National Aeronautics and Space Administration

NASA Perspective on the Future of TPS for Hypersonic Flight

6/18/2025

Workshop on Materials Challenges in Reusable Rocket Systems

Adam Sidor / NASA JSC (ES3)

Nate Olson / NASA JSC (ES3)

Stan Bouslog / NASA JSC (ES3)

Notes

- These are some of *our* thoughts on TPS and its implications for future reusable launch vehicles – we work at NASA but we are not representing any official stance of the agency!

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Outline

- Background
  - Why TPS?
  - Overview of TPS
  - TPS Qualification
- Future of Reusable Launch Vehicles
  - TPS Considerations for Launch Vehicles
  - Future Directions for TPS
- AMTPS Workshop

Background

Hypersonic flight generates high heating behind shock

- Hypersonic flight (>Mach 5) through an atmosphere generates shockwave(s)
  - Entry velocity from Low Earth Orbit (LEO) is ~7 km/s (~Mach 25)
- Flow enthalpy remains constant across shock
  - Converts from kinetic energy primarily to other modes → **convective heating to vehicle**
  - Also can produce **radiative heating** from hot shock layer
- **Composition of the atmosphere matters**
  - Earth: boundary layer contains high temperature dissociated oxygen (and possibly nitrogen if speeds are high enough)
- Ablators introduce additional complex physics
  - Ablation products injected into boundary layer

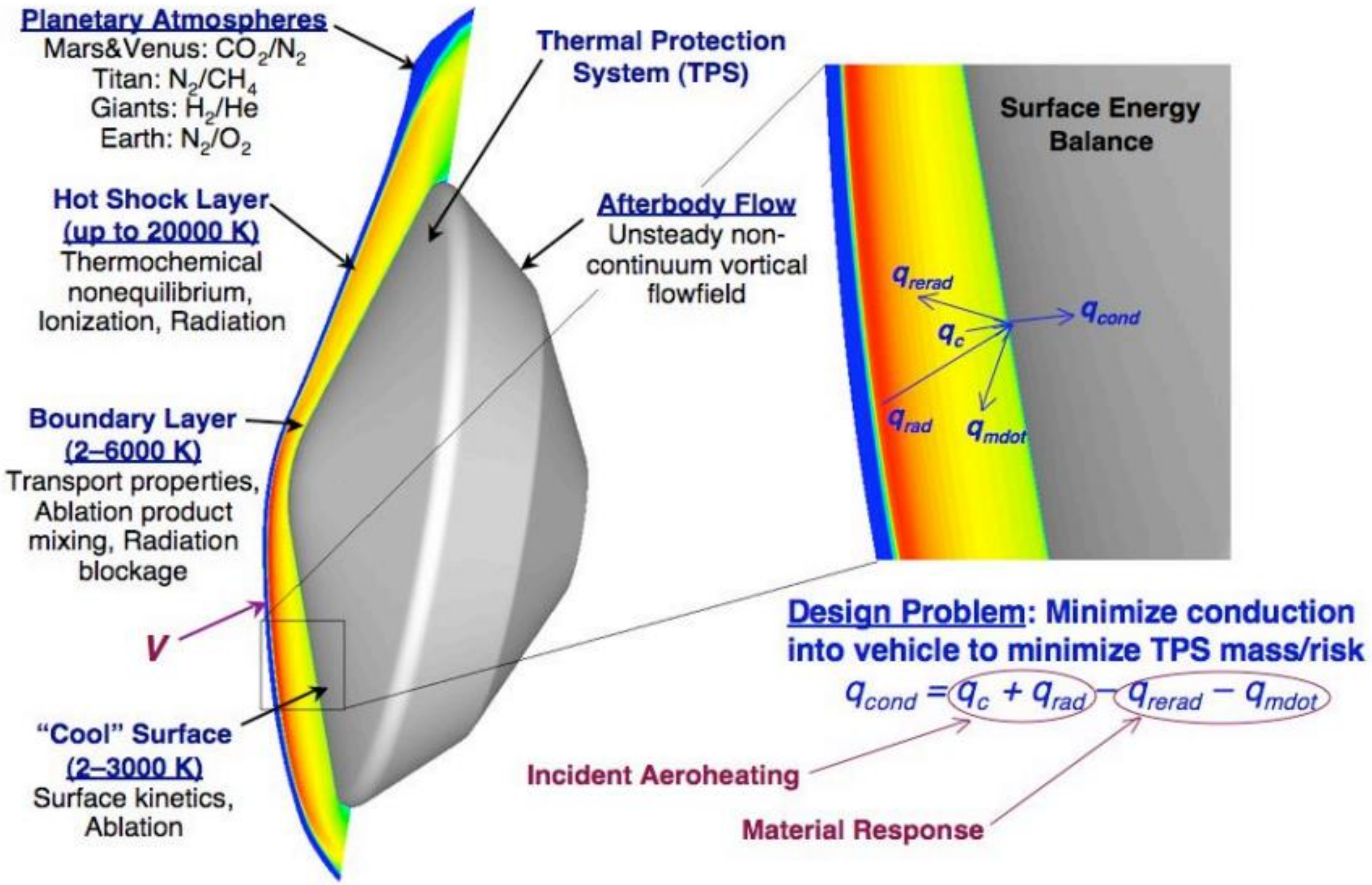
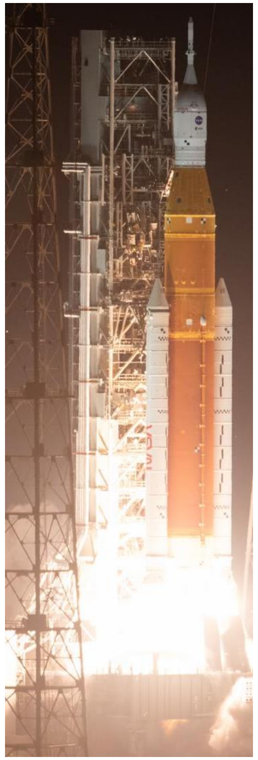


Image Credit: Michael (NASA ARC), "Aerothermal Modeling for Entry and Aerocapture", 2007.

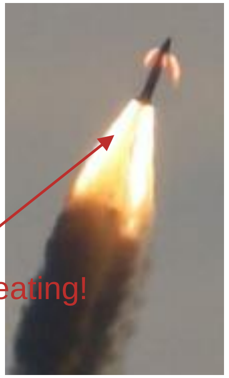
Aerothermodynamic heating scales with velocity

Convective heating ($\propto v^3$), radiative heating ($\propto v^8$), and plume heating can all impart energy to vehicle. Thermal protection systems (TPS) serve as a barrier against this extreme environment and drop temperatures through their thickness to maintain internal structure/components below temperature limits.

Launch and Ascent

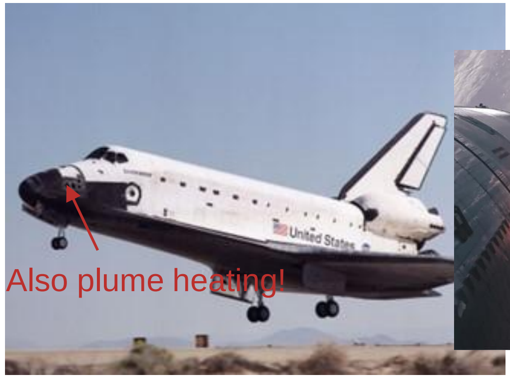


Aborts



Mild Aerodynamic Heating
(Convective + Plume)

Returning from Low-Earth-Orbit
~7 km/sec



Moderate/High Aerodynamic Heating
(Convective + Plume)

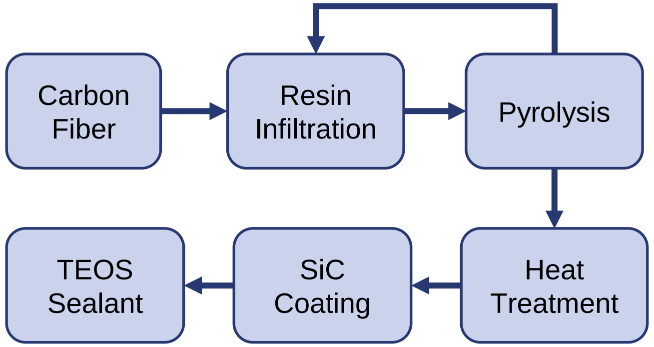
Returning from Moon
~11 km/sec

Very High Aerodynamic Heating
(Convective + Radiative + Plume)

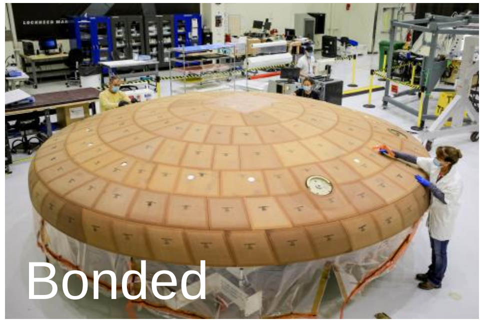
A Thermal Protection System

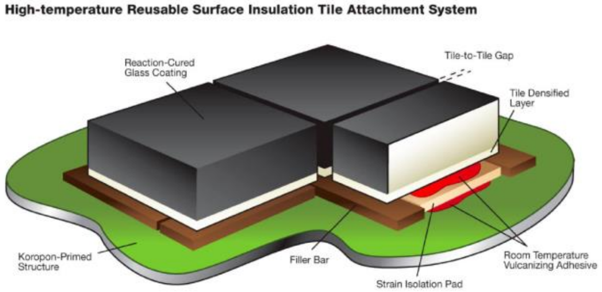
Material

Manufacturing



Integration





Operation

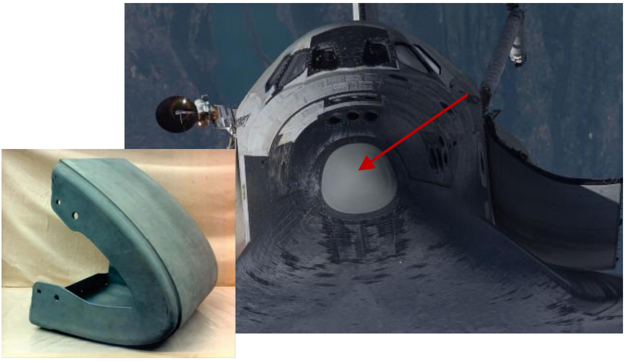
Categories of TPS

Shape-stable ("reusable") materials

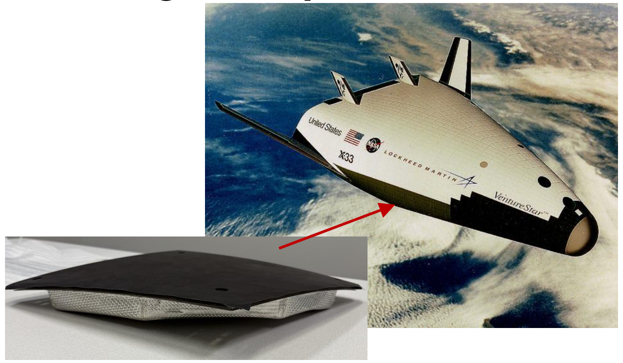
Low Density Insulating Ceramics

Energy management through **storage, transport, and re-radiation**

Hot Structures

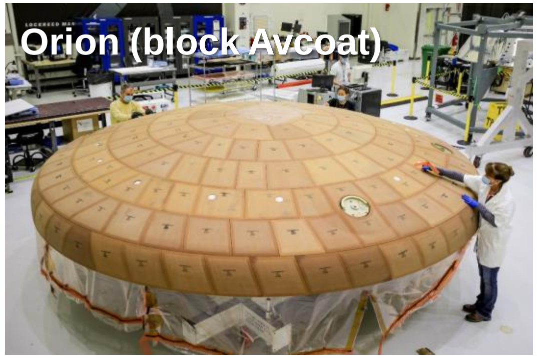


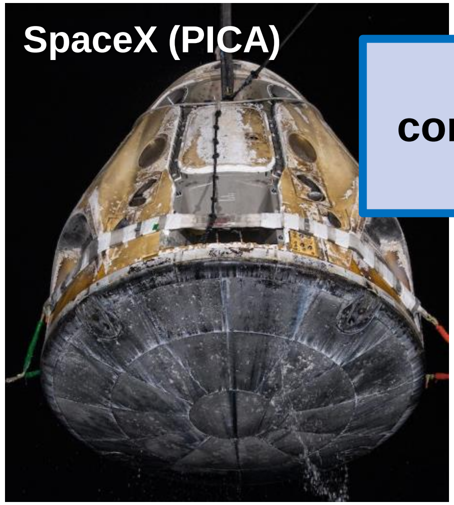
High Temp Metals



Shape-changing ("non-reusable") materials

Ablative TPS



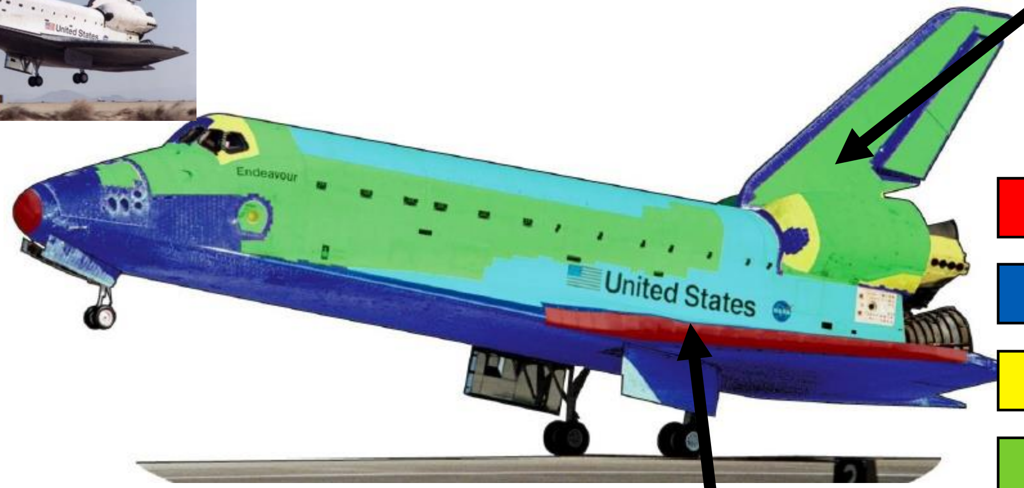


Energy management through **controlled material consumption, charring, and re-radiation.**

Shape-stable TPS

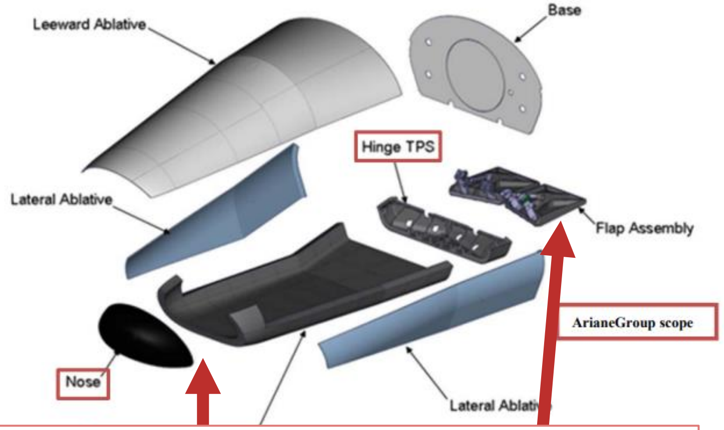
Image Credits
Top right: Bernard, R, et al. “From IXV to Space Rider: CMC Thermal Protection System evolutions”, 2019.
Bottom right: CIRA/PetroCeramics/ESA, [CIRA qualifies CMC structures for the reusable Space Rider | CompositesWorld]

NASA Space Shuttle Orbiter

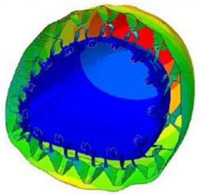


- Reinforced C/C
- HRSI Tile
- LRSI Tile
- AFRSI Blanket
- FRSI Blanket

ESA Space Rider



Ceramic matrix composite (CMC) nose cap, body flap, and windward acreage recently qualified by CIRA/Petroceramics



Shape-stable TPS

X-33

Image credit: Myers, et al. (NASA LaRC), “Parametric Weight Comparison of Advanced Metallic, Ceramic Tile, and Ceramic Blanket Thermal Protection Systems”, 2000.

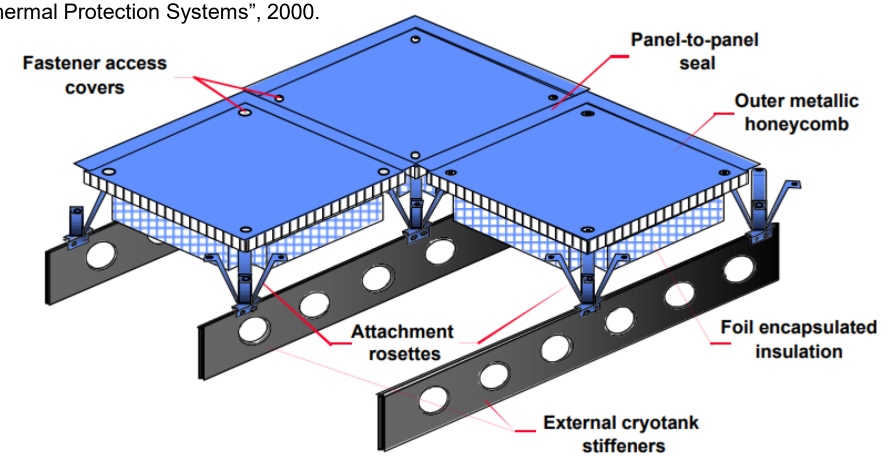
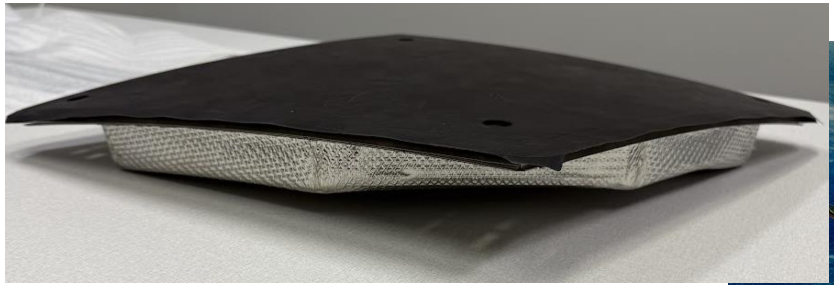
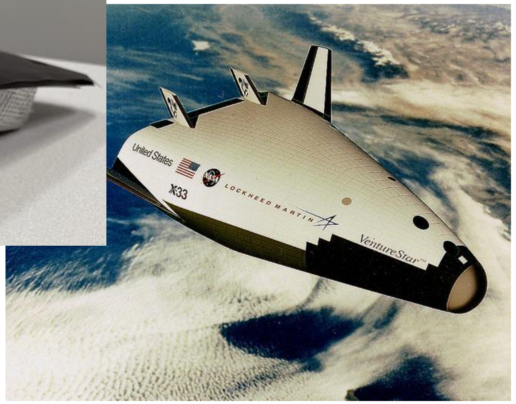


Figure 30. X-33 metallic TPS panel concept and attachment to the vehicle.





X-37B

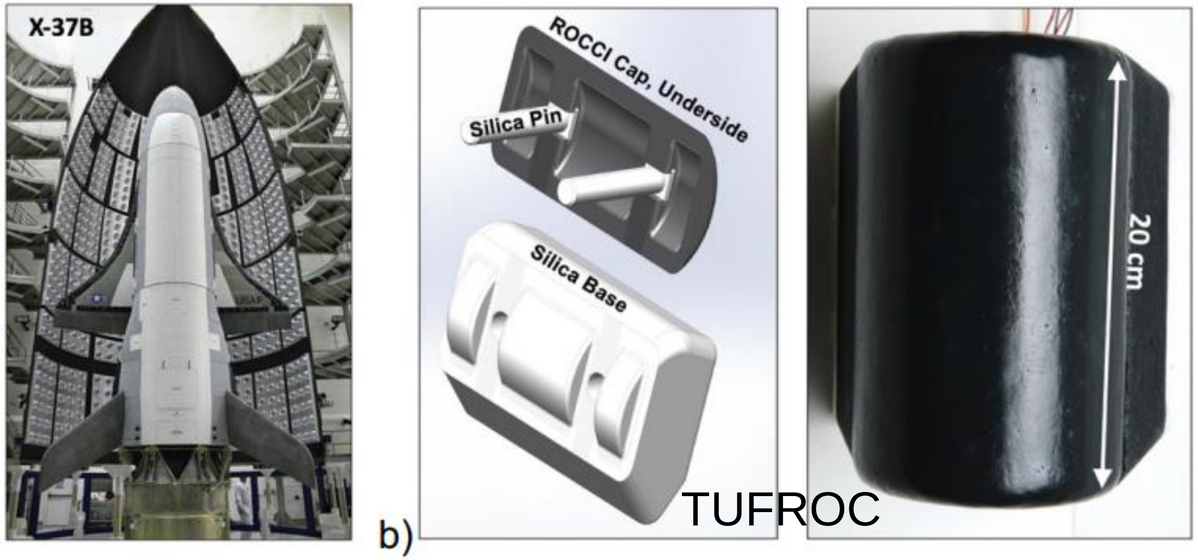
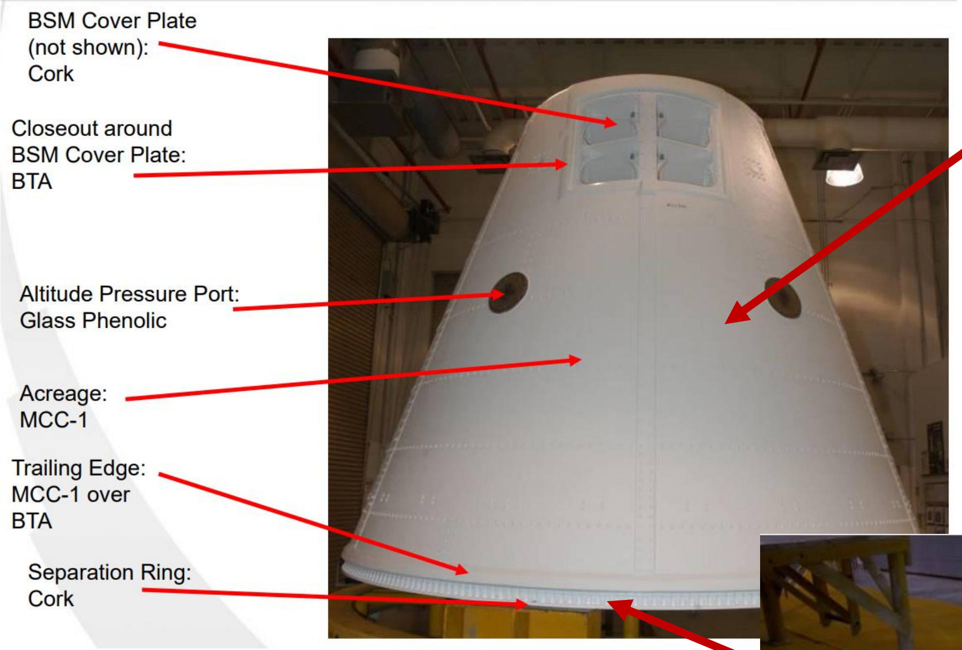


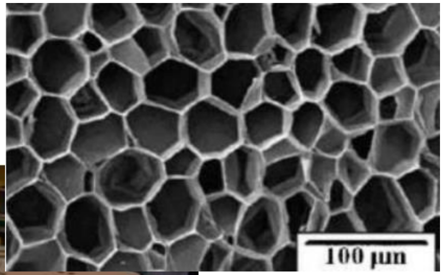
Image credit: Stewart, et al. (NASA ARC), “Advanced Lightweight TUFROC Thermal Protection System for Space Plane Applications”, 2024.

Shape-changing TPS (ablators)

Space Shuttle Solid Rocket Booster (SRB)



MCC-1 (Marshall Convergent Coating) is a robotically sprayable ablative TPS

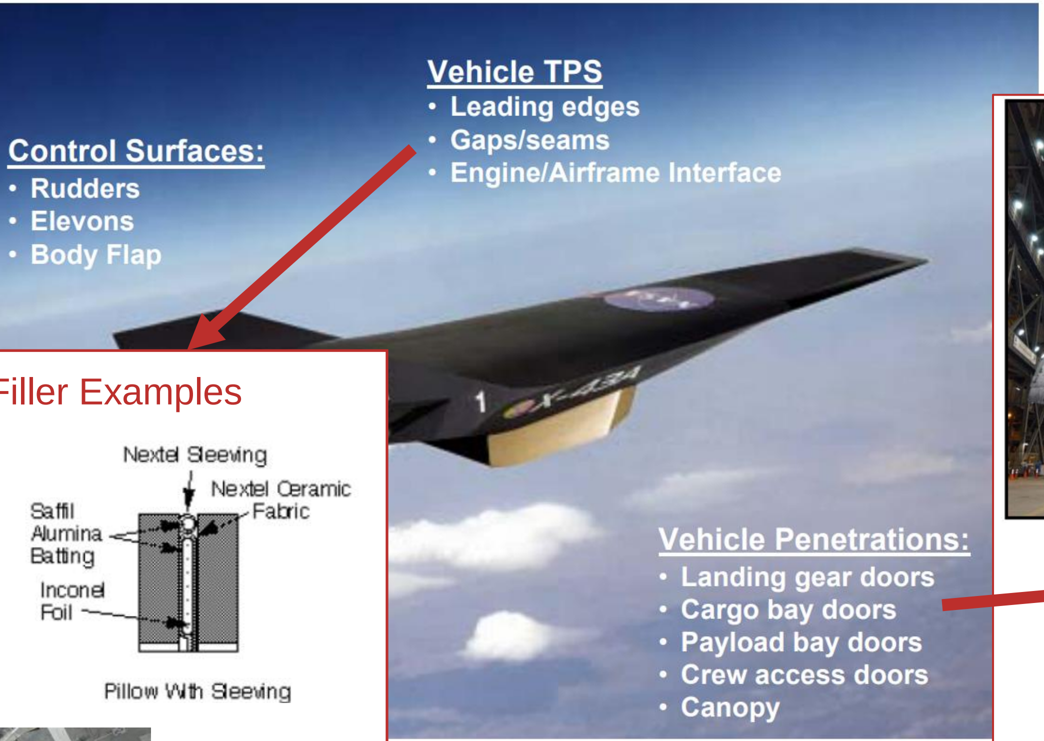


P50 cork has good insulating properties and has been used extensively as an ablative TPS on launch vehicles

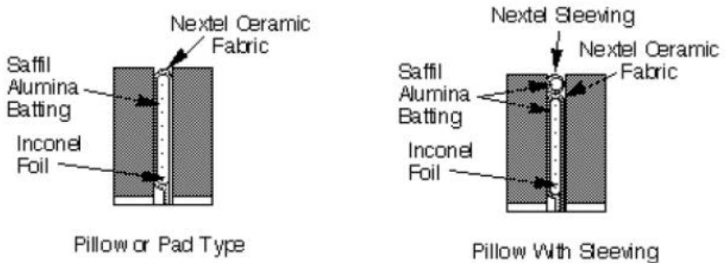
Image Credits: Davis, D. (NASA MSFC), "Fundamentals of Launch Vehicle Ablative Thermal Protection System (TPS) Materials", 2017.

Interface TPS

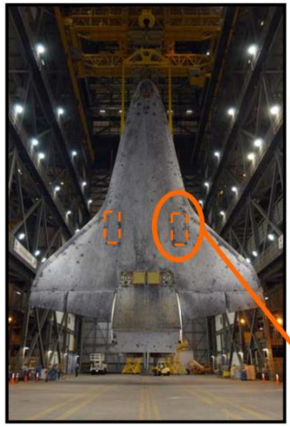
Vehicle Seal Locations



Shuttle Tile Gap Filler Examples



Space Shuttle Main Landing Gear Door



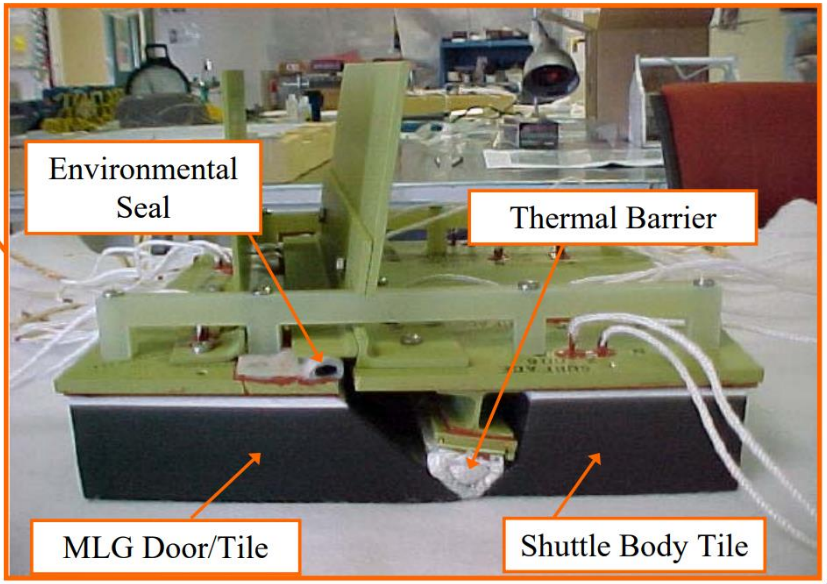


Image credits: Steinetz, B. (NASA GRC), "Seal Technology for Hypersonic Vehicles and Propulsion Systems: An Overview", 2008.

Qualification of a TPS

Characterizing material properties

- Need properties **at relevant temperatures** (potentially up to ~3000 K)
- Thermomechanical
  - Thermal conductivity, specific heat
  - Strength, stiffness, CTE
  - Decomposition behavior, pyrolysis gas composition (ablators)
- Optical
  - Re-radiation is significant factor in material response
  - **High temperature emissivity needed but hard to measure**
  - Spectropyrometers are one option

Modeling material behavior & performance

- **Models needed to predict performance across full range of flight conditions**
  - Ground facilities can't fully replicate all flight conditions
- Boundary conditions / environments
  - Driven by trajectory and vehicle geometry/location
  - CFD is computationally expensive… leverage lower fidelity approximations anchored to CFD
- Models must be validated against test
  - Lots of model and environment error/uncertainties
  - Predicting in depth temperatures within ~100K is pretty good!

Validating performance

- Need to expose to relevant environment (high enthalpy air for Earth)
  - **Arcjet**
    - Higher power
    - Higher pressures and/or larger test articles
    - Larger, more expensive infrastructure
  - **Inductively coupled plasma (ICP) torch**
    - Lower power
    - Lower pressures and/or smaller test articles
    - Less expensive
- Scale / integrated system performance is important
  - **Does my material survive?**

    vs.
  - **Does my system survive?**

TPS qualification is hard! Flight environments can not be fully reproduced on the ground. Analysis is required to evaluate full range of anticipated flight conditions… but measuring material properties at flight-relevant temperatures and material states is difficult at best.

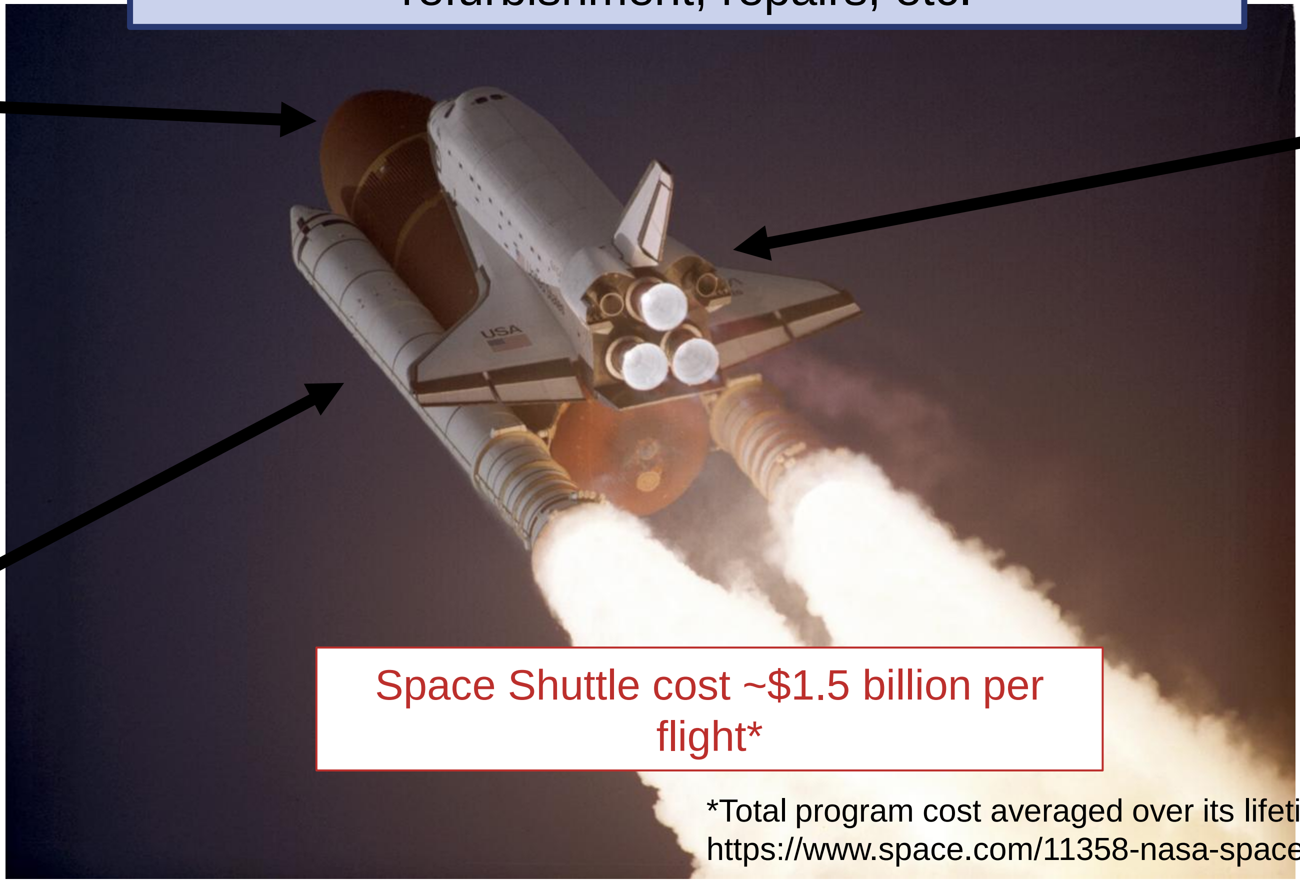
Future of reusable launch vehicles

A reusable launch vehicle?

Reusability is not just about material survivability! Need to consider certification; operations; environments; recovery; flight-to-flight inspection, refurbishment, repairs, etc.

External Tank (ET): sprayable foam TPS, **expendable**

Solid Rocket Boosters (SRB): sprayable foam TPS, recovered followed by **removal and re-application of TPS**



Orbiter TPS: Nominally reused but **significant flight-to-flight refurbishment** (post-flight inspection, repairing and/or replacing damaged TPS, re-waterproofing of tiles, RCC mass loss monitoring)

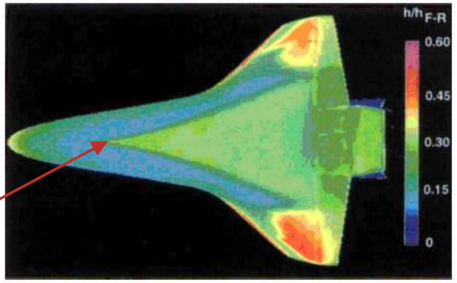
Space Shuttle cost ~$1.5 billion per flight*

*Total program cost averaged over its lifetime
https://www.space.com/11358-nasa-space-shuttle-program-cost-30-years.html

Considerations for future reusable launch vehicles

- Components
  - <u>Base heat shield</u>: Plume heating; aerothermodynamic heating
  - <u>Control surfaces</u>: Aerothermodynamic heating
  - <u>Acreage</u>: Plume heating (some places); aerothermodynamic heating
  - <u>Interfaces</u>: Hatches, deployed hardware, penetrations, control surfaces, gaps, etc. **may need seals (static and/or dynamic) or thermal barriers**
- Environments
  - Severity of aerothermodynamic heating scales with velocity
    - 1st stage: low speed (1-2 km/s)
    - 2nd stage: orbital entry speeds (~7 km/s or higher)
  - Flow alteration/augmentation occurs near geometric disruptions (e.g. penetrations, protuberances, **steps & gaps**)
  - Disturbances can drive **boundary layer transition** from laminar to turbulent flow (with increased heat transfer)

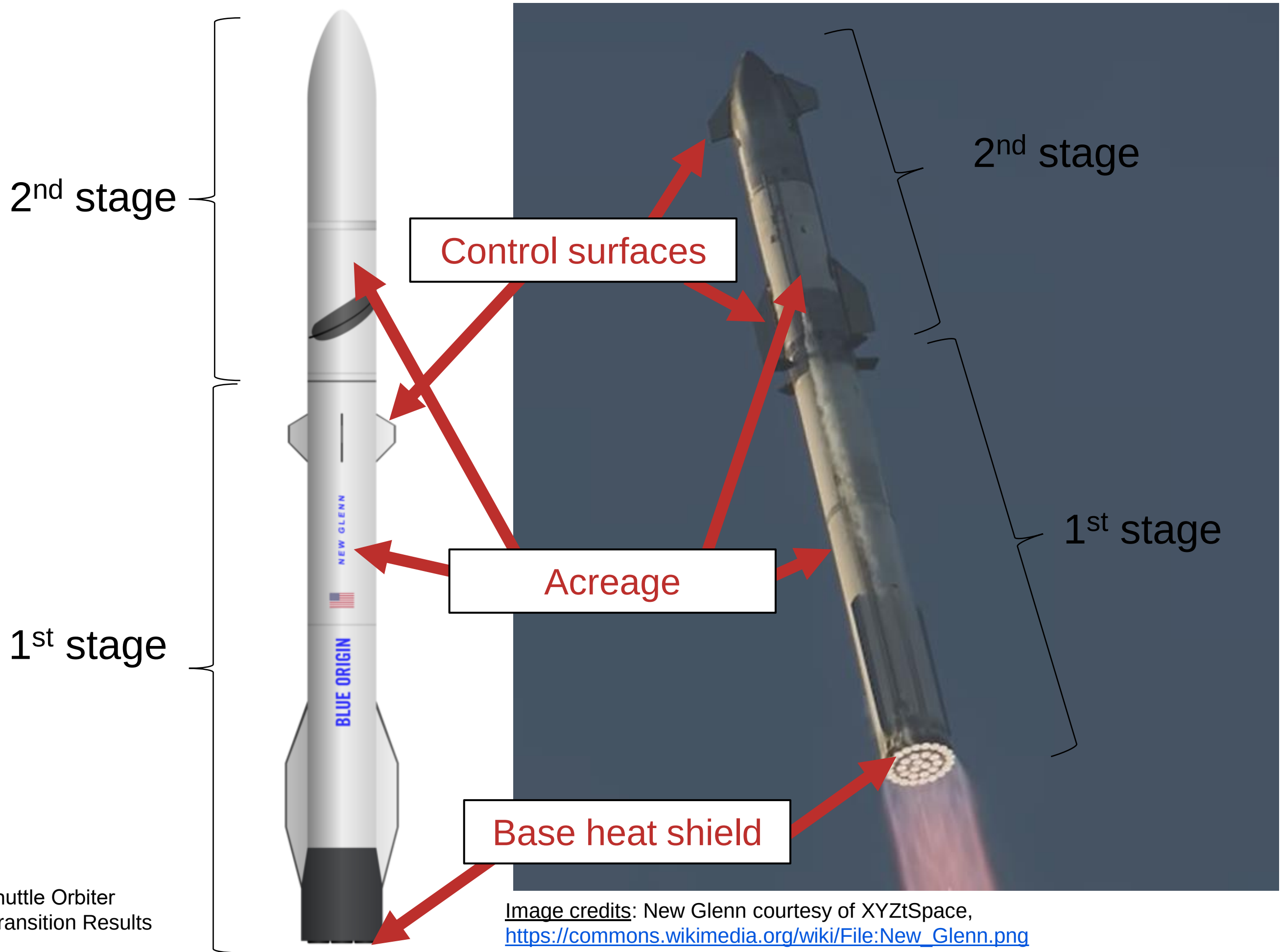
Trip point is equivalent to a single 6”x6” tile with 0.3” step up



0.0025-in. roughness element and $Re_\infty = 5.8 \times 10^6$/ft

<u>Image credit</u>: Berry, S., et al. “Shuttle Orbiter Experimental Boundary-Layer Transition Results with Isolated Roughness”, 1998.

Blue Origin New Glenn *SpaceX Starship*

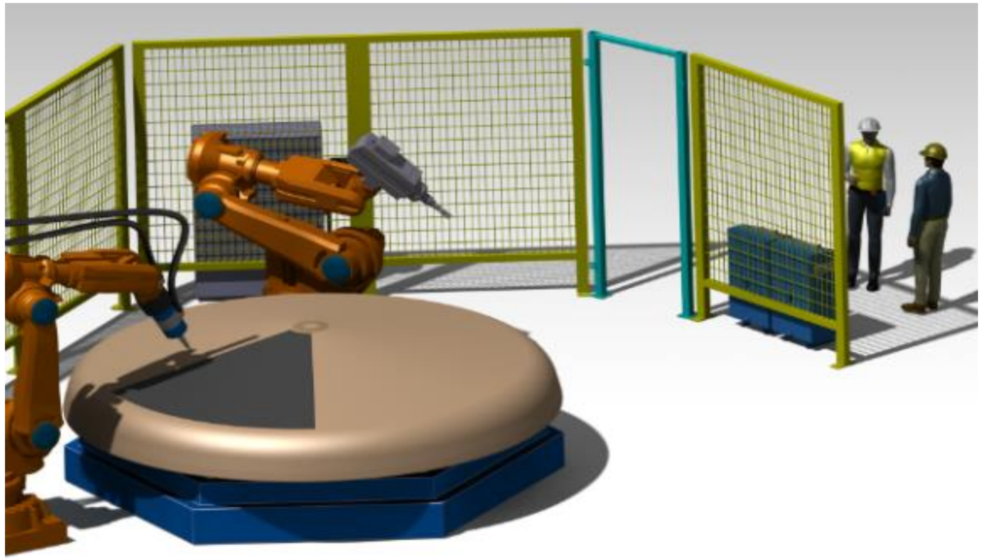


<u>Image credits</u>: New Glenn courtesy of XYZtSpace, https://commons.wikimedia.org/wiki/File:New_Glenn.png
Starship from NASA video, https://www.nasa.gov/wp-content/uploads/2024/02/video-2-part-1-of-2-0-to-253-2023-11-18-gss-starship2-land-720p.mp4

Why even talk about ablators?

- Shouldn't necessarily be discounted!
- *If* they can be implemented cheaply, they *may* make sense for certain uses
- Likely would require…
  - Cheap, readily available raw materials (not too hard)
  - Fast, efficient manufacturing processes
  - Fast, efficient refurbishment and/or replacement between flights
- They *could* function in a limited re-use capacity (~a few flights)
  - Coatings can limit/mitigate recession
  - But plenty of challenges to achieving ablator re-use

Concept for future Robotic TPS Manufacturing Cell



Additive manufacturing of TPS (AMTPS)

Traditional Approaches

Manual fabrication, bonding in segments, single formulation

Apollo

Orion

Mars Science Laboratory

Photo Credits
Left: B. Anthony Stewart/National Geographic/Getty Images, The Amazing Handmade Tech That Powered Apollo 11's Moon Voyage – HISTORY
Top right: NASA/Isaac Watson, Heat Shield Milestone Complete for First Orion Mission with Crew | NASA
Bot right: NASA/JPL-Caltech/Lockheed Martin, Large Heat Shield for Mars Science Laboratory – NASA's Mars Exploration Program

AMTPS

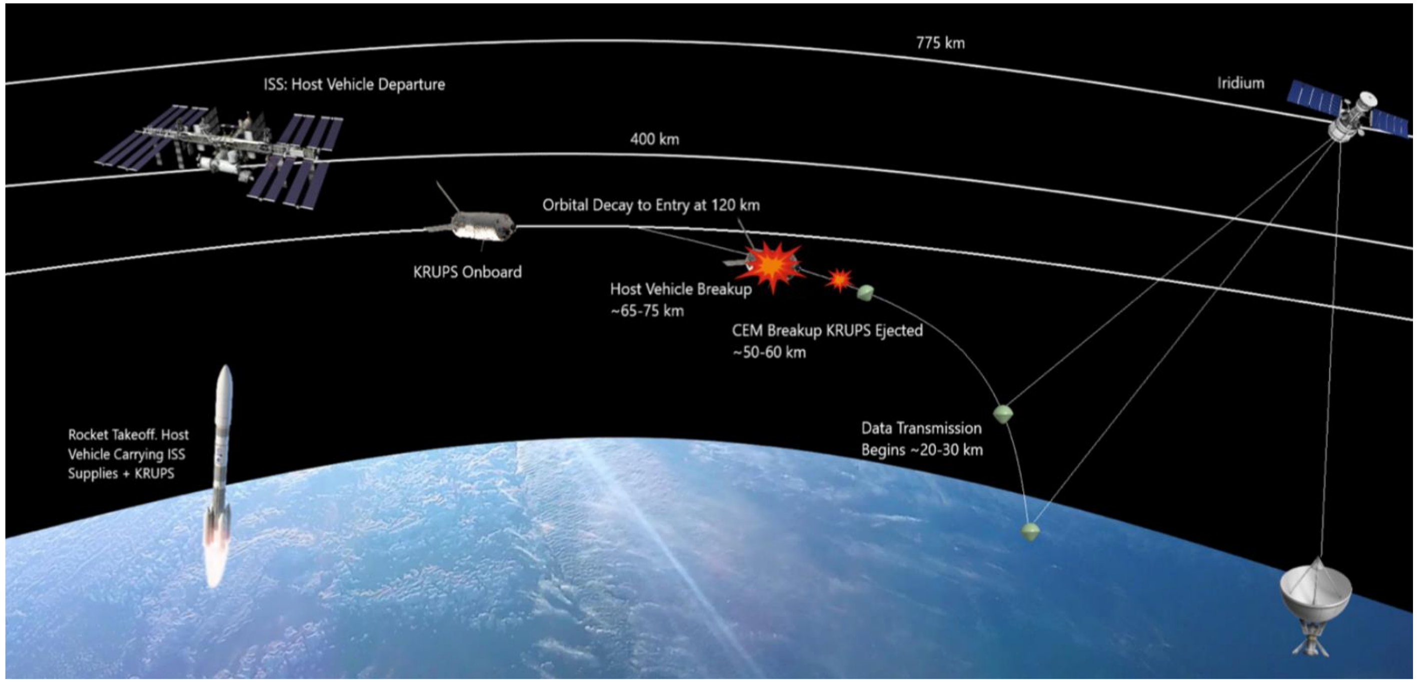
Automated, monolithic fabrication, graded formulation

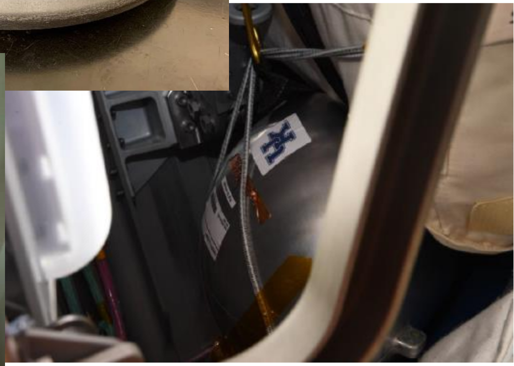
Robust Layer
(Transition Layers)
Insulative Layer
3D Printed Structure

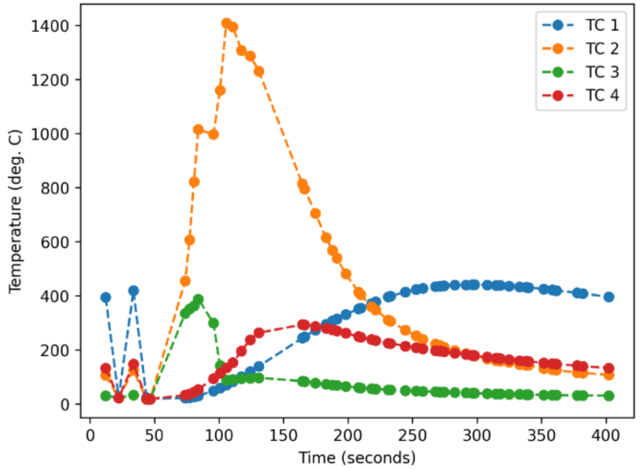
AMTPS Flight Test

- Univ. of Kentucky developed KREPE capsules as TPS testbeds
- 3 KREPE capsules flew in 2021; one with an AMTPS heat shield
- Successful entry from LEO confirmed by embedded T/Cs

Concept of Operations





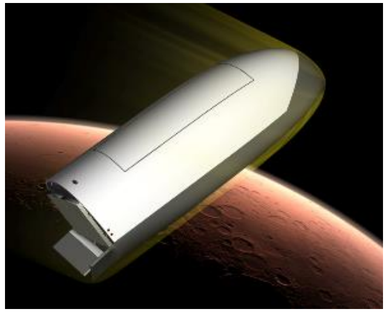


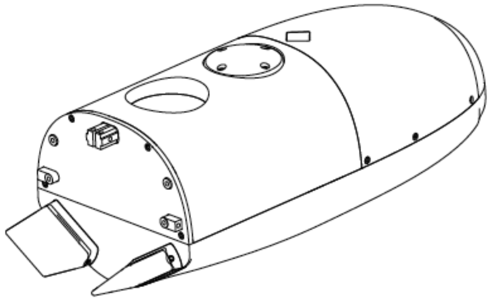
AMTPS Robotic Manufacturing Cell

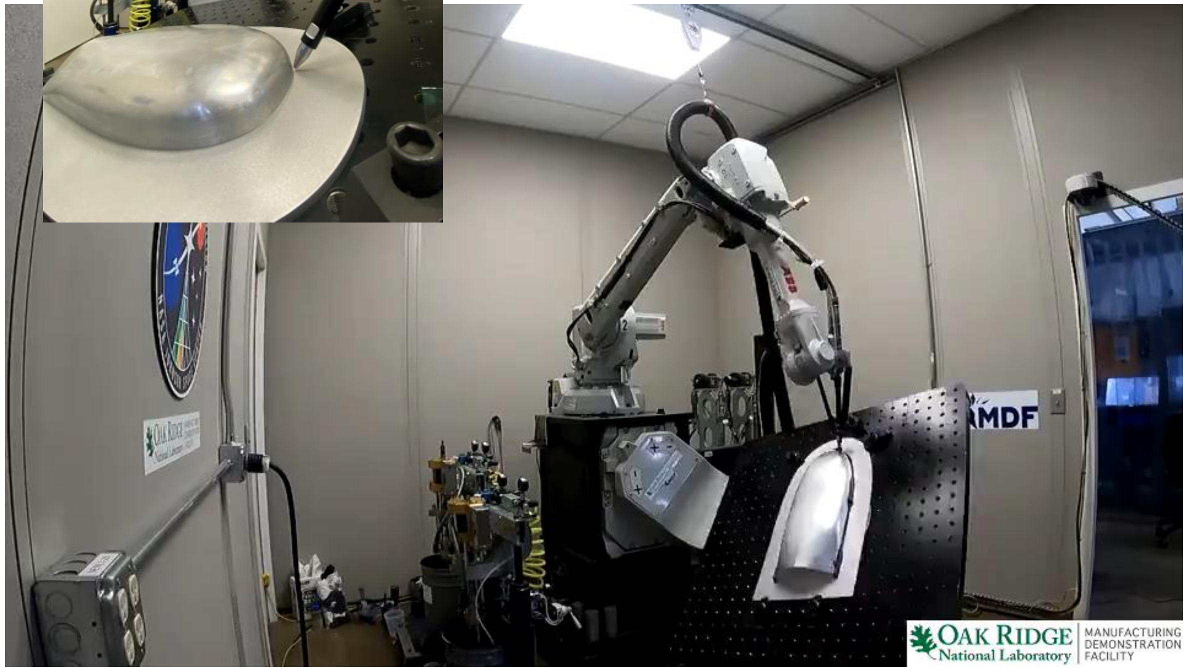
- NASA partnered with Oak Ridge National Lab to develop an automated robotic cell for AMTPS manufacturing
  - 6 axis robot arm + 2 axis table
  - Up to ~1 meter x 1 meter build footprint
- 2-component pumping system (resin + catalyst, resin A + resin B, etc.)

HyperSTEP (Hypersonic Testing for Entry Platform)

- Mid-L/D vehicle under development at NASA JSC for testing entry technologies, including TPS
- 1st flight test of sub-scale vehicle planned for FY26

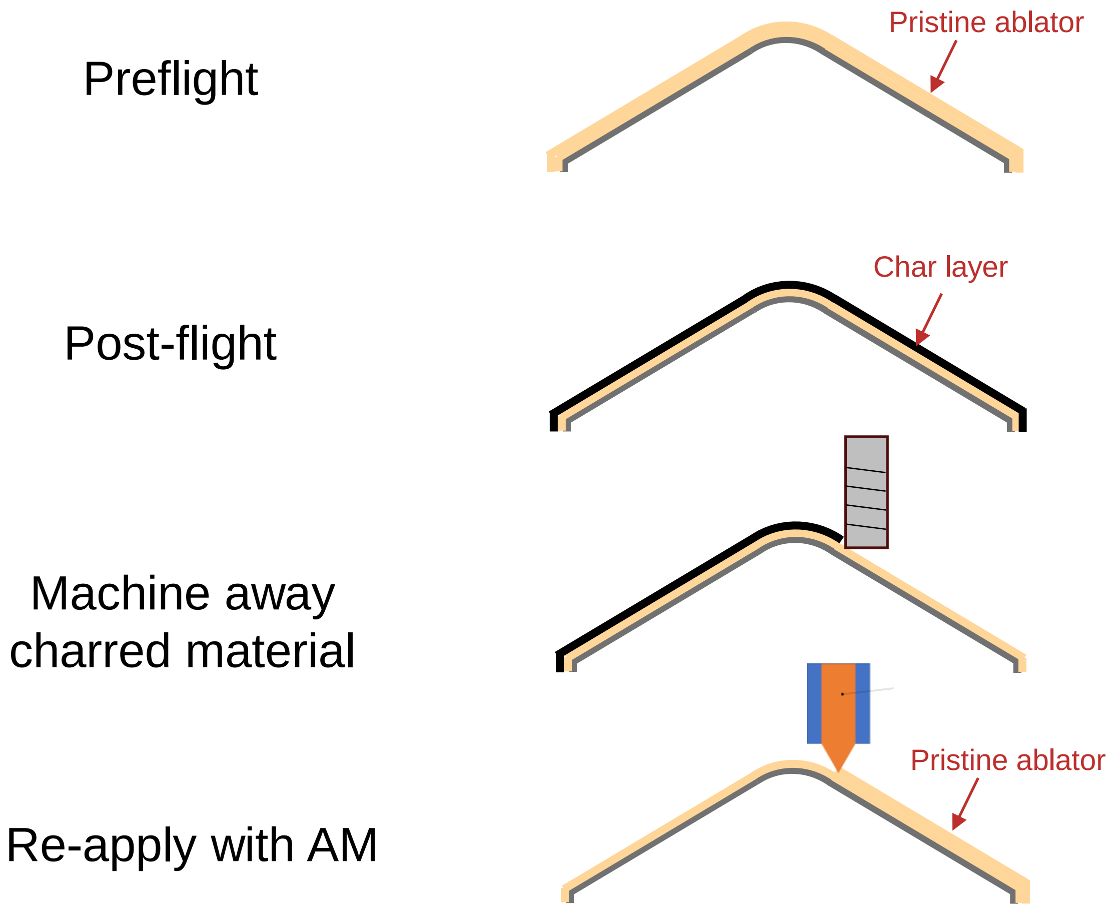






Ablator refurbishment / re-use

- Notional Ablator Refurbishment

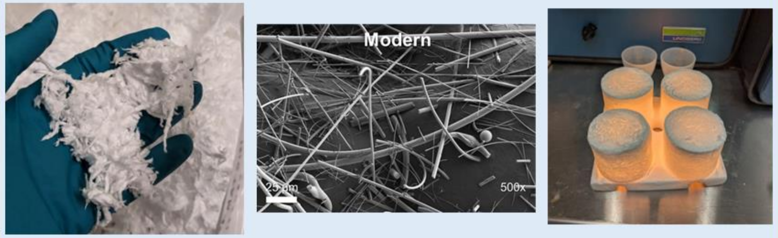


- Re-use
  - Coatings can limit recession
    - **<u>Idea</u>**: protect/seal off recession-prone constituents (carbon) from environmental exposure
    - Silica-containing coatings/additives can react in the presence of carbon to form SiC which can act as a protective layer
    - Maybe other ideas?
  - Oversize ablator thickness to sufficiently insulate for multiple heating cycles
  - Challenge: how to qualify an ablator for multiple uses?
    - Show that material can survive multiple cycles of thermomechanical loading
    - Combo of test and analyses

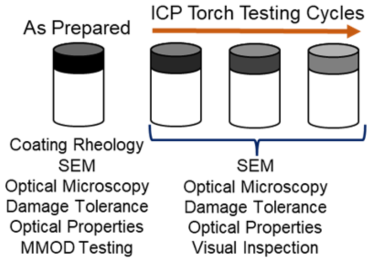
Advancing low density ceramic TPS

- NASA is devoting significant R&D to advancing both current and next generation ceramic-based TPS
- JSC leading efforts in several key areas:
  - Characterizing constituent materials
    - Modern vs. heritage silica fibers
  - Developing higher temperature capable, oxidation-resistant coatings
    - Re-formulated heritage coatings
    - Novel coatings
  - Leveraging computational methods to design new materials
    - Predicting material behavior from microstructure
    - **STMD Early Career Initiative (ECI) recently awarded for FY26-FY27 (PROTECT)**

Silica Fiber Characterization

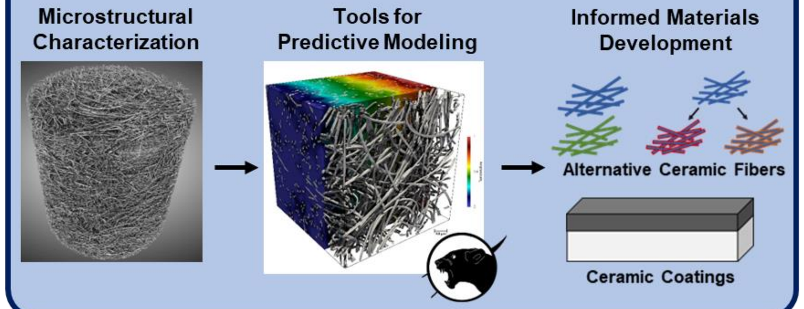


Advancing Reusable TPS Coatings



SPACEX
SIERRA SPACE
CURTISS-WRIGHT
OAK RIDGE National Laboratory
NASA GRC JSC KSC/TPSF

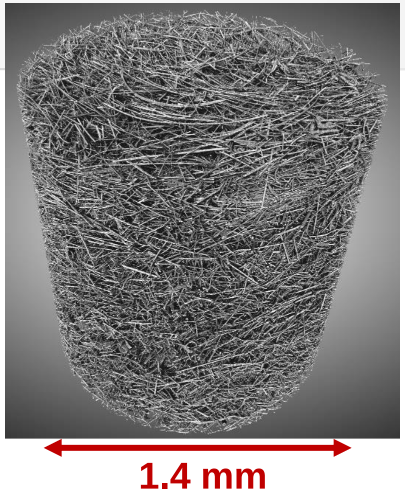
PROTECT: NASA ECI-26 Project



Microstructural characterization of fibrous ceramic TPS

Goal: Capture the microstructure of reusable TPS for modeling of key properties (thermal transport, mechanical properties).

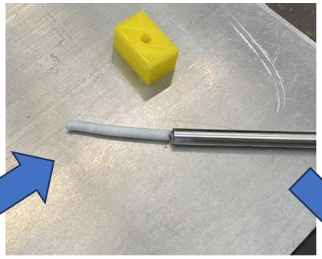
Sample = pure silica fiber billet made at JSC

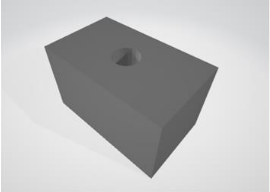


Micro-CT images courtesy of Prof. Francesco Panerai (UIUC)

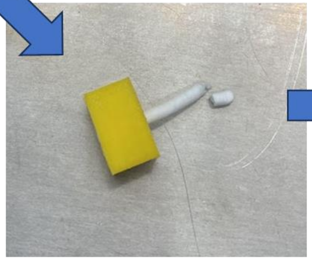
Using the cutting tool as sample holder in the mill

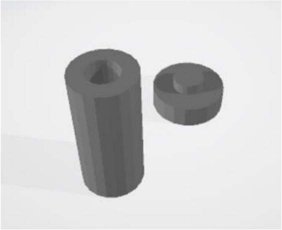
Drill samples using a 4 mm tube

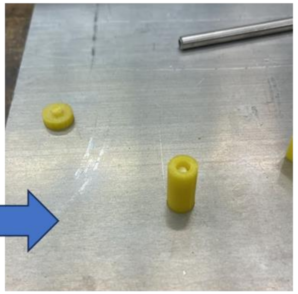




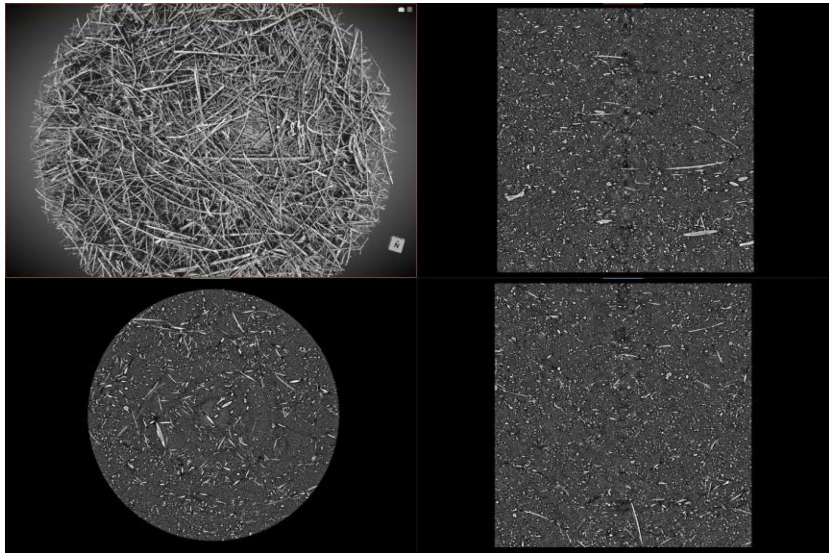
Insert sample into holder and cut to 15 mm height







Insert sample into custom containers for protection in transit



Capability to resolve fibrous microstructure with UIUC's Zeiss Xradia 630 Versa has been demonstrated.

Improving heritage coatings and testing new coatings

In-House R&D

Goal: (1) Stand up capability to prepare RCG/TUFI coatings at JSC, (2) Evaluate alternate precursors and processing approaches for RCG/TUFI

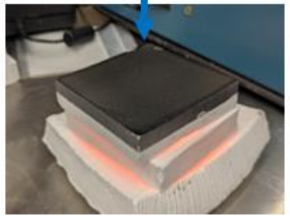
Glass Frit

+

Emittance Agent

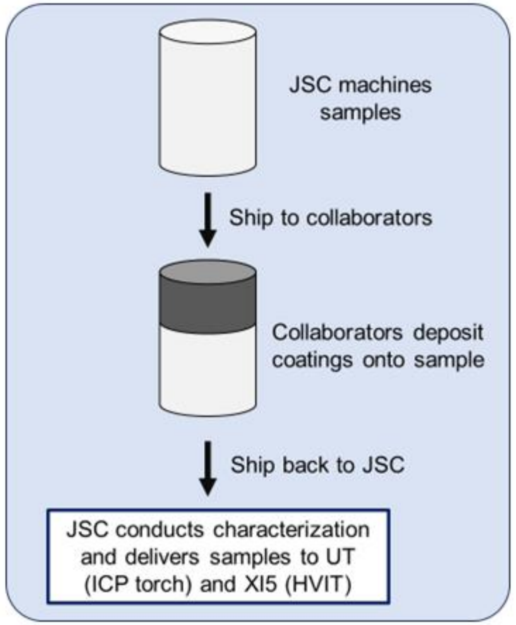
+

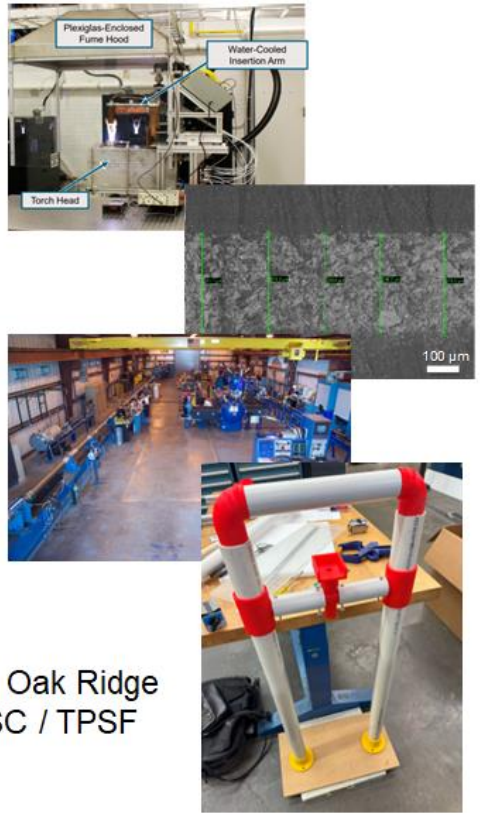
Carrier Fluid



Collaborator Testing

Goal: Screen thermal and mechanical properties of novel coatings compared to heritage systems.





Collaborators: SpaceX, Sierra Space, Oak Ridge National Lab, NASA GRC, NASA KSC / TPSF

PROTECT ECI-26 Project: Changing our approach to tile development

Determine tile recipe*

Fabricate billets

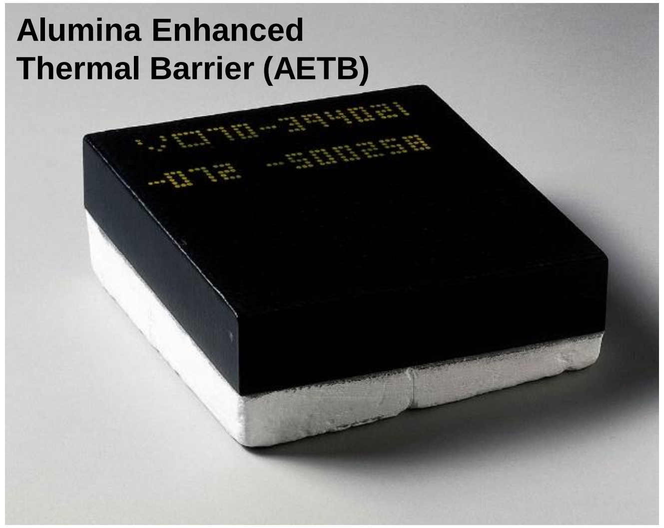
Machine test articles

Conduct testing

Review test results

Revise recipe

Qualify for flight

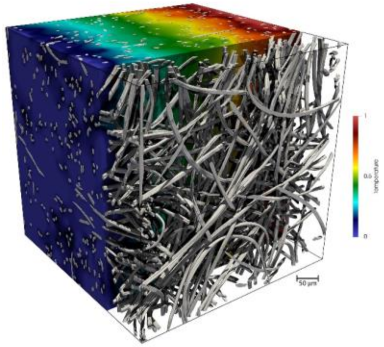


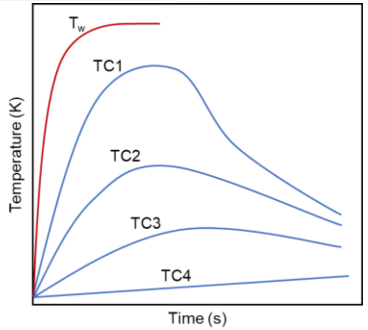
1st Gen: LI → 2nd Gen: FRCI HTP → 3rd Gen: AETB BRI

~30 years of tile development…

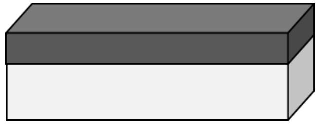
Extremely time & resource intensive approach inhibits development of new materials

x% A_aX_x
y% B_bY_y
z% C_cZ_z
+

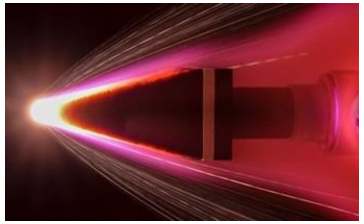




New Approach: Use microstructure and raw material property data to *predict* the performance of novel, not-yet-made materials.



Fabricate most promising materials



Ground and flight testing

Result = Targeted, rapid development of reusable TPS capable of surviving demanding environments.

Metallic TPS

- Oxide-dispersion strengthened (ODS) alloys offer potential for improvement over Ni-based superalloys
  - Higher temperature capability
  - Good oxidation resistance
- Manufacturing of ODS alloys greatly simplified using powder-based AM processes
- GRX-810 is a NiCoCr alloy with dispersed Y2O3 particles
  - Excellent high temperature strength and creep performance

GRX-810 or other printable ODS alloy?

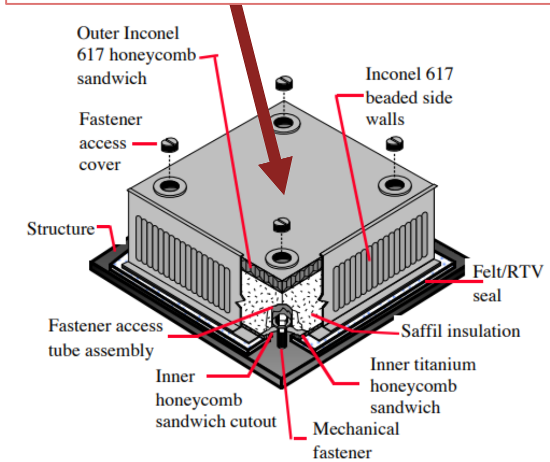


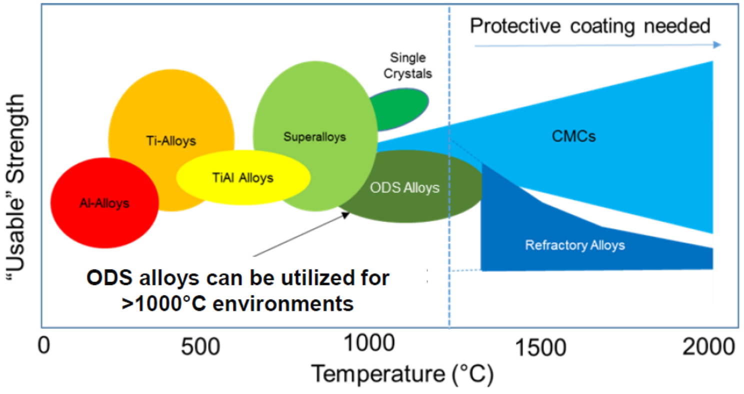
Image credit: Blosser, et al. (NASA LaRC), "Reusable Metallic Thermal Protection Systems Development", 1998.

National Aeronautics and Space Administration

High Temperature AM Compatible Materials

High Temperature Materials:

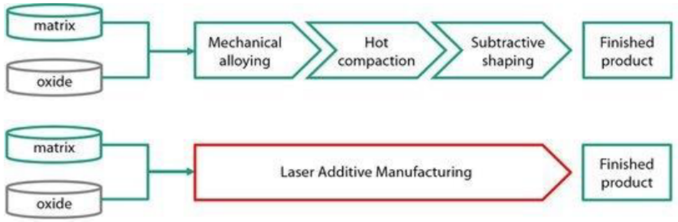
- Refractory metals
- Carbon-Carbon composites
- CMC's
- Ni-base superalloys
- **Oxide Dispersion strengthened (ODS) alloys**



Inspired by Andy Jones. ODS alloy Development.

(ODS) alloys offer higher temperature capabilities compared to Ni-base superalloys. However, it has been a challenge to produce ODS alloys through conventional manufacturing methods.

Conventional Manufacturing vs AM



Can AM improve ODS alloy manufacturability?

Slide courtesy of Tim Smith (NASA GRC)

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Other advanced TPS manufacturing: Industry highlights

- Several commercial companies pursuing AM capability for C/C and CMCs
  - Northrop Grumman
    - https://www.northropgrumman.com/what-we-do/advanced-weapons/scram-c-c
  - Mantis Composites
    - https://www.mantiscomposites.com/
  - Continuous Composites
    - https://www.continuouscomposites.com/
  - Orbital Composites
    - https://www.orbitalcomposites.com/
- Developing advanced manufacturing capabilities for other types of TPS
  - Canopy Aerospace
    - https://www.canopyaerospace.com/
  - Raven Space Systems
    - https://www.ravenspacesystems.com/
- There are others…

Northrup Grumman SCRAM (Scalable Composite Robotic Additive Manufacturing)

Image Credit: Northrup Grumman, https://www.northropgrumman.com/what-we-do/advanced-weapons/scram-c-c

AMTPS Workshop 4.0: October 21-23, 2025

- Grassroots effort that grew from AMTPS project in 2021 with goal of identifying and addressing key TPS challenges
  - Focus on advanced and additive manufacturing, but not exclusive to that
  - Collaborative workshop with emphasis on group discussions and networking

Goals:

1. Establish a coordinated strategy to sustain the current state of art of TPS and hot structures and develop new lower cost, production ready TPS and hot structures in collaboration with DoD and commercial space industry.
2. Establish a diverse leadership community (NASA, industry, DoD, other Government Agency) of subject matter experts that will inform and guide the development of TPS and hot structures for use by the commercial space and hypersonics Industry.
3. Serve as catalyst for initiating connections and collaborations spanning suppliers, vehicle builders and operators, and government.

Contact me if you would like to be added to distro for updates!

National Aeronautics and Space Administration

Thank you!

Adam Sidor / adam.t.sidor@nasa.gov