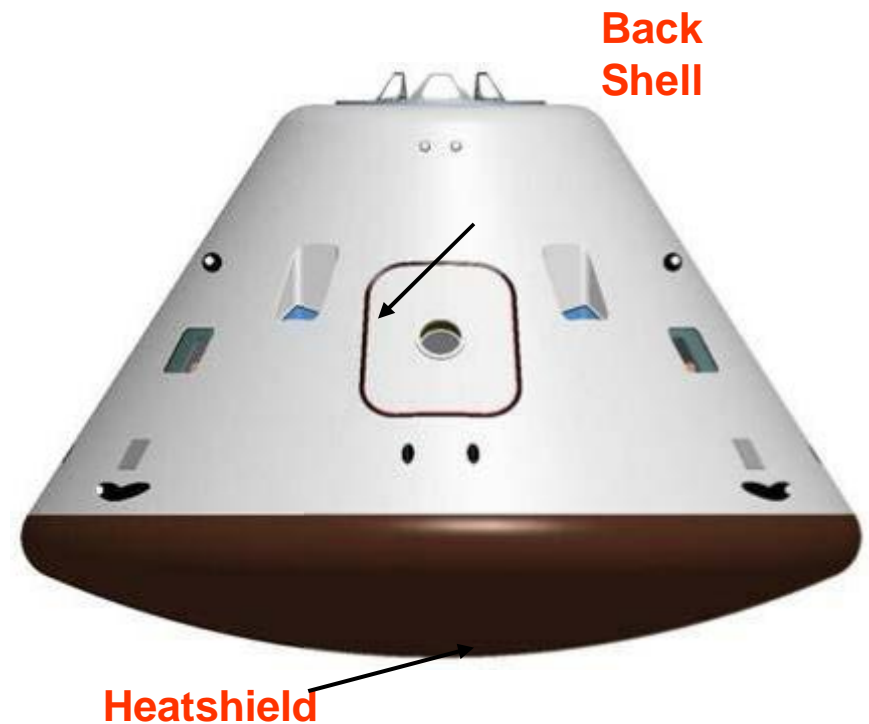
A Tale of Two Heatshields

- 2 Vehicles
 - CEV/Orion/MPCV
 - Mars Science Lab (MSL)
- 2 destinations
 - Earth from the moon
 - Mars from Earth
- 2 materials
 - PICA
 - Avcoat



MPCV (Orion) TPS Requirements

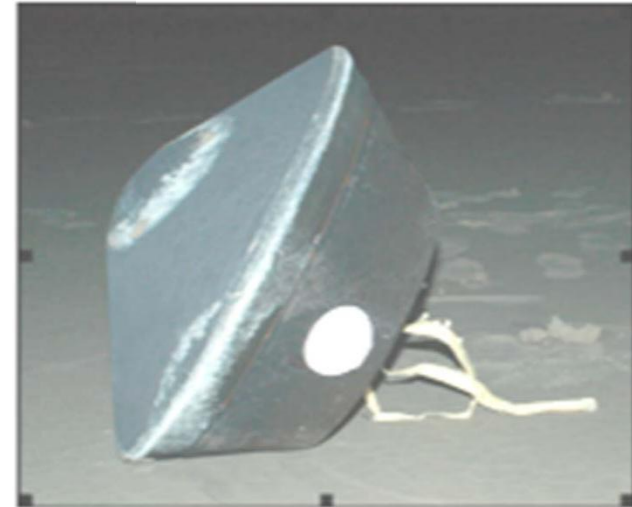
- Multi-purpose Crew Vehicle (MPCV) Lunar Direct Return (LDR) conditions:
 - 11 km/s atmospheric entry
 - peak heat rate $> 1000 \text{ W/cm}^2$
- MPCV Low Earth Orbit (LEO) return conditions:
 - 8 km/s atmospheric entry
 - peak heat rate $> 150 \text{ W/cm}^2$
- **Early TPS development work focused on PICA for this application**





PICA Background

- Phenolic Impregnated Carbon Ablator (PICA) was an enabling TPS material for the Stardust mission (sample return from a comet) where it was used ***as a single piece heatshield***
- ***PICA reached TRL9 for this application and configuration***
- PICA has the advantages of low density ($\sim 0.27\text{g/cm}^3$) coupled with efficient ablative capability at high heat fluxes
- ***As-flown PICA was characterized and compared to model predictions***



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





From PICA

- PICA had heritage...for Stardust
 - Needed development effort for new applications
- PICA was to be used in a tiled configuration
 - Tiles require gap fillers or a way to deal with gaps
 - PICA is a rigid material with a relatively low strength and strain to failure
 - Risk analysis and design indicated that many small tiles would be required, increasing the number of gaps.
- PICA was extensively characterized and considerable effort was put into scale-up and manufacturing



.....to Avcoat

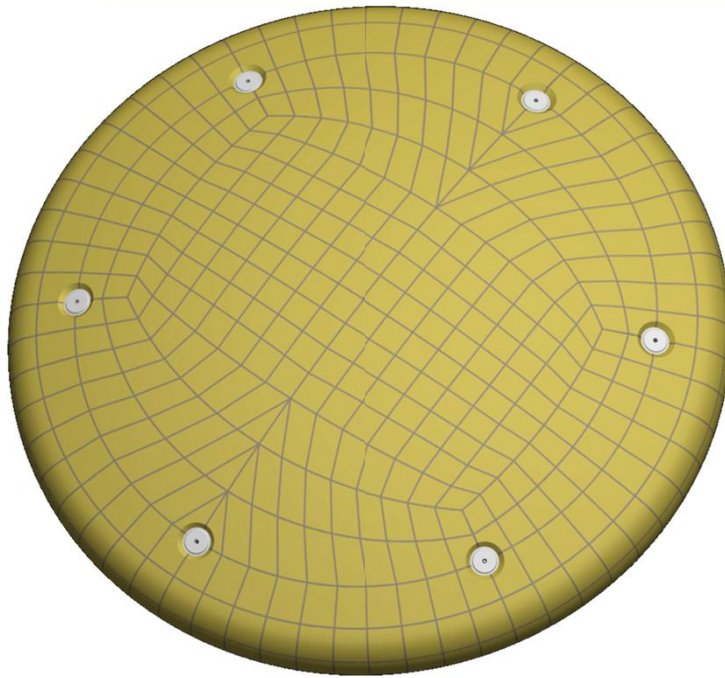
- Avcoat was used on the Apollo vehicles: “heritage” material
- Consists of a honeycomb filled with an ablative mixture
- Reduces gaps
- Complex material requiring hand assembly
- Not made for many years



Before and after
Avcoat arc jet
models



Heatshield Comparison

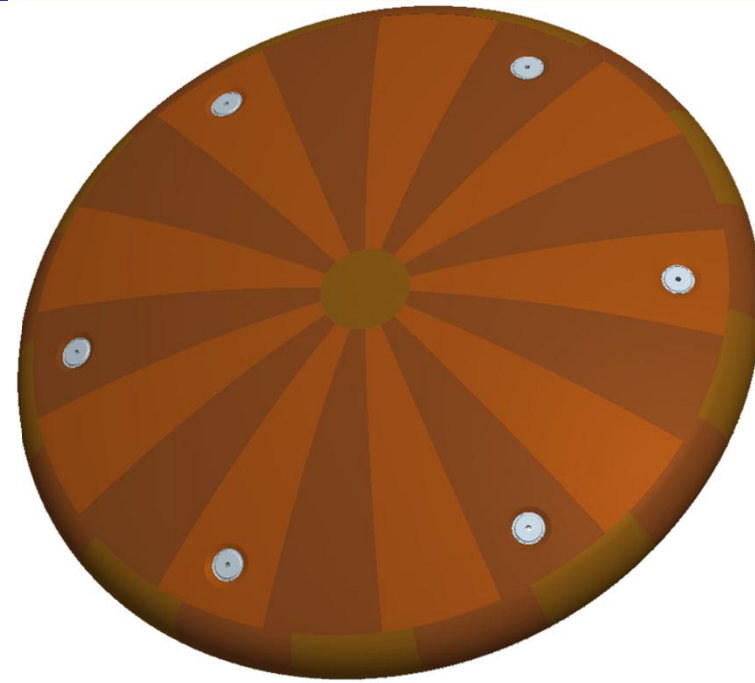


PICA Acreage TPS

Layout:

- 440 tiles
- 133 Unique Tile Planforms
- 832 Gap Fillers

RTV-SIP-RTV attachment to carrier structure



Avcoat Acreage TPS

Layout

- 18 Gore Honeycomb Panels
- 18 Shoulder Panels
- 1 Center Panel

Bond honeycomb to carrier structure and ablator filled-in and cured.



AVCOAT Process Steps

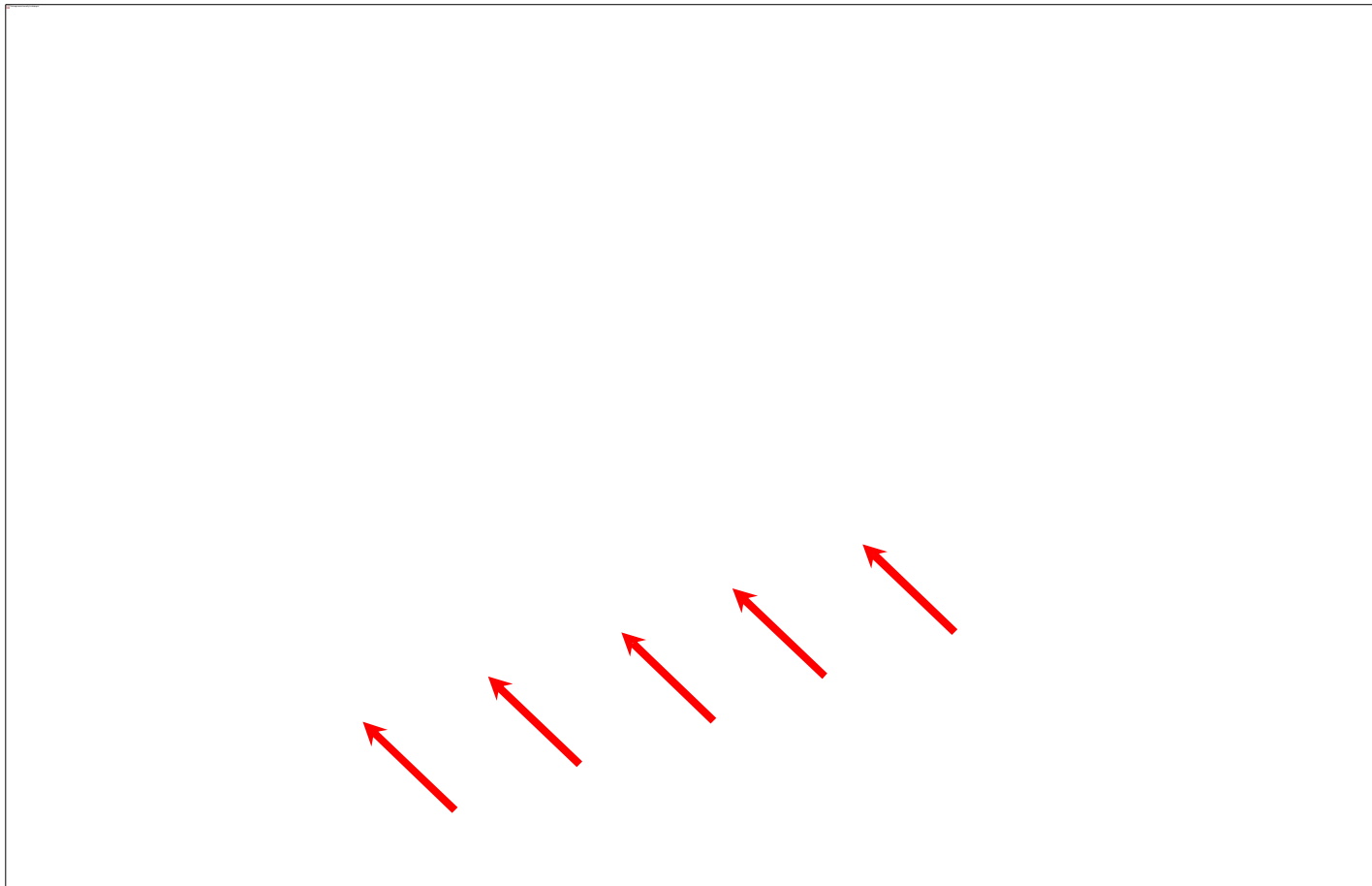
- 9 stages in AVCOAT process
- Complex processes require extensive characterization and understanding to
 - Ensure reliability/reproducibility
 - Prepare/maintain meaningful process specifications





Avcoat for MPCV Heatshield

- Avcoat construction schematic showing the various steps and processes involved in building the honeycombed ablator
- Red arrows indicate areas where process changes were implemented





Issues with “Heritage” Materials

- Know-how may be lost over time
- Materials/components may no longer be available
- Environmental/safety regulations may not allow the use of certain processes
- Recreation of materials can be time and money-consuming
 - \$25+million and 5 years has been spent on recreating Avcoat
- Is it really “Avcoat”?



Meanwhile, Mars Science Lab in Development

- MSL was being fabricated simultaneously with CEV/Orion (MPCV)
- Initial choice for a heatshield TPS was SLA-561V, a heritage honeycomb-based material from Lockheed
- SLA-561V was used on all previous NASA Mars entry missions
- **However**, MSL was much larger



Change of TPS Late in the Game

- Original choice of TPS did not pass shear tests
- Needed to use a more capable TPS
- PICA was chosen
- Previous/ongoing development of PICA for CEV/Orion

Availability of data/processes critical in enabling the heat shield material to be qualified, certified and fabricated in time (18 months)



The Mars Science Laboratory

Launch Date: 11/26/2011

Arrival Date: 08/05/2012





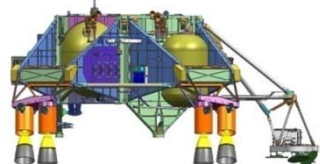
Mars Science Lab (MSL) Spacecraft



Cruise Stage



Backshell



Descent Stage



Rover



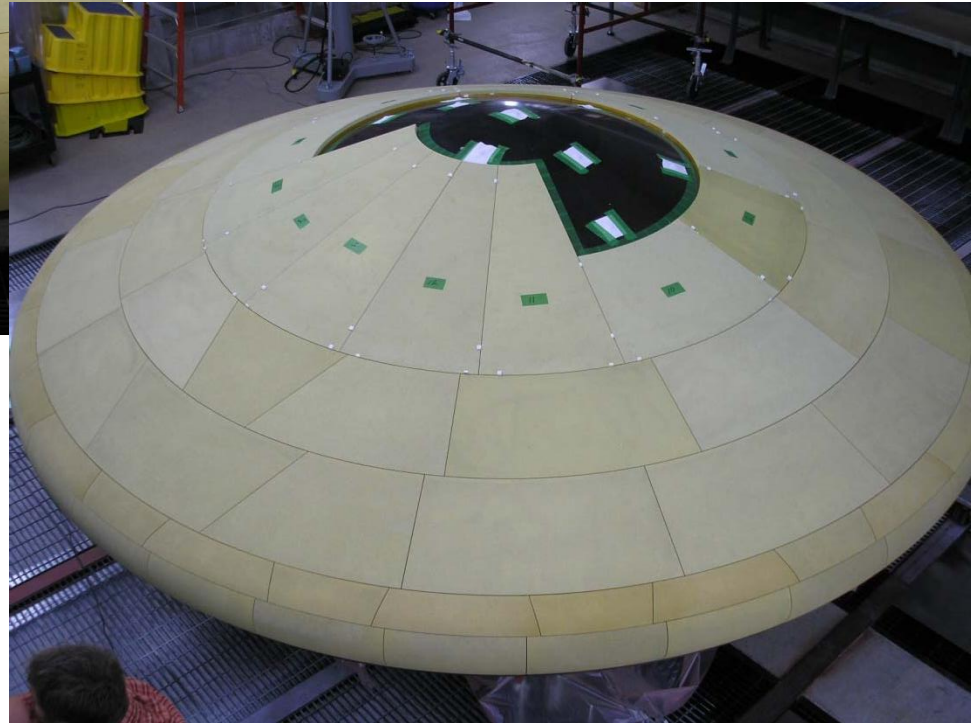
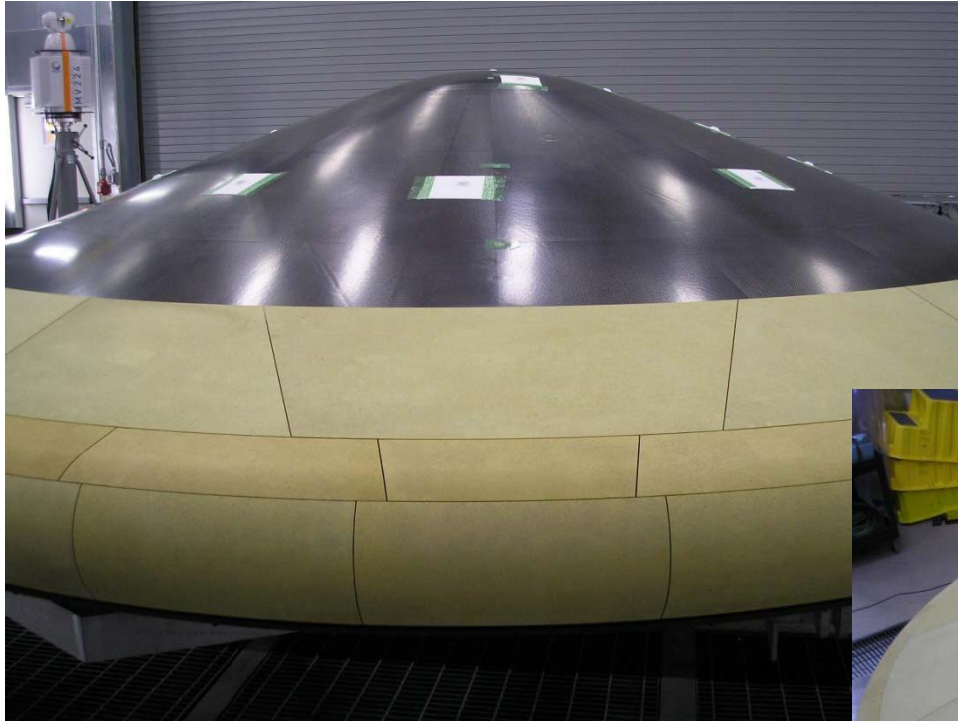
Heatshield

Entry Vehicle





Heatshield Fabrication in Process



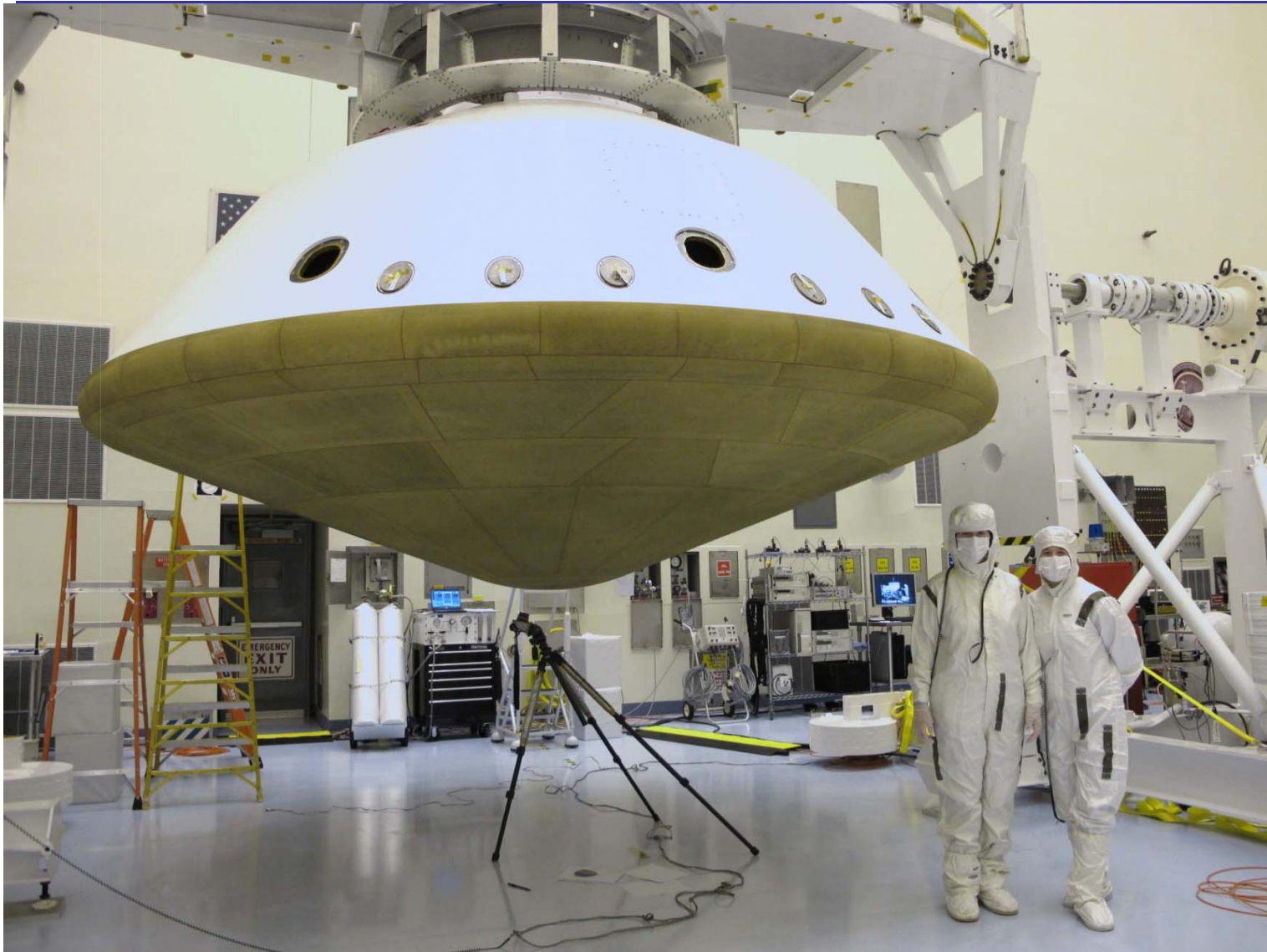


Heatshield Fabricated (gaps filled)



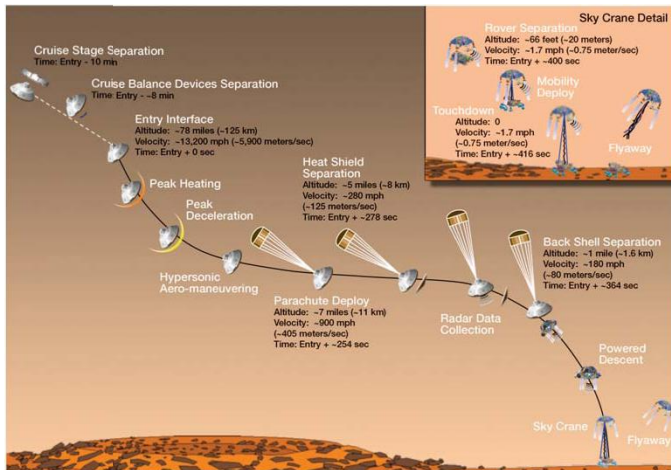


Spacecraft Assembled

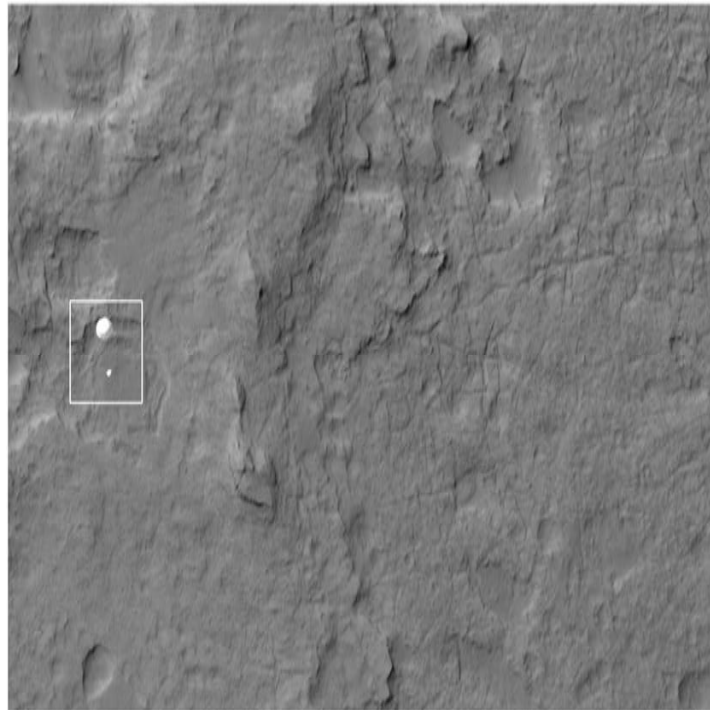




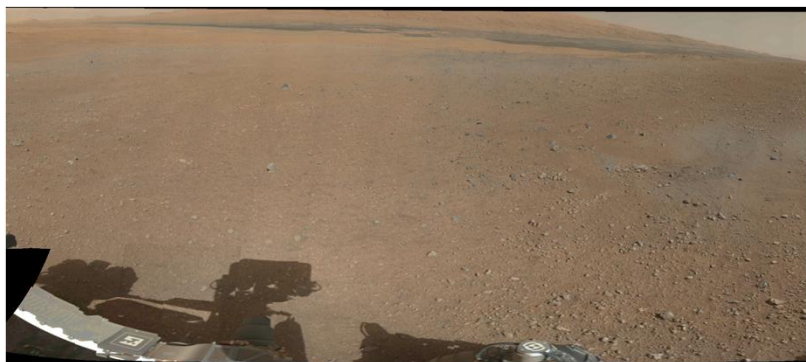
MSL/Curiosity Landed Successfully on August 5, 2012 (PDST)



Landing sequence



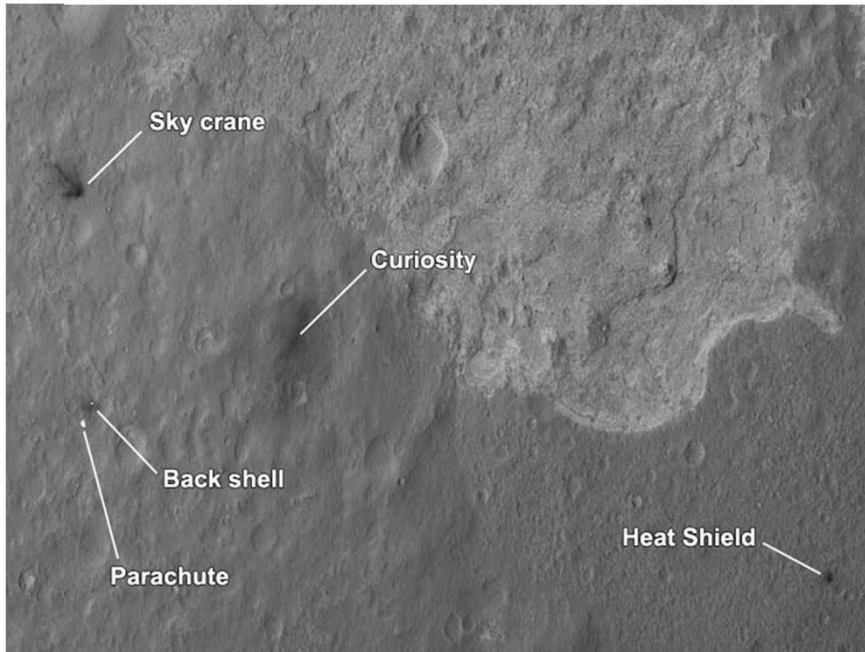
Picture of capsule on parachute descending towards Mars



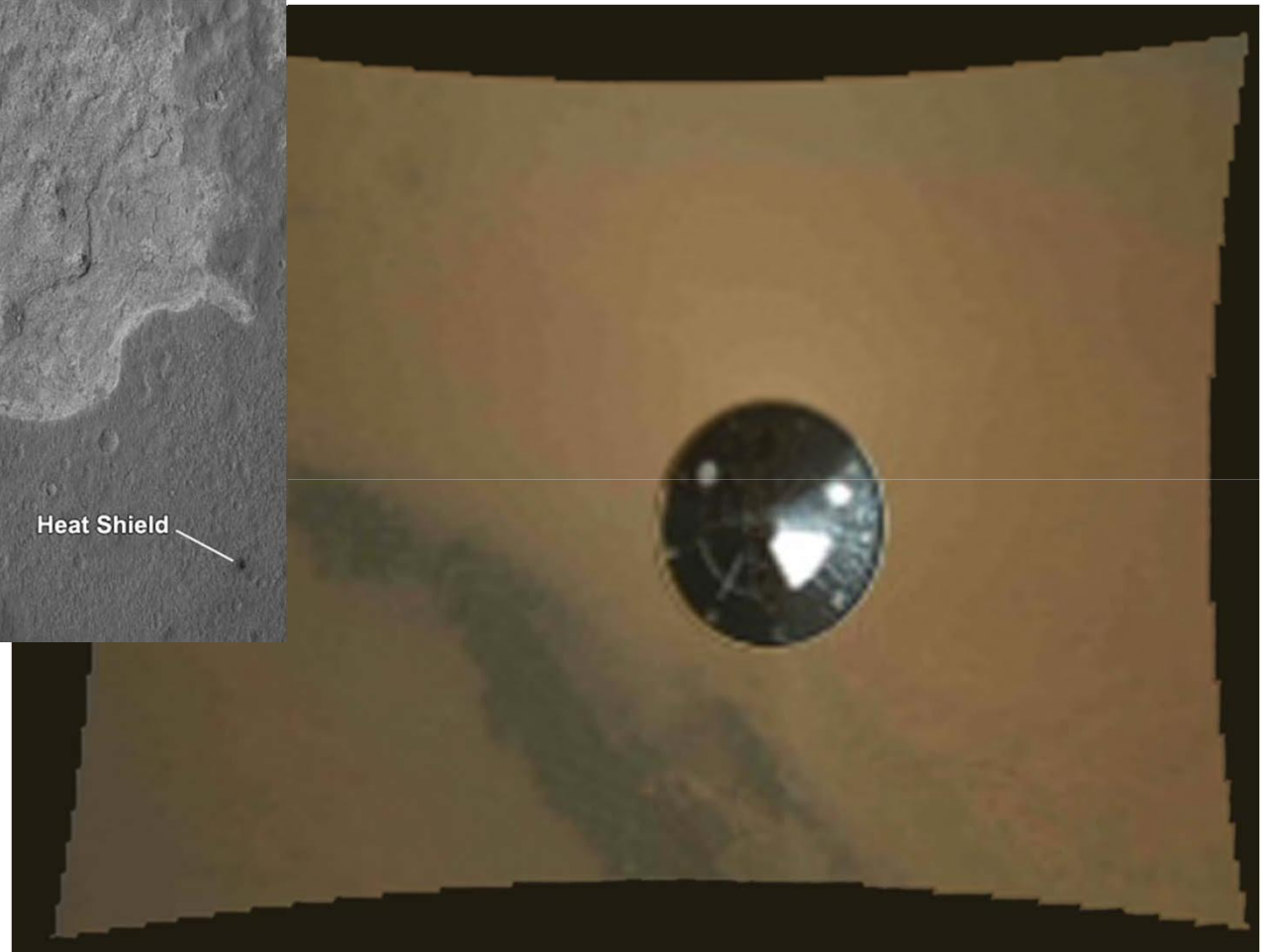
Curiosity on Mars



MSL Heatshield on Mars



The four main pieces of hardware that arrived on Mars with NASA's Curiosity
Image credit: NASA/JPL-Caltech/Univ. of Arizona



Heat shield about 50 feet (16 meters) from the spacecraft.
Image credit: NASA/JPL-Caltech/MSSS

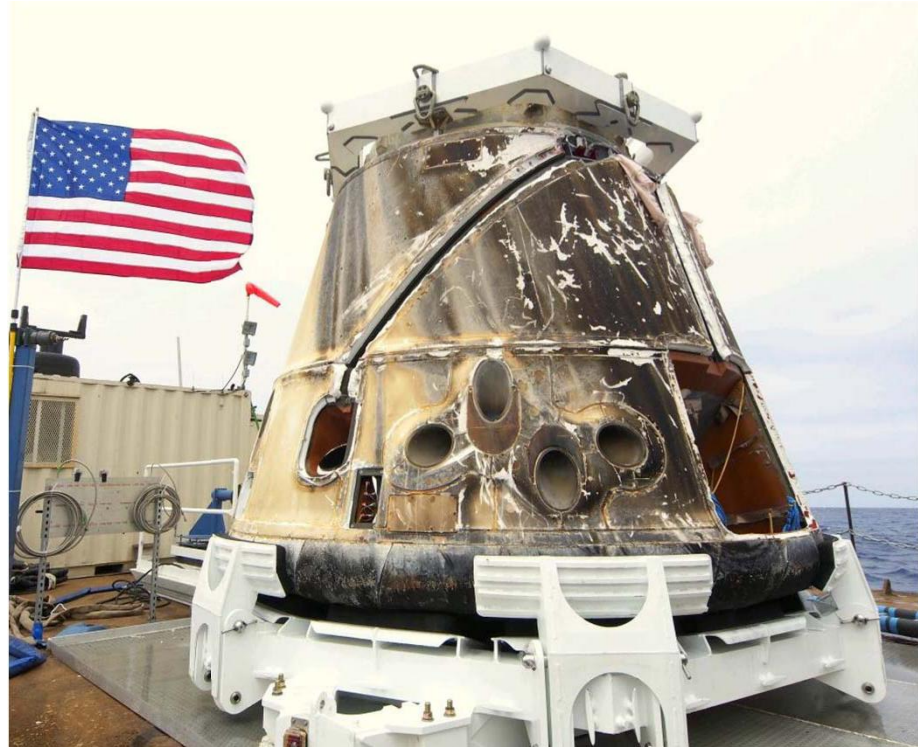


Space-X Dragon Capsule

2nd Successful Flight May 2012



Before: capsule is painted



After landing: note charring on heatshield

Space-X used their own version of PICA known as PICA-X
www.spacex.com



Instrumentation

- All atmospheric entries are essentially “experiments” from which we should gather data
- Data used to validate models and understand materials behavior better
- MSL was instrumented
 - MEDLI: Mars Entry Descent Landing Instrumentation



Importance of MSL Instrumentation

- MEDLI is the most extensive ablative heat shield instrumentation suite since Apollo
 - 7 pressure sensors, 26 near surface and in-depth thermocouples, 6 isotherm sensors
- Data will be used to validate and improve Mars entry aerothermodynamic and TPS response models
- Better models mean TPS safety margin can be reduced and science payload increased



Conclusions

- Two main classes plus specialized materials
 - Insulating, e.g. space shuttle tiles
 - Ablators for higher heat fluxes
 - High temperature materials and composites
 - New materials under development for new missions – woven, conformable, etc.
- TPS needs to fit the application—location on vehicle, expected environment
- Heritage materials may not always be heritage
- Need to gain full data value from flights/experiments: instrumentation is key
- **Critical to characterize materials and archive data**
 - For selecting appropriate material
 - To ensure material demonstrates desired behavior
 - To have materials ready for new missions

Goal of all TPS is reliable and efficient performance!