

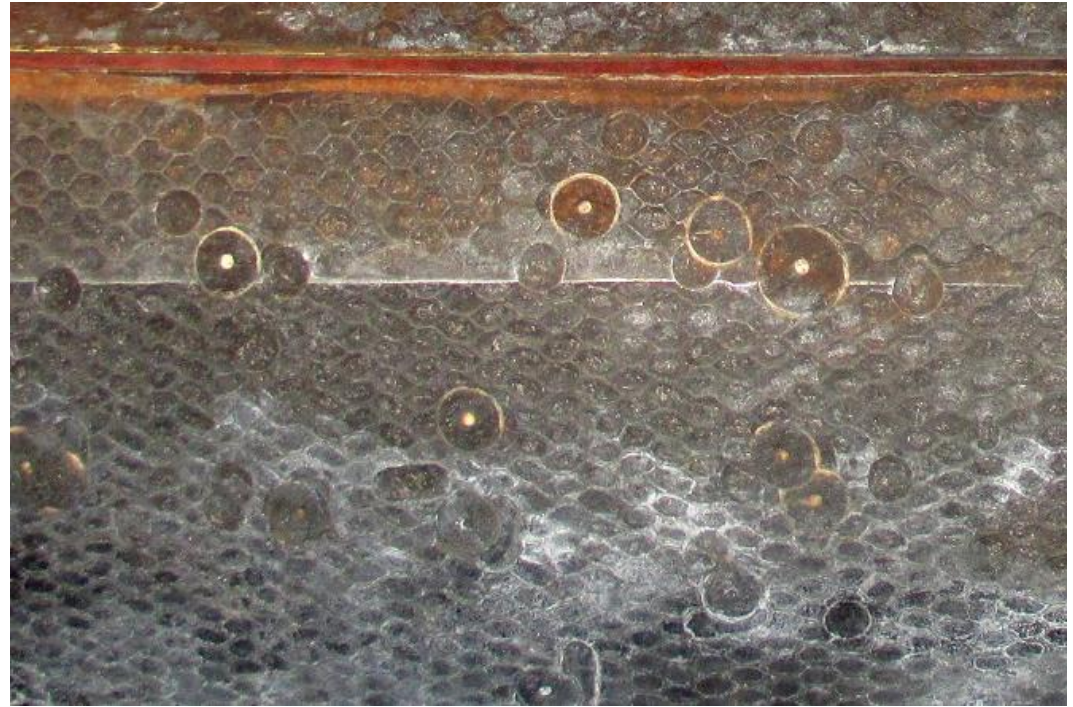
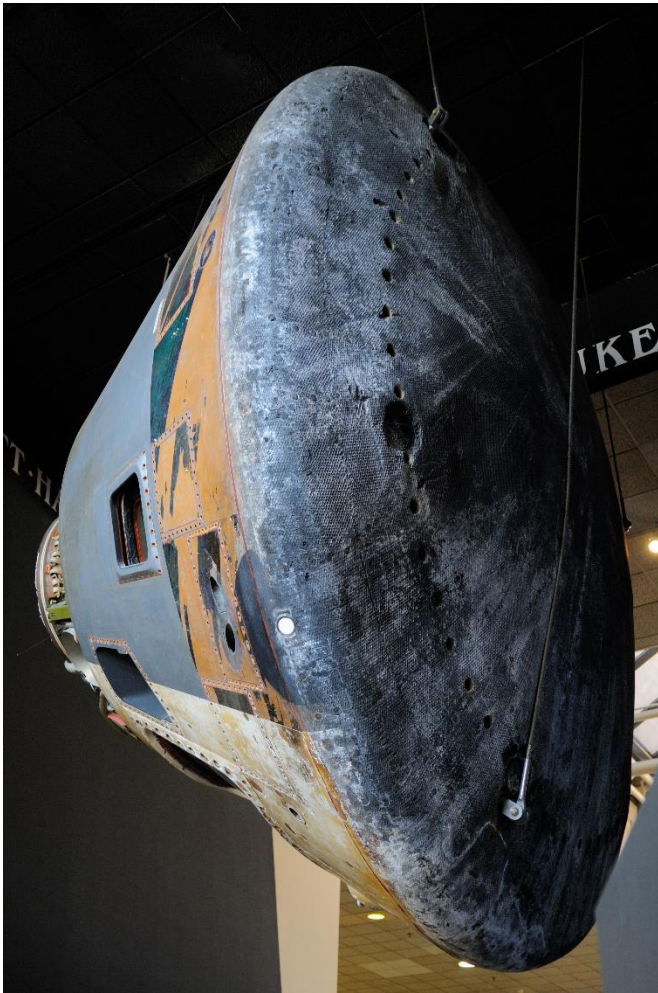


Thermal Protection Materials and Systems: Past and Future

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NASA Ames Research Center**

**40th International Conference and Exposition
on Advanced Ceramics and Composites
Daytona Beach
January 25, 2015**

Apollo Heatshield: After Entry!



Material: AVCOAT

Atmospheric entry is tough on materials!



- Introduction to Thermal Protection Systems (TPS)
- Reusable TPS
 - Shuttle materials
 - Current reusable material
- UHTCs
- Ablative TPS
 - Recent materials
 - Materials selection
 - Orion TPS
- Challenges for the future
New materials/concepts



- NASA uses TPS for entry vehicles that carry people, cargo, experiments, samples and/or instruments
 - Entries usually involve descending into the atmosphere followed by a trajectory that aims to burn off energy and result in a controlled landing.
 - Not usually ballistic entries
 - Not long hypersonic operations in atmosphere.
 - Entry to Earth, Mars, Venus, gas and ice giant planets

TPS Development



- NASA Ames focuses 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

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)

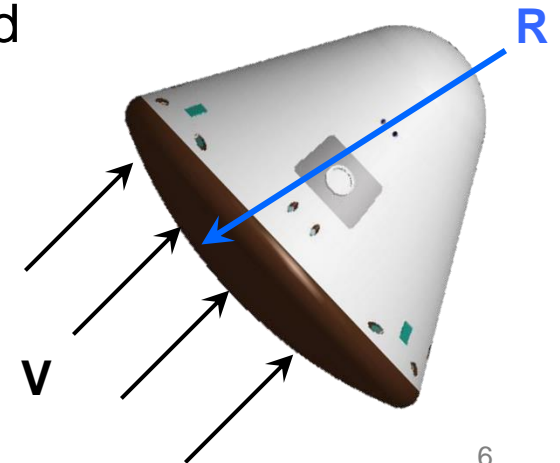
$$\dot{q}_{conv} \propto V^3 \left(\frac{\rho}{R} \right)^{0.5}$$

Convective Heating

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

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

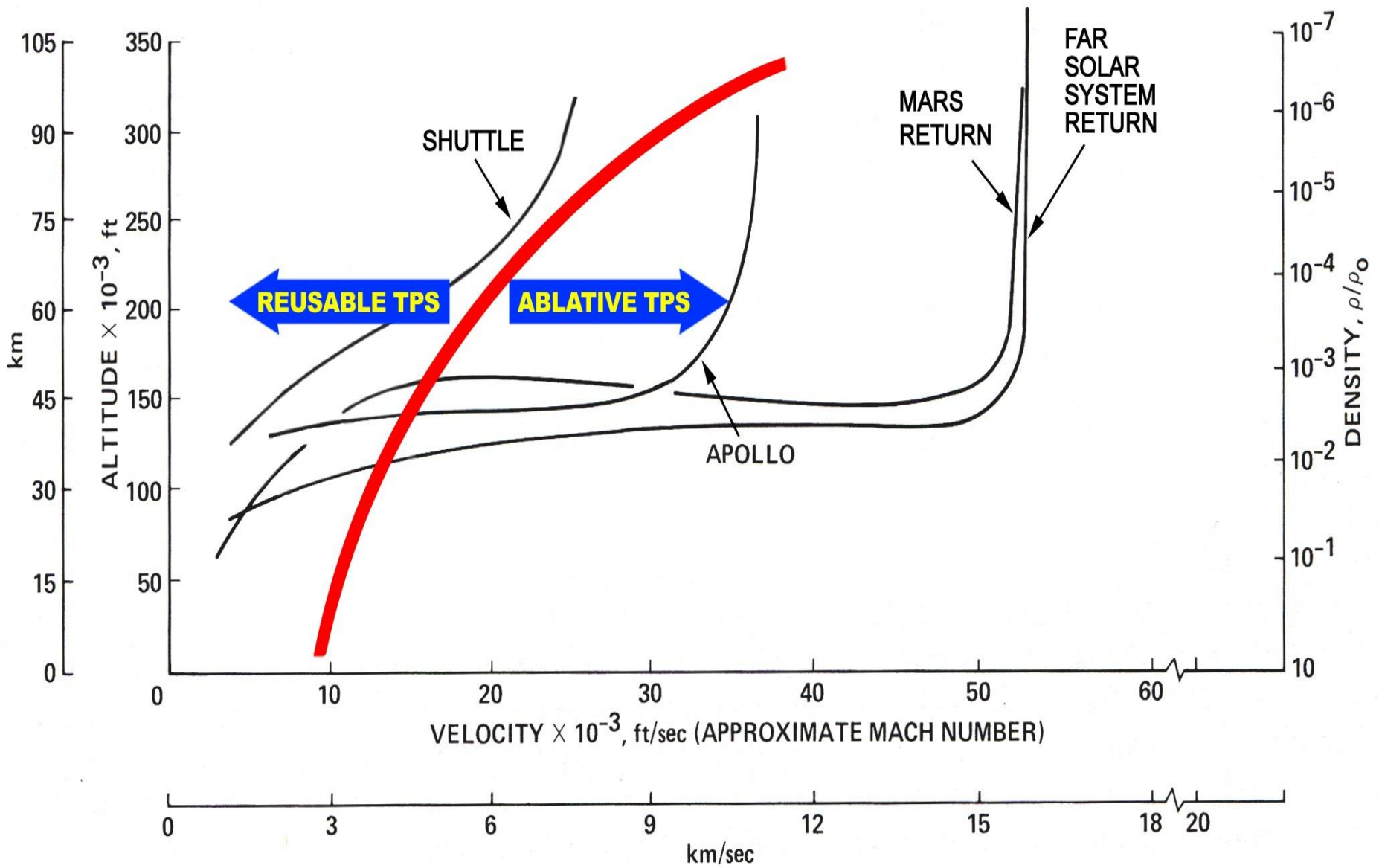
Specifically addresses challenges of mass reduction and reliability



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

Reusable vs. Ablative TPS



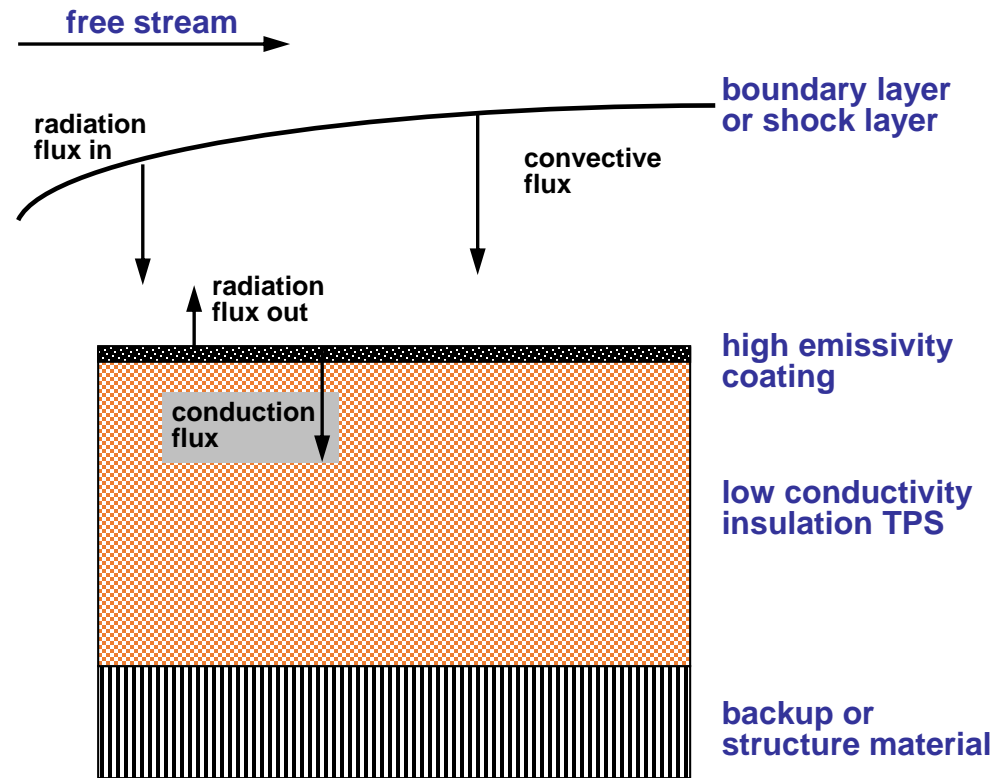
Insulative/Reusable TPS



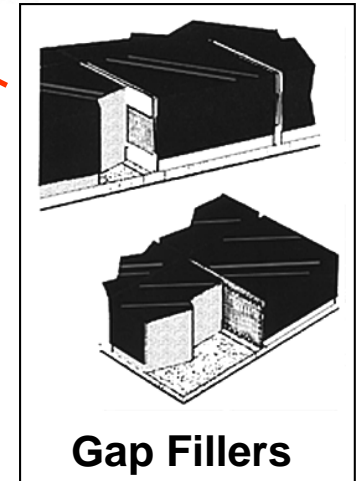
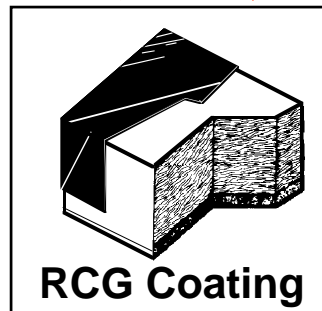
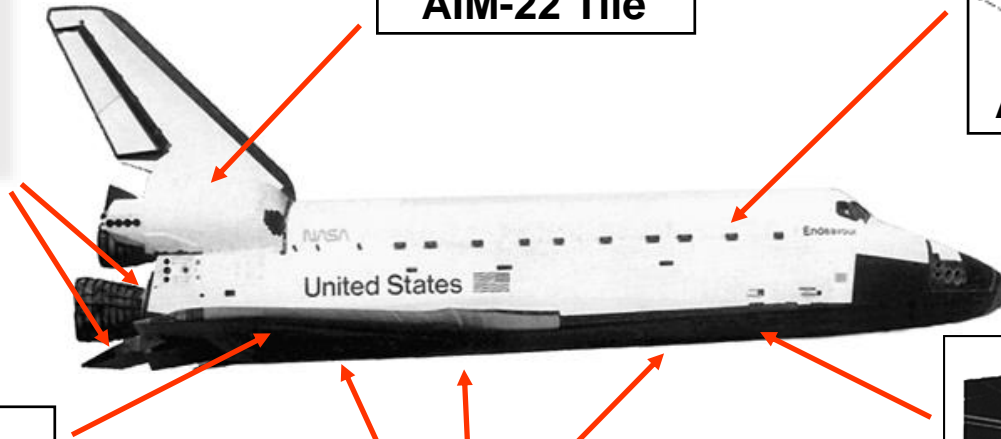
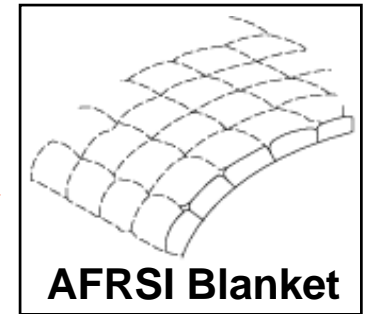
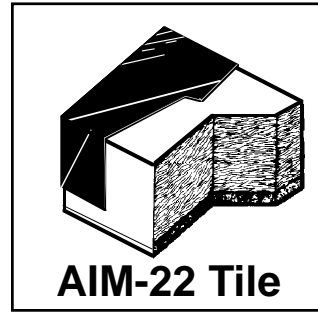
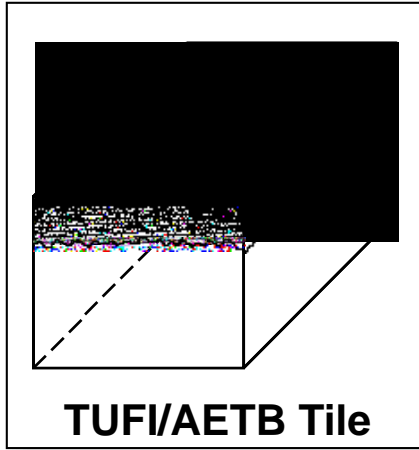
Energy management through storage and re-radiation — material unchanged

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

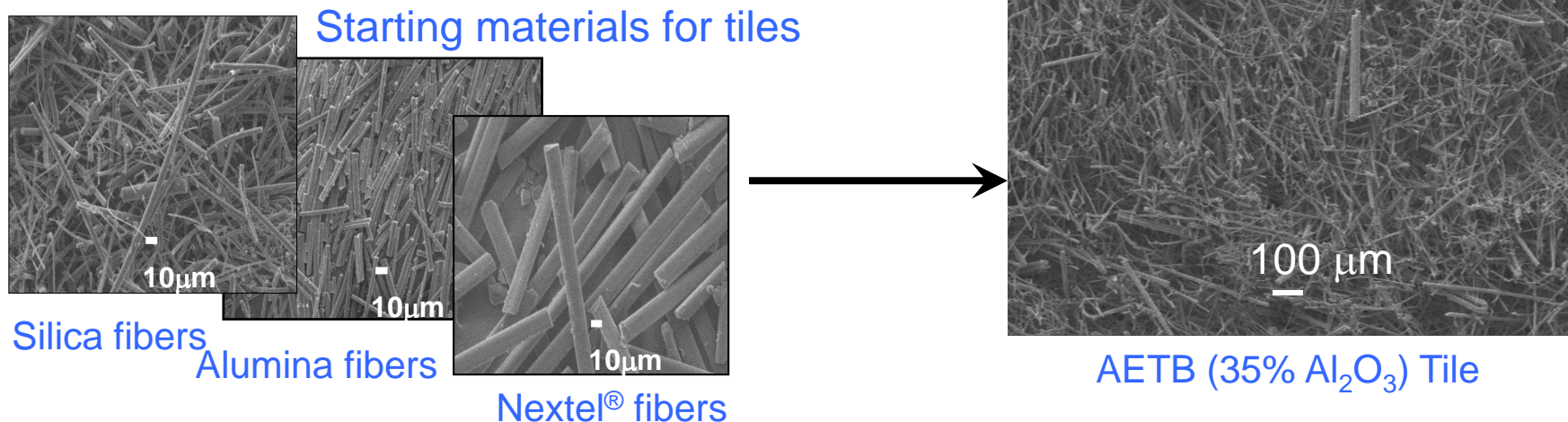


Ames-Developed Thermal Protection Materials Adopted on Shuttle



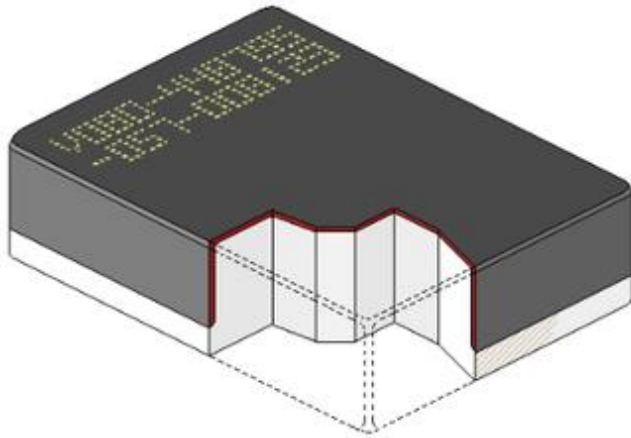
Reusable TPS: Tiles

- 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

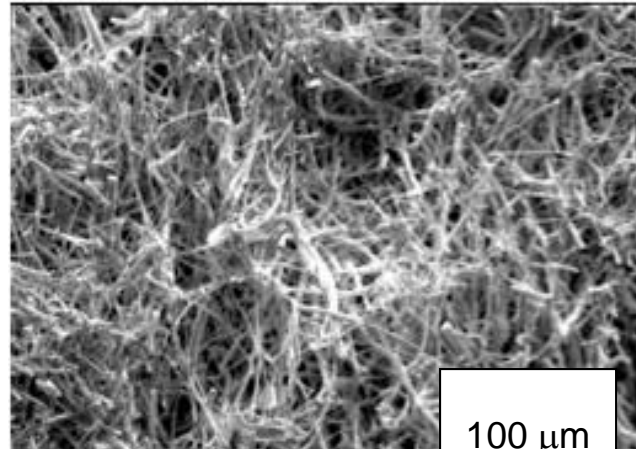


Tiles are heterogeneous with regions of low density and clumps of fibers with some non-fibrous inclusions

Reusable TPS: Tiles and Coatings

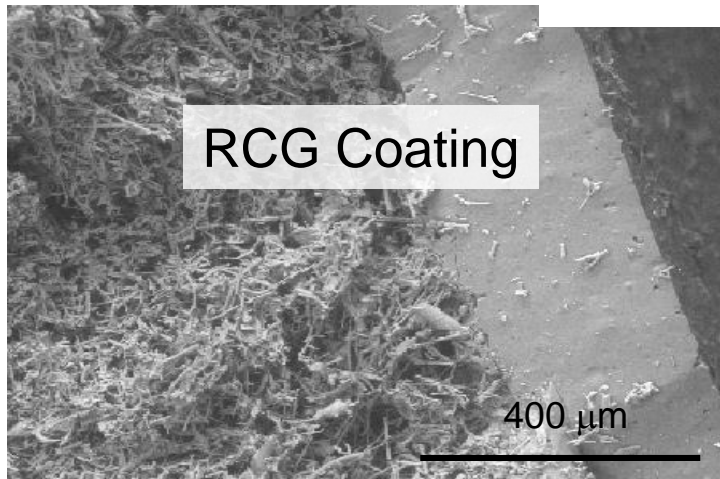


Density: 0.14 to 0.19 g/cm³



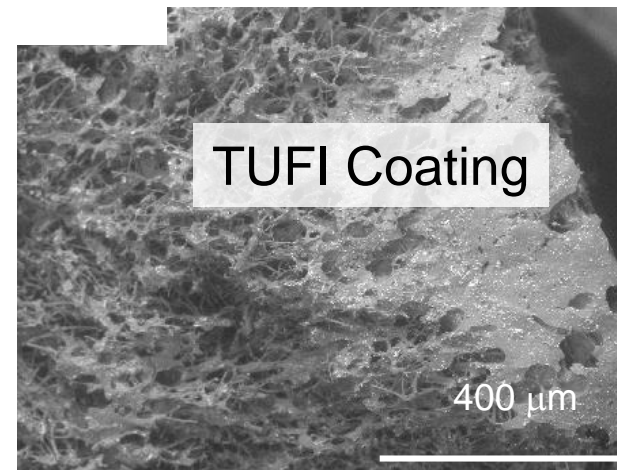
“Space Shuttle Tile”

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



RCG Coating

- RCG (Reaction Cured Glass) is a thin dense high emittance glass coating on the surface of shuttle tiles
- Poor impact resistance



TUFII Coating

- TUFII (Toughened Unipiece Fibrous insulation) coatings penetrate into the sample
- Porous but much more impact resistant system

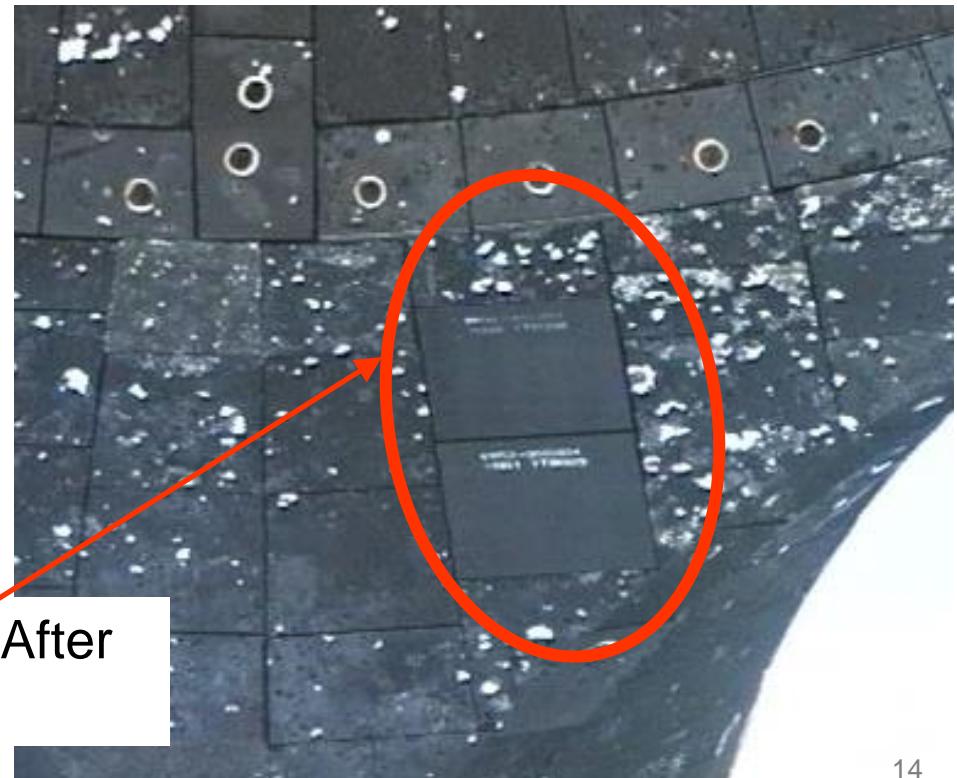
Shuttle Flight Testing of TUFI Tiles in Base Heatshield



RCG Hybrid Overcoat

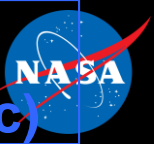
Impregnated surface treatment

TUFI tiles used on base heatshield of Shuttle to protect against damage from debris incurred during liftoff



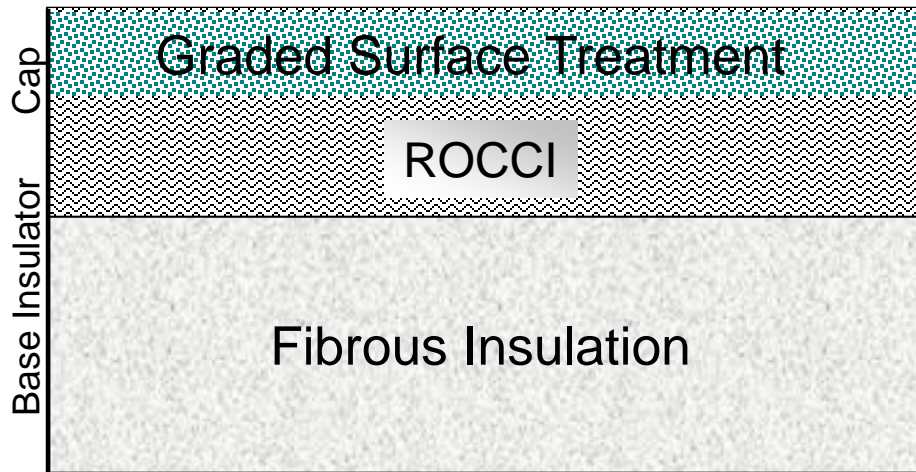
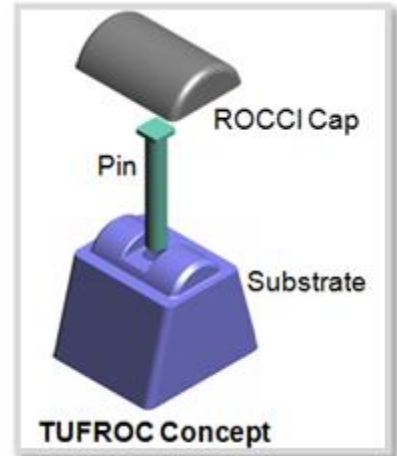
TUFI/AETB-8 Tiles Undamaged After Three Flights

TUFROC TPS

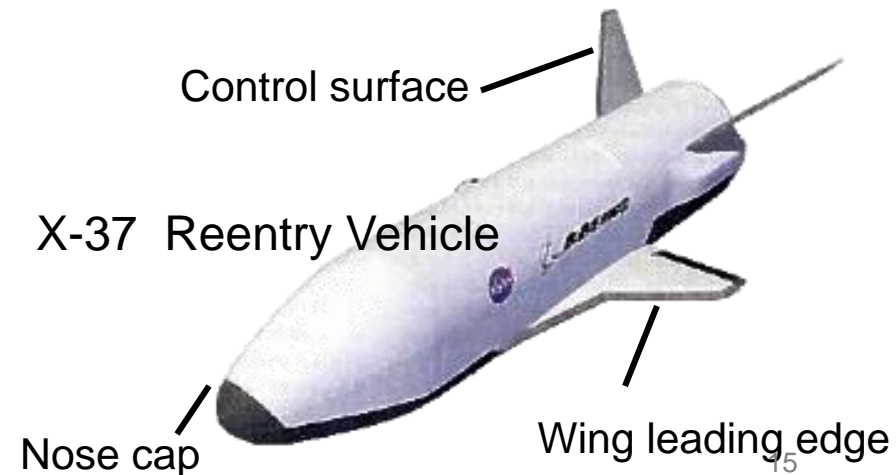


(Toughened Unipiece Fibrous Reusable Oxidation Resistant Ceramic)

- Developed TUFROC for X-37 application
- Advanced TUFROC developed recently
- Transferred technology to Boeing and others
- 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



Standard TUFROC

2 Piece Approach

Re-radiate enough heat so that conduction through

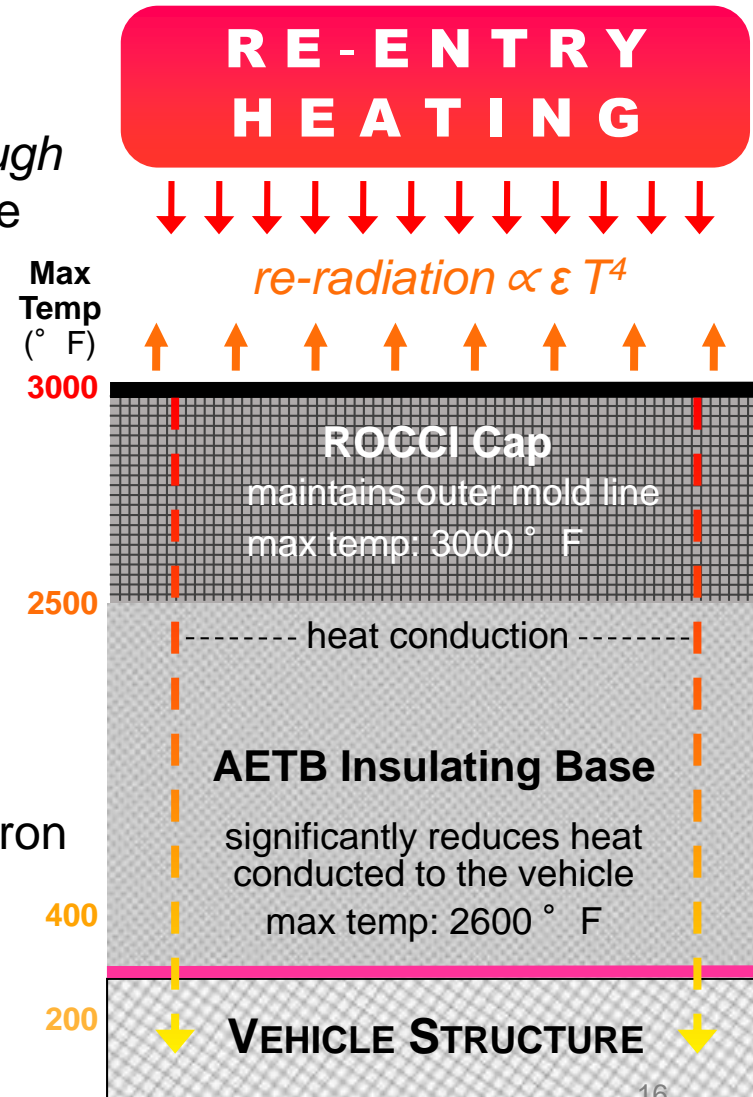
- Cap is within temp limits of the insulating Base
- Base is within temp limits of the Vehicle

ROCCI Carbonaceous Cap

- Silicon-oxycarbide phase slows oxidation
- HETC, treatment near surface slows oxidation and keeps emissivity high ($\epsilon \sim 0.9$)
- Coated with borosilicate reaction cured glass (RCG) for oxidation resistance

AETB Silica Insulating Base

- Solved thermo-structural issues by adding boron oxide (B_2O_3) and alumino-borosilicate fibers, which also improved mechanical strength
- Increased temp capability to 2500+ ° F by adding alumina (Al_2O_3) fiber



TUFROC on X-37

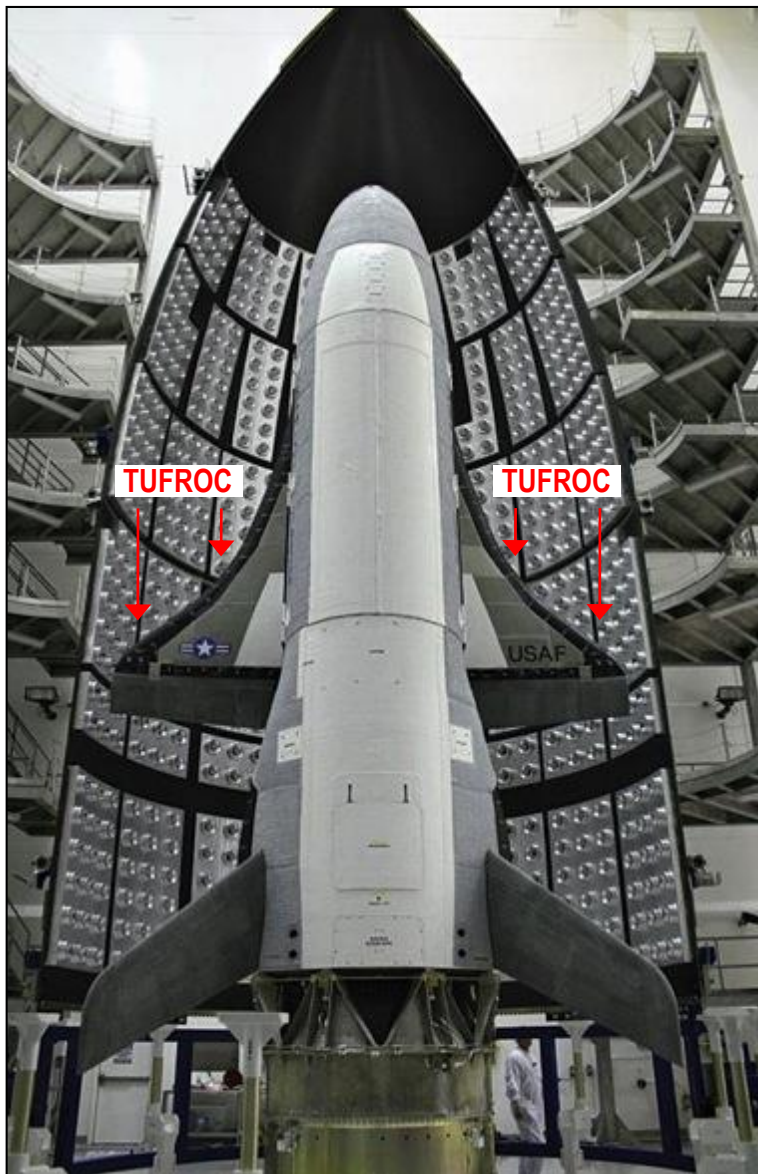


Flight Proven Standard TUFROC

TUFROC spans USAF X-37b wing leading edge

- NASA developed Standard TUFROC and transferred it to X-37b Prime - Boeing
- Enabling technology for critical USAF Program
- 3 successful missions, 4th mission in progress

Reusability of Standard TUFROC? ⇒ Advanced



X-37b Preparing for 1st launch, Apr 2010

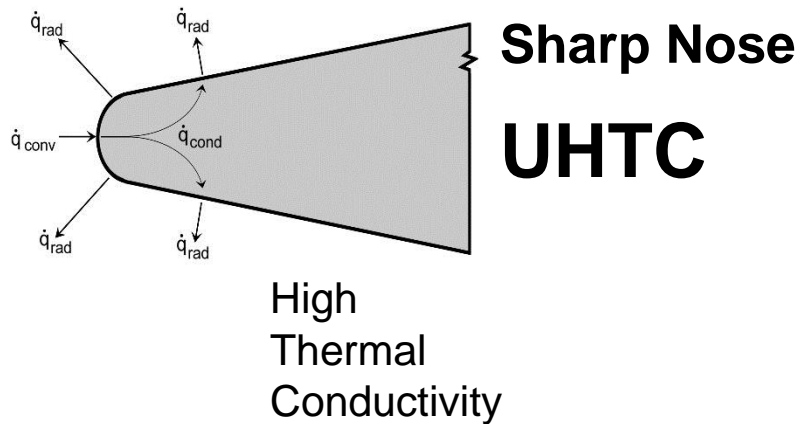


X-37b after 224 days (90 million miles) in orbit, Dec 2010

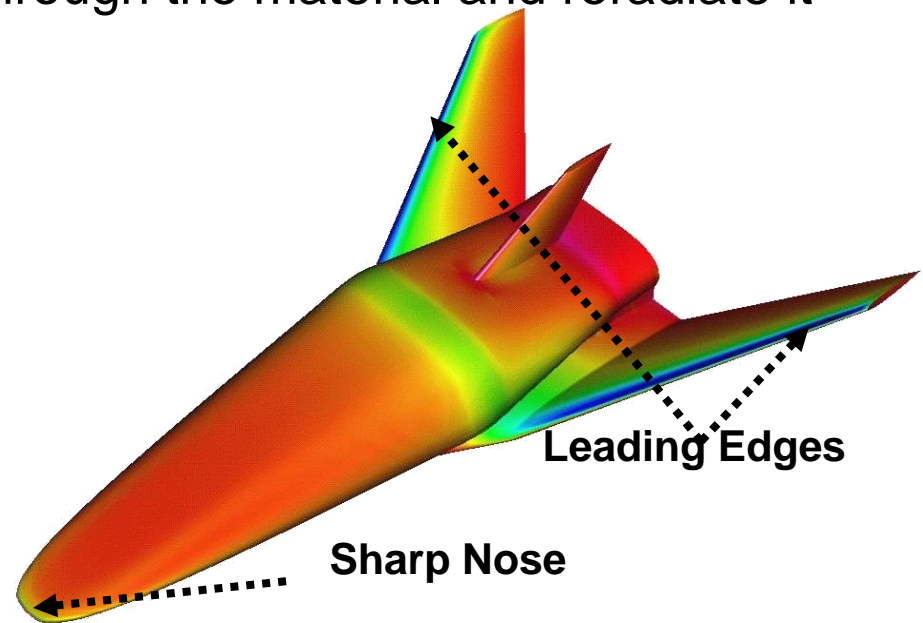
Sharp Leading Edge Energy Balance



- 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



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

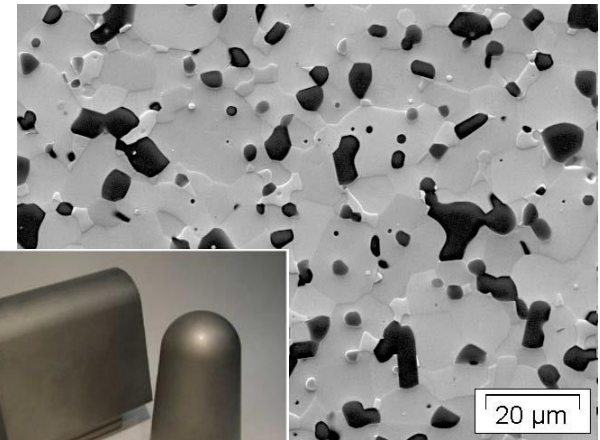
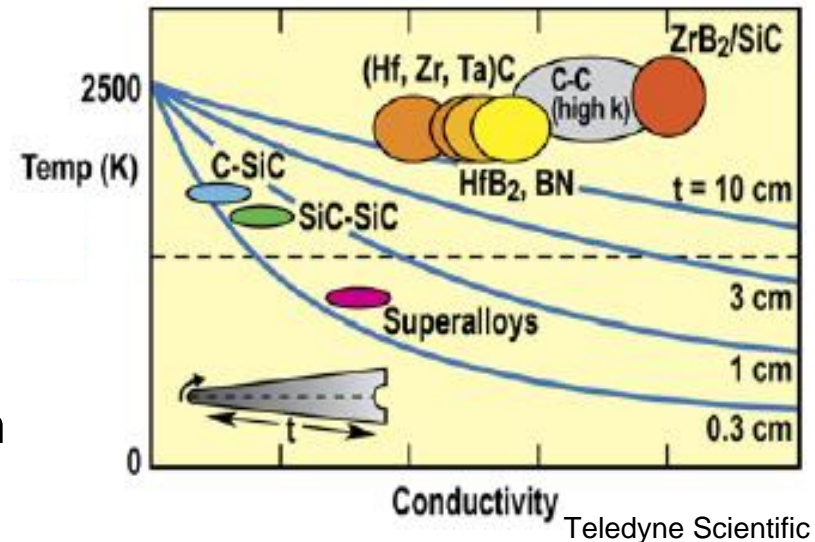


Dean Kontinos, Ken Gee and Dinesh Prabhu. "Temperature Constraints at the Sharp Leading Edge of a Crew Transfer Vehicle." AIAA 2001-2886 35th AIAA Thermophysics Conference, 11-14 June 2001, Anaheim CA

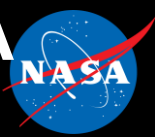
Ultra High Temperature Ceramics (UHTCs) : A Family of Materials



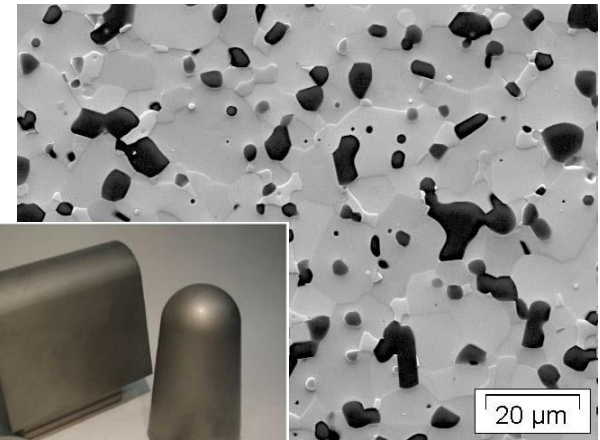
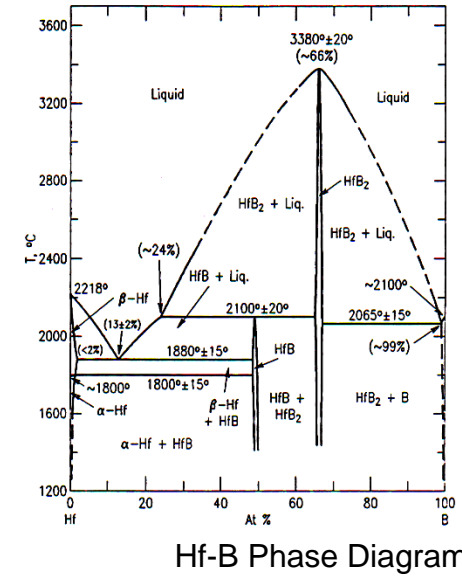
- Borides, carbides and nitrides of transition elements such as hafnium, zirconium, tantalum and titanium
- Some of highest known melting points
- High hardness, good wear resistance, good mechanical strength
- Good chemical and thermal stability under certain conditions
 - High thermal conductivity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



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



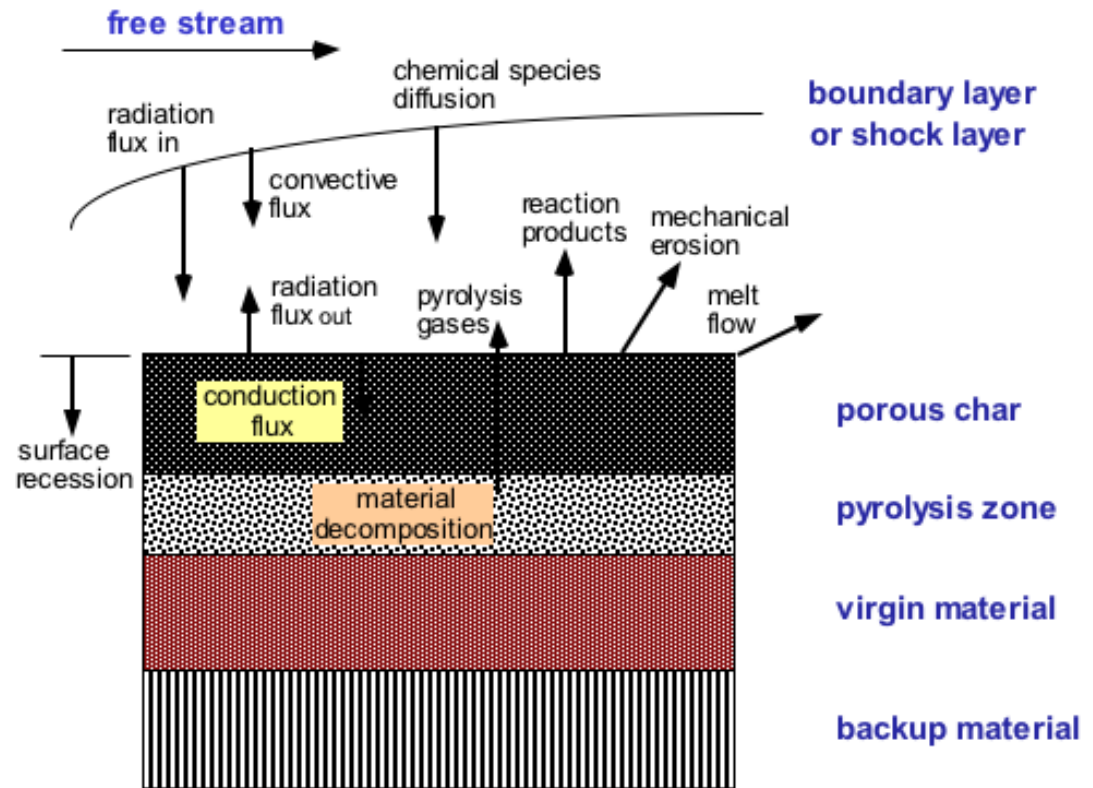
Ablative TPS



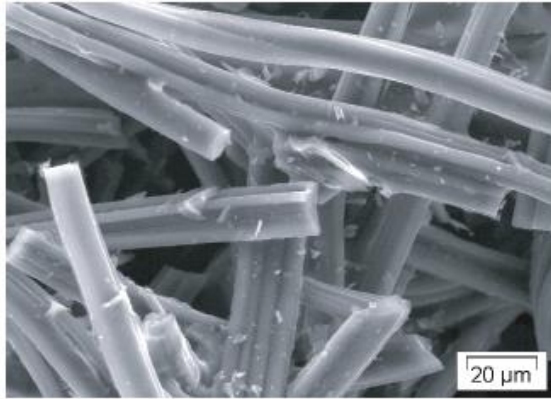
Energy management through material consumption

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

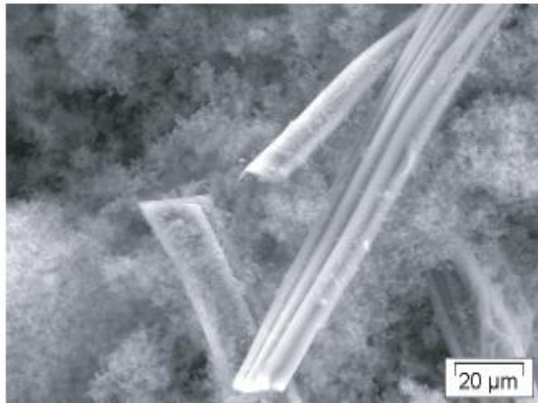
- Endothermic decomposition of polymer
- Blowing of ablation products into the boundary layer reduces convective heating
- Formation of char layer and re-radiation



Processing Detail



Fiberform™ before impregnation

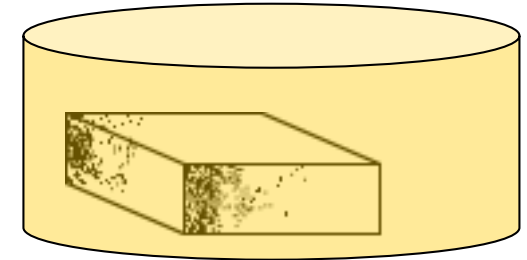


PICA: Fiberform™ with phenolic resin



Carbon Fiberform™

Phenolic Resin



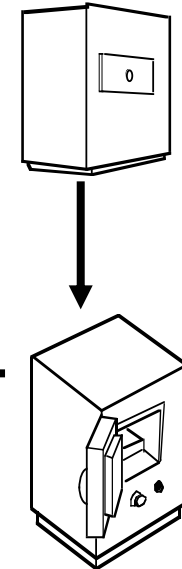
Resin Impregnation

PICA has low density ($\sim 0.27\text{g/cm}^3$) and is an efficient ablator at high heat fluxes



PICA Arc Jet Model

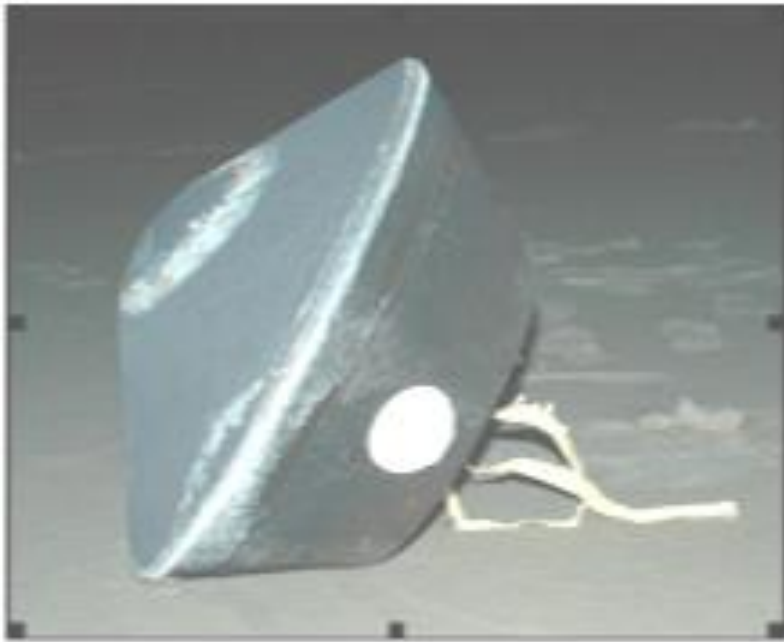
Drying Cycle



PICA Applications

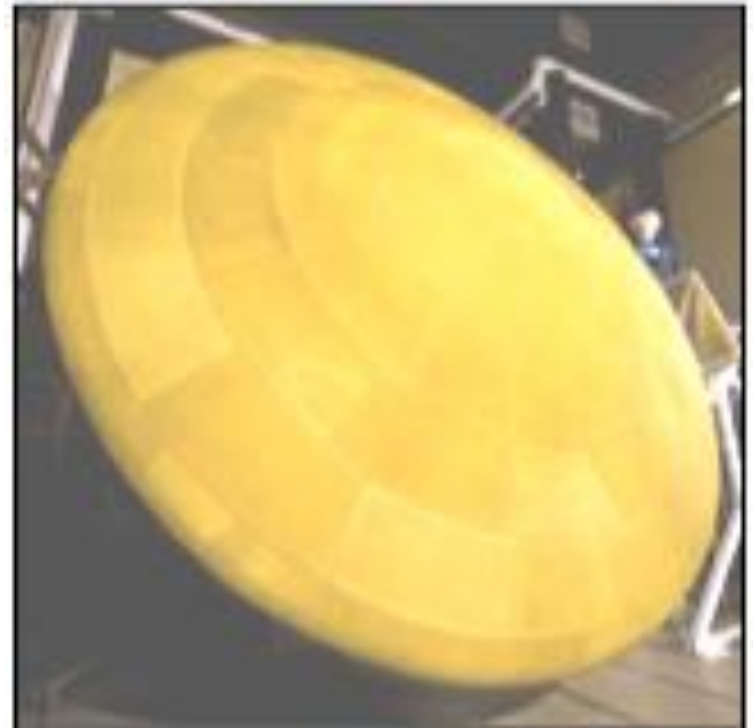


PICA was the enabling TPS material for the Stardust mission where it was used *as a single piece heatshield*



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

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



MSL Heat Shield (4.5m diameter)

Selection of Appropriate Material

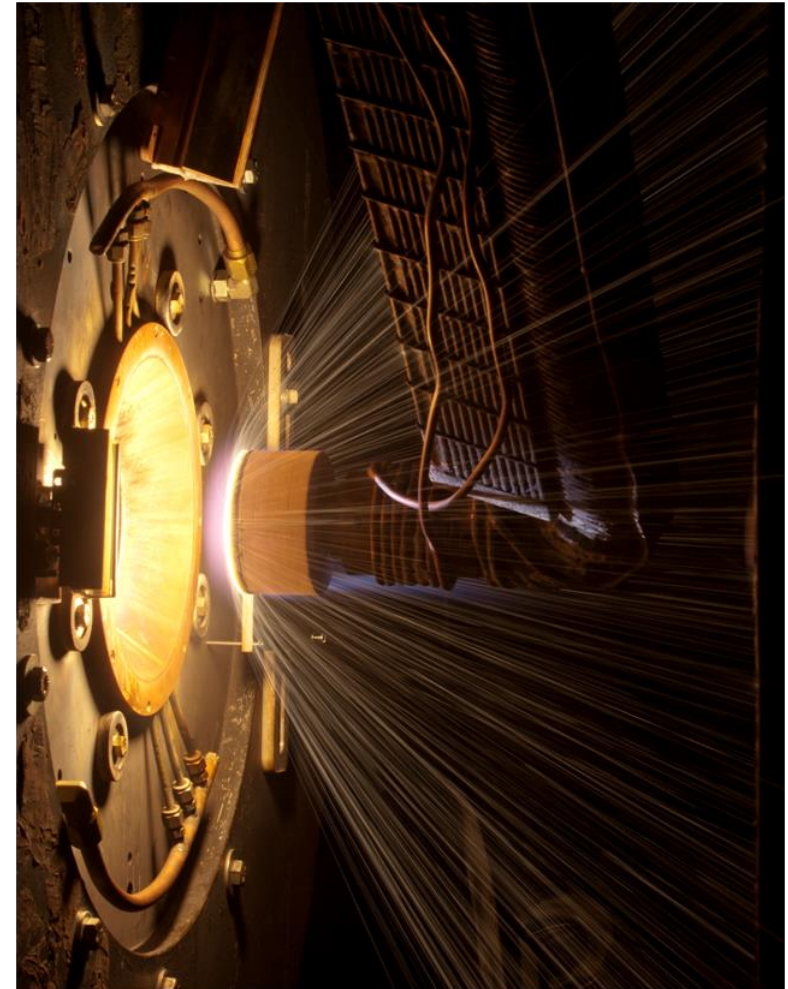


- Historical approach:
 - Use heritage materials: “It’s worked before...”
 - Risk-reduction strategy
 - Limited number of flight-qualified ablative materials
 - Different vehicle configurations and reentry conditions (need to qualify materials in relevant environments)
- As missions become more demanding, 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

Need for Arc Jet Testing



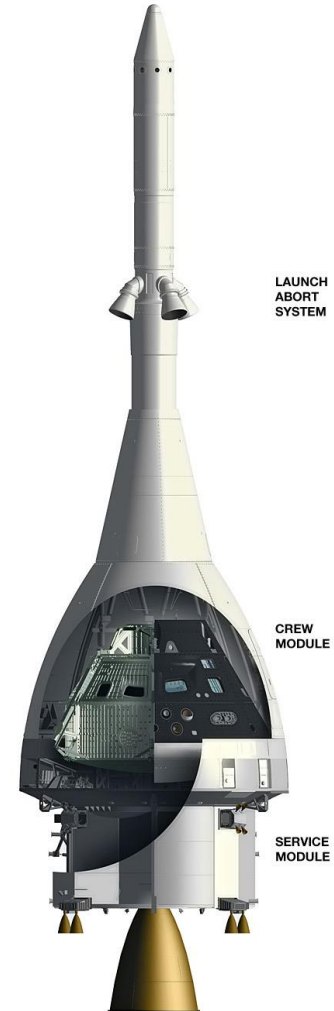
- Arc jet testing is the best **ground-based method** of evaluating a material's oxidation/ablation response in re-entry environments
- Oxidation/ablation behavior on heating in static or flowing air at ambient pressures is likely to be significantly different than in a re-entry environment.
 - O₂ and N₂ may be dissociated
 - Catalycity of the material
 - Recombination of O and N atoms adds to surface heating
 - Stagnation pressures may be <1 atm.



Orion



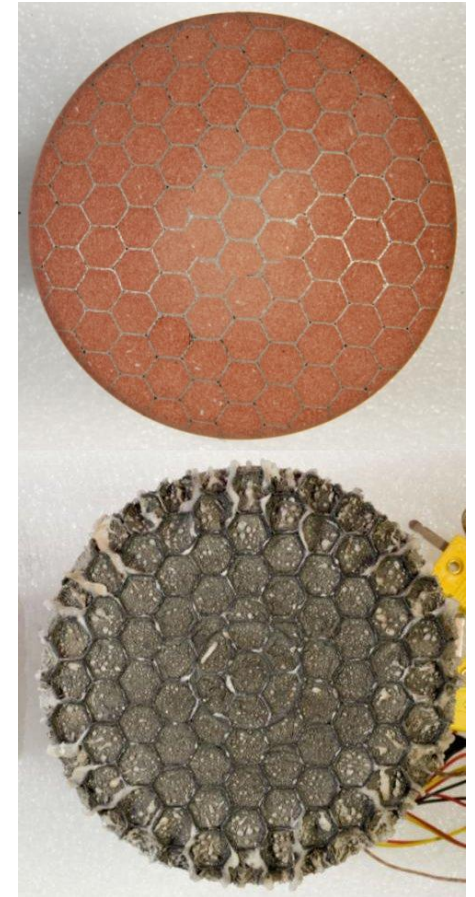
- **The Orion spacecraft will take astronauts beyond low Earth orbit (LEO) to deep space.**
 - emergency abort capability,
 - sustain the crew
 - provide safe re-entry from deep space.
- **Exploration Flight Test-1, an uncrewed mission flew in 2014.**
 - Orion travel farther into space than any spacecraft had gone in more than 40 years.
 - EFT-1 data used to influence design decisions, validate existing computer models and innovative new approaches to space systems development, as well as reduce overall mission risks and costs.
- **What TPS was used?**
 - Decision was made to use Avcoat, material first used on Apollo



Orion TPS: AVCOAT



- Avcoat was used on the Apollo vehicles: “heritage” material
- Consists of a honeycomb filled with an ablative mixture
- Complex material requiring hand assembly
- Next Orion flight will use a variant of Avcoat without the honeycomb

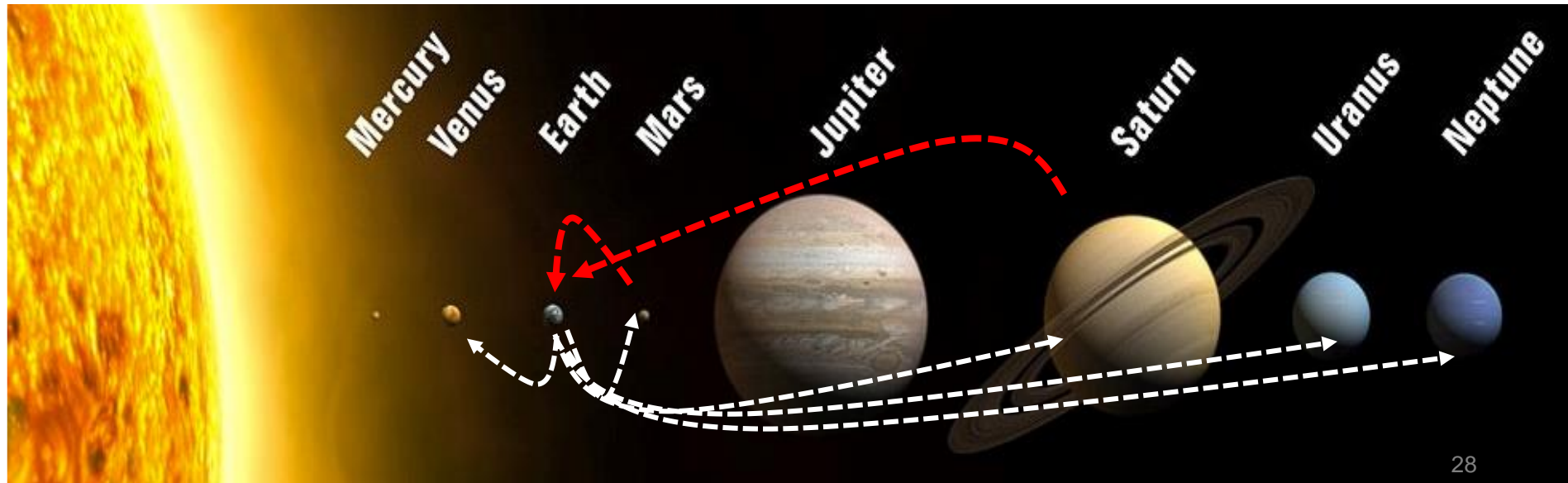


Avcoat arc jet models: pre and post test

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



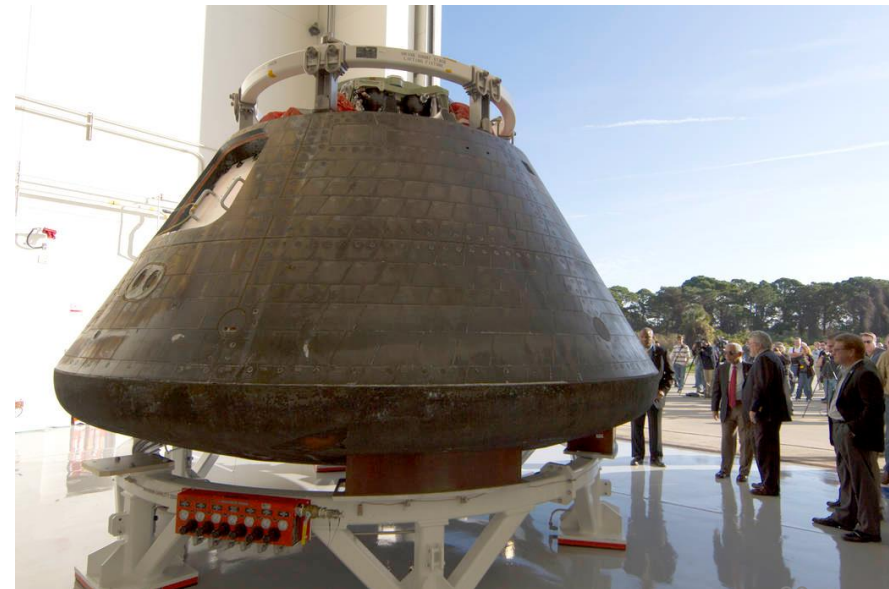
TPS Selection



- 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

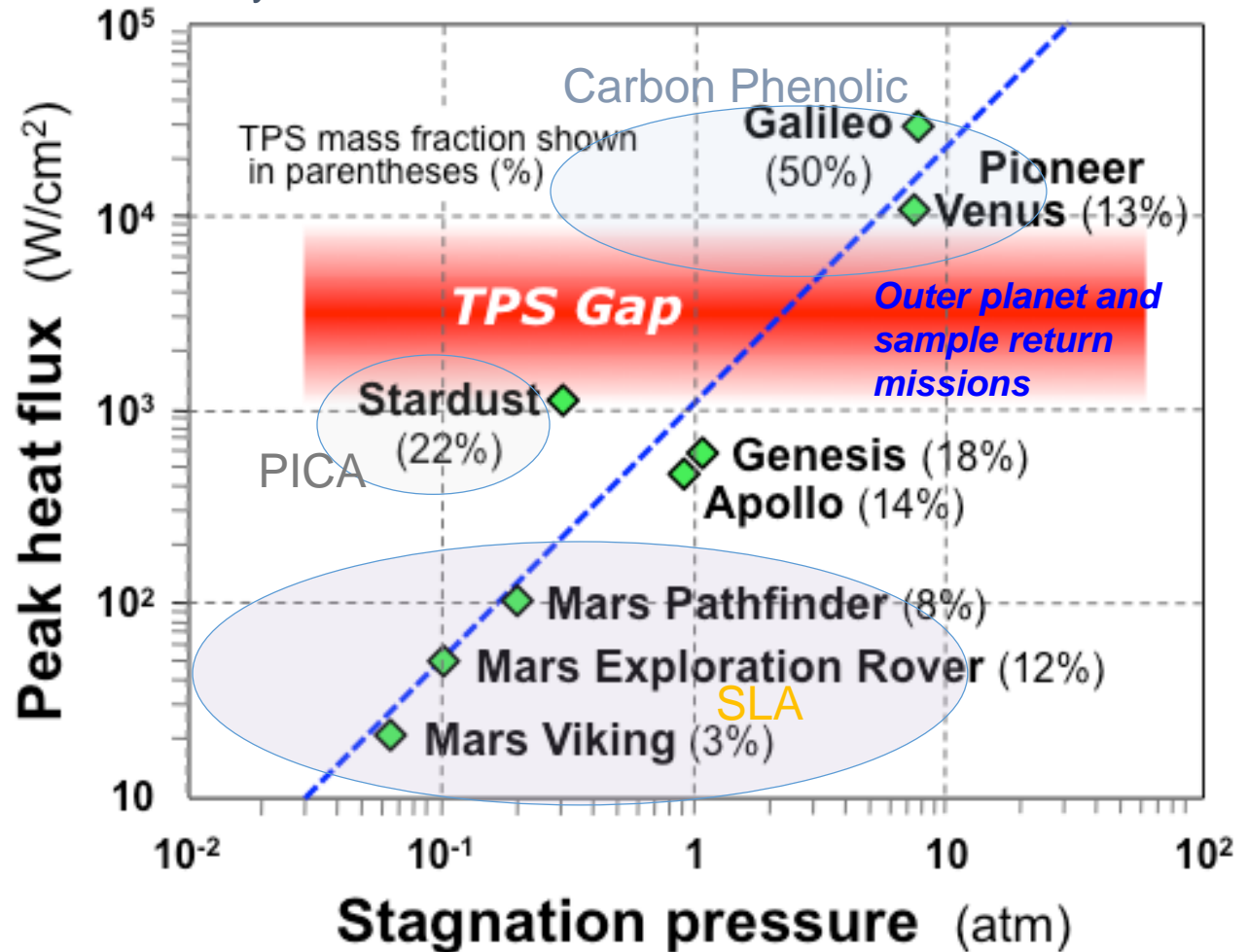
1. Prabhu, D.K., et. al.; IEEE Aerospace Conference, Big Sky, MT, March 2-9, 2013
2. Allen, G. A. and Prabhu, D. K.; private communication



Future Missions: TPS Availability and “Gap”



Historical TPS Mass Fraction
by Heat Flux and Pressure



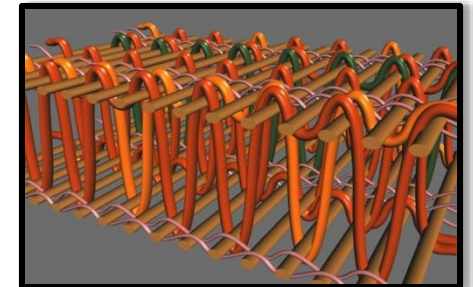
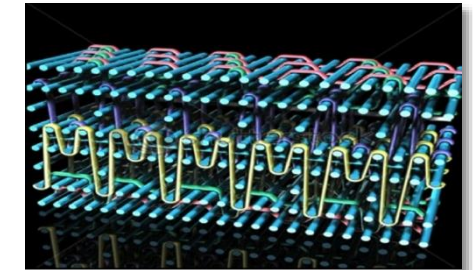
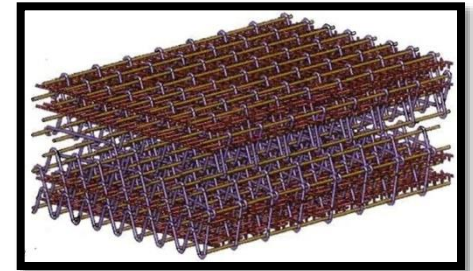
- Carbon phenolic
 - high heat fluxes
- PICA/other ablators
 - < ~ 2,000 W/cm²

No efficient TPS for the gap from ~1000W/cm² to 10,000W/cm²

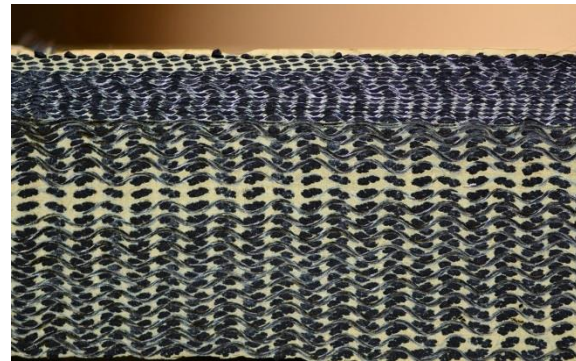
3D Woven TPS

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

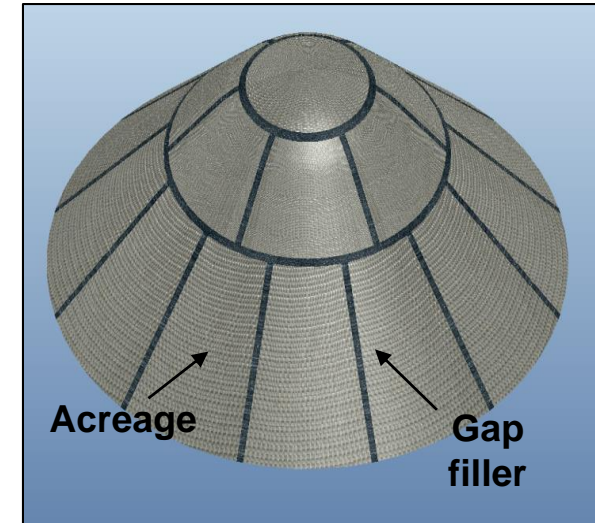
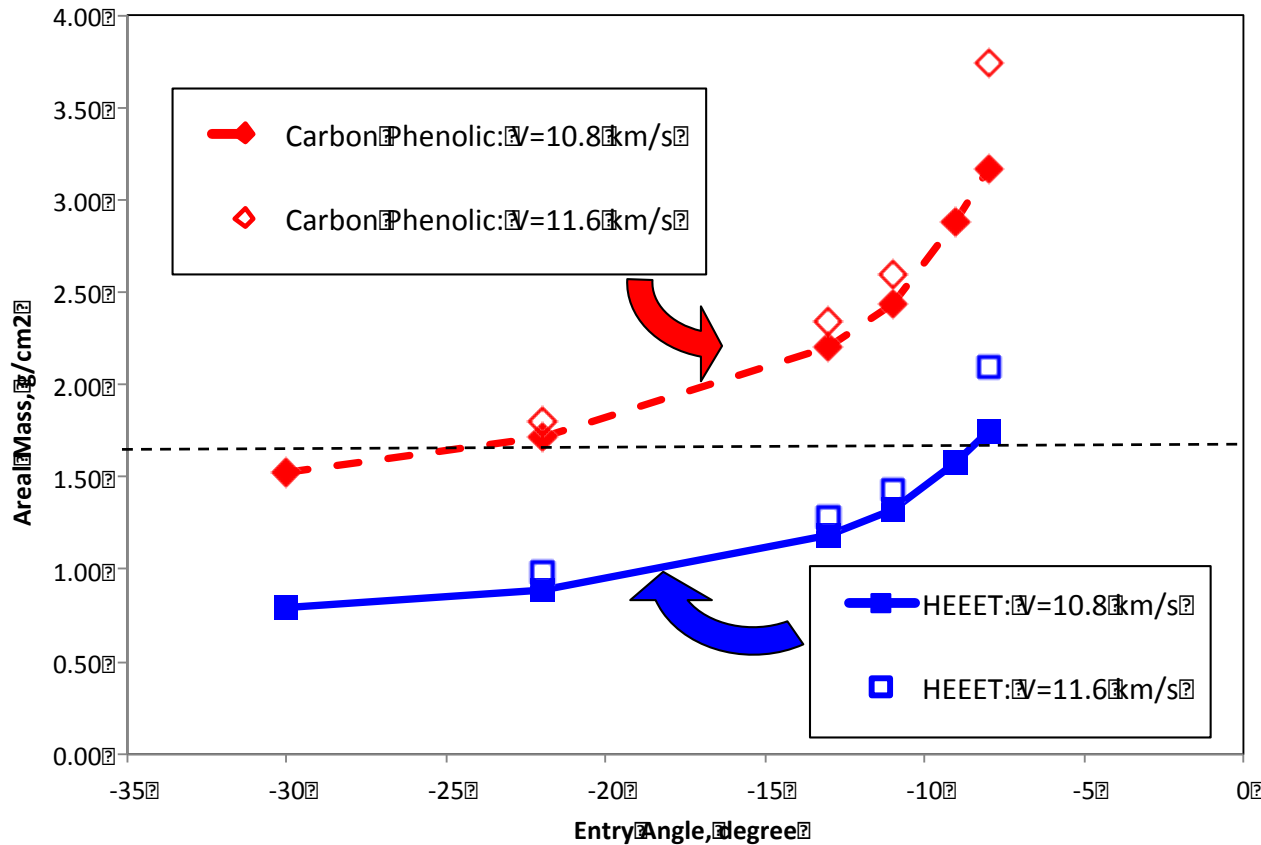


Blended Yarn



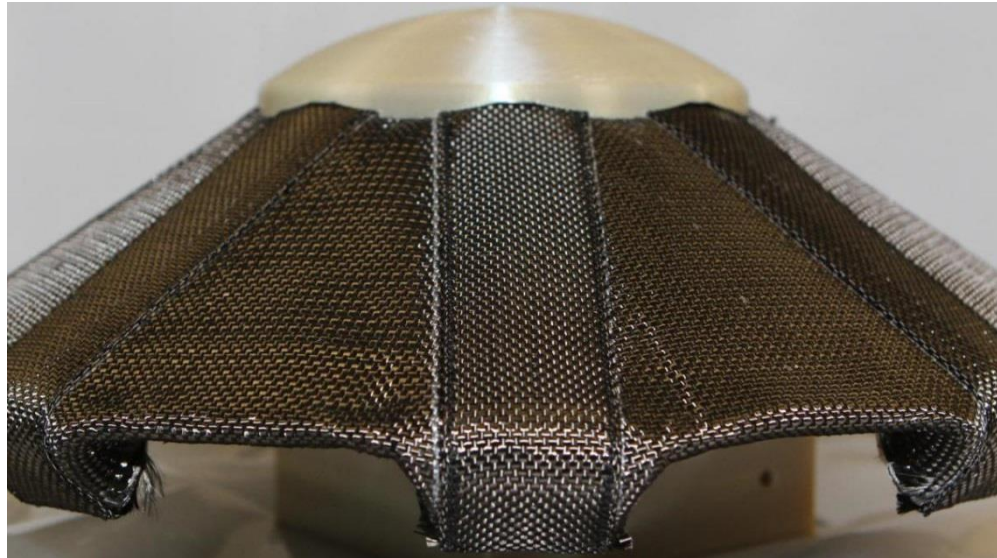
Resin infused

Potential Mass Savings!



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

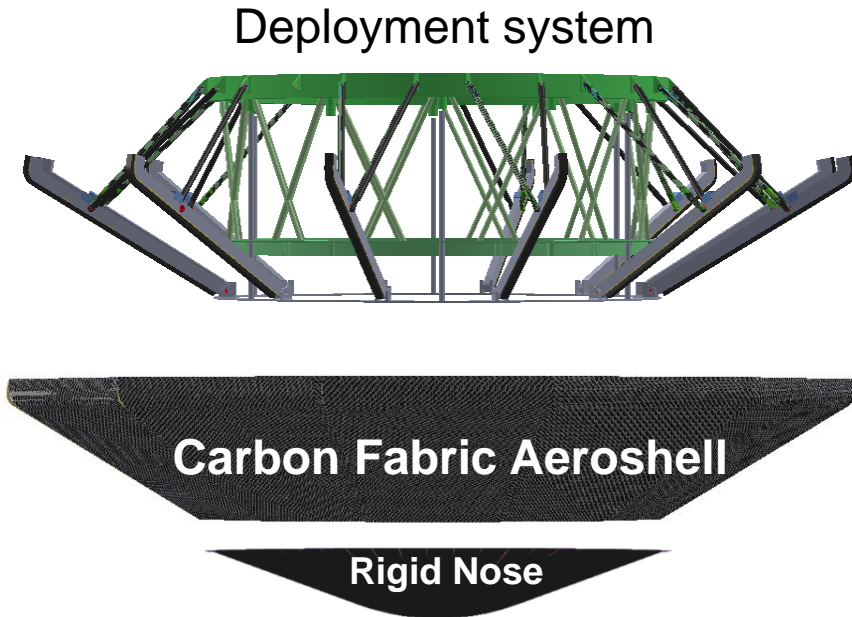
Deployable Heat Shield Concept



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)



Current concepts for Venus exploration

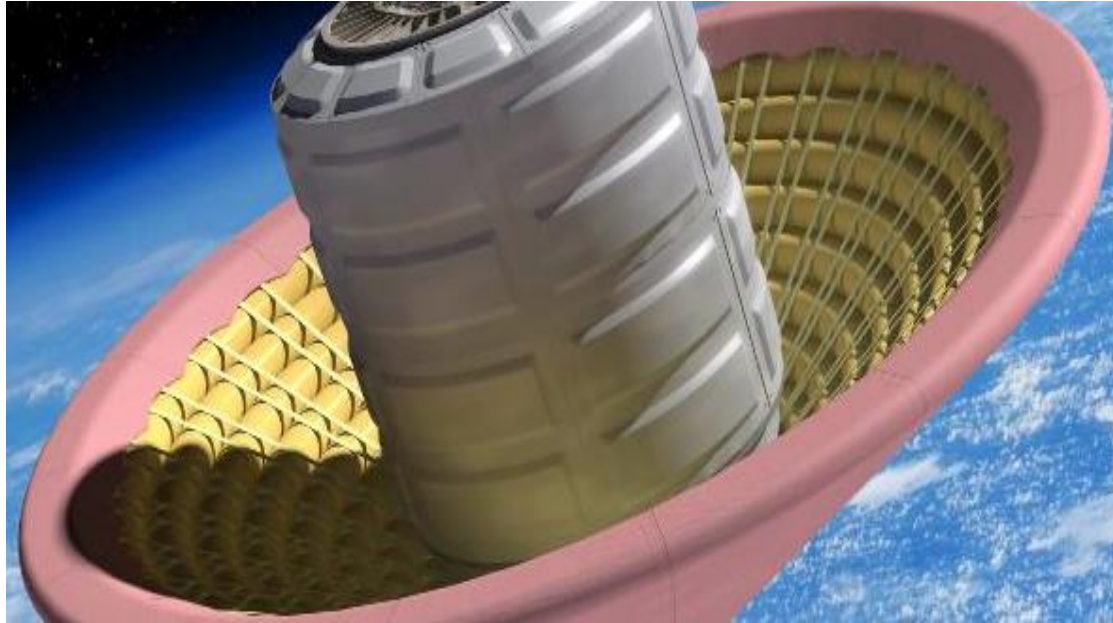
Potential for expansion to Mars entry (~16m diameter)

Large sizes will place significant demands on structure and mechanisms

Inflatable Heatshield Concept



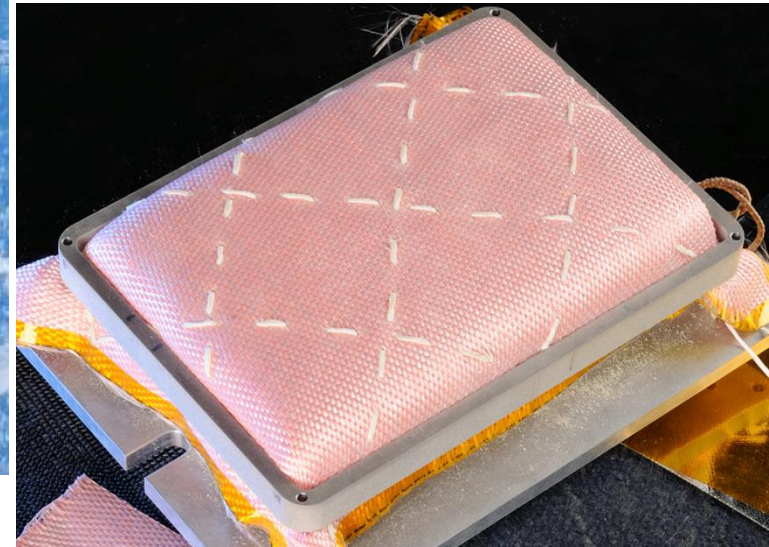
Inflatable structure with a flexible TPS



Inflatable aeroshell covered in TPS

High Energy Atmospheric Reentry Test (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/cm²)
 - Testing up to 2000W/cm² in progress
- Woven TPS: tested up to 8000W/cm²
- Conformable PICA capable maybe up to 1000W/cm², 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 ($> \sim 13.5 \text{ km/s}$) entry of Orion type vehicle
 - Can design mission to involve transfer or use of smaller vehicles but involves risk and complexity

Summary



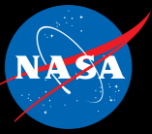
- Select thermal protection material based on entry conditions
 - Ablative materials were used in early vehicles
 - Insulative materials were used for Shuttle as it was a reusable system
 - Ablative materials used in current systems for heatshield
 - Insulators still used on certain vehicles (X37b) and on back shell of capsules such as Orion where heat flux is lower.
- Outer planets and high speed earth entry require more capable materials
 - 3d woven materials for heat shields
 - Flexible and deployable materials
- On-going development of materials for NASA missions

Remaining TPS Needs



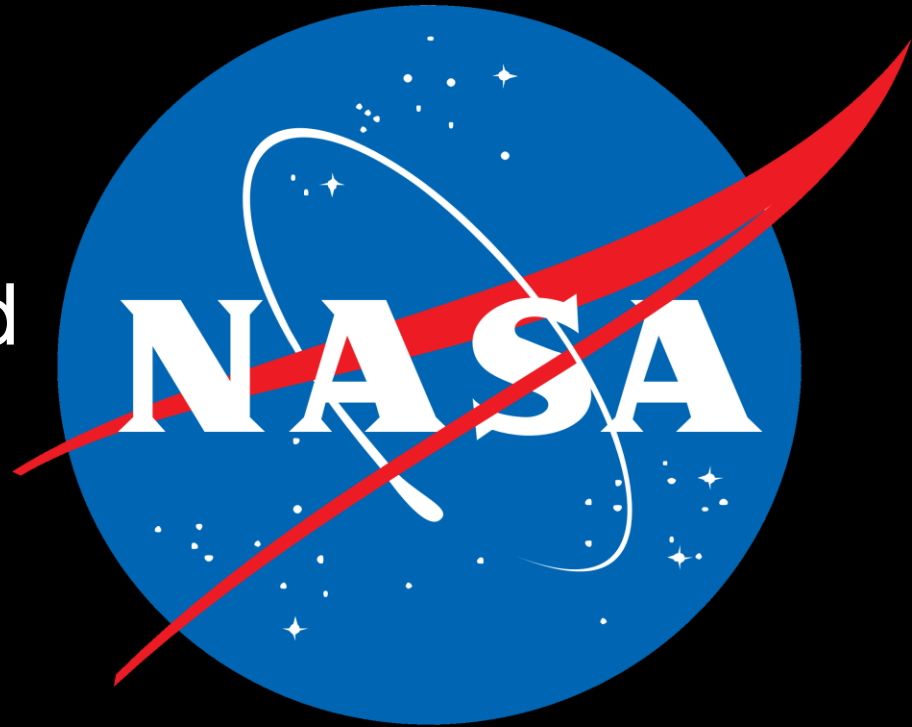
- Improve existing concepts and develop higher capability materials
- Capability to test in relevant environments and provide data for modeling
- Characterize materials to understand behavior
- Develop computational materials approaches to design, processing and lifetime prediction

Acknowledgements



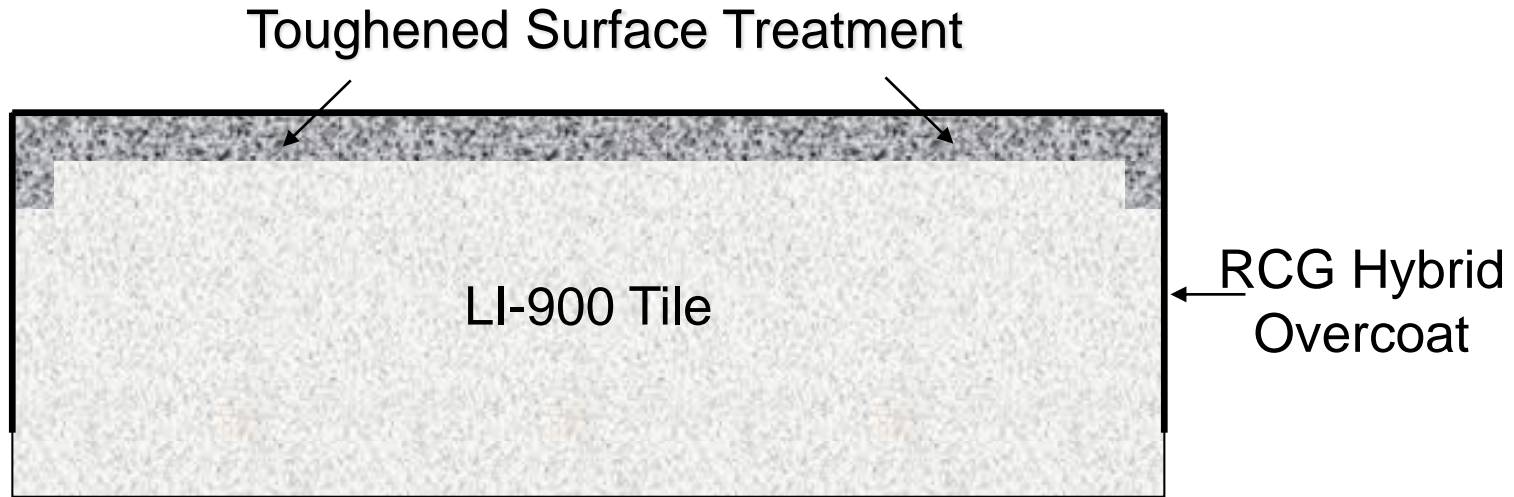
- Thomas Squire (NASA-ARC)
- Joseph Conley (NASA-ARC)
- Mairead Stackpoole (NASA-ARC)
- Alan Cassell (NASA-ARC)
- All the people who have worked on these technologies over many years

National Aeronautics and
Space Administration



Ames Research Center
Entry Systems and Technology Division

Optimized LI-900/TUFI



This system reduces the weight of TUFI/LI-900 to an acceptable level by limiting the area where the surface treatment is applied while retaining the improved damage resistance of the TUFI system.

X-37B after Landing



TUROC is on Leading Edges