Thermal Protection Systems: State of the Industry

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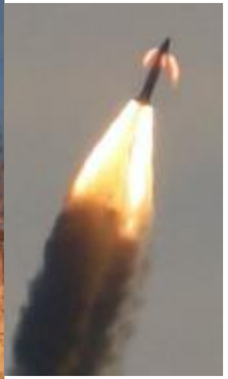
Outline

- Why TPS
- Process for Selecting TPS
- Types of TPS
- Flight Proven TPS
- Developed but Not Flown TPS
- Current TPS Challenges
- Future of TPS

Spaceflight Requires High Velocities >>> High Temperatures

Launch and Ascent

Aborts



Plume Heating
Aerodynamic Heating

Returning from Low-Earth-Orbit
7 km/sec

High
Aerodynamic Heating

Returning from Moon
11 km/sec

Very-High
Aerodynamic Heating

Convective Heating Scales with Velocity^3
Shock-Layer Radiation Scales with Velocity^{8+}

Launch Vehicles and Space-Return Vehicles Require Thermal Protection and/or Hot Structures

TPS Selection Process

Mission Requirements
- Destination
- Trip frequency & duration
- Cargo and/or crew

Mission & Vehicle Design
- Trajectories
- Vehicle Size/Shape

Design Environments
- Rocket motor induced
- Aerodynamic heating & pressure
- Shock-layer radiation
- Micrometeroid/Orbital Debris Impact

TPS Material Trade Study
- Reusable or single use
- Functional over range of environments
- Cost/availability

Viable Options ?

No

Change Design

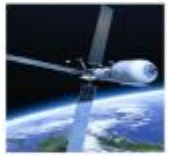
Yes

Select Types of TPS

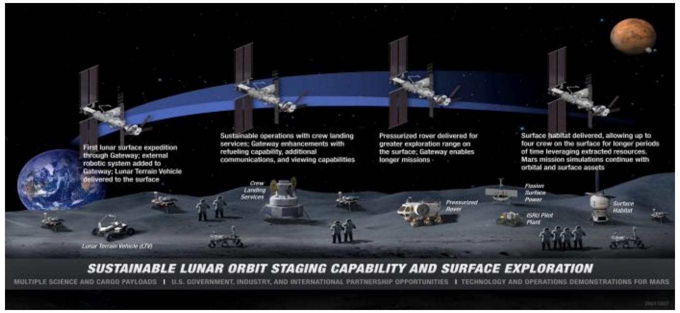
Low-Earth Orbit Operations


Blue Origin/ Sierra Space

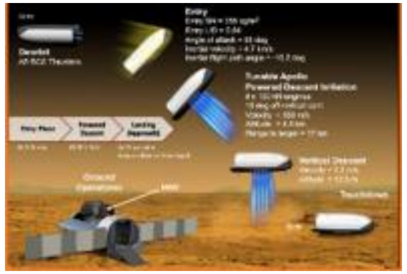

Axiom

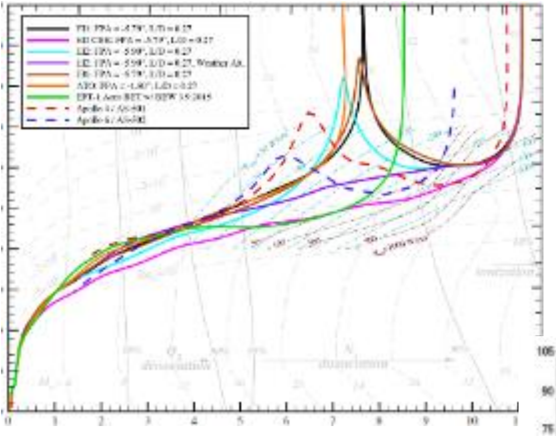

Nanoracks, LM, NG, Voyager Space

Lunar Operations

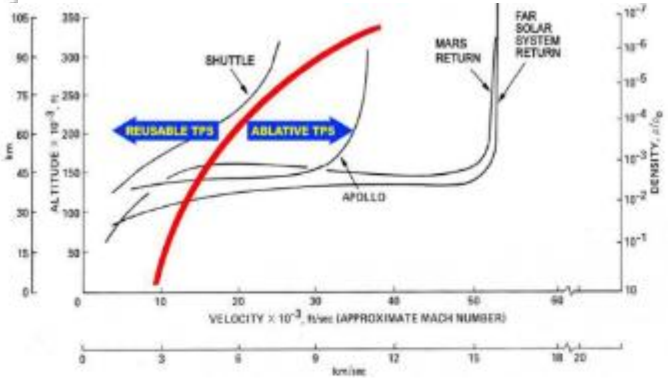


Mars Missions





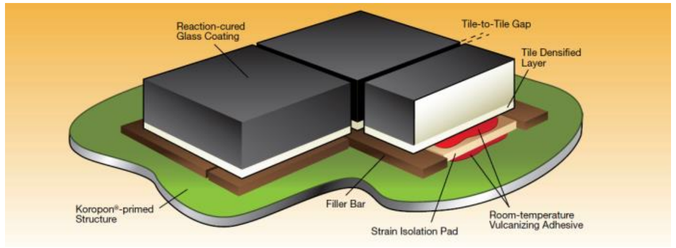
Trajectories
Drive Environments



Types of TPS

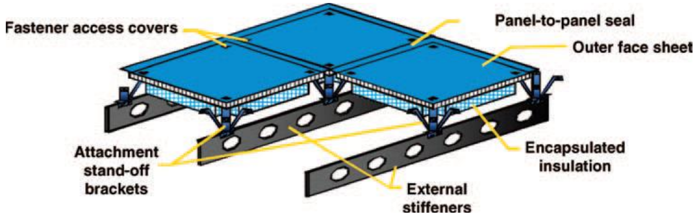
Reusable TPS

- High-temperature insulation attached to monocoque structure
- Flown multiple times (10+) with no to minimal refurbishment
- Usually bonded but not always



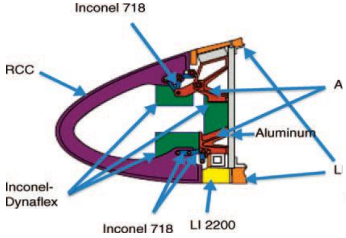
Structurally Integrated TPS

- High-temperature structural panels with integrated insulation
- Reusable depending on coatings
- Usually attached with fasteners



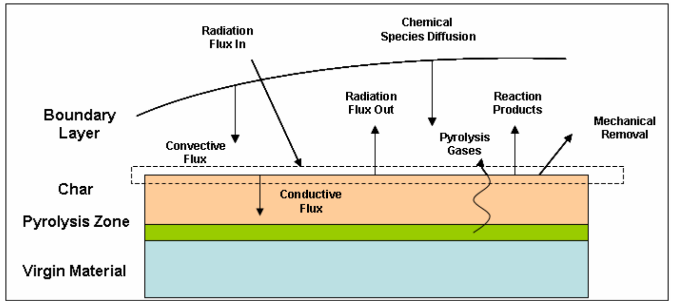
Hot Structure

- High-temperature structure
- Insulation on internal components
- Reusability depends on coatings



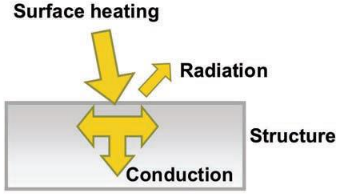
Ablator

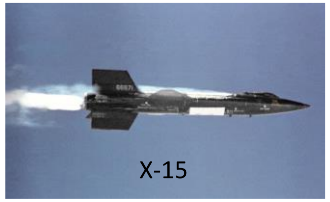
- Material decomposes during heating
- Decomposition gases cool boundary layer
- Recession of surface
- Single use (sometimes refurbished/reused)



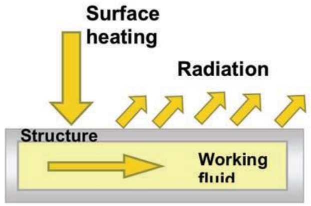
Other Types Not Often Used

Heat Sink

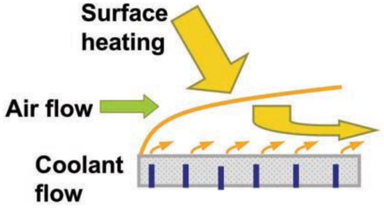




Heat Pipe



Transpiration



David Glass, 'Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles', AIAA-2008-2682, 2008

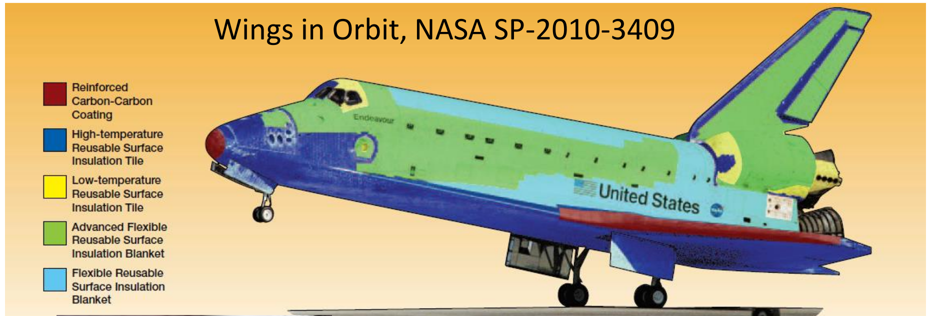
Flight Proven Reusable TPS

NASA Space Shuttle Orbiter

- 5 flight vehicles
- 135 total flights

High-Temperature Tiles

- Shuttle Era
  - LI900, LI2200, FRCI-12, BRI-18, AETB
  - Silica fiber based
  - 2000+ F temperature capability
- Current Tiles
  - AETB (Alumina Enhanced Thermal Barrier)/BRI (Boeing Reusable Insulation)
    - Silica + alumina fibers
  - Stronger
  - Tougher coating (TUFI)
- Availability
  - NASA TPSF (Govt. facility)
  - Boeing
  - Multiple companies starting to manufacture


Wings in Orbit, NASA SP-2010-3409

High-Temperature Blankets

- Shuttle Era
  - AFRSI – Advanced Flexible Reusable Surface Insulation
    - Stitched blanket with ceramic fabric & silica fiber batting
    - <1800 F temperature capability
  - FRSI – Felt Reusable Surface Insulation
    - Felt with silicone coating
    - <800 F temperature capability
- Availability
  - NASA TPSF (Govt. facility)
  - Boeing
  - Hi-Temp

Air Force X-37B

- 2 vehicles
- 6 missions

TUFROC

- Flown on X-37B
  - High-temperature tile ~3,000 F
- Availability
  - NASA Ames
  - Boeing

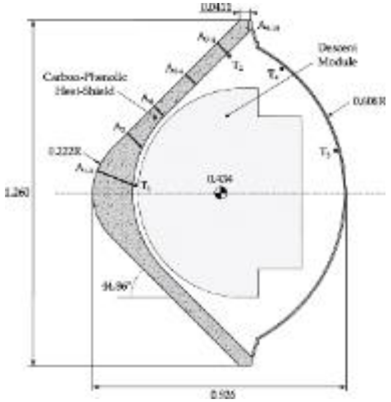
Thermal Barriers

- Shuttle Era
  - High-temperature ~2,500 F
  - Ceramic fabric tube with silica fiber fill
- Availability
  - NASA TPSF
  - Boeing
  - Hi-temp
  - Jackson-Bond Enterprises
  - Textum

Flight Proven Ablative TPS – Part 1

AVCOAT-5026-HCG

- **Flight Vehicles**
  - Honeycomb version – Apollo, Orion EFT-1
  - Molded block version flown on Orion Artemis 1
- **Description**
  - Honeycomb version – gunned filling of bonded honeycomb
  - Molded version – blocks bonded to structure and gaps between blocks filled
- **Availability**
  - Order or license from Textron Systems



High-Density Carbon/Silica-Phenolic

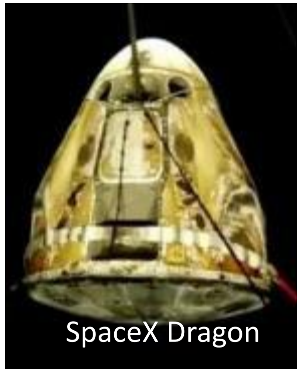
- **Flight Vehicles**
  - Pioneer-Venus, Hayabusa Earth-return, Galileo
  - Ballistic missiles
- **Description**
  - Chopped/molded and tape wrapped
  - 3D-woven carbon fiber
- **Availability**
  - Northrop Grumman
  - Spirit Aerostructures
  - Textron Defense Systems
  - Solvay

Planetary Mission Entry Vehicles
Quick Reference Guide, Version 3.0
NASA/SP-2006-3401


Mars Science Lab

Phenolic-Impregnated Carbon Ablator (PICA)

- **Flight Vehicles**
  - Stardust, Mars Science Lab, Mars 2020
- **Description**
  - Carbon fiber preform infiltrated with phenolic resin
  - Blocks bonded to structure and gaps filled
- **Availability**
  - NASA Ames


SpaceX Dragon

PICA-SpaceX

- **Flight Vehicles**
  - SpaceX Dragon capsule
- **Description**
  - Carbon felt infiltrated with phenolic resin
  - Blocks bonded to structure and gaps filled
- **Availability**
  - SpaceX

Flight Proven Ablative TPS Part 2

Silicone Syntactic Foam

- **Flight Vehicles**
  - SpaceX Dragon Backshell
  - Mars Science Lab and Mars 2020
- **Description**
  - Light-weight silicone foam
  - RF transparent
  - Hand molded onto structure and cured or blocks bonded to structure and gaps between blocks filled
- **Availability**
  - SPAM – SpaceX Proprietary Ablative Material
  - Acusil ® - Peraton

Boeing Lightweight Ablator (BLA)

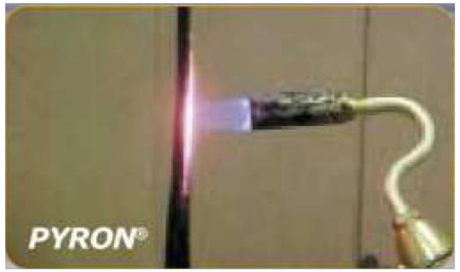
- **Flight Vehicles**
  - CST-100 Heat Shield
- **Description**
  - Filled silicone resin
  - Hand-packed into honeycomb and cured
- **Availability**
  - Boeing

SLA-561V

- **Flight Vehicles**
  - Viking, Pathfinder, MER, Insight, Shuttle External Tank
- **Description**
  - Honeycomb version – hand-packing of bonded honeycomb
  - Molded version – blocks bonded to structure and gaps between blocks filled
- **Availability**
  - Lockheed Martin

Cork/MCC-1

- **Flight Vehicles**
  - Launch vehicles including SLS
- **Description**
  - Natural material
  - Sheets bonded to structure and gaps between filled
  - MCC-1 – Marshall Convergent Coating
    - Epoxy, cork and microballoons
    - Sprayable
- **Availability**
  - Cork – Amorim
  - MCC-1 – NASA MSFC



Pyron

- **Flight Vehicles**
  - SpaceX Falcon
- **Description**
  - Coated carbon felt
- **Availability**
  - Zoltek

Davis, D, 'Fundamentals of Launch Vehicle Ablative Thermal Protection System (TPS) Materials', TFAWS-2017

Flight Proven Hot Structures

Carbon/Silicon-Carbide Nose Cap and Body Flap

ESA Intermediate Experimental Vehicle (IXV)
(1 flight)

- **Description**
    - Ceramic Matrix Composite
    - Carbon/Silicon Carbide materials

- **Availability**
    - HERAKLES Group Safran, France

The IXV Experience, from the mission conception to the flight results, G. Tumino, S.Mancuso, J-M.Gallego, S.Dussy, J-P. Preaud, G. DiVita, P. Brunner, Acta Astronautica 124 (2016) 2–17.

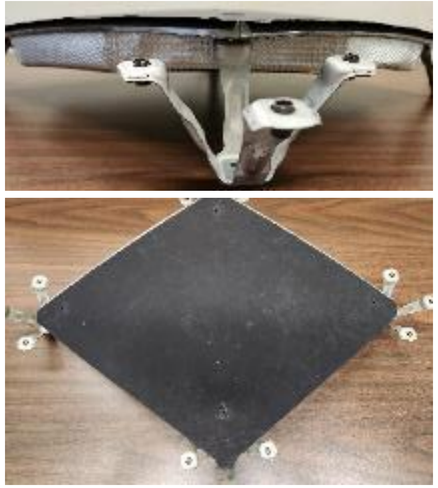
Reinforced Carbon-Carbon (RCC) Nose Cap and Wing Leading Edges

Space Shuttle Orbiter – Leading Edge Sub-System
(135 flights)

- **Description**
    - Carbon/carbon structure with silicon carbide coating
    - Internal insulation
    - High-temperature metallic attachments
- **Availability**
    - RCC is no longer available
    - ACC-6 is similar – C-CAT (Carbon-Carbon Advanced Technologies)

David Glass, ‘Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles’, AIAA-2008-2682, 2008

Developed But Not Flown TPS



X-33 Metallic Panels

- **Description**
  - Designed and fabricated by Goodrich Aerospace for Lockheed SkunkWork's X-33
  - Metallic bond panel with enclosed insulation bag
  - Thermal/structural testing completed
  - Ship set fabricated but X-33 canceled due to LH2 tank failure
- **Availability**
  - No longer available

Bouslog, S. 'An Overview of the X-33 Thermal Protection System', NASA/CR-2003-212660

X-38 Body Flap

- **Description**
  - Designed and fabricated by Man Technologie for NASA X-38
  - Coated Carbon/Silicon Carbide Ceramic Matrix Composite
  - Thermal/structural testing completed
  - Ship set fabricated but X-38 canceled
- **Availability**
  - Similar materials used for ESA IXV

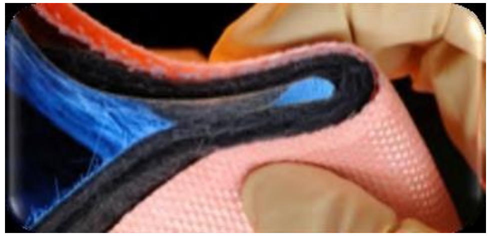
David Glass, 'Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles', AIAA-2008-2682, 2008

HEEET

(Heatshield for Extreme Entry Environment Technology)

- **Description**
  - Designed and 1-meter diameter Engineering Test Unit fabricated by NASA Ames
  - 3D woven carbon fiber with phenolic resin
  - Dual-layer high-density outer layer and medium-density insulation layer
  - Thermal/structural testing completed
- **Availability**
  - NASA Ames

Ellerby, D. 'Overview of Heatshield for Extreme Entry Environment Technology (HEEET)', International Conference on Flight Vehicles, Aerothermodynamics and Re-entry Missions & Engineering, 2019



Flexible TPS
(One flight 2022)

- **Description**
  - Develop and designed by NASA LaRC and GRC for Hypersonic Inflatable Aerodynamic Decelerator (HIAD)
  - Nextel fabric with Pyrogel insulative layers and a gas barrier layer
- **Availability**
  - Jackson Bond Enterprises

Dillman et al, Planned Orbital Flight Test of a 6m HIAD, 2018 International Planetary Probe Workshop

Current TPS Challenges

Changing the Mind Set:

Past

1) Government operated vehicles for government-defined needs;
2) Infrequent flights

→

Future

1) Commercially operated vehicles;
2) Routine flights

Supply Chain

- Raw Materials
  - Limited aerospace-grade domestic suppliers
  - Specialty materials not commercially available
- Limited TPS Vendors
  - State of Art Reusable TPS not readily available
  - Ablators limited to Govt. and large aerospace companies
  - Hot structure demand driven by DoD

Consequence:

Commercial space companies develop own infrastructure and capability to produce TPS at significant cost

Testing

- High-temperature Material Property Testing
  - Few facilities available
  - Testing is difficult
- High-Enthalpy (Arc-jet) Testing
  - Few facilities available
  - Very expensive
- Radiant Heat Testing
  - Minimal investment
- Guidance lacking for what is required for TPS certification

Consequences:

1) Hesitancy to develop new TPS
2) Reduce testing and take the risk with potential flight failures

Costs and Production Rates

- Manual processes dominate
- Focus on performance improvement and not cost reduction
- Manufacturing infrastructure not available
- Not optimized for production

Consequences:

1) Vehicle development and flight delays
2) Fewer companies successful

Future of TPS/Hot-Structures

NASA is incentivizing the development of a commercial space economy – starting with Low-Earth Orbit and rapidly extending to the Moon and eventually to humans on Mars.

Missions to Earth Vicinity

- Commercial Space companies are driving these missions and need new lower cost, readily available TPS and Hot-structures.
  - Cost reduction is a major driver.
  - Reusable vehicles needed to reduce costs.
  - Lower cost coated ceramic tiles is current need.
  - Ceramic matrix composites (CMCs) wanted but expensive with limited availability.

Focus on Reusable TPS and Hot-Structures

&

Advanced Manufacturing

Hypersonic Technology Project/NASA

Missions to Lunar-Vicinity

- High Earth-return velocities result in high heat fluxes
  - Ablators needed for heat shield
  - Lower cost ablators are needed
- Propulsive landings on Moon will drive base heat shield designs
  - Reusable lunar landers will require base heat shield innovation
- Commercial Space companies are establishing role in lunar sample-return and lunar crew/cargo transportation
  - Mission design options and TPS innovation needed

Planetary Missions

- Low flight frequency results in using current ablator options
  - NASA focus will be on sustaining current suppliers
- Commercial Space role is developing
  - TPS needs are TBD

Innovation in the world of TPS and Hot-Structures is just beginning!