



Thermal Protection Materials and Systems: Past, Present, and Future

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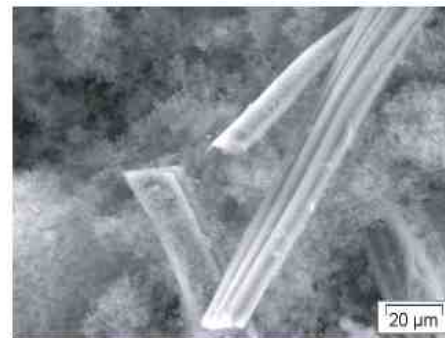
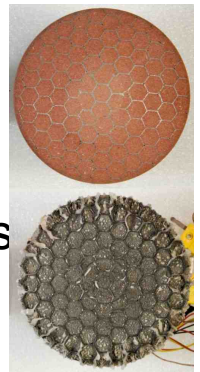
Acknowledgements

- 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, John Lawson
- ERC: Jay Feldman



Outline

- Introduction
 - NASA and TPS
- Thermal Protection Materials and Systems (TPS)
 - Reusable materials
 - UHTCs
 - Ablative materials
- Characterization of TPS for Performance and Design
- A Tale of Two Heat Shields
 - Recent Uses and Development of Heat Shields and Materials Issues
- New Trends in TPS
- Modeling of TPS





NASA Ames Research Center

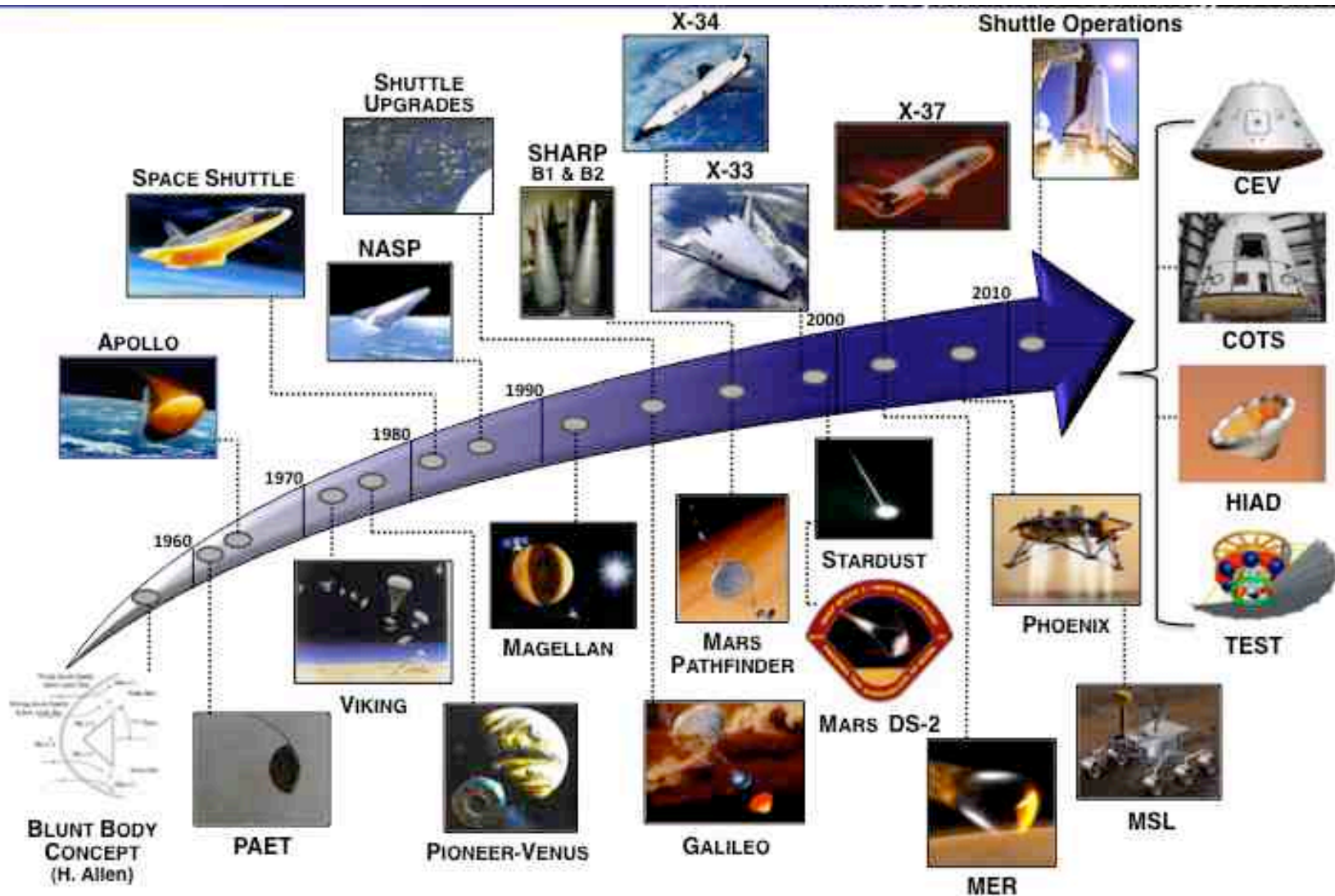


- Located in Moffett Field (Mountain View) California
- 2480 employees*
- \approx 900M + annual revenue (including reimbursable)
- *in addition, 900 students, summer 2012

- Science
 - Space, Earth, Biological Sciences
 - Astrobiology, Lunar Science
- Exploration Systems
 - Exploration Technology Development
 - Entry System Technology
 - Supercomputing
- Projects and Missions
- Aeronautics & Aviation
 - NextGen Airspace Systems
 - Fundamental Aeronautics
 - Aviation Safety
 - Green Aviation
- Affordable Small Satellites
- Innovation, Education, & Entrepreneurial Collaborations
 - NASA Research Park



NASA Entry Vehicles / Missions Supported by Ames





Introduction to TPS

- 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



Earth Reentry Overview

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





Reentry Heating Parameters

- Magnitude of stagnation heating is dependent on a variety of parameters, including reentry speed (V), vehicle effective radius (R), and atmospheric density (ρ)

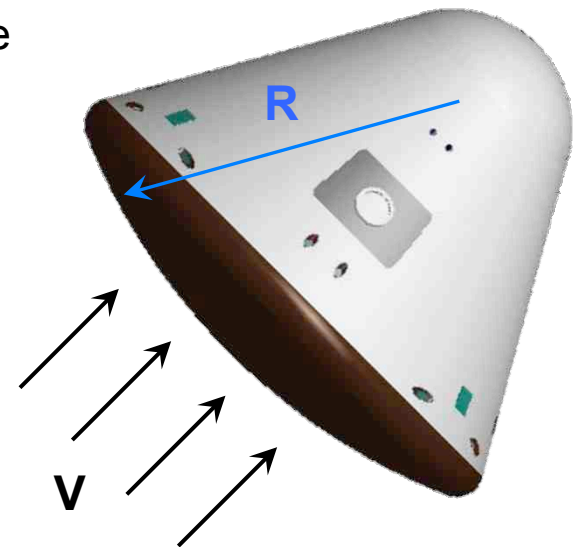
$$\dot{q}_{conv} \propto V^3 \left(\frac{\rho}{R} \right)^{0.5}$$

Convective Heating

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

Shock Radiation Heating

- As reentry speed increases, both convective and radiation heating increase
 - At high speeds, radiation heating can quickly dominate
- As the effective vehicle radius increases, convective heating decreases, but radiation heating increases
- Reentry g-loading is a parameter we are considering





Thermal Protection Systems

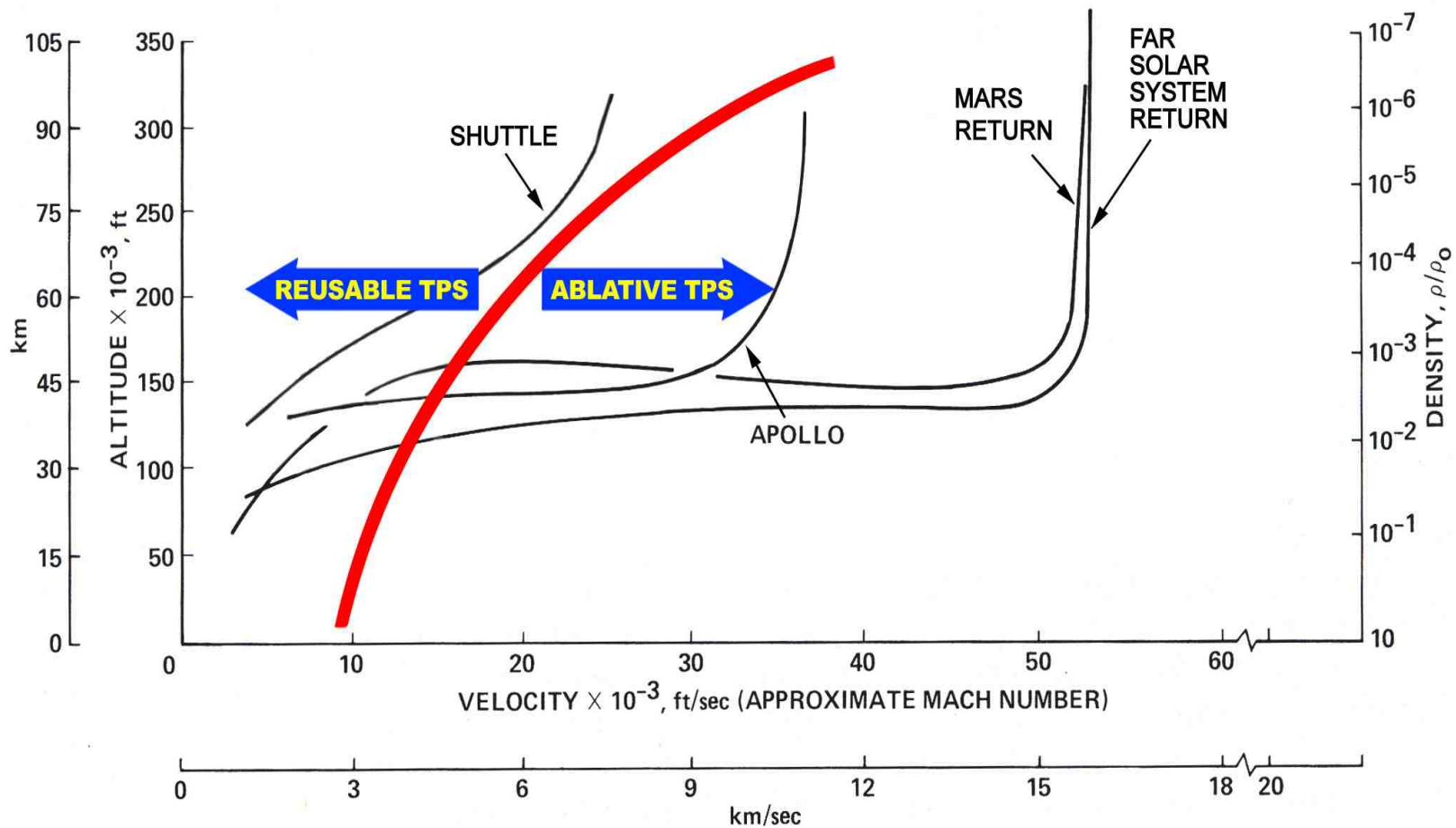
- Protect vehicle structure and contents (people and things) from the heat of entry through an atmosphere
- Rely on materials response to environment
- Response depends on
 - Material properties
 - Configuration of the system
 - Specific conditions (heat flux, pressure, flow)

One size does not fit all!

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



Reusable (Insulative) vs. Ablative TPS



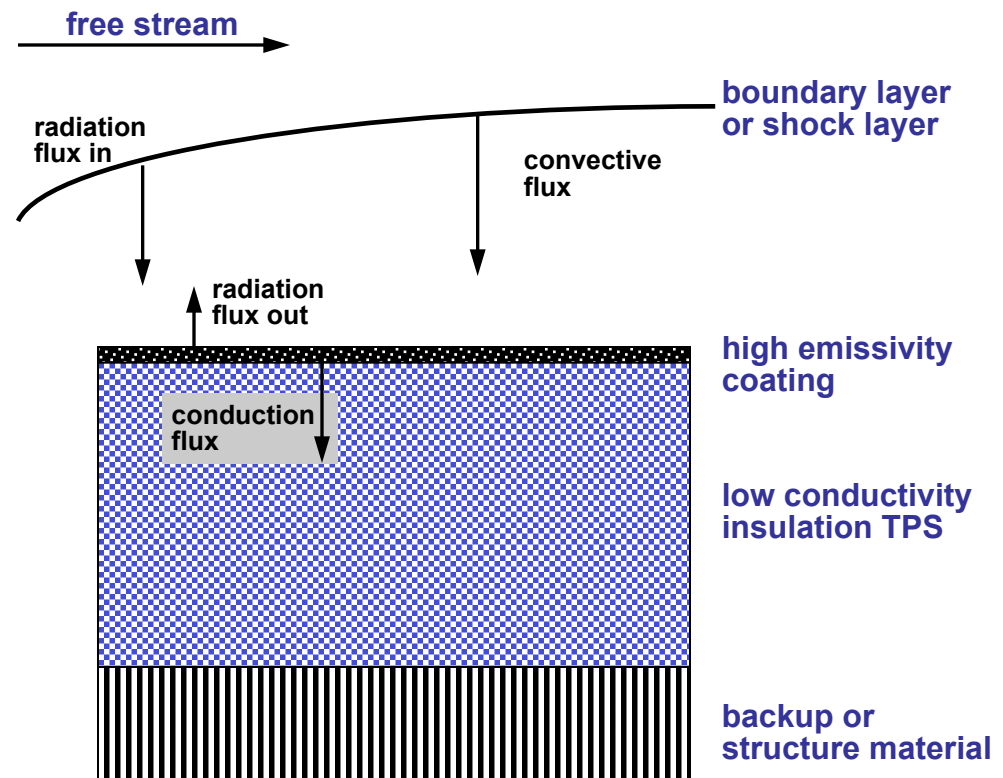


Insulative TPS

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:

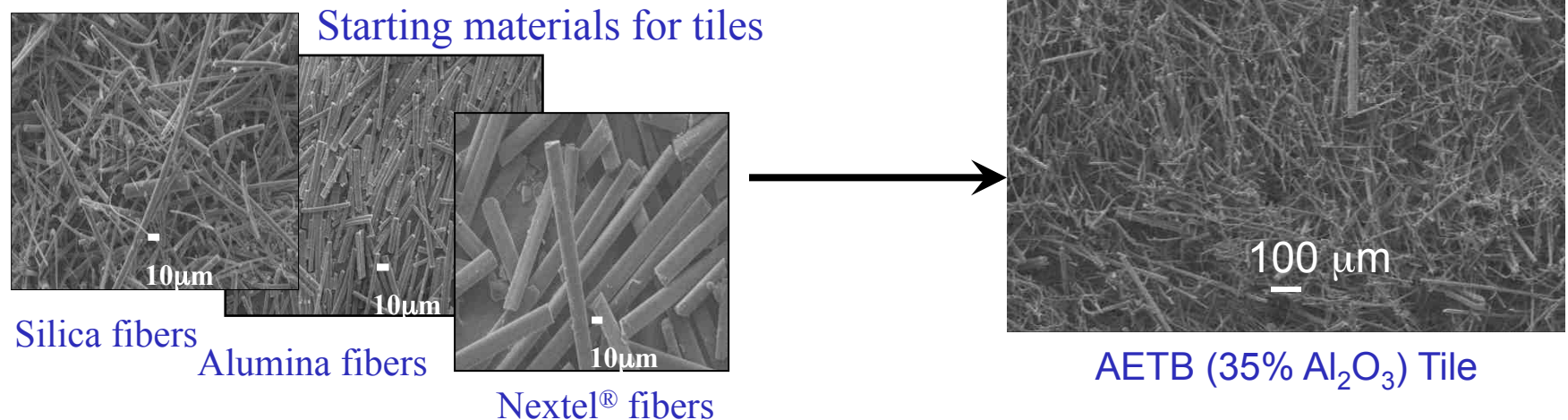
- Re-radiation from the surface and internal storage during high heating condition
- Re-radiation and convective cooling under post-flight conditions





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



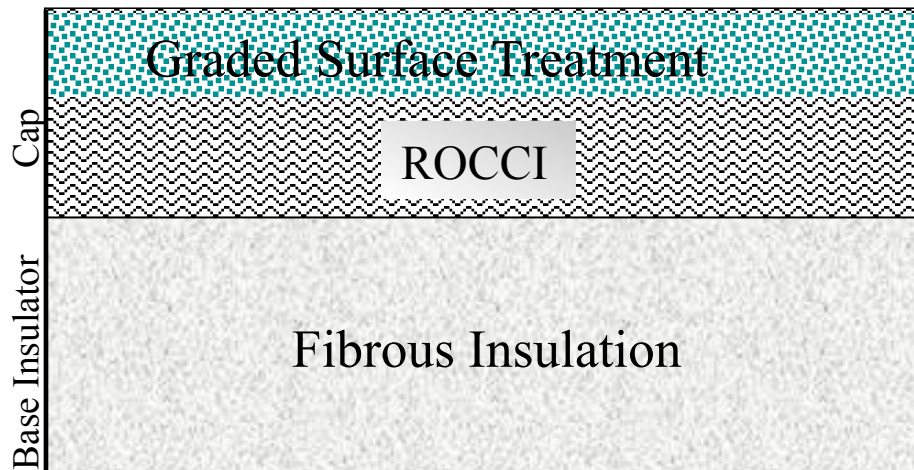
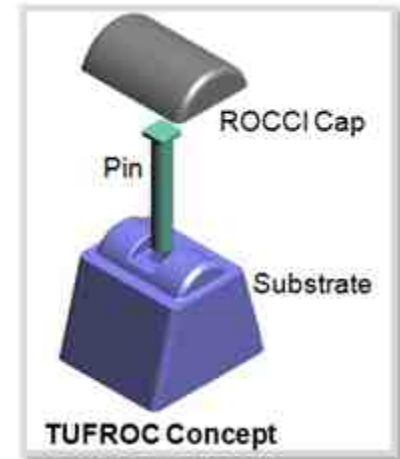
Tiles are heterogeneous with regions of low density and clumps of fibers with some nonfibrous inclusions



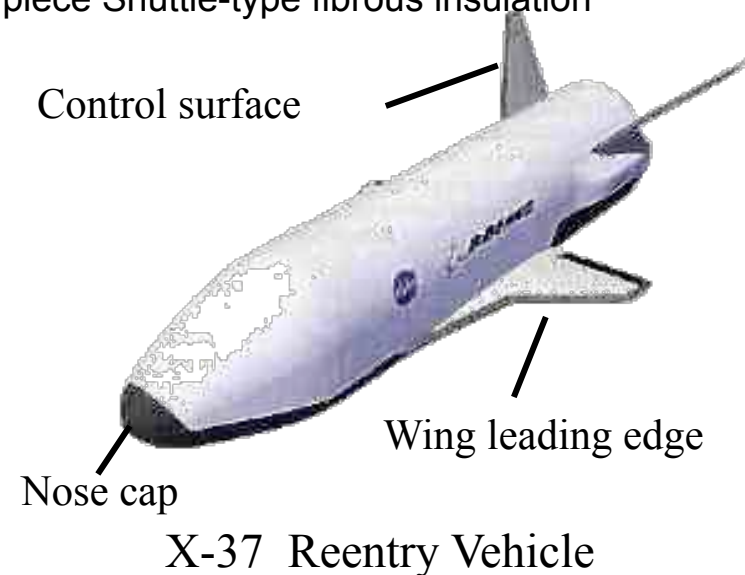
Development of Advanced TUFROC TPS

(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



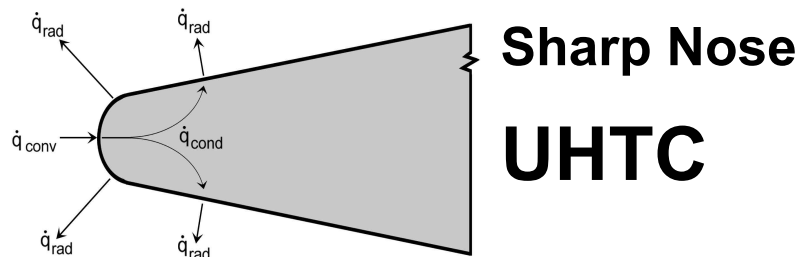
TUROC is on Leading Edges

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

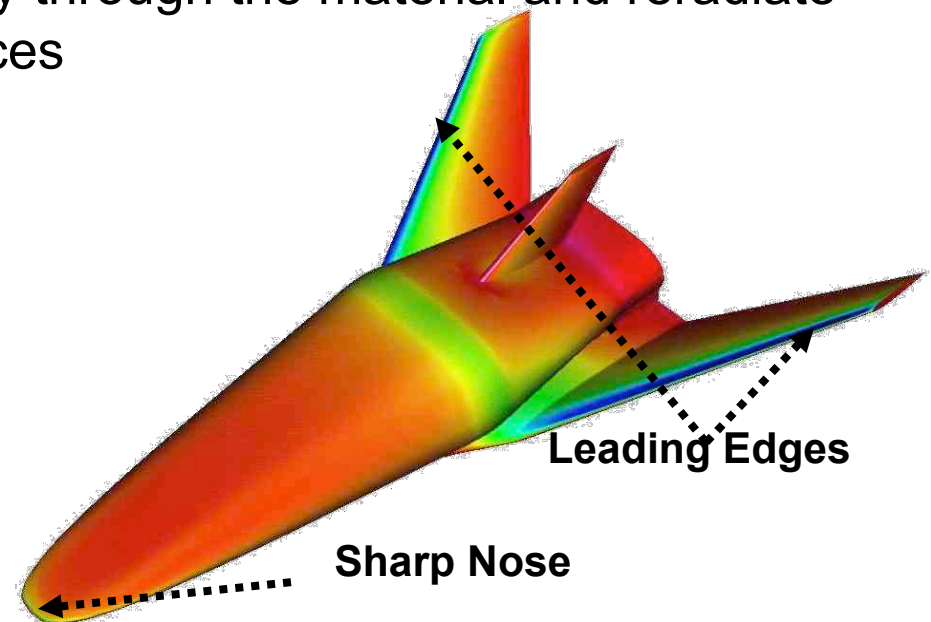


Sharp Leading Edge Energy Balance

- 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



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

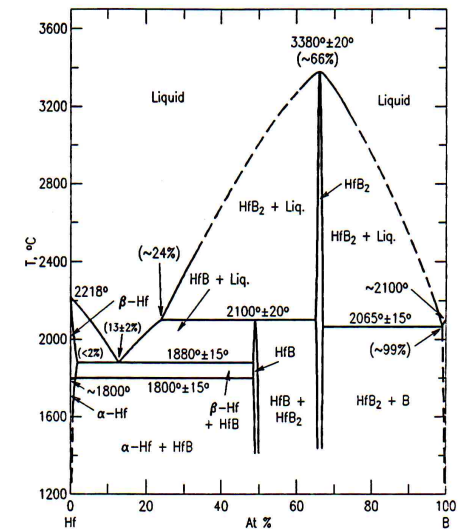


Dean Kontinos, Ken Gee and Dinesh Prabhu. "Temperature Constraints at the Sharp Leading Edge of a Crew Transfer Vehicle." AIAA 2001-2886 35th AIAA Thermophysics Conference, 11-14 June 2001, Anaheim CA

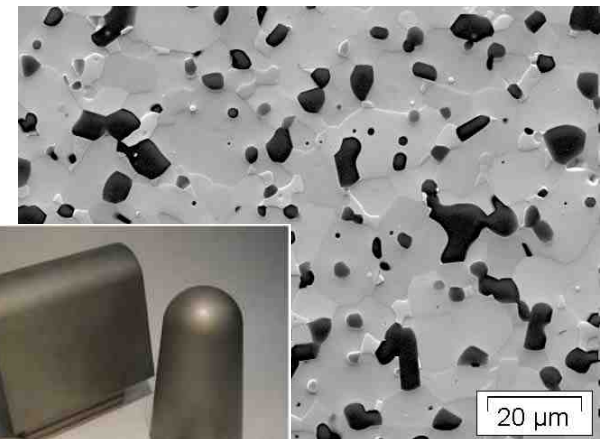


Ultra High Temperature Ceramics (UHTCs) : A Family of Materials

- 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
- Considerable effort in many institutions to improve properties and processing of UHTCs



Hf-B Phase Diagram



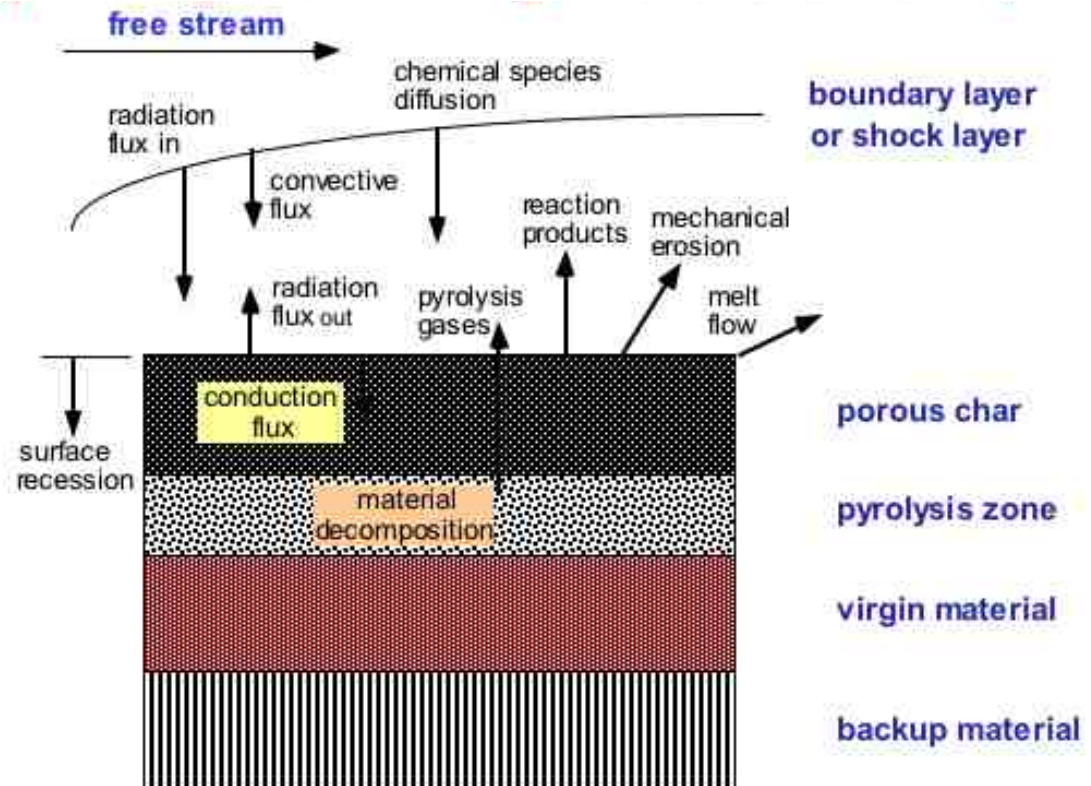


Ablative TPS

Energy management through material consumption

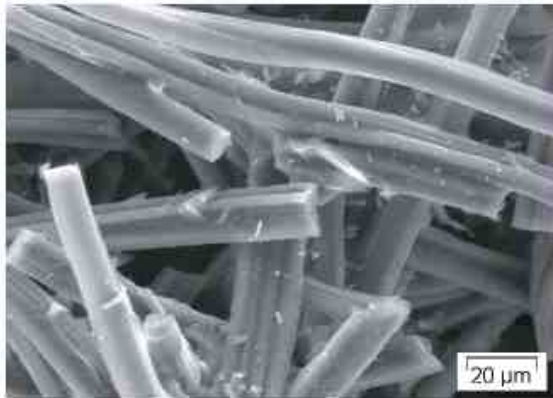
When exposed to atmospheric entry heating conditions, material will pyrolyze (char), and reject heat in the following ways:

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

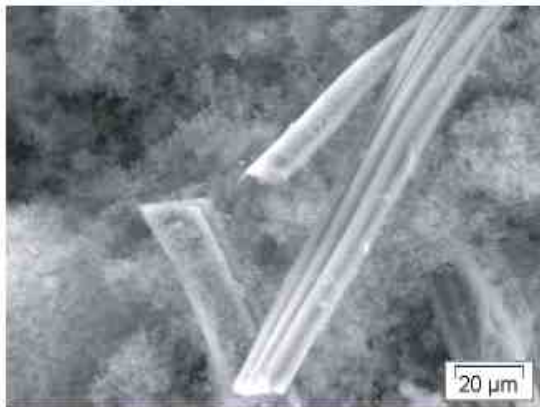




PICA Processing



Fiberform™ before impregnation

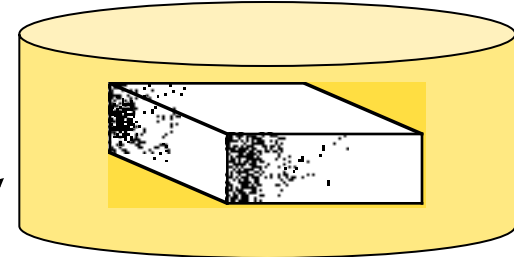


PICA: Fiberform™ with phenolic resin

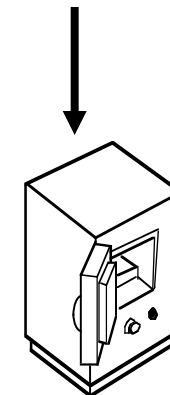
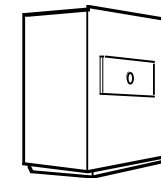


Carbon Fiberform™

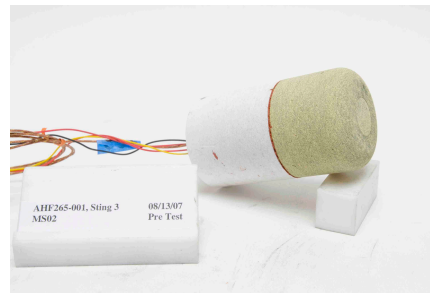
Phenolic Resin



Resin Impregnation



Drying Cycle



PICA Arc Jet Model



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**

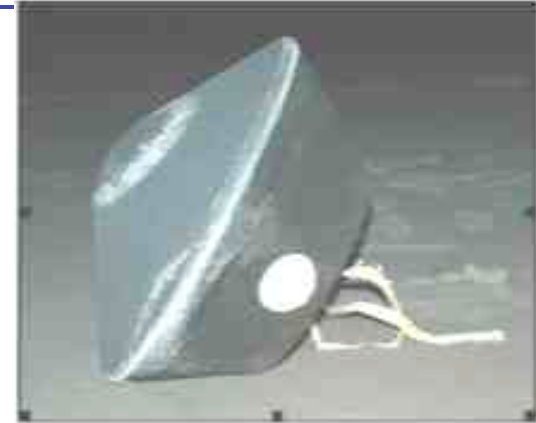


Image of the sample return capsule post flight with PICA as the forebody TPS. (0.8m diameter)



MSL Heat Shield
(4.5m diameter)



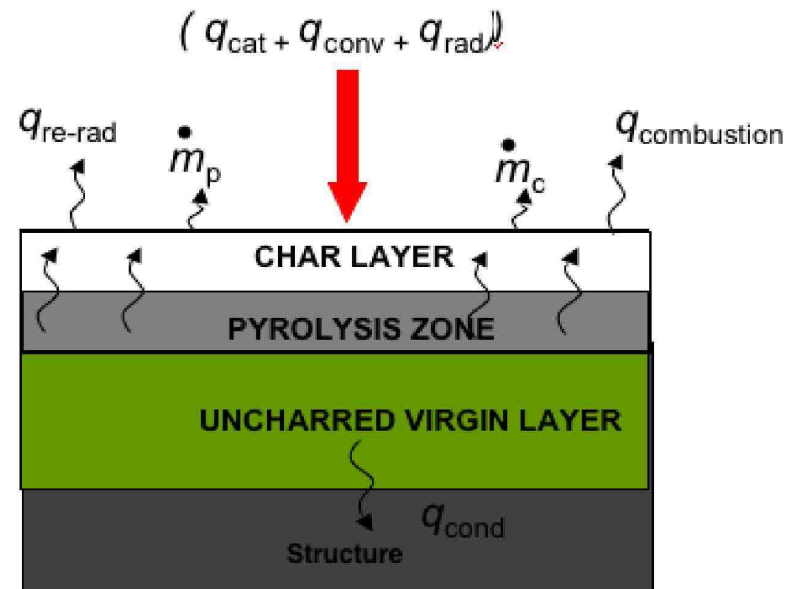
Characterization of TPS

- 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



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

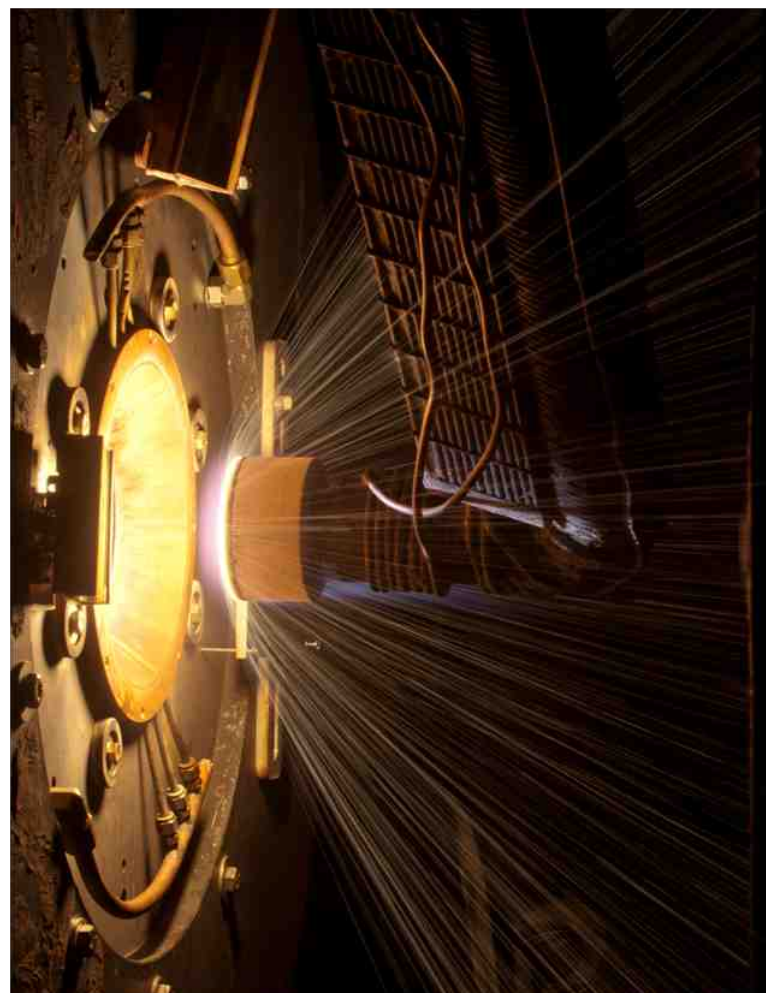
Tensile strength

Shear strength



Need for Arc Jet Testing

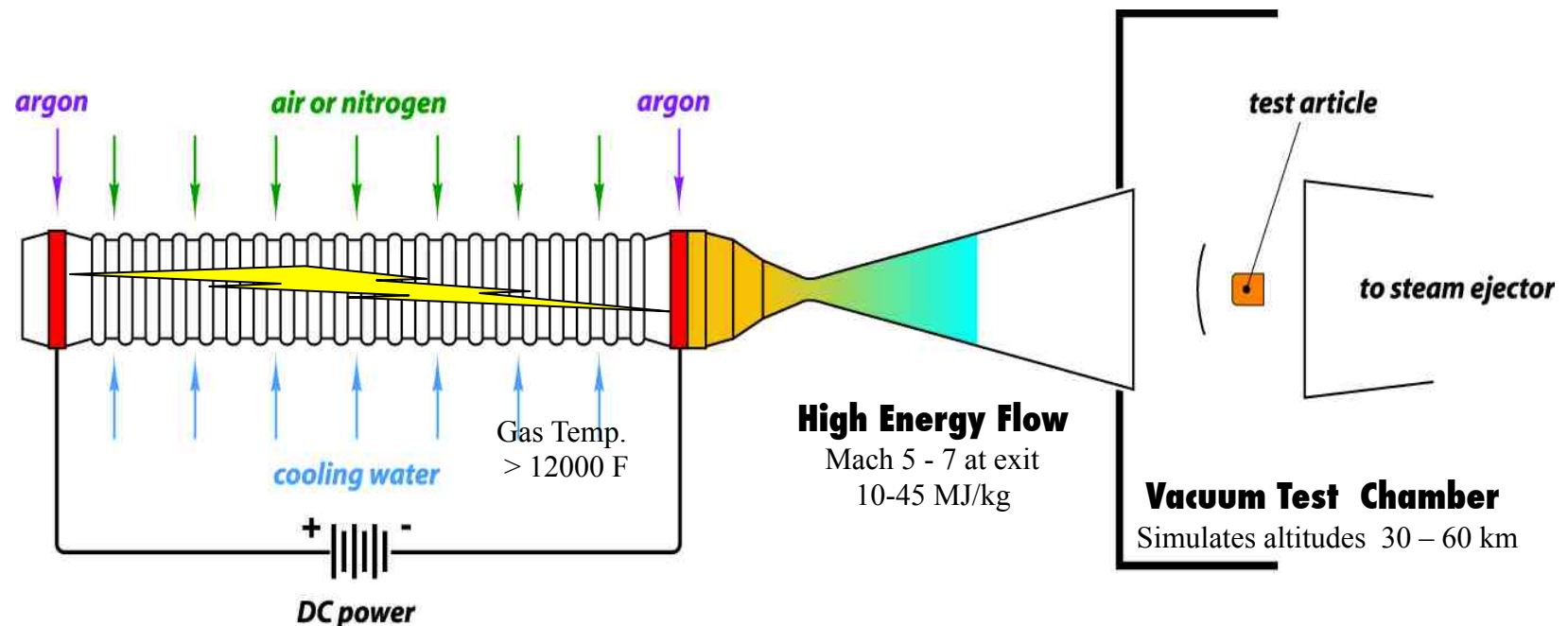
- Arc jet testing is the best **ground-based method** of evaluating a material's oxidation/ablation response in re-entry environments
- Oxidation/ablation behavior on heating in static or flowing air at ambient pressures is likely to be significantly different than in a re-entry environment.
 - O_2 and N_2 may be dissociated
 - Catalycity of the material
 - Recombination of O and N atoms adds to surface heating
 - Stagnation pressures may be <1 atm.
 - active to passive transitions in oxidation
 - SiC : protective SiO_2 layer is removed as SiO





Arc Jet Schematic

Simulates reentry conditions in a ground-based facility



Method: Heat a test gas (air) to plasma temperatures by an electric arc, then accelerate into a vacuum chamber and onto a stationary test article

Stine, H.A.; Sheppard, C.E.; Watson, V.R. Electric Arc Apparatus. U.S. Patent 3,360,988, January 2, 1968.

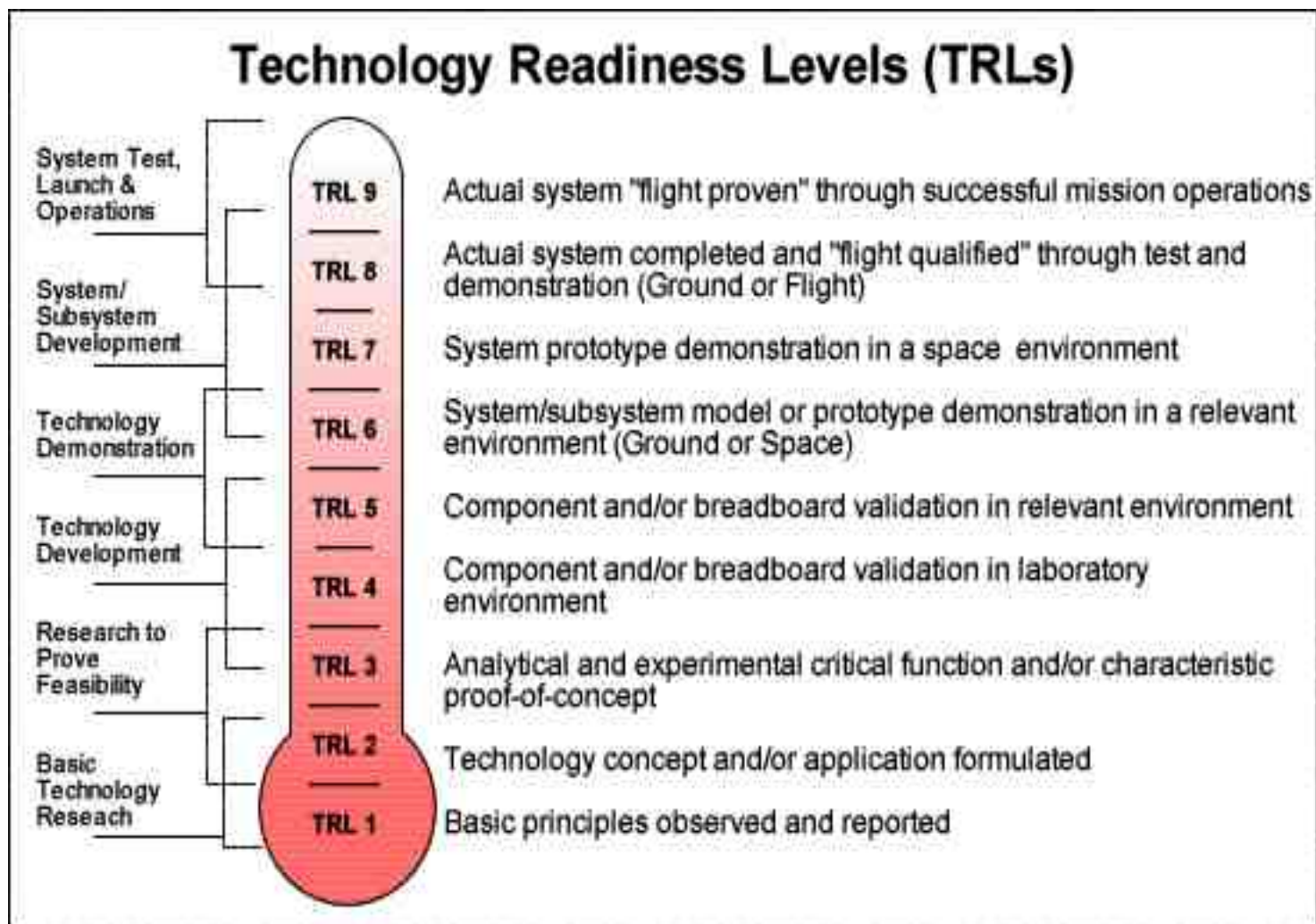


Selection of Appropriate Material

- 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





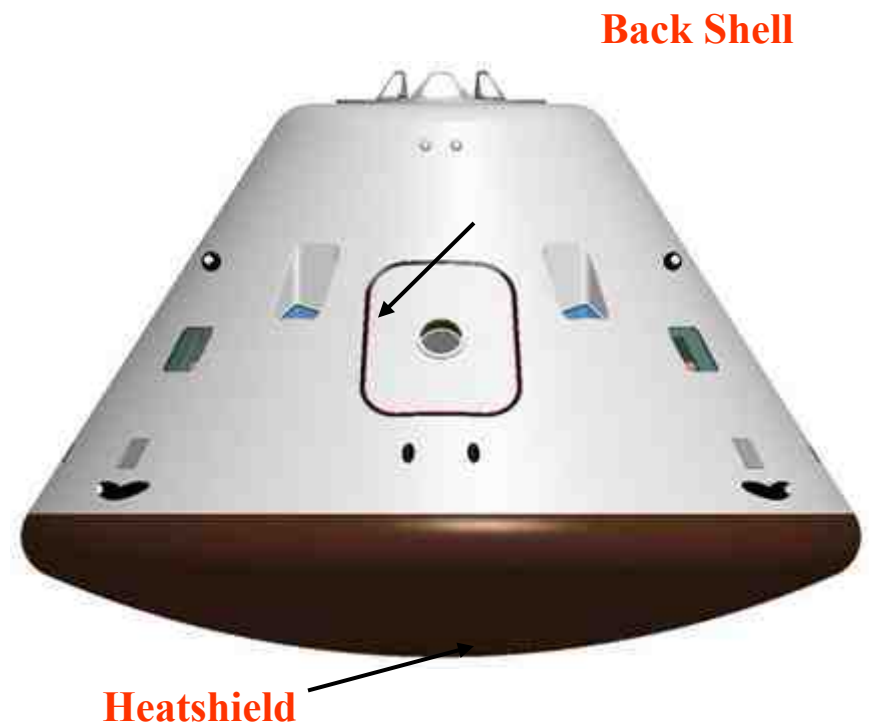
A Tale of Two Heatshields

- 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

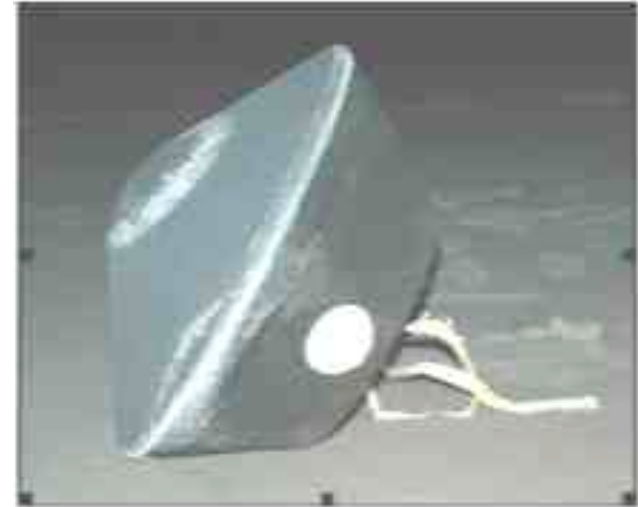
- Multi-purpose Crew Vehicle (MPCV) Lunar Direct Return (LDR) conditions:
 - 11 km/s atmospheric entry
 - peak heat rate $> 1000 \text{ W/cm}^2$
- MPCV Low Earth Orbit (LEO) return conditions:
 - 8 km/s atmospheric entry
 - peak heat rate $> 150 \text{ W/cm}^2$
- **Early TPS development work focused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

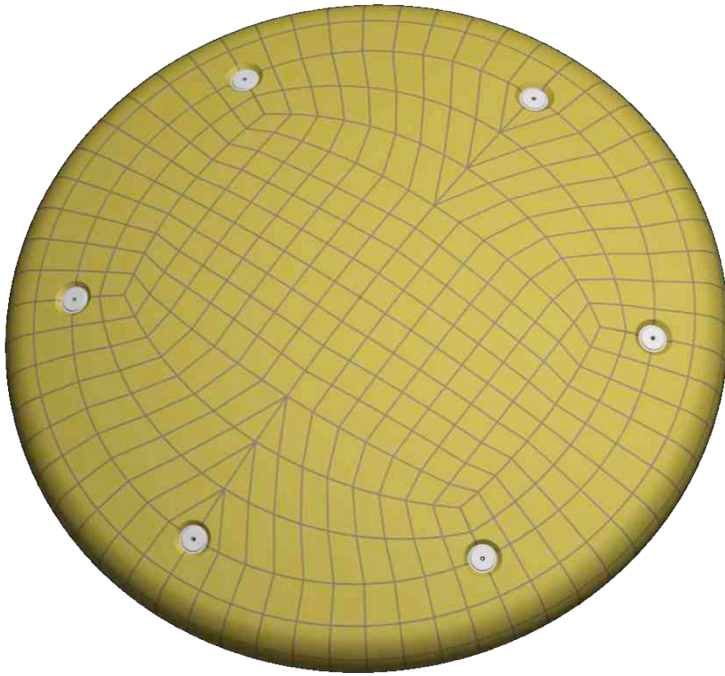
- Avcoat was used on the Apollo vehicles:
“heritage” material
- Consists of a honeycomb filled with an ablative mixture
- Reduces gaps
- Complex material requiring hand assembly
- Not made for many years



Before and after
Avcoat arc jet models



Heatshield Comparison

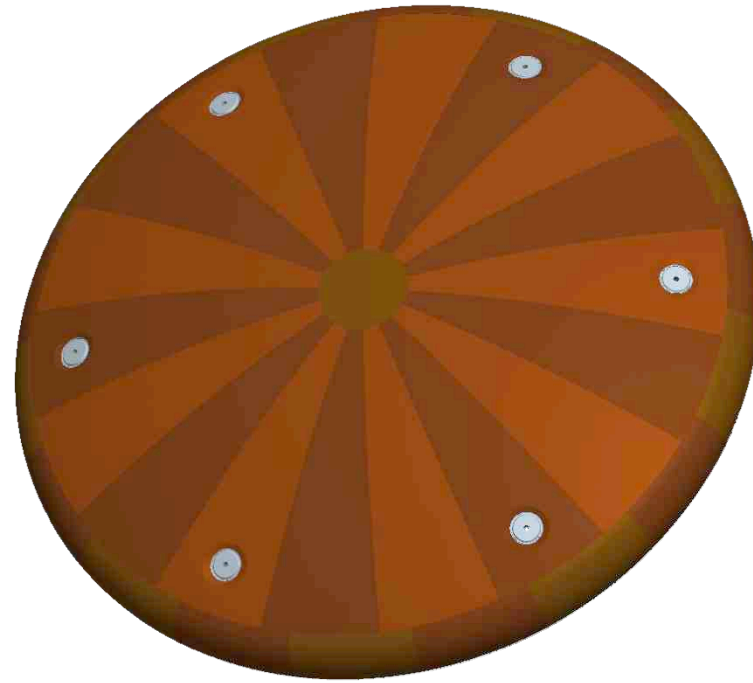


PICA Acreage TPS

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

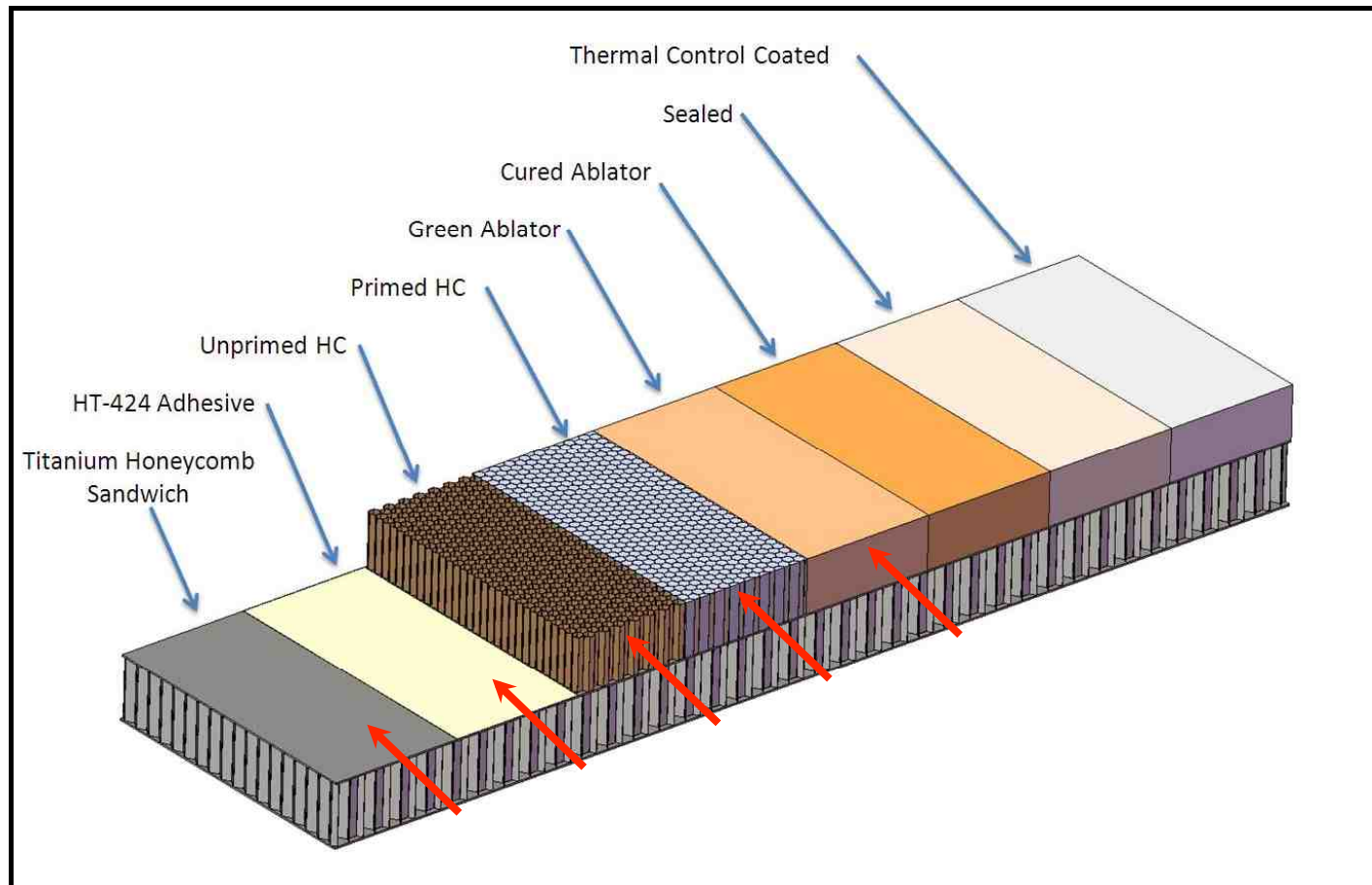
- 9 stages in AVCOAT process
- Complex processes require extensive characterization and understanding to
 - Ensure reliability/reproducibility
 - Prepare/maintain meaningful process specifications





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”?

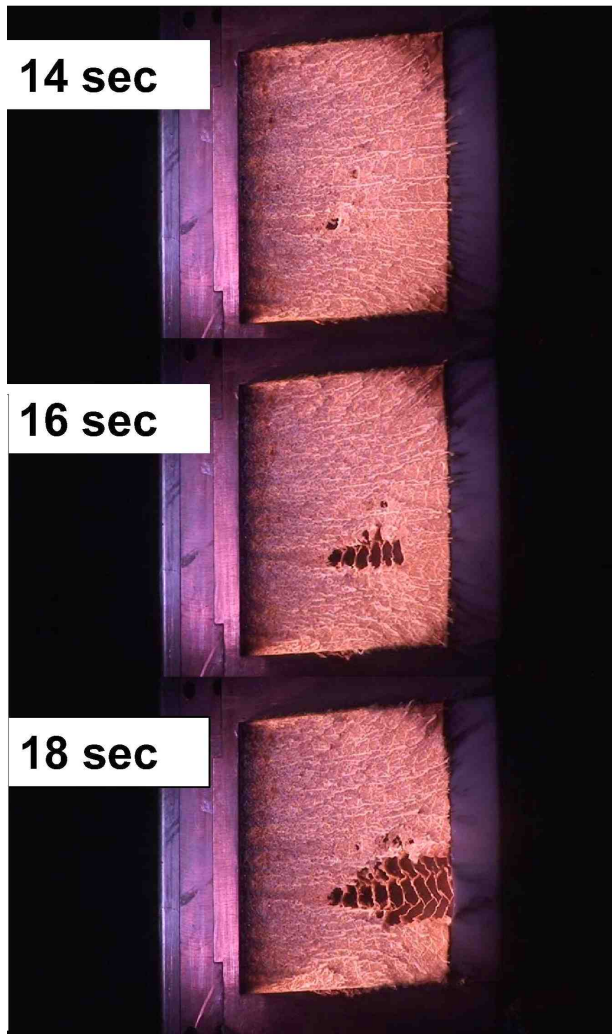


Meanwhile, Mars Science Lab in Development

- 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

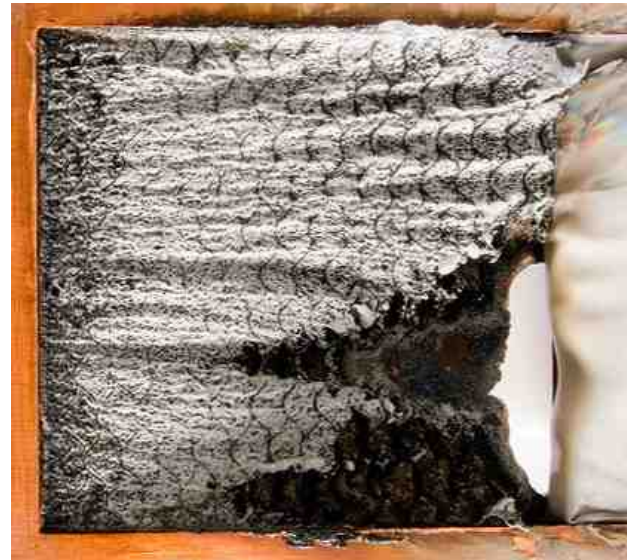


SLA Subjected to Shear in Arc-Jet



During test

Post test photo



Note many cells completely emptied



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)



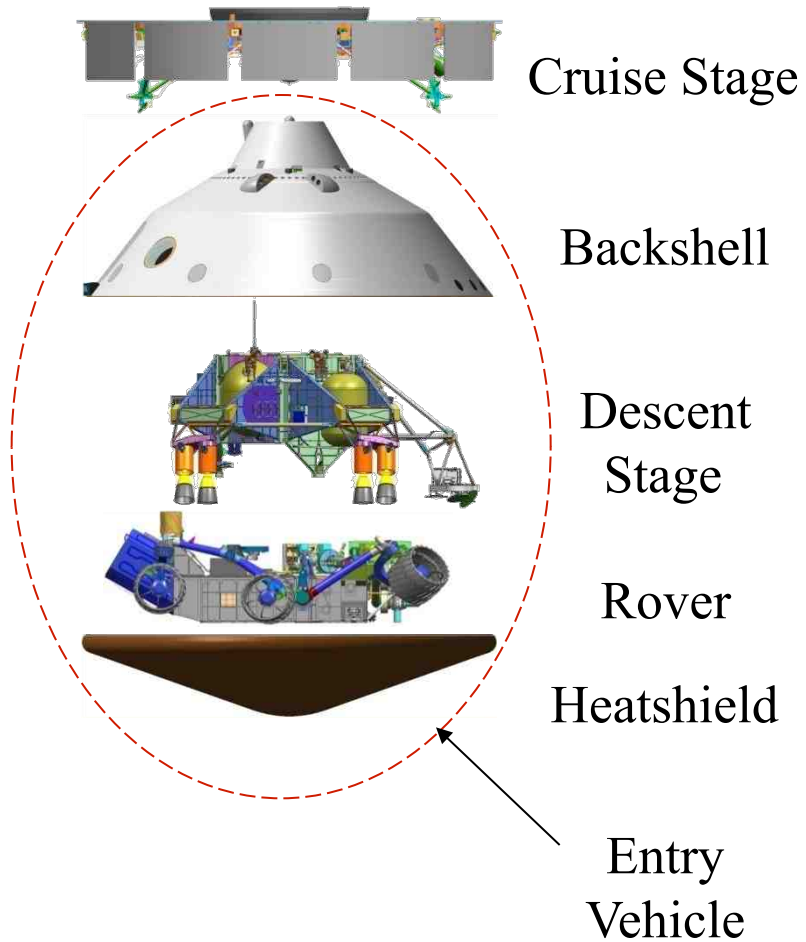
The Mars Science Laboratory

Launch Date: 11/26/2011

Arrival Date: 08/05/2012

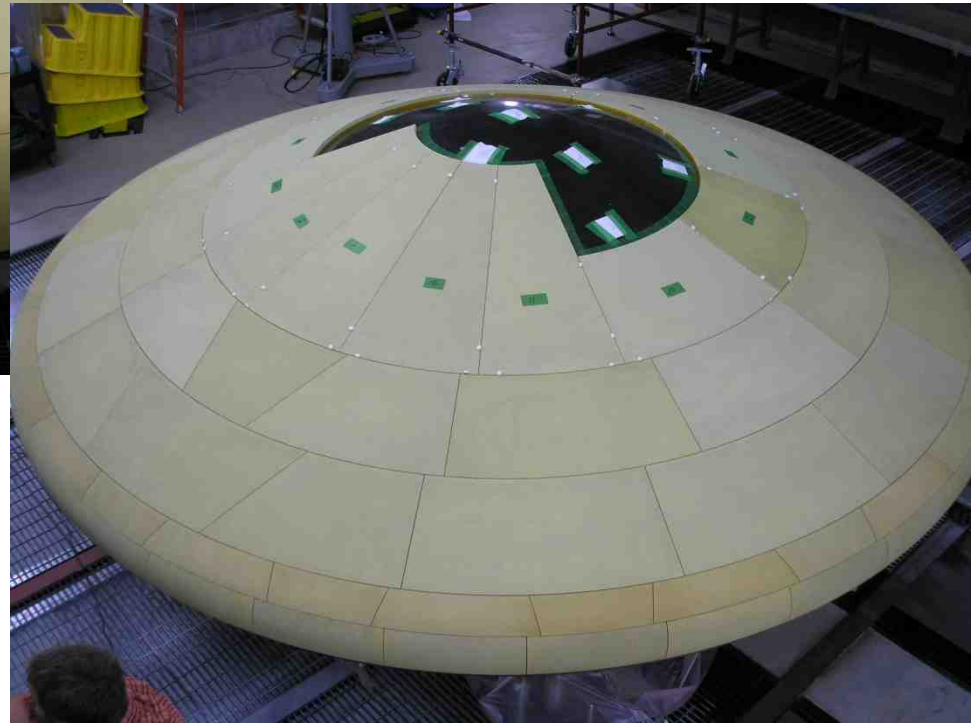


Mars Science Lab (MSL) Spacecraft





Heatshield Fabrication in Process





Heatshield Fabricated (gaps filled)



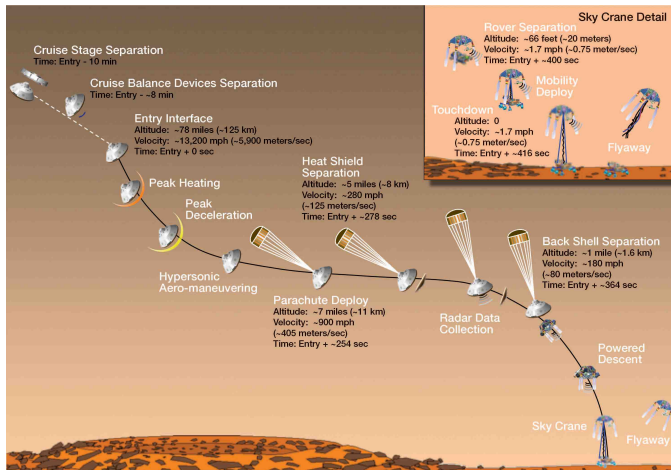


Spacecraft Assembled

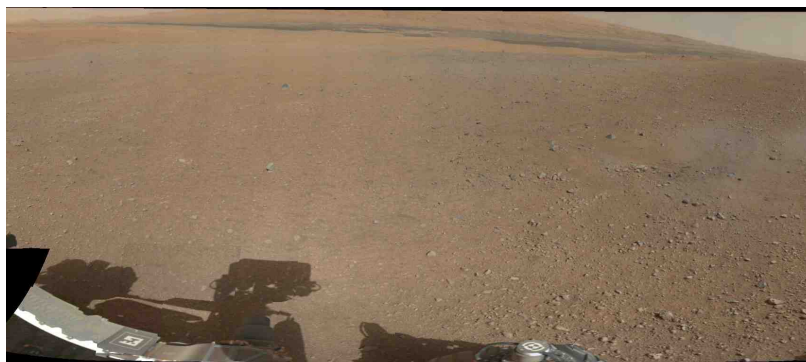




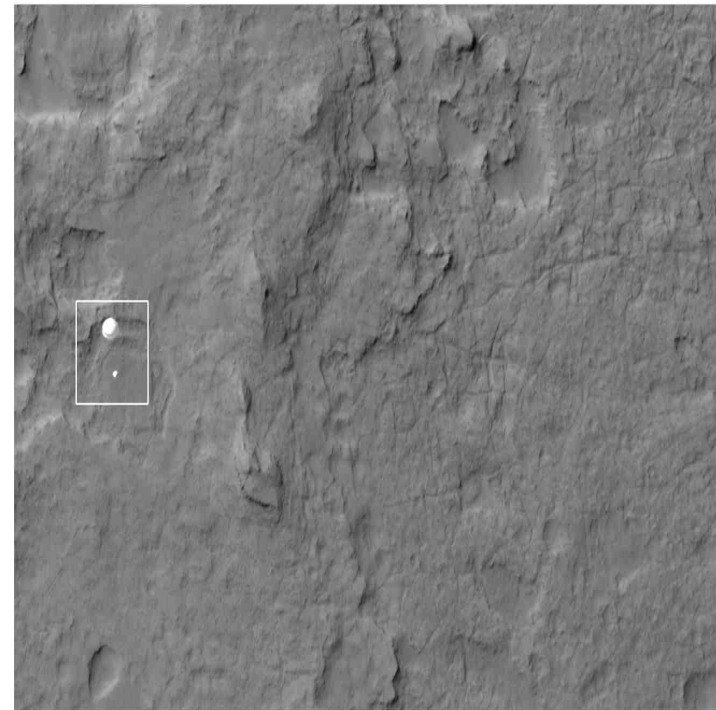
MSL/Curiosity Landed Successfully on August 5, 2012 (PDST)



Landing sequence



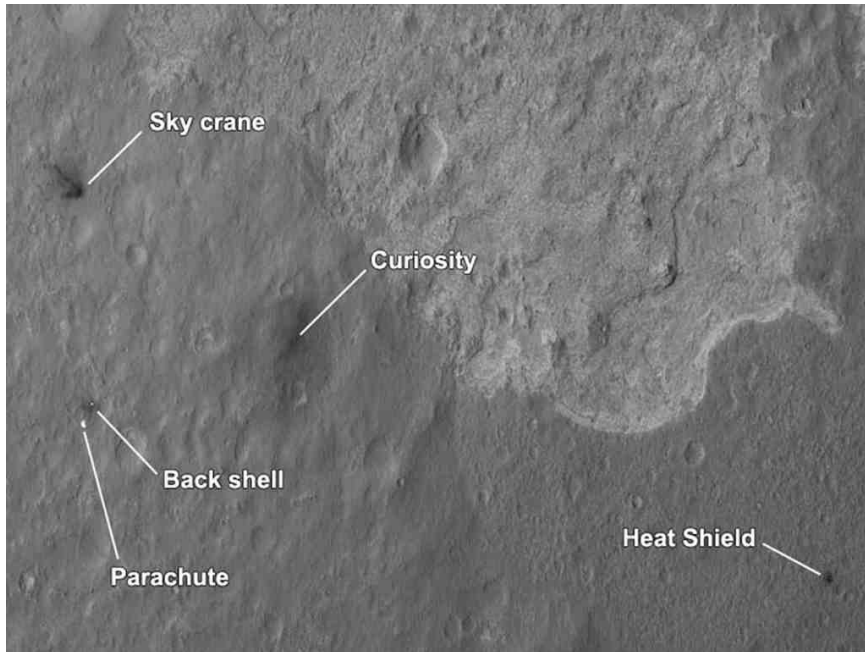
Curiosity on Mars



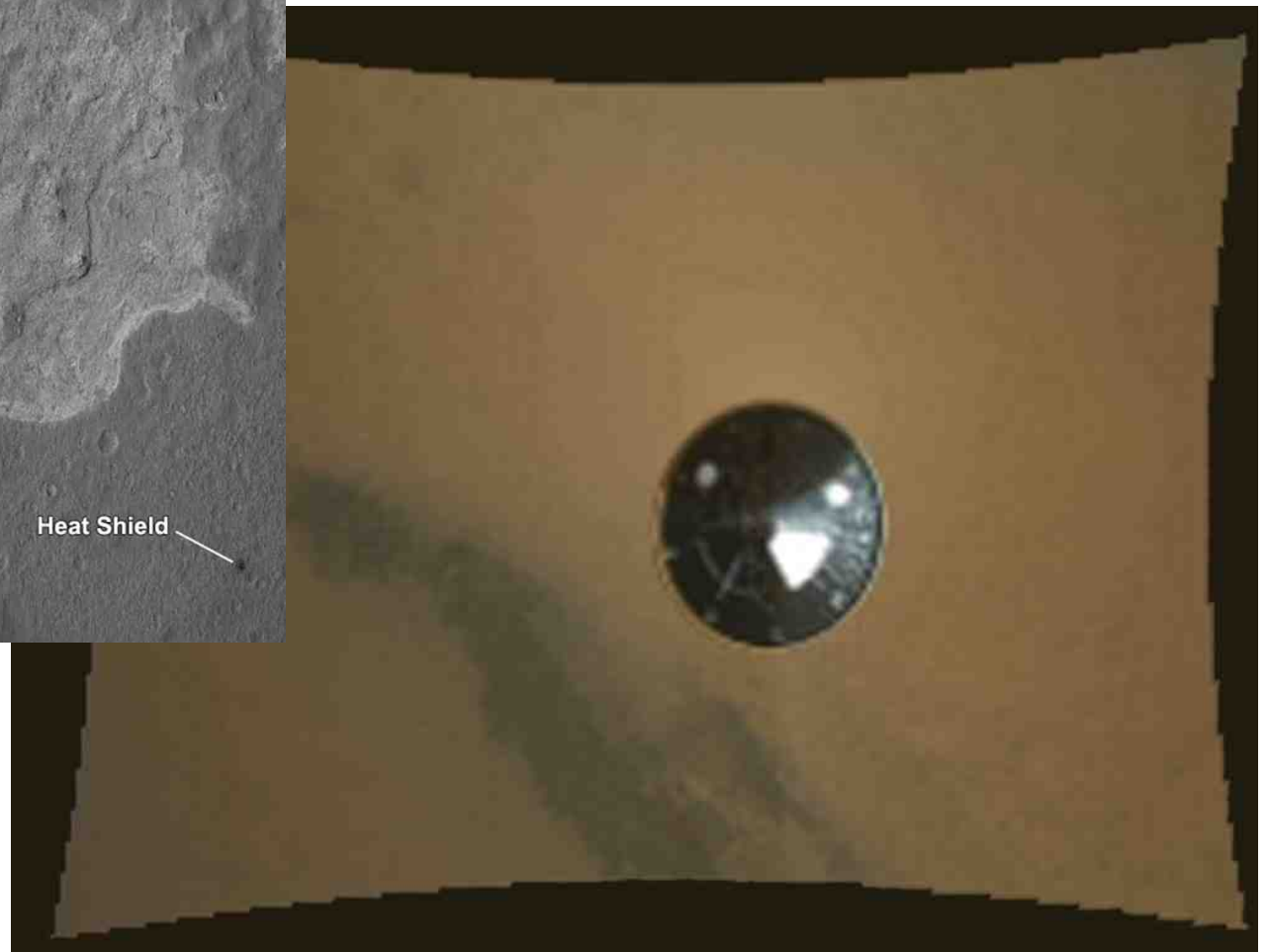
Picture of capsule on parachute descending towards Mars



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



Orion

- The Orion spacecraft will take astronauts beyond low Earth orbit (LEO) to deep space.
 - emergency abort capability,
 - sustain the crew
 - provide safe re-entry from deep space.
- Exploration Flight Test-1, an uncrewed mission planned for 2014.
 - Orion will travel farther into space than any human spacecraft has gone in more than 40 years.
 - EFT-1 data will influence design decisions, validate existing computer models and innovative new approaches to space systems development, as well as reduce overall mission risks and costs.
- Lockheed Martin is the prime contractor for the EFT-1 flight.
- System has 5 elements
 - Launch Abort System (LAS) – Propels the Orion Crew Module to safety in an emergency during launch or ascent
 - The Orion Crew Module (CM) – Houses and transports NASA’s astronauts during spaceflight missions•
 - The Service Module (SM) – Contains Orion’s propulsion, power and life support systems
 - The Spacecraft Adaptor and Fairings – Connects Orion to the launch vehicle
 - The Multi-Purpose Crew Vehicle to Stage Adaptor (MSA) – Connects the entire vehicle structure to the kick stage of the rocket





Exploration Flight Test One



Orion will launch atop a Delta IV Heavy rocket for the test flight, as shown in this configuration. The planned two orbit flight will send Orion out farther into space than any human spaceflight vehicle since the Apollo 17 mission in 1972.



Crew Module in Construction



- Crew module is being constructed by Lockheed Martin
- Heatshield for EFT1 is Avcoat



Orion During EFT1

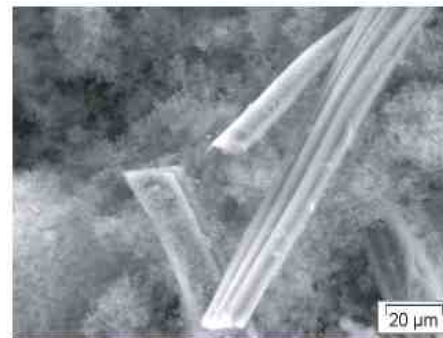


Artist's rendition of Orion during EFT 1



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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 or woven cloth
- Matrix of various resins and fillers
- Significant design, system integration, and performance advantages over rigid ablators
 - Manufacturability
 - Reduction in piece-parts
 - Ease of assembly
 - Enables larger diameter aeroshells
 - Eliminates gap and seam issues



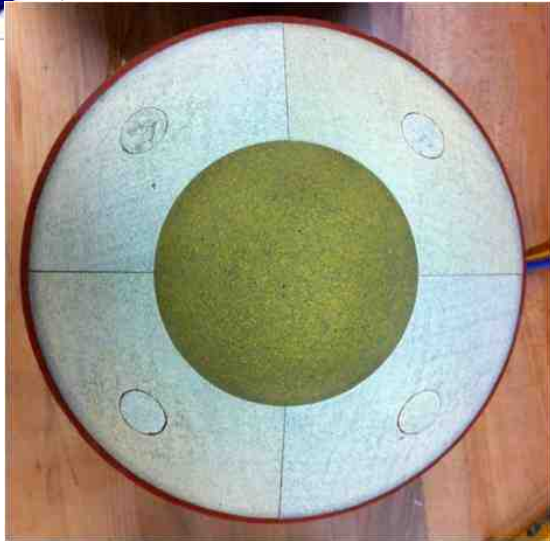
Conformable PICA



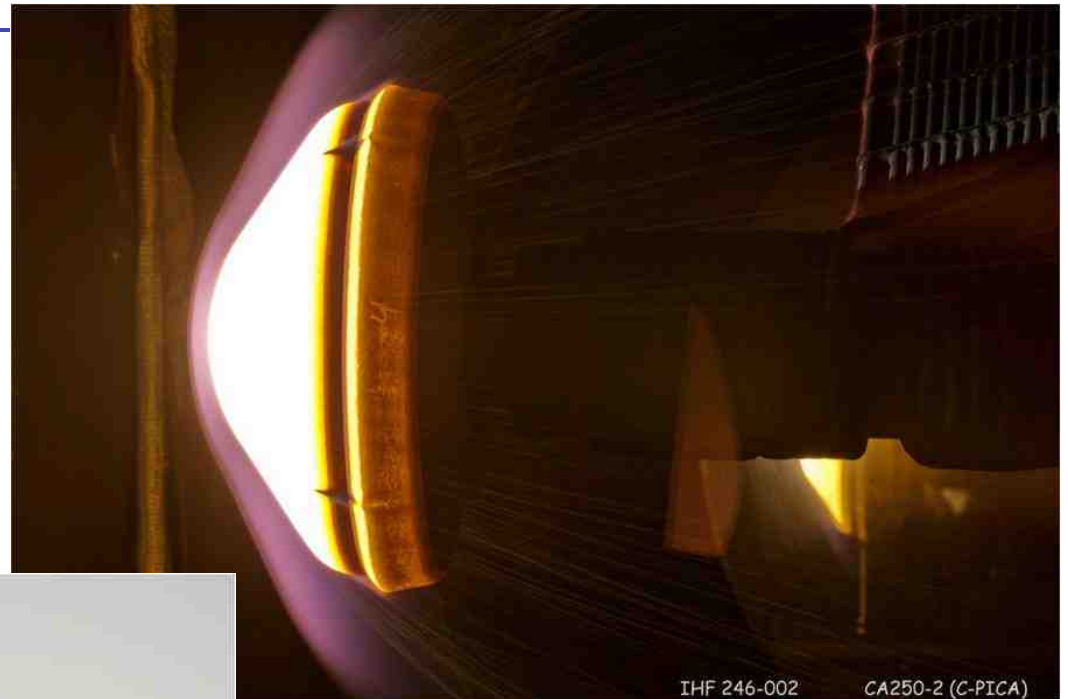
Flexible PICA



Conformable Ablator (C-PICA) Testing



Model Before Testing



During Testing

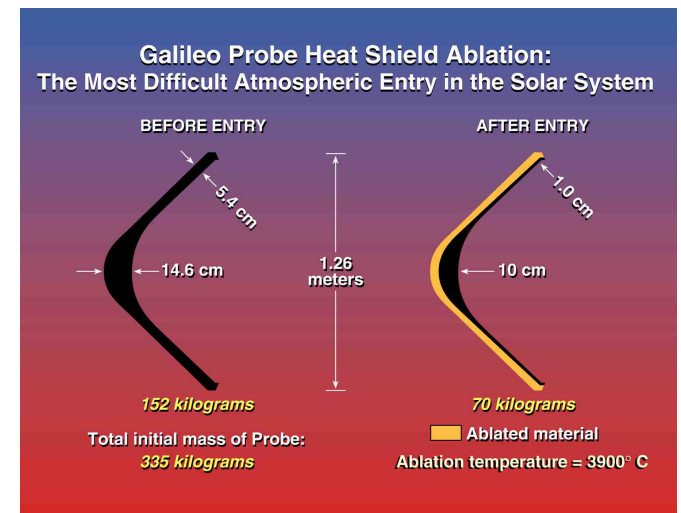


Post Test



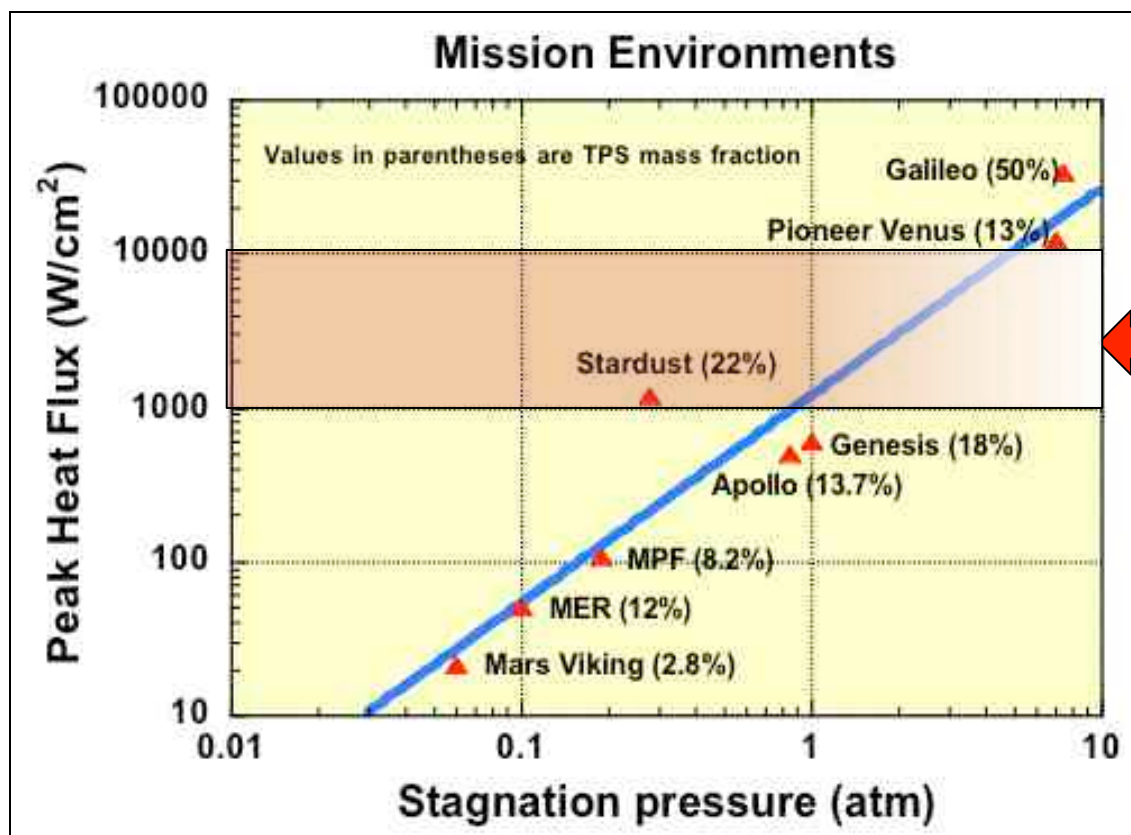
Carbon Phenolic TPS

- 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
- Carbon phenolic TPS was used on Galileo heat shield for very demanding entry into Jupiter's atmosphere
- Current effort to investigate approaches to fabricating carbon phenolic materials
 - Issues with fiber supplies
 - Entry Grade CP needs Avtex Rayon – not produced since 1986





TPS for Saturn and Uranus Probes



- The only flight proven TPS that can meet the extreme entry environment (heat-flux, pressure, etc) for Saturn and Uranus Probes, is heritage, entry grade carbon phenolic (HEGCP)



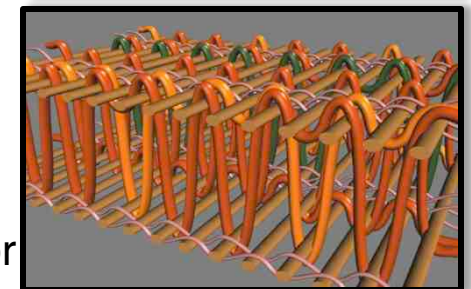
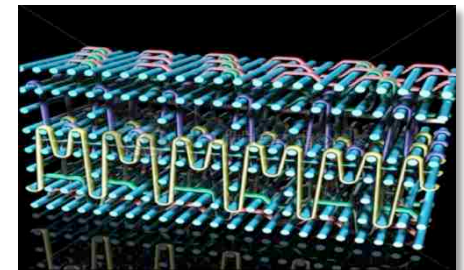
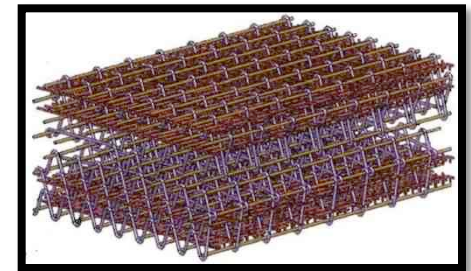
What is Woven TPS?

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

Woven TPS Project Goals:

- Develop and prove feasibility of woven TPS manufacturing technique
- Demonstrate via testing low, mid and high-density WTPS to fill the mid-density gap as well as finding a superior replacement for the heritage carbon phenolic





Arc Jet Tested Woven TPS

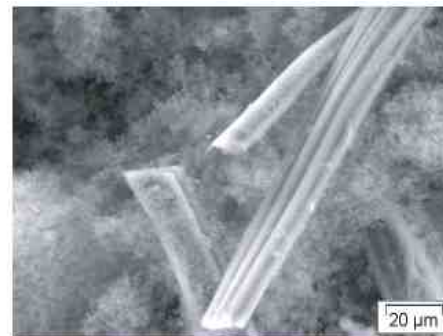


3-D WTPS materials recess more uniformly and have better recession performance than traditional chop molded carbon phenolic



Outline

- Introduction
 - NASA and TPS
- Thermal Protection Materials and Systems (TPS)
 - Reusable materials
 - UHTCs
 - Ablative materials
- Characterization of TPS for Performance and Design
- A Tale of Two Heat Shields
 - Recent Uses and Development of Heat Shields and Materials Issues
- New Trends in TPS
- Modeling of TPS





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 being 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



Computational Modeling of UHTCs Will Enhance Development

Goals

- Reduce materials development time
- Optimize material properties/tailor materials
- Guide processing of materials
- Develop design approaches

Approach

- Develop models integrated across various length scales
- Correlate models with experiment whenever possible



Modeling UHTCs – What's Next?

- **Accomplishments**

- *Ab initio* calculations of lattice structure, bonding characteristics, elastic constants, phonon spectra and thermal properties of ZrB_2 and HfB_2
- *Ab initio* calculations of formation and migration energies for simple defects (vacancies)
- Development of interatomic potentials for ZrB_2 and HfB_2 for atomistic simulations

- **Opportunities**

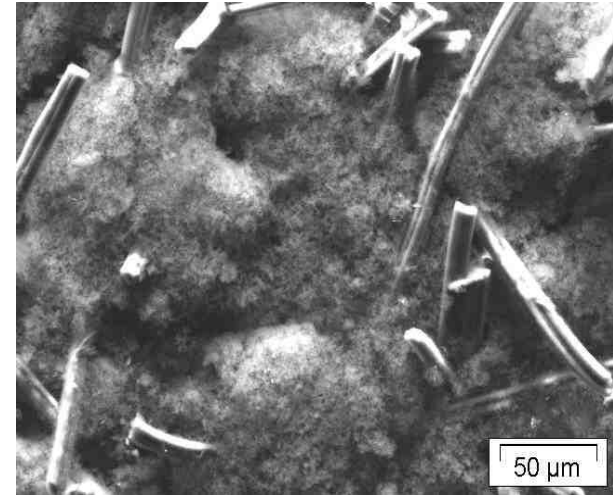
- *Ab initio* calculations of simple/ideal grain boundary structures with and without chemical impurities
- *No UHTC atomistic simulations exist in the literature. New potentials mean the field is wide open!*
- FEM modeling of microstructure to relate processing and properties



Fundamental Modeling of Ablators

- Ablators for most demanding atmospheric entries
- Intrinsically multi-scale materials and phenomena

- Pyrolysis chemistry (ab initio)
 - Pyrolysis simulation is very challenging: no current solution
- Phenolic networks (atomistic)
 - Virtual mechanical and thermal testing
 - Phenolic network design parameters: Linkage Sites and Cross-linking
- Microstructure Modeling (continuum)
 - X-ray CT images gives 3D micron scale, realistic microstructure
 - FEM models for thermal/mechanical analysis



PICA - carbon fiber/phenolic matrix



Summary

- Two main classes plus specialized materials
 - Insulating, e.g. space shuttle tiles
 - Ablators for higher heat fluxes
 - New materials for new missions – woven, conformable, etc.
- TPS needs to fit the application—location on vehicle, expected environment
- Heritage materials may not always be heritage
 - Substantial effort required to recreate
- 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
- Modeling and analysis are critical to better understanding and prediction of material behavior in reentry

Goal of all TPS is reliable and efficient performance!



The End





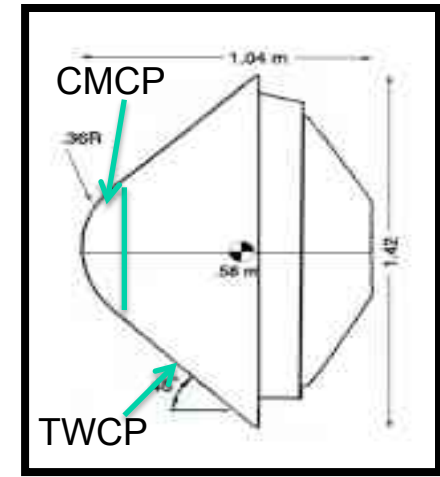
Manufacturing Variability

- 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.



TPS for Outer Planet Missions: Carbon Phenolic Current Status

- Heritage Entry Grade Carbon Phenolic (HEGCP)
 - Most capable and robust TPS
 - Baseline TPS for the Saturn and Uranus Probe Missions
 - HEGCP is very capable, robust and enabled P-V & Galileo & is flight proven
- **Carbon Phenolic (CP) heat-shield is made of two types**
 - Chop Molded and Tape Wrapped CP
- **Tape wrap manufacturing needed for Rocket nozzles and DoD's slender entry body missiles – sustainable**
- **Chop Molded CP is needed only for NASA entry missions**
- **HEGCP needs Avtex Rayon – no longer produced (since 1986)**
- **NASA held two CP workshops (2010, 2012) to assess the SOA**
 - Heritage rayon based CP no longer viable for Venus (or Saturn)
 - The industry is shrinking; especially for CMCP and longer term sustainability of any CP is a ??



**NASA is addressing this challenge through Innovative TPS development
Funded by Game Changing Development Program of STP and SMD**



Models After Testing @ 250 W/cm² on flank – 60 sec





Examples of conAblators Under Development

Rigid Ablators



Advanced PICA-like ablators



Graded Ablators

Conformable Ablators



Conformable PICA

Flexible Ablators

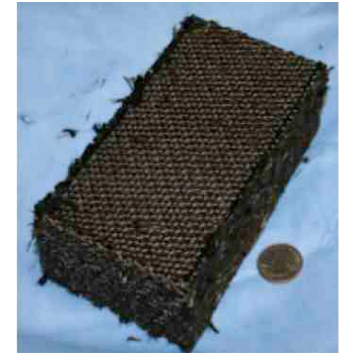


Flexible PICA

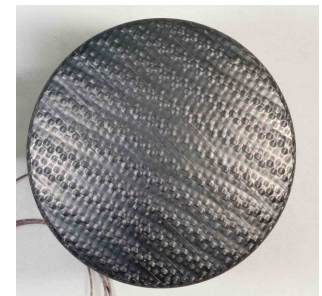


Flexible SIRCA

Woven TPS



Mid density TPS



Carbon phenolic replacement



Completed SPRITE 250





Models After Testing @ 500 W/cm² on flank – 30 sec



C-SICA

