Current & Future Challenges in Ceramics for TPS

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TPS for Space Applications Day 2

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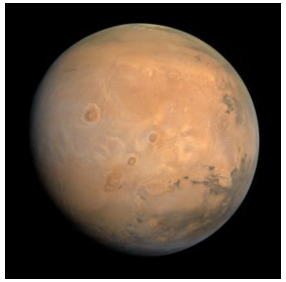
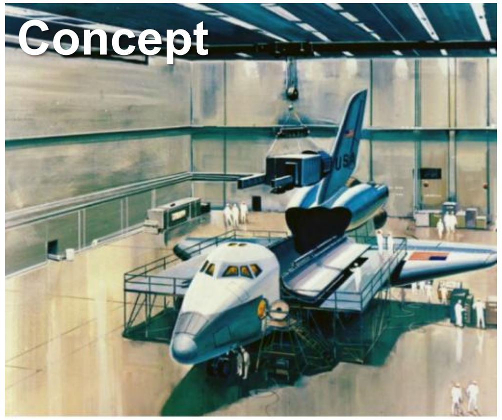
The big picture: focus on rapidly reusable and low-cost thermal protection systems

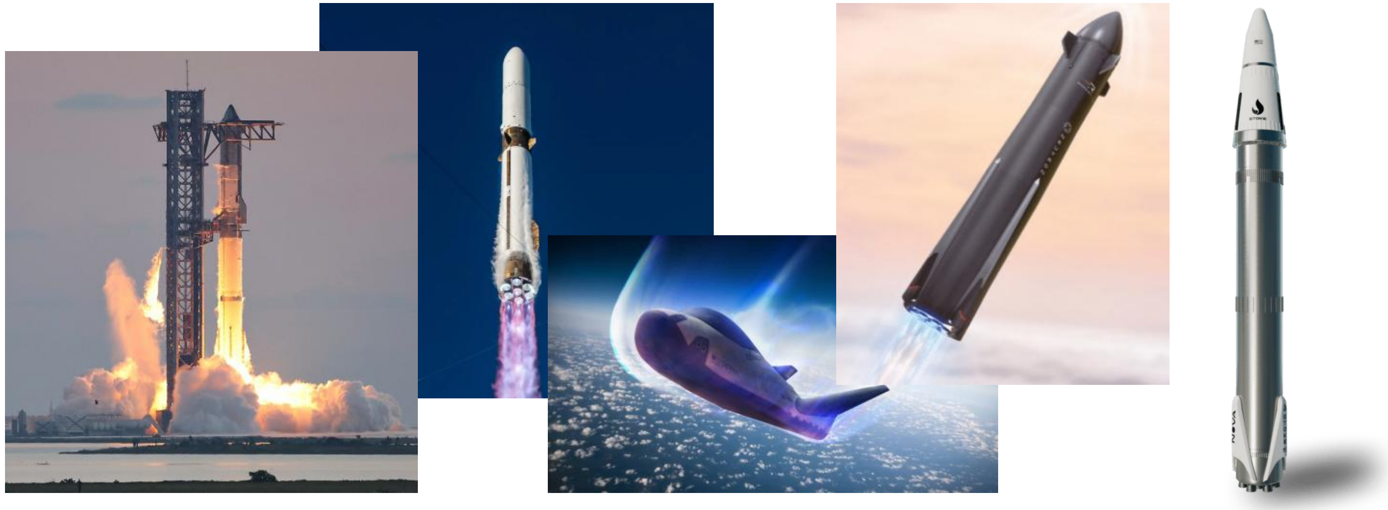
<u>All</u> crew and cargo transport vehicles, to and from low Earth orbit (LEO) and the Moon, need TPS and/or hot structures. Reusable vehicles (and therefore TPS) are key to cost reduction





The Space Shuttle was an attempt at a reusable spacecraft and initiated many technologies we have discussed the past two days but…





New launch vehicles & spacecraft are more ambitions in terms of both reusability requirements and capability. With this, comes significant challenges (both new & old, as we'll see).

Images from SpaceX, Blue Origin, Sierra Space, Rocket Lab, and Stoke Space

Selected challenges in ceramics for reusable TPS

1. Thermal Stability in Extreme Environments
2. High Temperature Waterproofing
3. Integration Beyond Bonding for Rapid Reusability
4. Funding & Path to Flight
5. Supply Chain Challenges
6. Meeting Requirements for Full “Sequence of Operations”
7. Reusable Launch Vehicles & Lunar Landers

Today’s discussion is *not* inclusive of all challenges, but focused on a few key topics discussed by instructors

Improvements in thermal stability are not a new goal…

LOCKHEED AEROSPACE RIGID FIBROUS CERAMICS

CERAMIC MATERIALS AND COATINGS FOR FUTU

APPLICATIONS: CHALLENGE OF THE

BY

J. O. DONALDSON & R. P. BANA

PRESENTED AT

41ST PACIFIC COAST REGIONAL MEE

OF THE

AMERICAN CERAMIC SOCIETY

PAPER 3-AS-88P
OCT. 26, 1988

THERM
ASTRONAUTICS DIVISION

Lockheed Missiles & Space Company, Inc.

- MATERIALS WITH USE TEMPERATURES FROM 2500 TO 3100°F.
  - LOW DENSITY (6-12 lb/ft³)
  - LOW THERMAL EXPANSION (3-15x10^{-7} IN/IN°F)
  - EASY MAINTAINABILITY
  - LOW THERMAL CONDUCTIVITY
  - STRENGTH GREATER THAN EXISTING RFC MATERIALS
- COATINGS COMPATIBLE WITH EXISTING RFC THAT ARE TOUGHER AND HAVE MORE IMPACT RESISTANCE THAN THE CLASS 2 COATING.
  - MATCHING C.T.E. BETWEEN COATING AND RFC SUBSTRATE
  - EMITTANCE $\geq$ 0.85 AT T $\geq$ 2000°F
  - INCREASED TOUGHNESS MAY BE OFFSET BY HIGHER UNIT WEI
  - WATER IMPERVIOUSNESS MAY NOT BE REQUIRED
- APPLICATIONS:
  - SHUTTLE "C"
  - SHUTTLE "2"
  - AEROASSIST FLIGHT EXPERIMENT (AFE)

Development of insulative reusable TPS (tiles and coatings) with temperature capability beyond 2800 °F / 1500 °C remains a significant challenge.

STABLE, ADVANCED FIBERS THAT CAN BE USED IN A 3200-4000°F USE TEMPERATURE RFC MATERIAL.

- REQUIRED FIBER CHARACTERISTICS:
  - LOW THERMAL EXPANSION (3-8x10^{-7} IN/IN °F)
  - SMALL AVERAGE FIBER DIAMETER (1.5-3 MICRONS)
  - HIGH MELTING POINT (4000-4500°F)
  - MODERATE TENSILE STRENGTH (150-220x10³ LB/IN²)
  - LOW FIBER POROSITY TO ENHANCE STRENGTH
  - THERMAL STABILITY TO 3200-4000°F

APPLICATIONS:

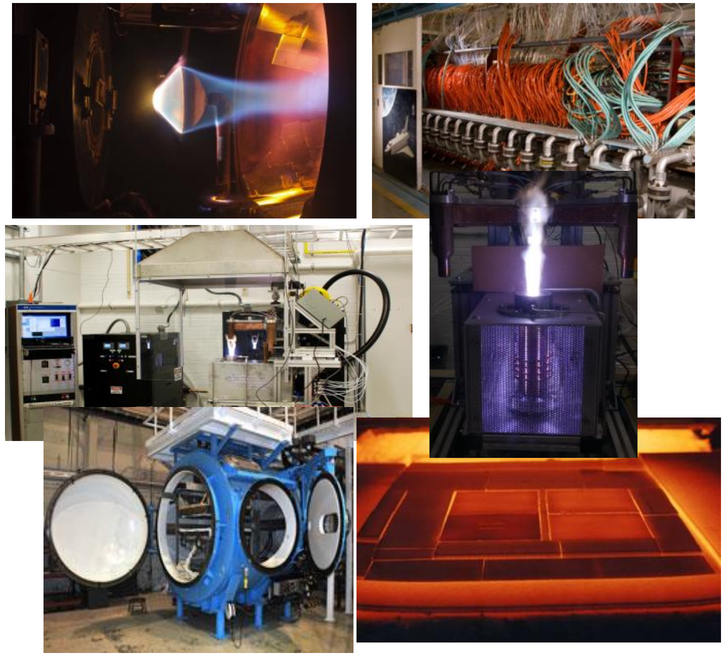
PROGRAM	PEAK DESIGN TEMPERATURE
NATIONAL AEROSPACEPLANE	3200-4000°F
AOTV RETURNING FROM THE MOON (SCALED UP AFE)	3100-3200°F
MARS AEROCAPTURE BI-CONIC VEHICLE	3000-3400°F
AEROASSIST ORBIT TRANSFER VEHICLE RETURNING FROM MARS (SIMILAR SHAPE AS AFE)	3200-4000°F

How is thermal stability defined and tested?

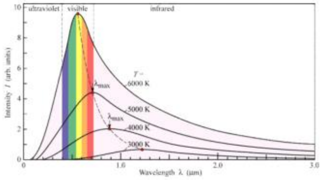
"Thermal Stability" can be defined in several ways, but I think of the following:

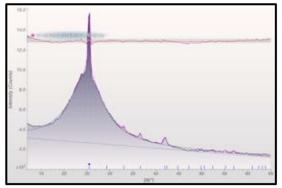
1. **Dimensional Stability** *(i.e., no change in shape)*
2. **Property Stability** (*e.g., no change in strength, thermal conductivity, CTE…)*

Ground testing exposes TPS to re-entry heating

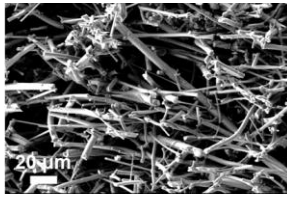


Post-test characterization quantifies impact on material properties

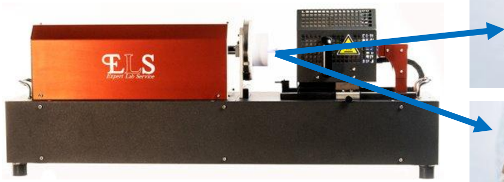


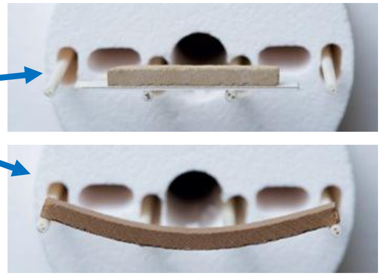


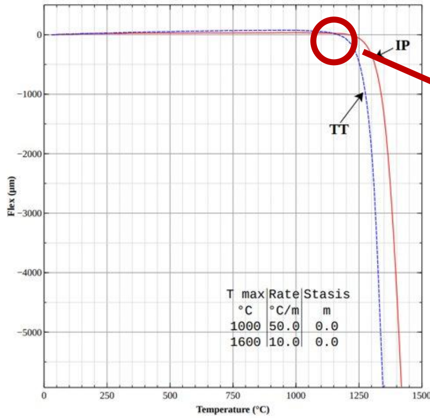
Microscopy (optical, SEM)
X-ray Diffraction (XRD)
Mechanical Testing
Optical Properties
Thermal Conductivity
Micro Computed Tomography
… and so on …



Rapid screening of thermal stability is promising future route.







Example of using optical dilatometer and "fleximeter" to assess thermal stability limits.

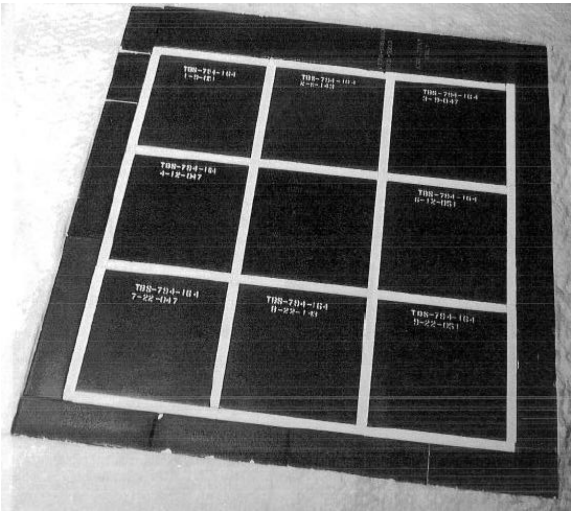
Interest in other rapid tests that inform thermal stability and material design.

Thermal stability in arc jet and radiant testing

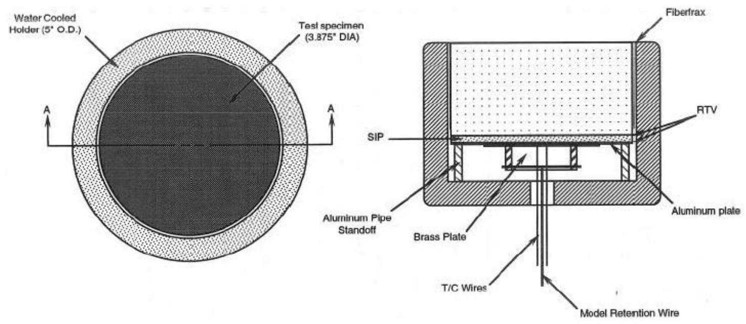
Arc jet testing and radiant heat testing can simulate the heating experienced on atmospheric entry.

Can assess:

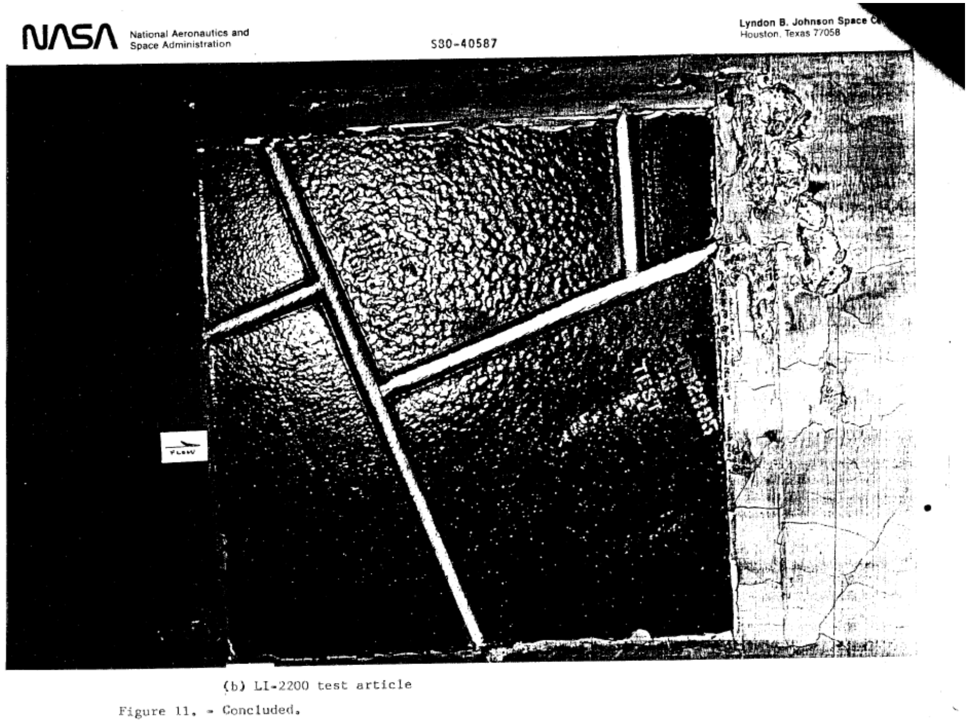
- Dimensional stability
- Reusability
- Changing emissivity
- Surface catalycity
- …



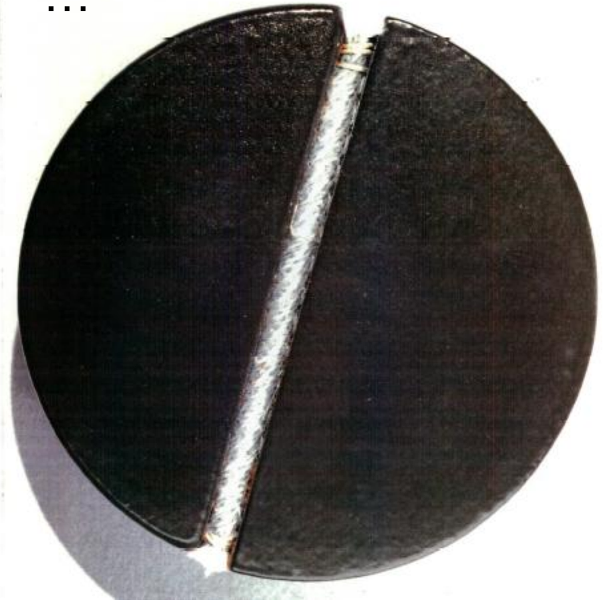
Tile array for JSC Radiant Heat Test Facility



Flat-face coupon for arc jet testing. Also run in iso-Q (rounded shape for equal heat flux across surface)



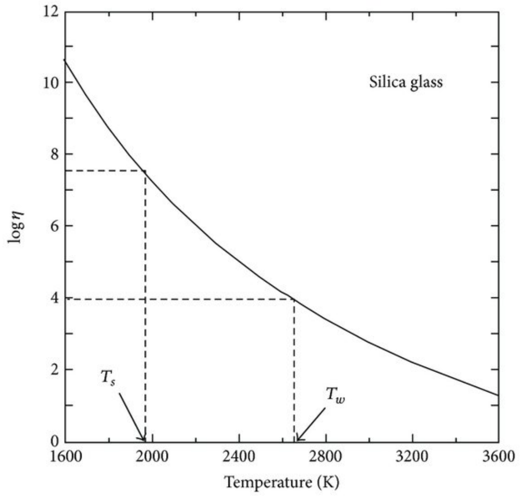
Exceeding temperature capability of tile leads to bubbling of RCG coating and shrinkage of tile substrate.

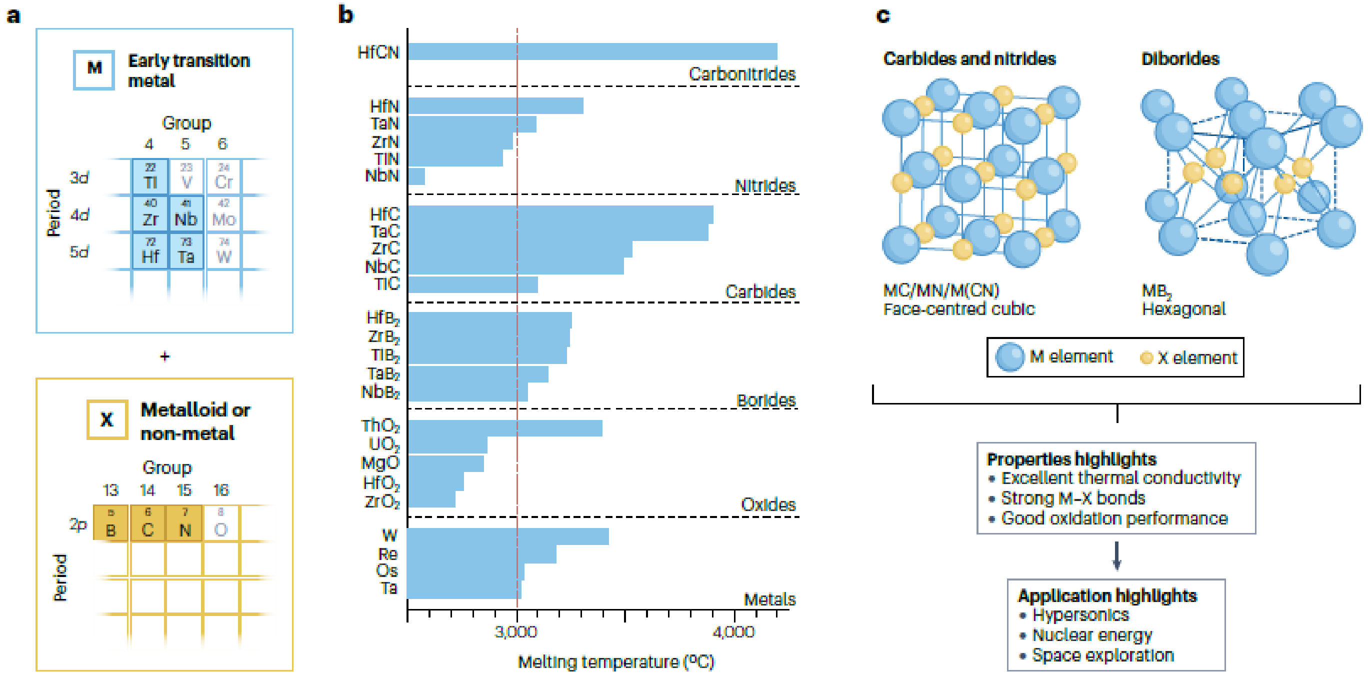


Assess thermal stability at a systems-level including tile-to-tile gaps and gap filling approaches.

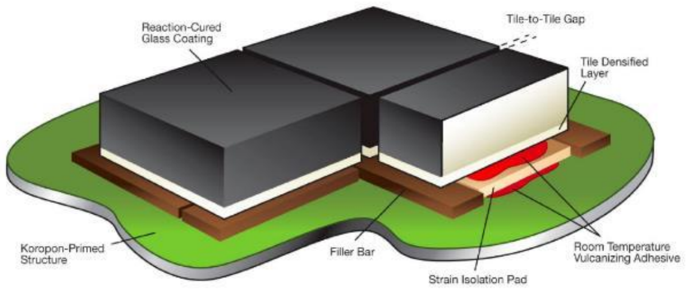
Potential avenues for incorporating adjacent fields of refractory ceramics and CMCs

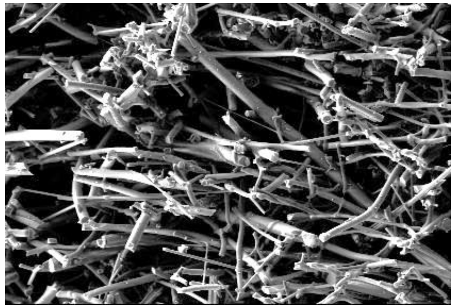
Fundamental limitation of silica-based TPS is a reduction in viscosity at high temperature: **tiles & coatings flow as temperature exceeds 1500 °C / 2800 °F**



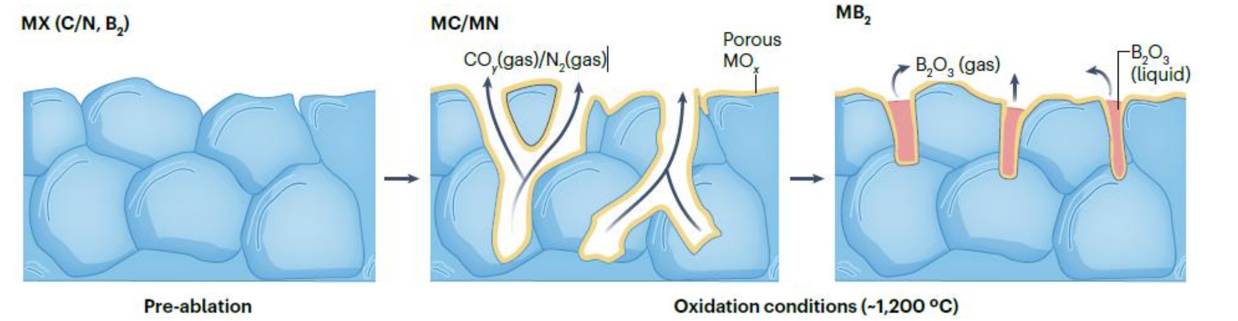


How can we leverage UHTCs to improve thermal stability of TPS that are lightweight, insulative, and reusable?





Challenges: Oxidation stability (high SSA), processing/sintering, high cost, high thermal conductivity, thermal shock resistance, …



Shuto, Yoshito. "End Face Damage and Fiber Fuse Phenomena in Single-Mode Fiber-Optic Connectors." *Journal of Photonics* 2016.1 (2016): 2781392.

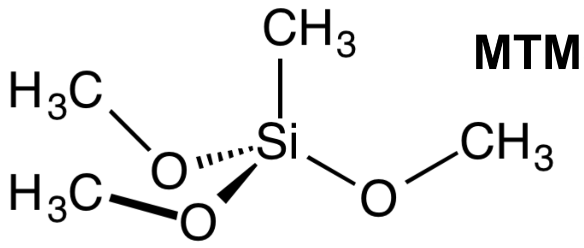
Wyatt, Brian C., et al. "Ultra-high temperature ceramics for extreme environments." *Nature reviews materials* 9.11 (2024): 773-789.

Why is waterproofing required?

- Silica (exclusive or primary component of all tile-based TPS) is extremely hydrophilic
  - Water adsorption from humidity, rain, etc.
- Two problems
  - (1) Tile cracking/failure
    - Water freezes on ascent
    - Contracts on orbit (T < -70 °F) → Expansion and contraction forms a fracture site
    - On re-entry, remaining ice will rapidly convert to steam, also leading to fracture of the tile
  - (2) Weight gain

Loss of tiles on STS-2 due to lack of waterproofing

Why is *re*-waterproofing required?



MTMS

Methyltrimethoxysilane (MTMS) is deposited from the vapor phase in large ovens onto tiles as one of the final steps in the manufacturing process

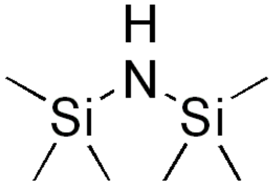
Results in roughly 0.2 wt. % pickup.

Issue: MTMS burns out at ~ 565 °C (1050 °F)

Scotchgard

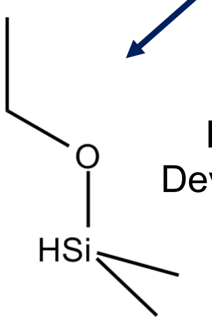
Spray on coating: Liquid pooling caused reversion of RTV (adhesive) to liquid state

HMDS



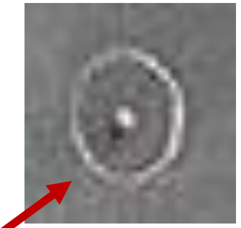
Internal re-waterproofer. Ammonia by-product caused reversion of RTV.

DMES



Internal re-waterproofer. Developed for STS-26 (1988) and used for remaining Shuttle Program.

Injection ports for tile-by-tile waterproofing for tiles that exceeded 1000 °F



Requirement to re-waterproof tiles significantly increases turnaround time between flights.

High temperature waterproofing is yet another challenge that remains from Shuttle era

LOCKHEED AEROSPACE RIGID FIBROUS CERAMICS

FUTURE CHALLENGES FOR REUSABLE, RIGID, FIBROUS CERAMICS
— ANCILLARY MATERIALS

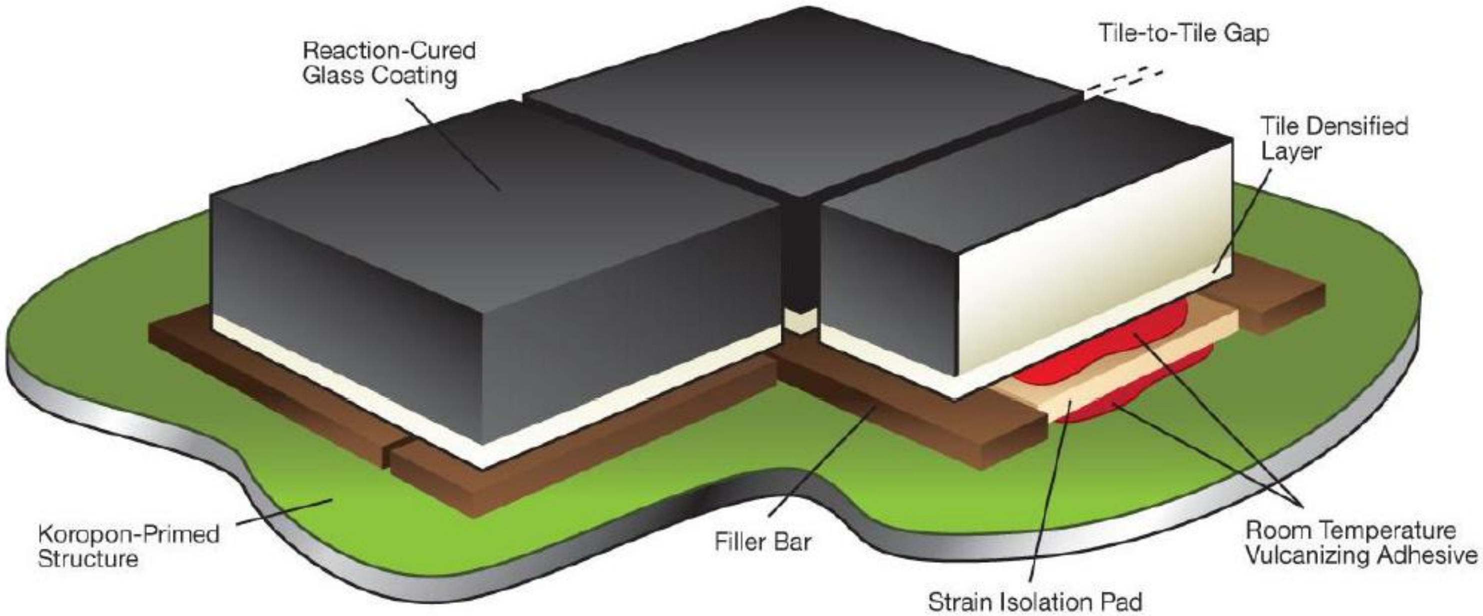
THE LAST CHALLENGE SHOWN IS A GOAL THAT HAS BEEN PURSUED BY NASA AND VARIOUS CONTRACTORS SINCE THE SECOND FLIGHT OF THE SHUTTLE ORBITER COLUMBIA IN LATE 1981. A FACTORY-APPLIED WATERPROOFING THAT PERMEATES THE ENTIRE INTERIOR OF THE RFC MATERIALS (I.E., LI900, LI-2200 AND FRCI-12) AND HAS A REUSE TEMPERATURE OF ABOUT 1800°F WOULD ALLOW ONLY 50% OF THE CURRENT TILES TO BE REWATERPROOFED AFTER EACH MISSION. THIS WOULD SIGNIFICANTLY REDUCE THE TIME REQUIRED TO REWATERPROOF THE ENTIRE SURFACE AREA OF THE ORBITER AS IS CURRENTLY PERFORMED AFTER EACH SHUTTLE MISSION. HENCE AN 1800°F CAPABILITY MATERIAL WOULD ALLOW THE ORBITERS TO SPEND LESS TIME IN THE ORBITER PROCESSING FACILITY AND WOULD SHORTEN THE TURNAROUND TIME.

- ADVANCED COATINGS COMPATIBLE WITH THE 3200-4000°F ADVANCED RIGID, FIBROUS CERAMICS.
  - REQUIREMENTS ARE SIMILAR TO CURRENT COATING CHARACTERISTICS.
- HIGHER TEMPERATURE CAPABILITY WATERPROOFING MATERIALS THAN THE PRESENT 1050°F METHYLTRIMETHOXY SILANE.
  - GOAL OF 1800°F WOULD ALLOW REWATERPROOFING OF ONLY 50% OF SHUTTLE ORBITER TILES.

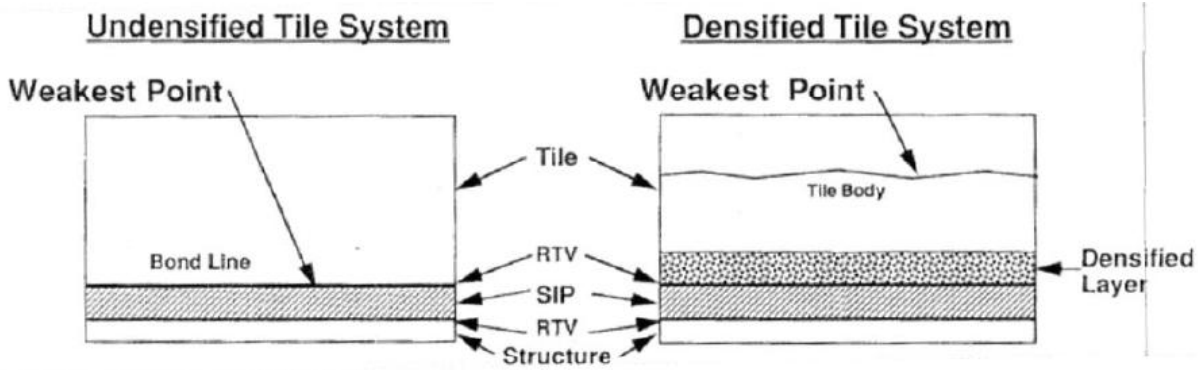
There is a critical need for either
(1) high temperature waterproofing or
(2) rapid re-waterproofing approaches.

Key enabler for rapid reusability

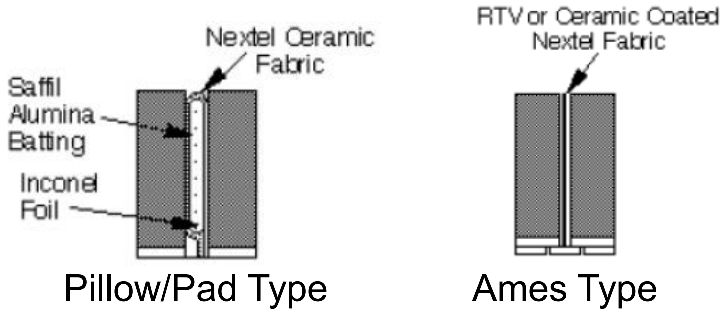
Integration approach: Space Shuttle tile



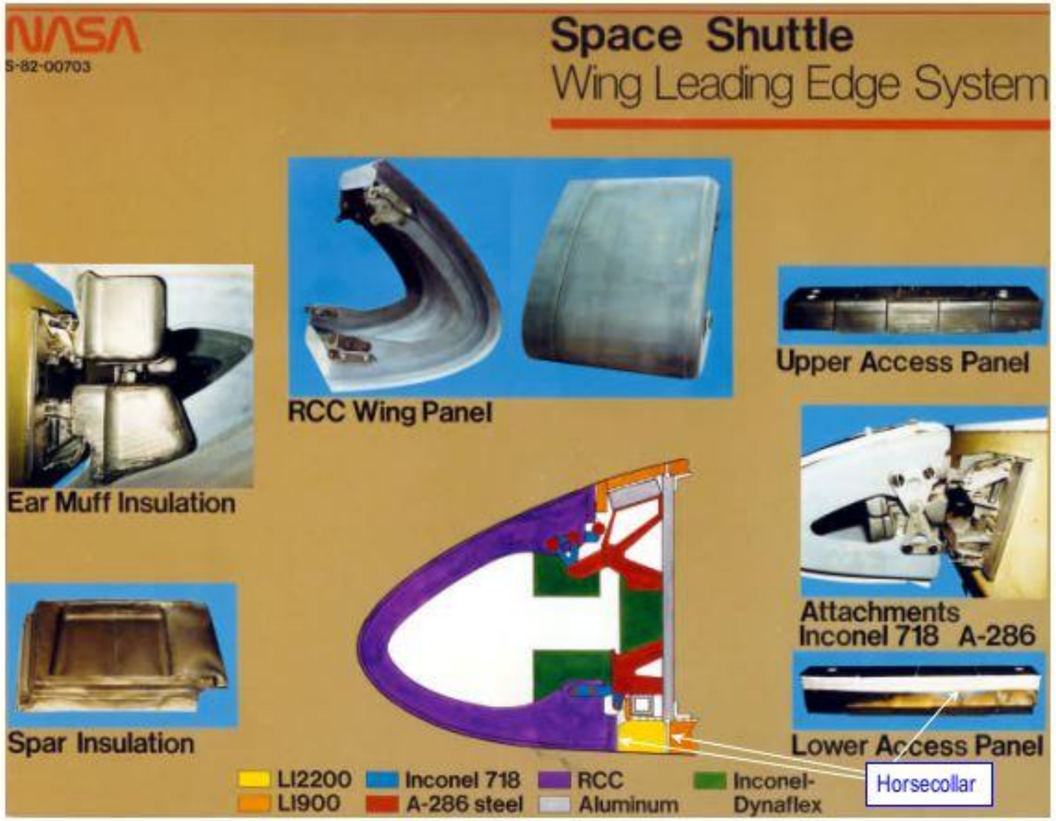
RTV 560 – Used as adhesive
Strain Isolation Pad (SIP) – Used to accommodate strain driven by both differential expansion and ascent vibration
Tile Densification – Bottom surface of tile was infiltrated with colloidal silica or TEOS to distribute stress loads at SIP/tile interface
Filler Bar – Used to protect structure between gaps. SIP was inset to prevent charring of edges and reduce tendency to fail by peeling.
Gap Fillers – In areas of high heating or high differential pressure, gap fillers were installed between the tiles.

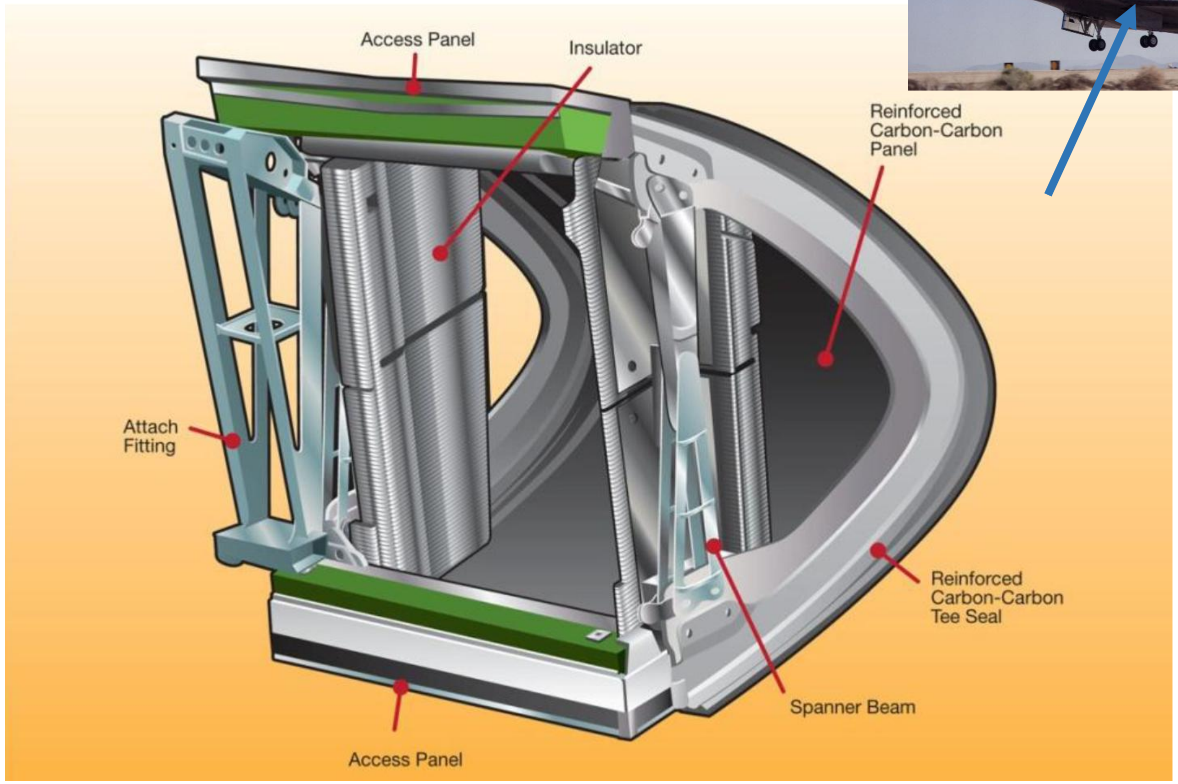


Gap Fillers



Integration approach: Shuttle RCC



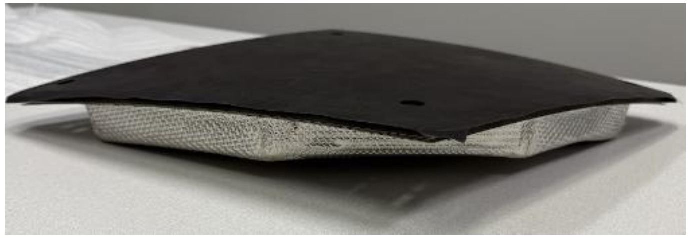


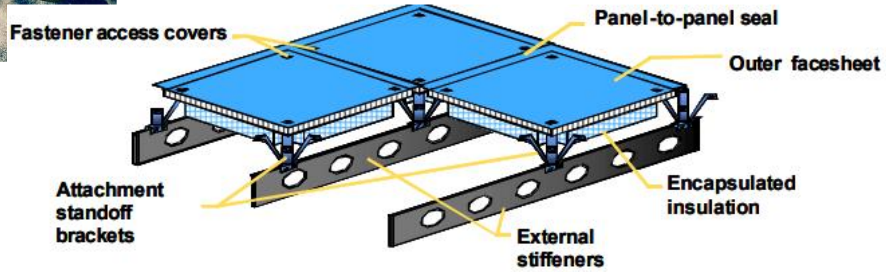
Nose cap and wing leading edge (shown above) were structure fairings that transmitted aerodynamic loads **via mechanical attachment**.

Inconel 718 and Ti 6AL4V fittings – Attached the RCC to the aluminum wing spar and forward bulkhead.
Inner insulation – Hollow shell of RCC parts allows for re-radiation from hot to cooler parts of the RCC. Inner insulation protected aluminum and attachments from radiant heat.
RCC Tee Seal – Mounted between RCC panels to eliminate gaps

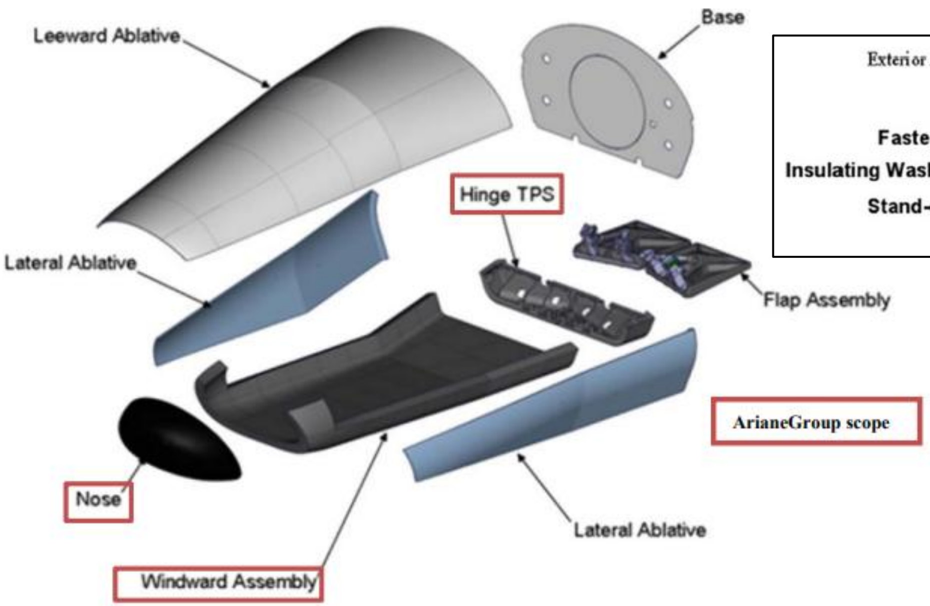
TPS integration for rapid refurbishment & repair

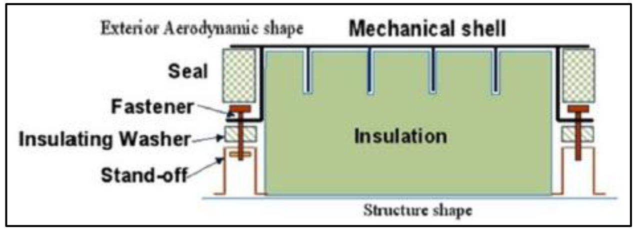
There is a need to go beyond bonding and develop TPS integration approaches that are conducive to rapid install, robustness through all phases of flight, and rapid refurb/repair when necessary.

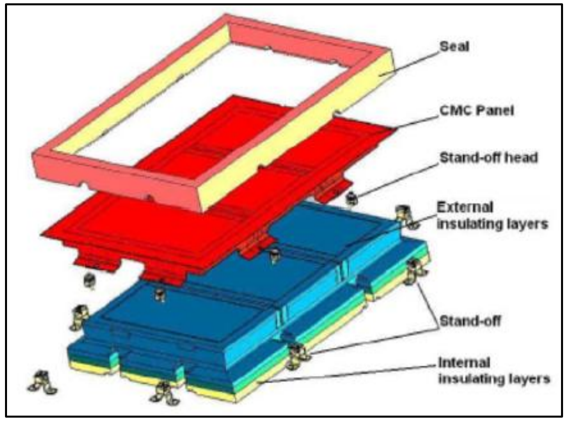




Metallic stand-off TPS developed for X-33. Metallic panels with encapsulated fibrous insulation and metallic stand-off attachment clips.







Space Rider (ESA) features a CMC shingle design developed by the ArianeGroup and manufactured by Petroceramics.

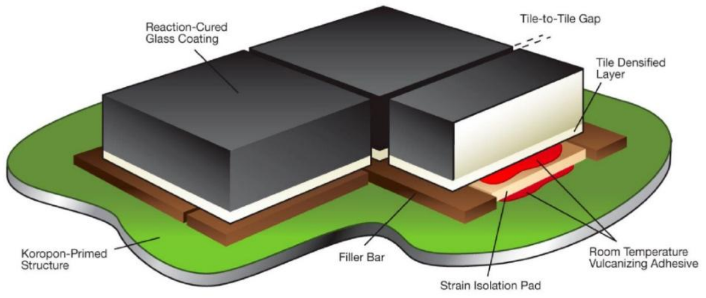
Many challenges with mechanically fastened system:

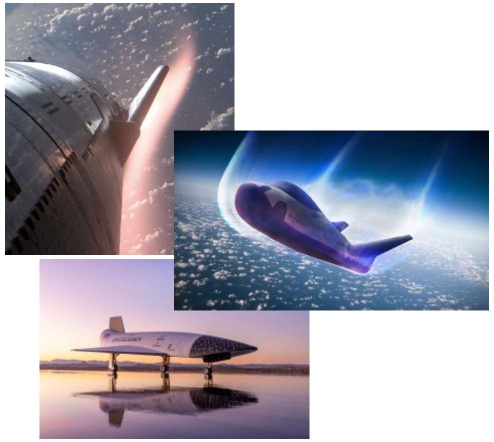
- Complexity & part count
- Heat shorts
- Protecting fasteners from heating while maintaining ease of access
- High temperature seals
- …

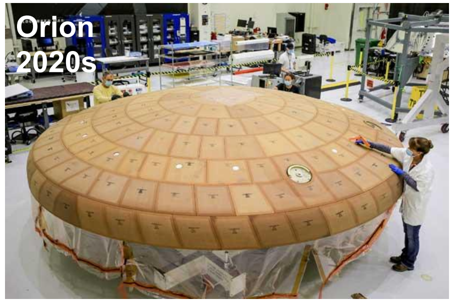
“Primary challenge with any stand-off TPS is attaching the external panel to the substructure and transferring aero and pressure loads, but not thermal loads.” – D. Glass

Space Rider schematic from Bernard, R, et al. “From IXV to Space Rider: CMC Thermal Protection System evolutions”, 2019.
For more schematics and background, please see David Glass’s 2008 paper, “Ceramic matrix composite (CMC) thermal protection systems (TPS) and hot structures for hypersonic vehicles.”

Taking a material to flight is costly and time intensive







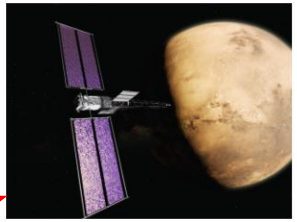
Reliance on heritage, “proven” TPS because of high cost and time requirements for qualification *and* criticality of the TPS for mission success.

With shift towards vertical integration, there can be a challenge “getting your foot in the door”.

NASA Research & Technology Mission Directorate (RTMD)


Aeronautics Division


Advanced Research and Technology Division


Space Reactors Division


Space Communications and Navigation (SCaN) Division

Funded opportunities to support development through NASA (CIF/ECI, SBIR/STTR, Flight Opportunities, NSTGRO, …)

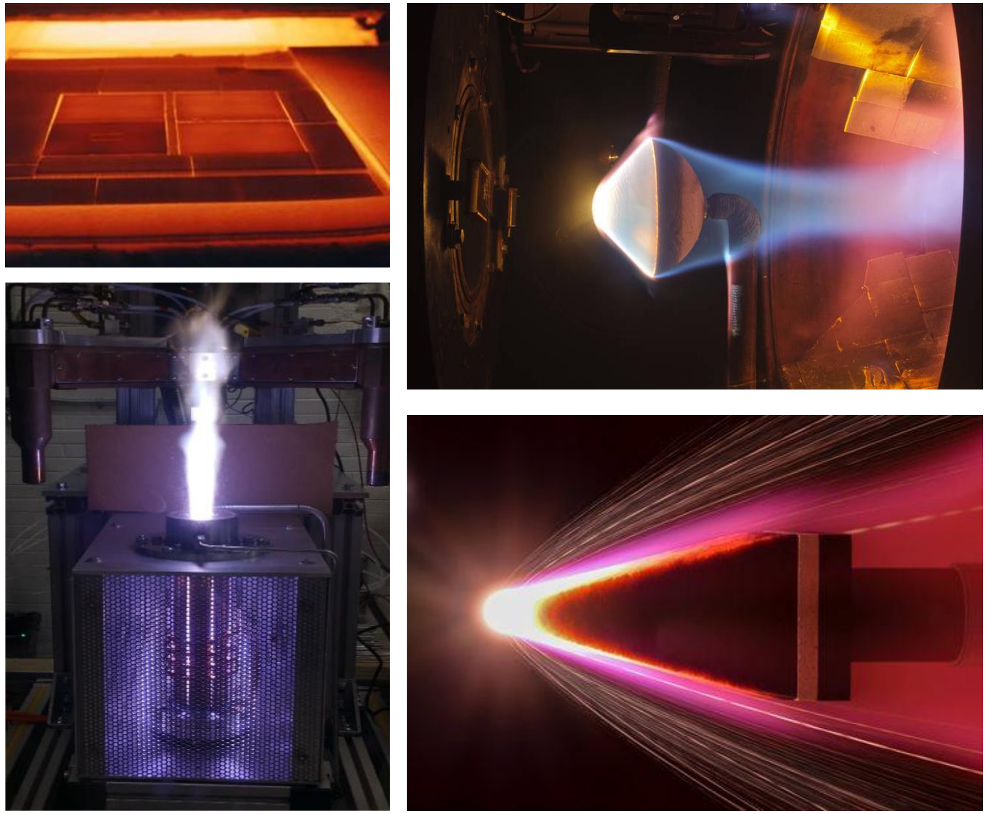
NTRS - NASA Technical Reports Server

TPSX Material Properties Database

DEPARTMENT OF WAR
Defense Technical Information Center
PRESERVING KNOWLEDGE • CONNECTING PEOPLE • INSPIRING INNOVATION

Leverage knowledge & lessons learned from heritage materials via improved data sharing.

Ground testing infrastructure needed to accelerate rate of development



If the cost of testing TPS in relevant environments can be reduced, the barrier to entry for new systems will reduce in turn.

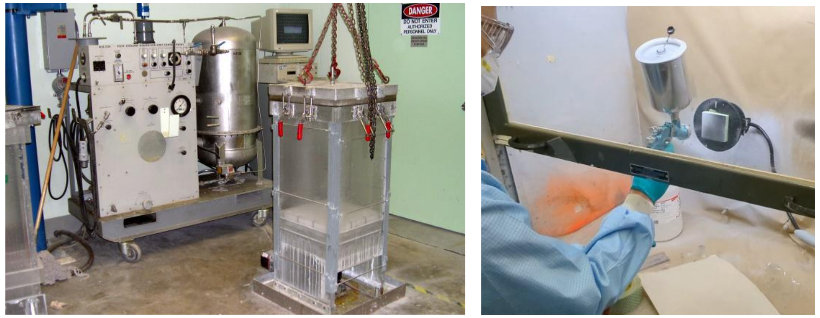
In addition to the high cost and low availability of high enthalpy testing, **high temperature material property data** (thermal, mechanical, optical) is also challenging to obtain at temperatures relevant to entry.

As launch costs are reduced and entry test platforms expand, look to **couple flight tests with targeted ground testing & characterization**. Flight tests can (and should) expose critical unknowns, but cannot replace ground tests, characterization, and modeling.

Testing images from NASA JSC and ARC, UT Austin, and U of Illinois Urbana-Champaign.
Spacecraft images from SpaceX, Intuitive Machines, Stratolaunch, Varda, and Blue Origin

Cost reduction needed from fabrication through integration

Beyond testing and qualification, the cost to manufacture, integrate, and operate TPS also needs to be reduced.



Manufacturing innovation required to bring down cost to manufacture TPS.

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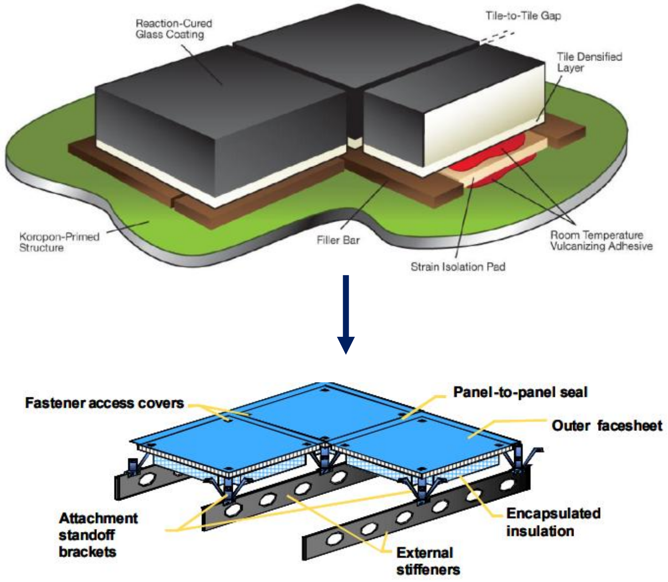
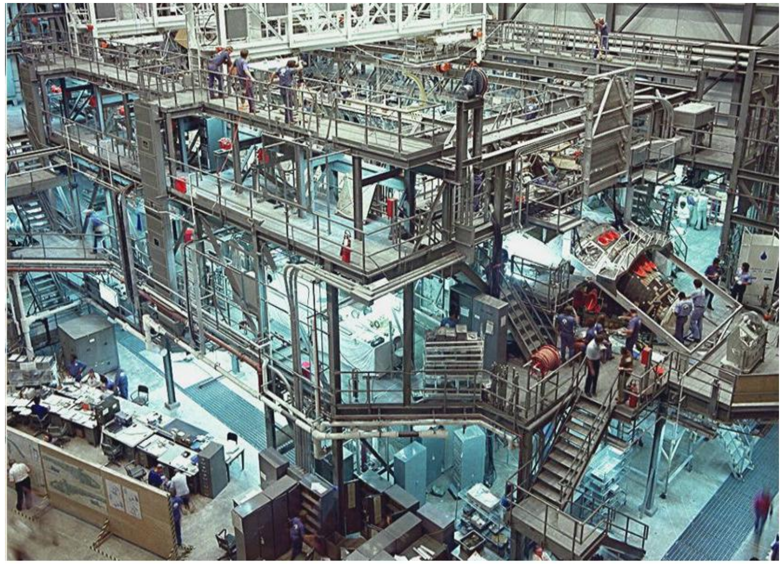
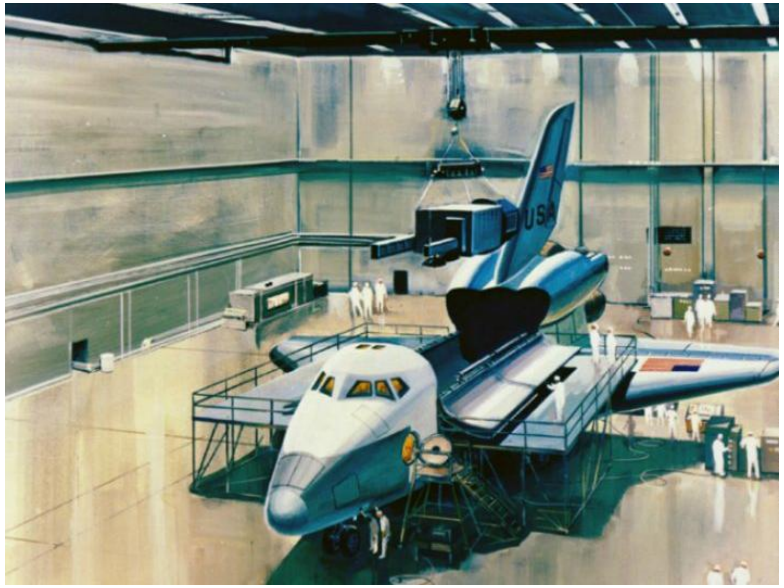


Integration approaches for ease of installation & repair/refurb.

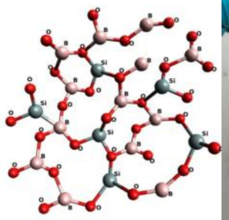


How do you **operate** a reusable TPS for “airline-like” operations?

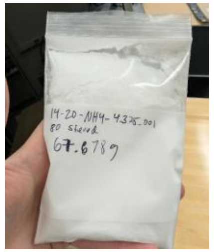


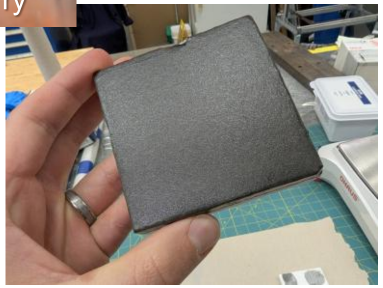
Supply chain challenges come in several forms

Material Obsolescence*



Glass frit for RCG and TUFI coatings made obsolete in the 90s. Lifetime buy for Shuttle (and now Orion). Other companies standing up capability to make their own.

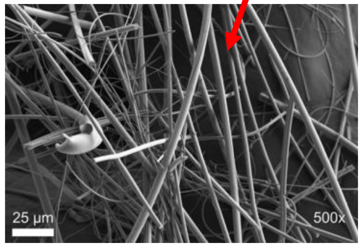


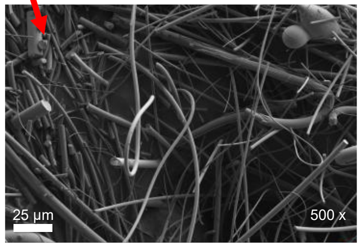


Loss of critical materials can eliminate technologies from use on future spacecraft. Stockpiles strictly controlled by existing programs.

Changes to Materials

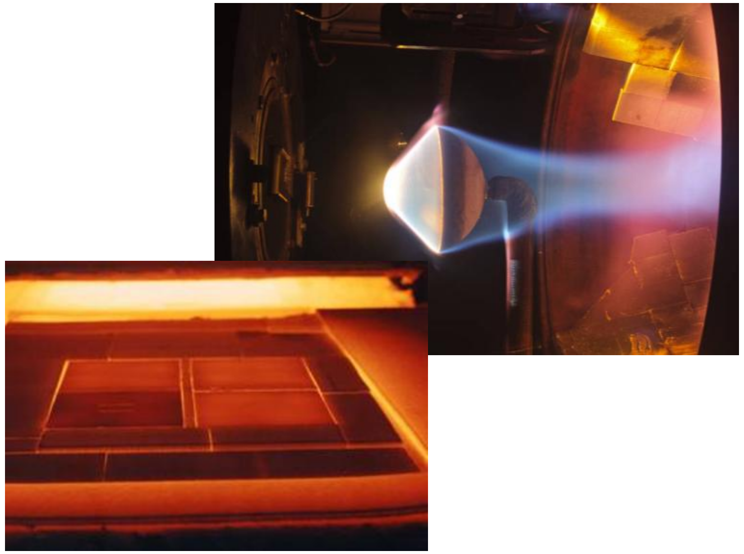
Q-Fiber used in tile ceased production in 90s and restarted in 2000s. Modern fiber requires different processing parameters to achieve similar tile.





Seemingly negligible (even imperceptible) differences to materials impact downstream processing and performance.

Cost to (Re)Qualify



In many cases, qualification essentially starts from the ground up. Significant cost associated with qualification as previously discussed.

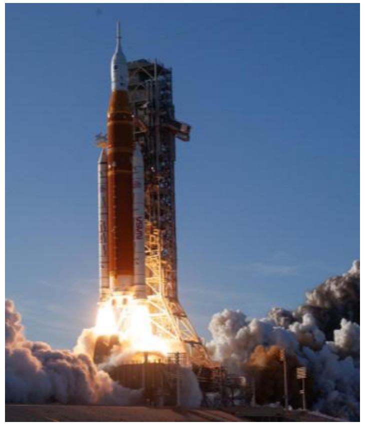
* Many other examples including SIP (for bonding), SiB_x (RCG/TUFI emittance aid), FiberForm (PICA & TUFROC substrate), …

TPS must satisfy requirements for all phases of flight

On the Pad

Humidity
Rain
Lightning
Wildlife

Launch



Vibroacoustic
Pressure
Debris Impact

Ascent

Aeroheating
Pressure Change
Plume Heating
Debris Impact

In Space

Temperature Cycles
Vacuum
Atomic Oxygen
MMOD impact

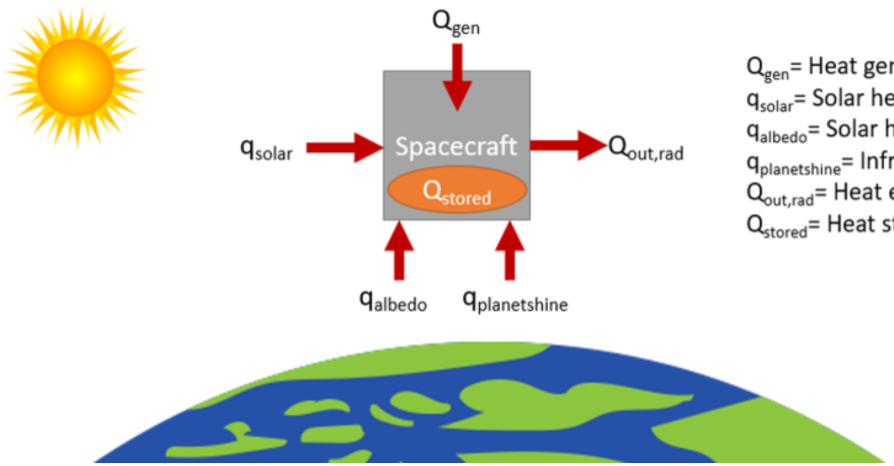
Re-Entry

High Heating
Dissociated Air

Landing

TPS must satisfy requirements for all phases of flight

In space, requirements for optical properties (solar absorptivity, emissivity) to maintain spacecraft temperatures



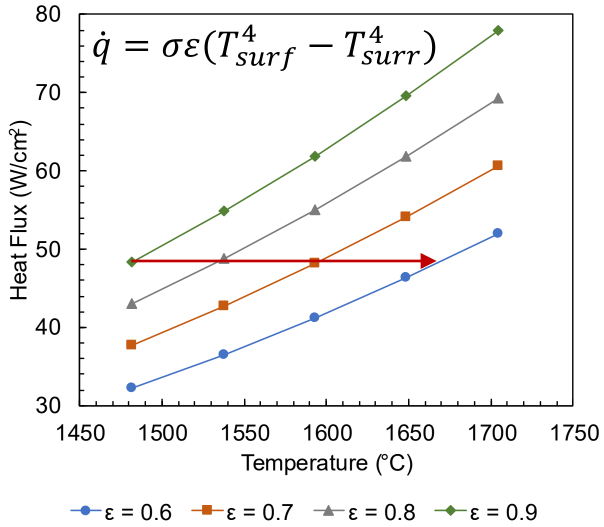
Q_{gen}= Heat generated by spacecraft
q_{solar}= Solar heating
q_{albedo}= Solar heating reflected by planet
$q_{planetshine}$= Infrared heating from planet
$Q_{out,rad}$= Heat emitted via radiation
Q_{stored}= Heat stored by the spacecraft

In Space

Temperature Cycles
Vacuum
Atomic Oxygen
MMOD impact

Re-Entry

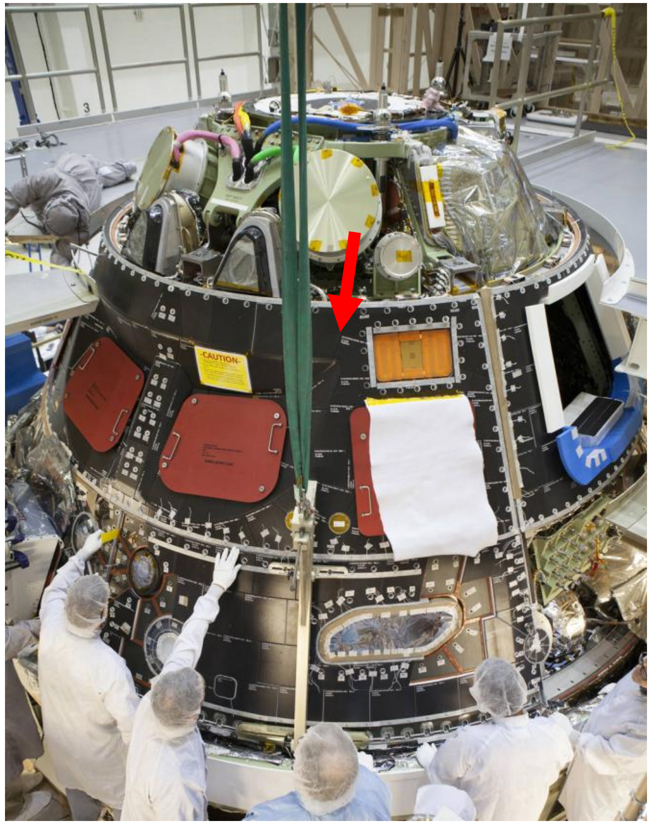
High Heating
Dissociated Air



On entry, emissivity controls how much heat is rejected by re-radiation. For a given heat flux, **surface temperature can be impacted by >200 °C** for ε from 0.6 to 0.9

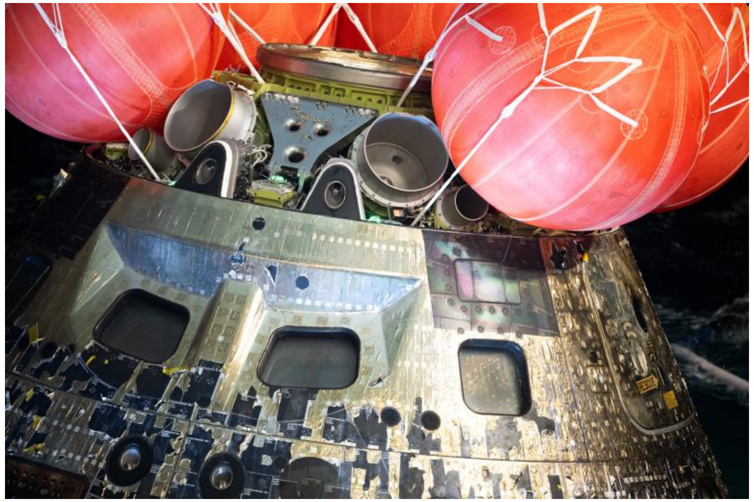
TPS must have properties that satisfy requirements for all phases of flight ***and*** maintain said properties for multiple flights.

TPS must satisfy requirements for all phases of flight



AETB tiles are used as the backshell TPS on Orion

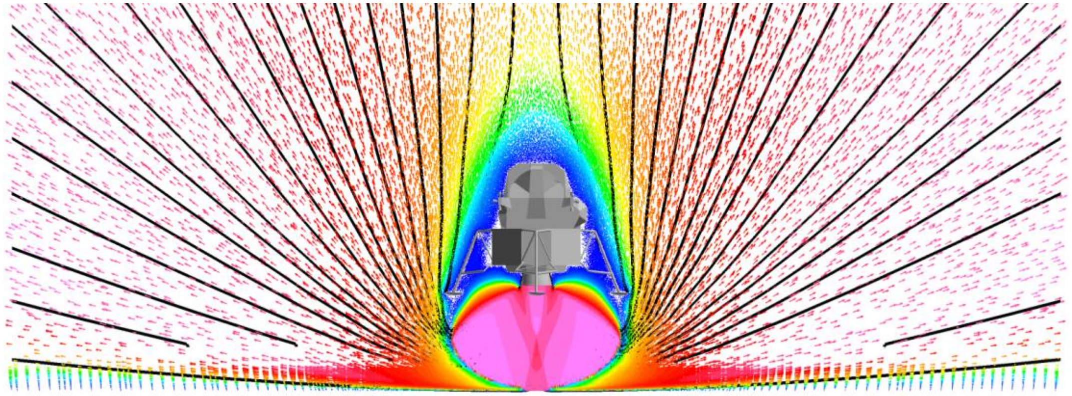
Aluminized thermal tape added for passive thermal control in-space (bondline temp, spacecraft needs) and for electrostatic charge dissipation.



The tape is burnt following flight so this would *not* be a suitable approach for a TPS that is intended to be reused.

TPS challenges extend beyond entry, including launch vehicles & lunar landers

During powered descent, **plume heating** present on base heat shield.

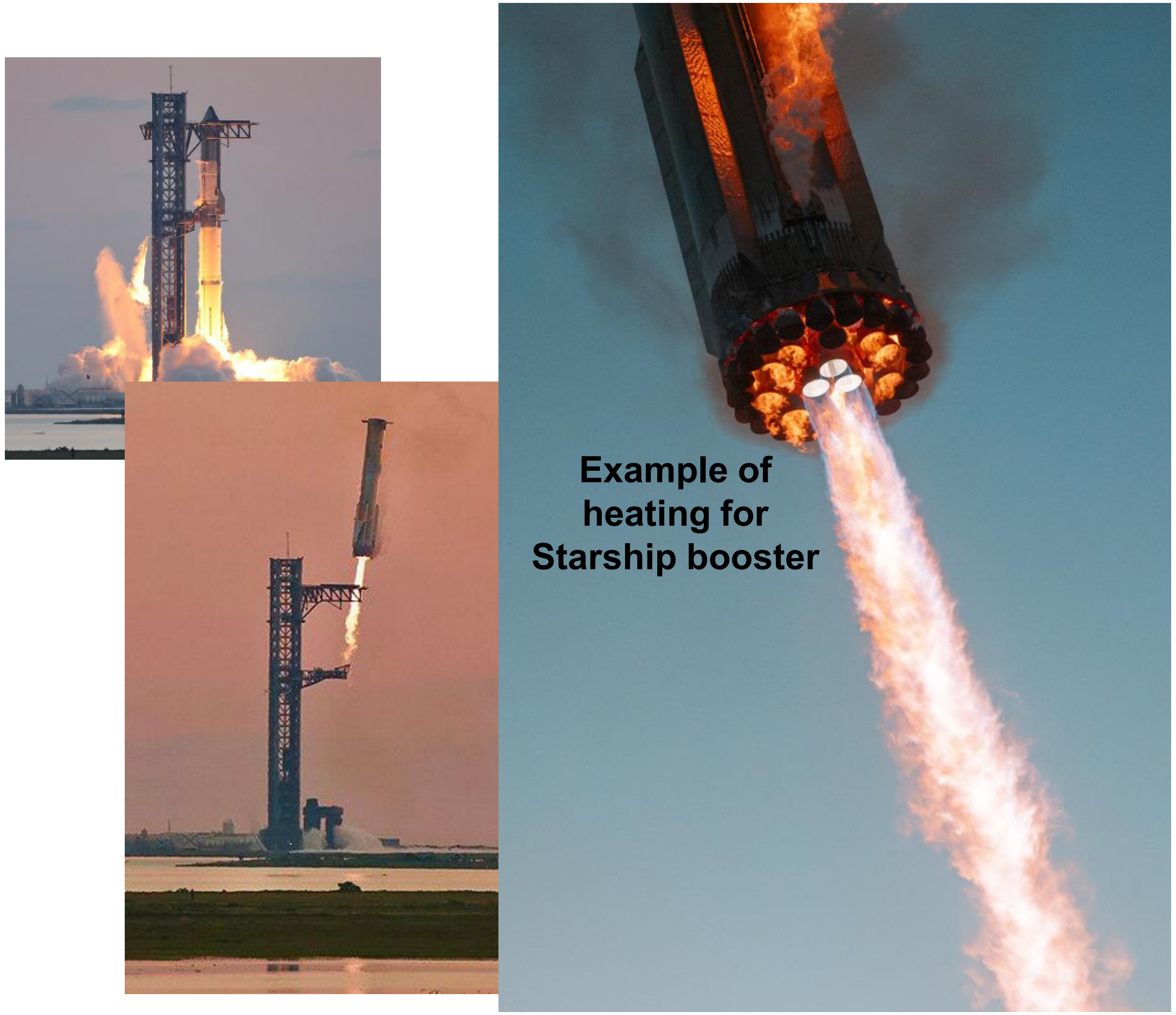


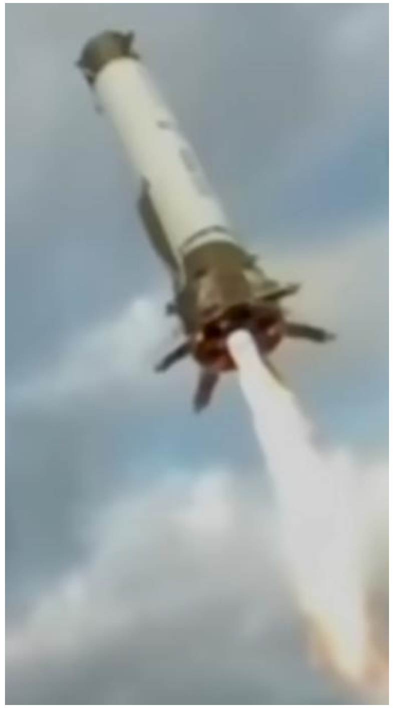
Near surface, Lunar regolith will be ejected and caught up in plumes, **impacting TPS at high velocities and high temperatures**

How do we develop (1) ground testing capability and (2) erosion-tolerant TPS for new generation of Lunar landers?

Lunar lander TPS may not need be reusable, but ceramics will likely play a role

TPS challenges extend beyond entry, including launch vehicles & lunar landers

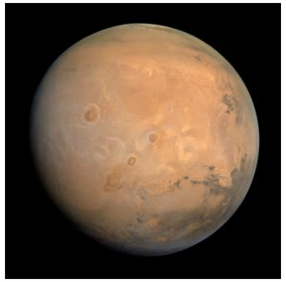




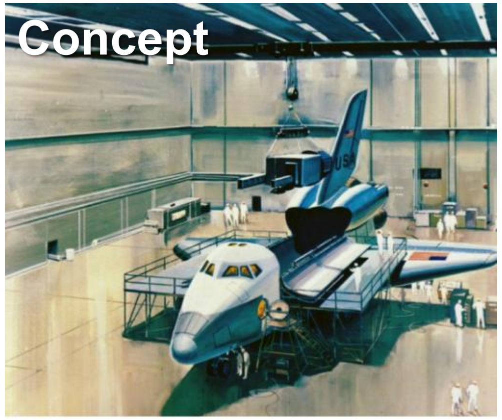
Reusable heavy launch vehicles with reusable first and second stages will require advanced materials that can survive radiant and plume heating in base heat shields.

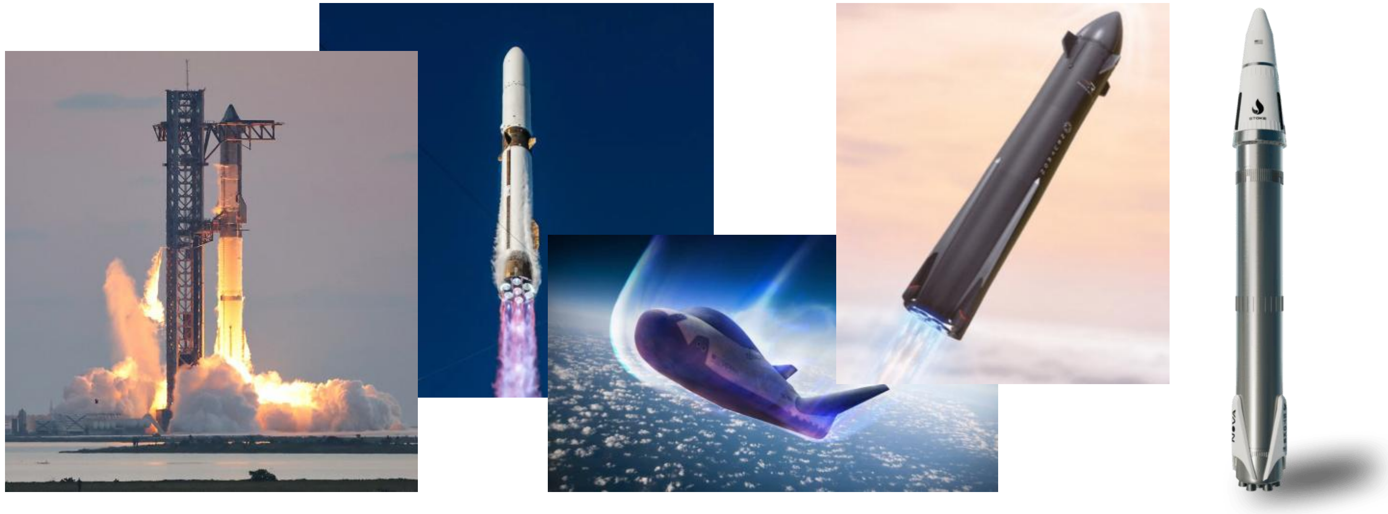
The big picture: focus on rapidly reusable and low-cost thermal protection systems

<u>All</u> crew and cargo transport vehicles, to and from low Earth orbit (LEO) and the Moon, need TPS and/or hot structures. Reusable vehicles (and therefore TPS) are key to cost reduction



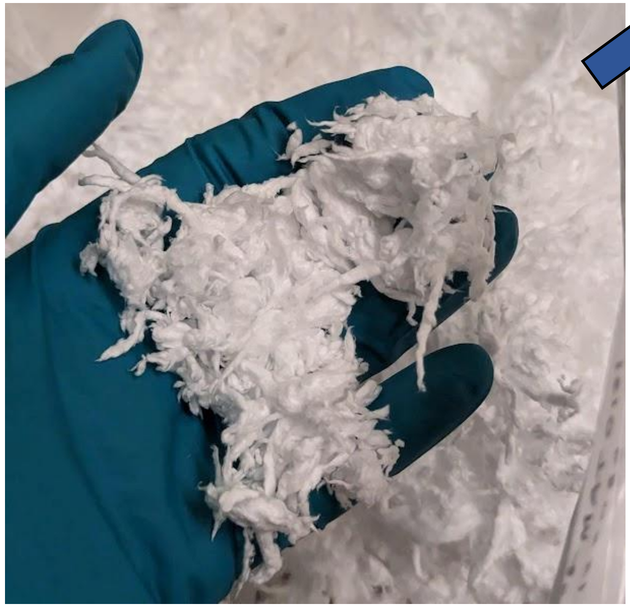
The Space Shuttle was an attempt at a reusable spacecraft and initiated many technologies we have discussed the past two days but…

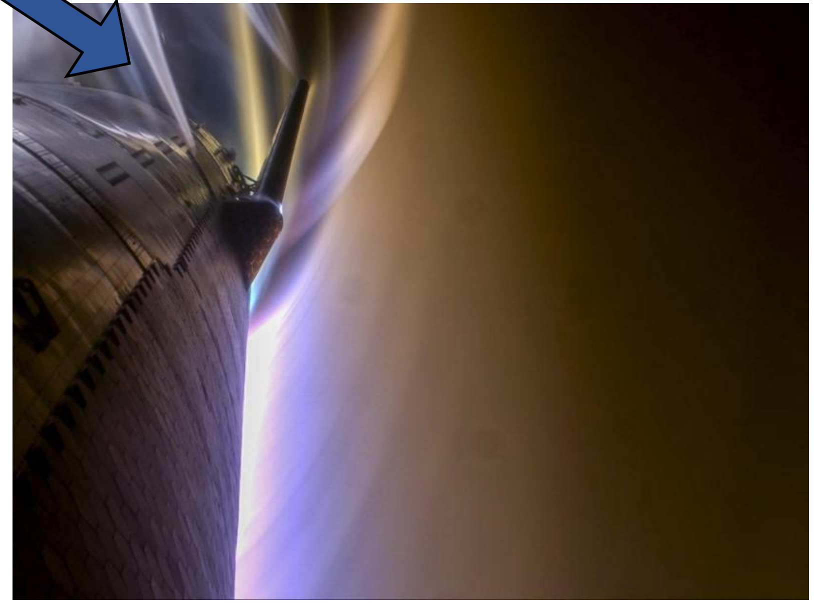




New launch vehicles & spacecraft are more ambitions in terms of both reusability requirements and capability. With this, comes significant challenges (both new & old, as we'll see).

Course Goal: Understand how a material is developed, tested, and qualified for spaceflight





From material to component to system
(and everything in between)
with a focus on reusable ceramic TPS