Introduction to Ceramics for Thermal Protection Systems (TPS)

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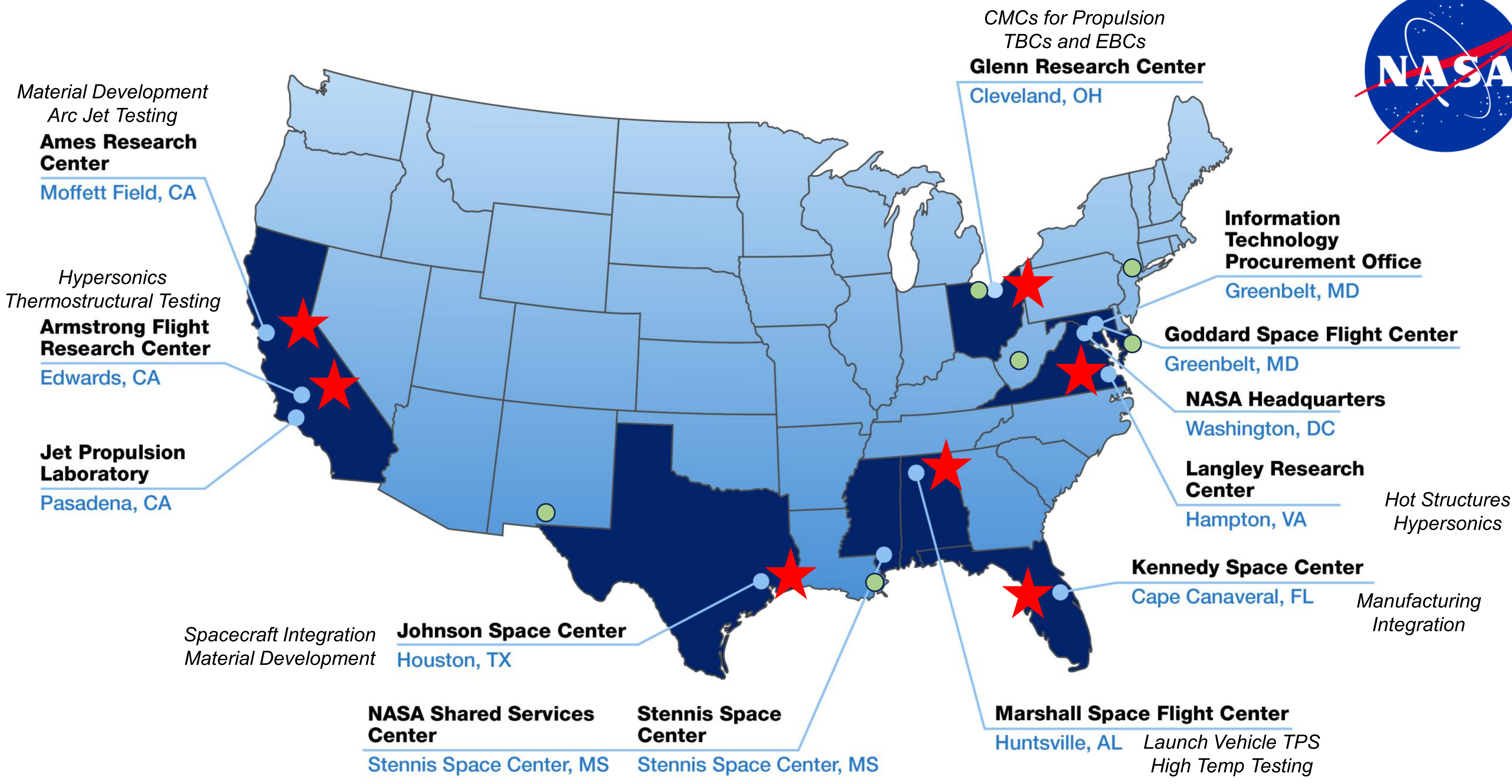
NASA Johnson Space Center

TPS for Space Applications Day 1

August 4th, 2026



Material Development
Arc Jet Testing
Ames Research Center
Moffett Field, CA
Hypersonics
Thermostructural Testing
Armstrong Flight Research Center
Edwards, CA
Jet Propulsion Laboratory
Pasadena, CA
Spacecraft Integration
Material Development
Johnson Space Center
Houston, TX
NASA Shared Services Center
Stennis Space Center, MS
Stennis Space Center
Stennis Space Center, MS
Marshall Space Flight Center
Huntsville, AL
Launch Vehicle TPS
High Temp Testing
CMCs for Propulsion
TBCs and EBCs
Glenn Research Center
Cleveland, OH
Information Technology Procurement Office
Greenbelt, MD
Goddard Space Flight Center
Greenbelt, MD
NASA Headquarters
Washington, DC
Langley Research Center
Hampton, VA
Hot Structures
Hypersonics
Kennedy Space Center
Cape Canaveral, FL
Manufacturing
Integration

NASA Johnson Space Center

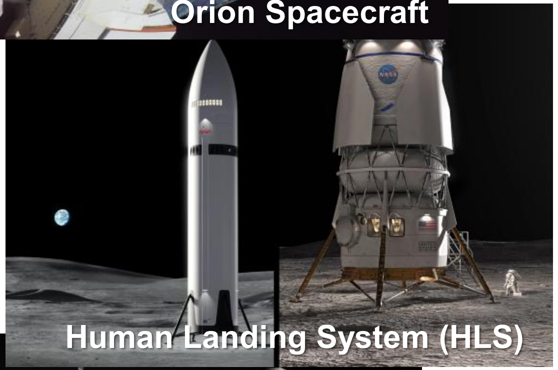
“The Hub of Human Spaceflight”

- Leads NASA’s human spaceflight programs and associated research & development
- Roughly 12,000 employees (contractors and civil servants)
- Formed 1961; opened 1963

TPS enable NASA's missions

Artemis Program

NASA's return to the moon to establish a permanent lunar base

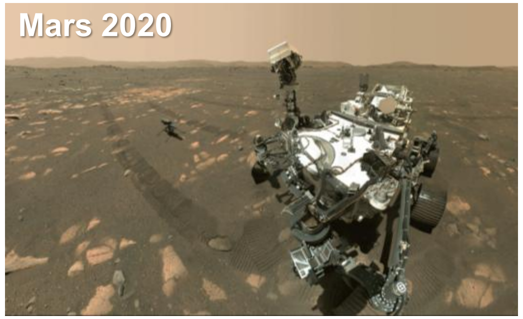


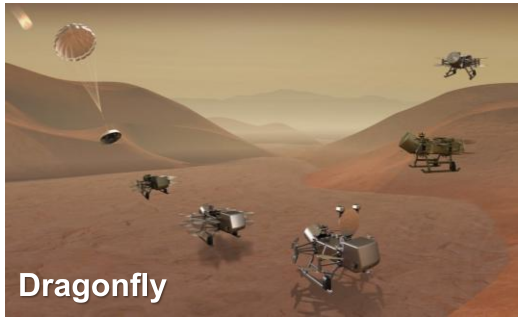
Commercial Crew Program

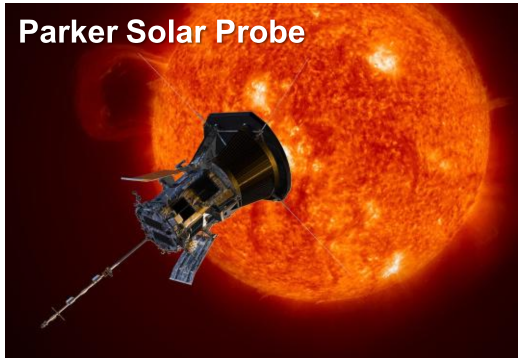
Transport astronauts to and from ISS

Planetary Exploration

Explore the Solar System for scientific purposes using robotic landers & planetary probes

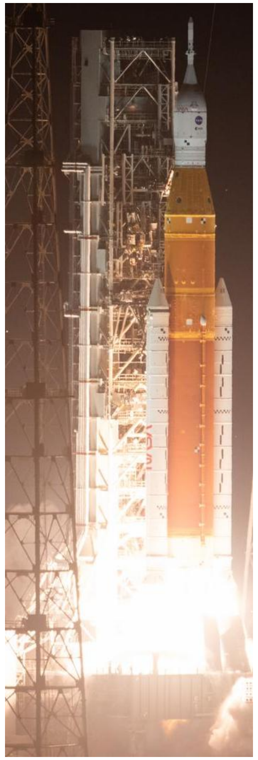






High velocities and extreme environments of spaceflight necessitate **thermal protection systems** (TPS)

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 $\dot{q}_{conv} \propto v^3$

Shock-Layer Radiation Scales with Velocity^8 $\dot{q}_{rad} \propto v^8$

Atmospheric entry leads to spacecraft heating

To return to Earth, the total energy (kinetic + potential) of a spacecraft must be reduced to zero. Taking the Space Shuttle as an example…

m = 100,000 kg | v = 7,700 m/s (17,225 MPH) | h = 300 km

E = 3.23 x 10^{12} Joules

Energy density: $\frac{E}{m} = \frac{V^2}{2} + g_o h$

Entry	V (km/s)	E/m (MJ/kg)
MER	5.6	16
Apollo	11.4	66
Mars Return	14.0	98
Galileo	47.4	1130

The energy is converted to heat during re-entry of the spacecraft via compression of air and drag.

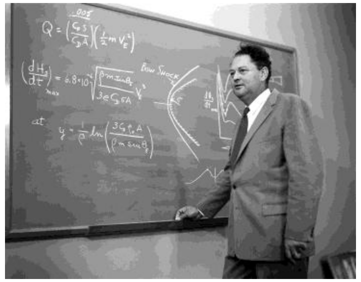
The TPS's role is to protect the spacecraft from the high temperatures associated with this conversion of energy.

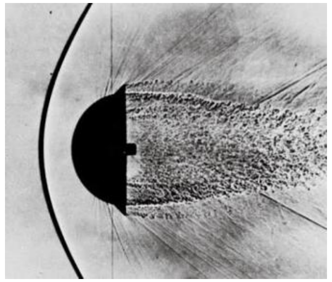
Note that:

Water boils @ 2.3 MJ/kg

Carbon vaporizes @ 60.5 MJ/kg

Note, not all energy heats the spacecraft or else this would be an impossible challenge.

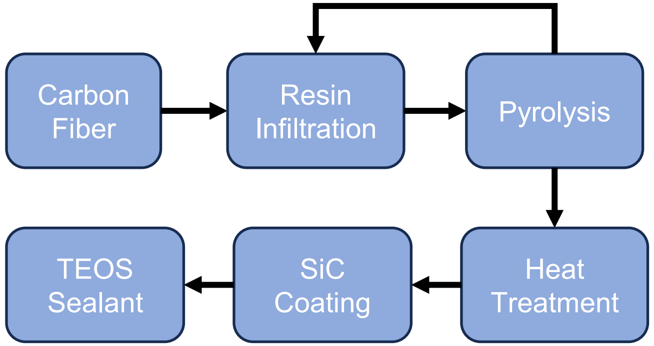




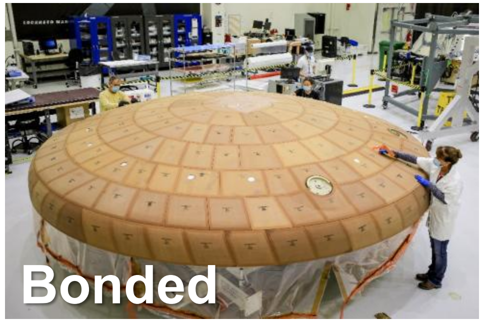
TPS = Thermal Protection **System**

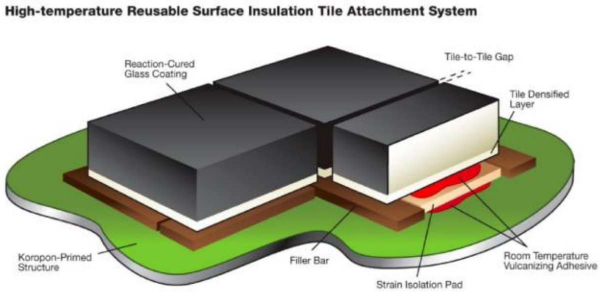
Material

Manufacturing



Integration





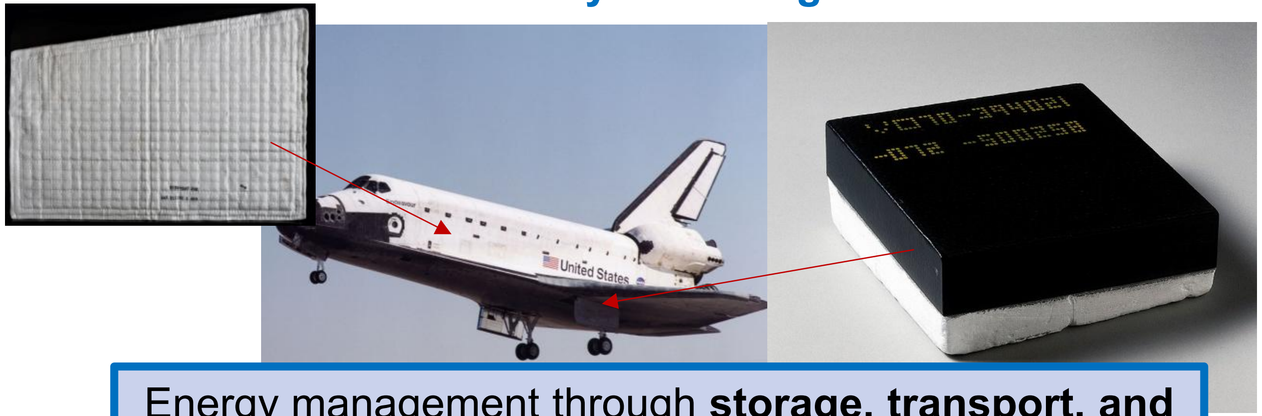
Operation

Categories of TPS

COURSE FOCUS

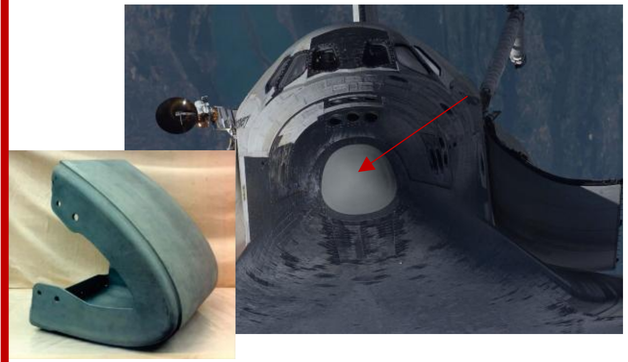
Shape-stable ("reusable") materials

Low Density Insulating Ceramics

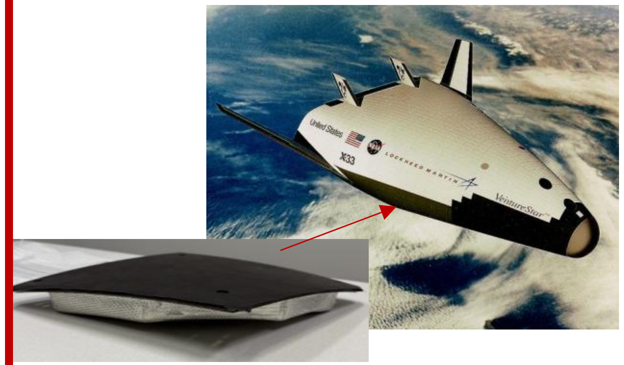


Energy management through **storage, transport, and re-radiation**

Hot Structures

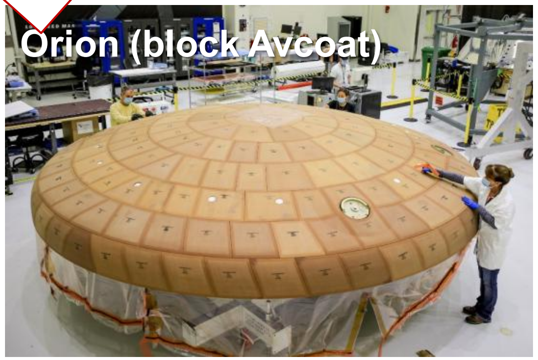


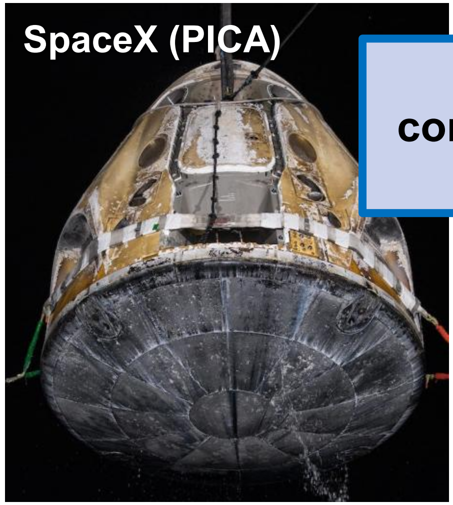
High Temp Metals



Shape-changing ("non-reusable") materials

Ablative TPS





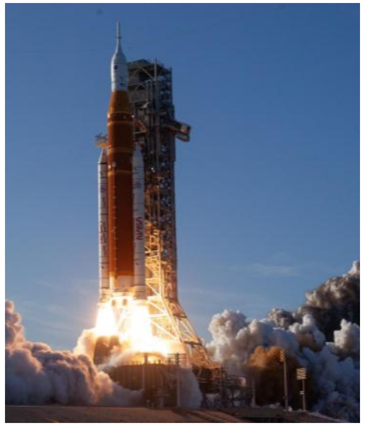
Energy management through **controlled material consumption, charring, and re-radiation.**

TPS "Sequence of Environments"

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

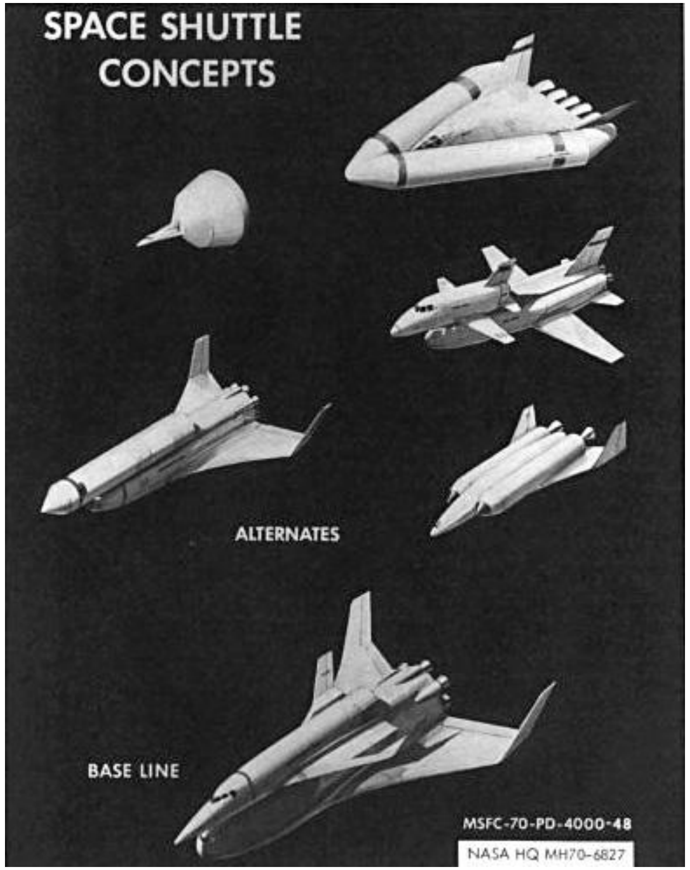
Re-Entry

High Heating
Dissociated Air

Landing

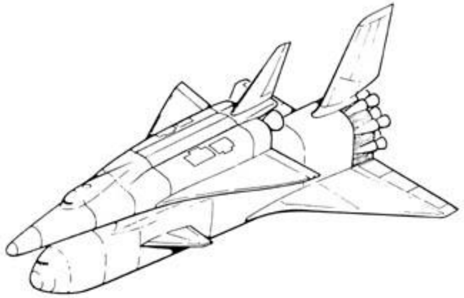
We must design and test the TPS for much more than just re-entry and the extreme heat, but also **weather**, **vibration**, **cold**, and **water impact** while being as lightweight as possible.

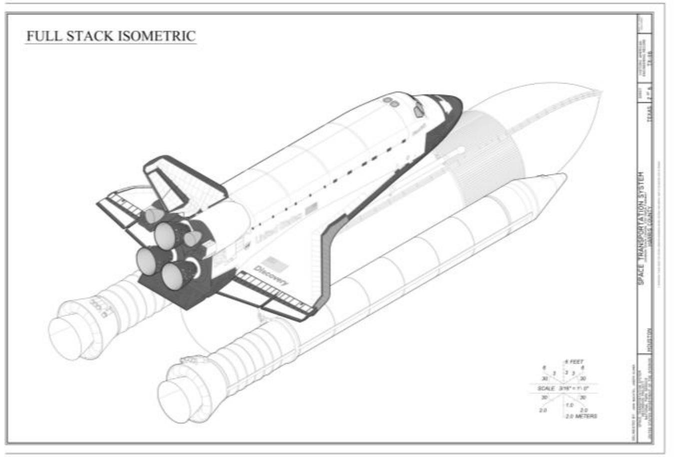
Reusable TPS technology developed for NASA’s first reusable vehicle: Space Shuttle Orbiter



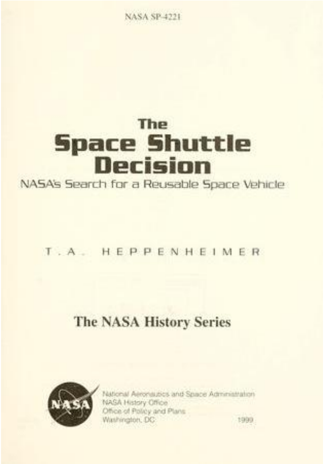
Shuttle design process started in 1968 with intent of being rapidly reusable and supporting crew/cargo to future space station (which would be delivered to orbit on a Saturn V).

Competing decisions into the 1970s as Saturn V was cancelled and need for larger Shuttle was determined. USAF involvement also swayed design (higher cross range, payload bay size).

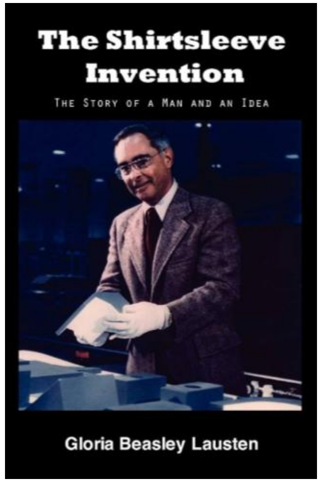




Final design selected in 1972, and Shuttle Orbiter contract awarded to North American Rockwell. Construction started in 1973.



The Space Shuttle Decision by Heppenheimer



The Shirtsleeve Invention by Beasly-Lausten

Shuttle TPS development history spans from 1960s through early 2000s

NASA Contractor Report 4227

Thermal Protection System of the Space Shuttle

John Cleland and Francesco Iannetti

CONTRACT NASW-3841-72
JUNE 1989

19960510 073

NASA

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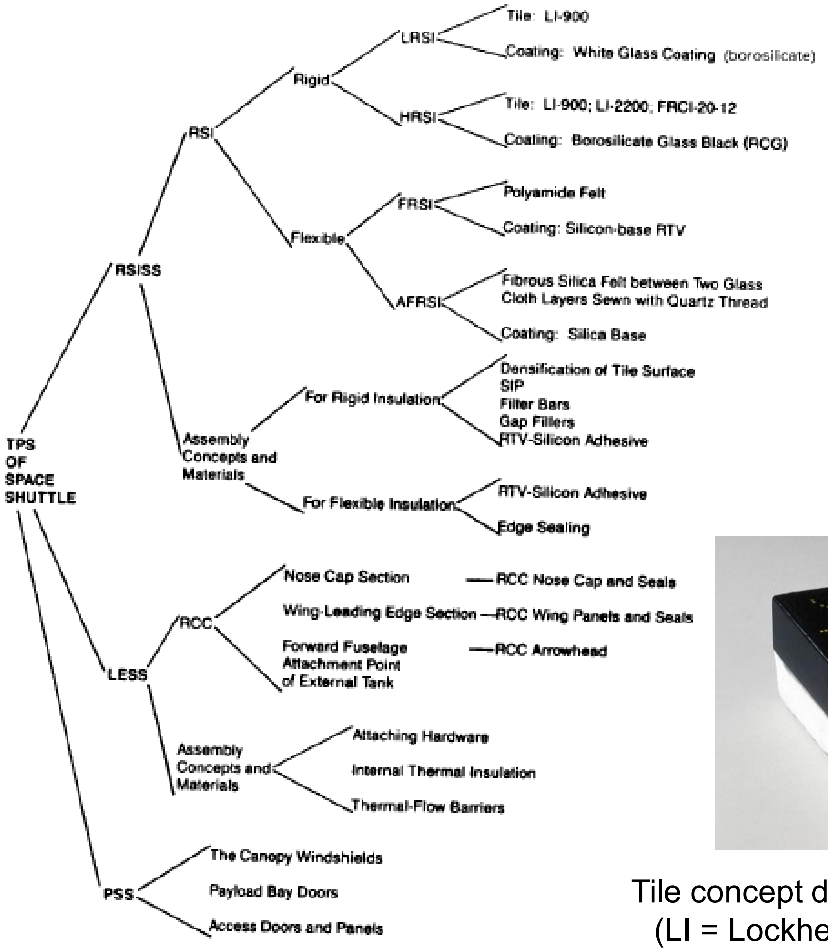
Cleland & Iannetti report (1989) tells history of design requirements, materials & systems development, and manufacturing of Shuttle TPS.



Major Design Requirements:

1. Limit structural temperature to 350 °F
2. Provide useful life of 100 missions
3. Withstand surface temperatures from -250 to 2750 °F
4. Withstand heat loads to 60,000 Btu/ft^2
5. Withstand acoustic levels to 166 dB
6. Withstand the aerodynamic pressure (freestream) to 5.7 psi
7. Provide the aerodynamic moldline
8. Attach to aluminum structure
9. Provide economical weight and cost

TPS Concepts Evaluated

1. Replaceable Ablator Panels
2. Metallic Re-Radiative Heat Shields
3. Carbon-Carbon Re-Radiative Hot Structure
4. Non-Ablating, Non-Metallic Insulative Re-Radiative Ceramic

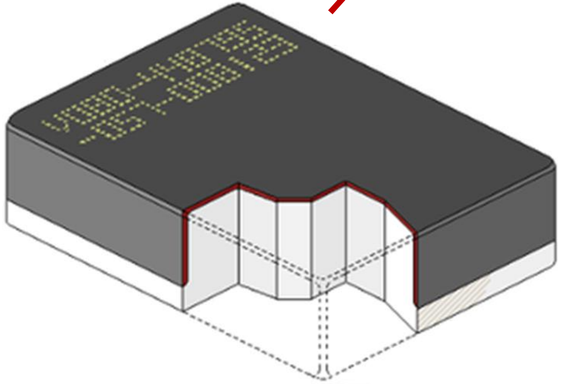
Tile concept developed by Lockheed in 1960s (LI = Lockheed Insulation) and selected by NASA in 1973 as primary TPS for Shuttle Orbiter.

Reinforced carbon-carbon (RCC) developed by Vought Corporation & NASA for areas of highest heating.

Insulative TPS protect the spacecraft for multiple uses via low thermal conductivity

AFRSI blankets developed at NASA ARC

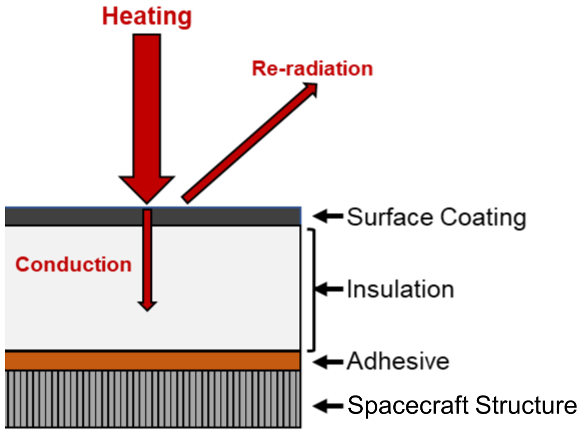
Space Shuttle Orbiter featured a variety of TPS, including flexible blankets and rigid tiles.

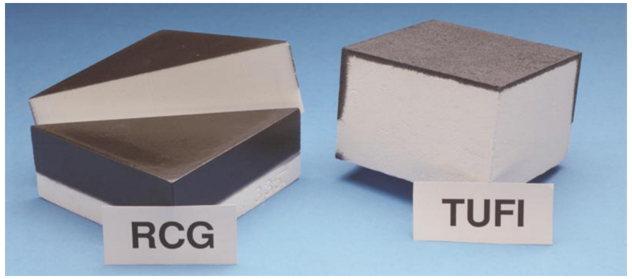


The tiles are composed primary of silica fiber, have extremely low thermal conductivities (~0.06 W/m·K), and are coated with borosilicate glass-based glazes.

Examples: LI-900, LI-2200, FRCI-12, HTP-12, BRI-18, AETB-8, …

Energy management through storage and re-radiation (material remains unchanged).

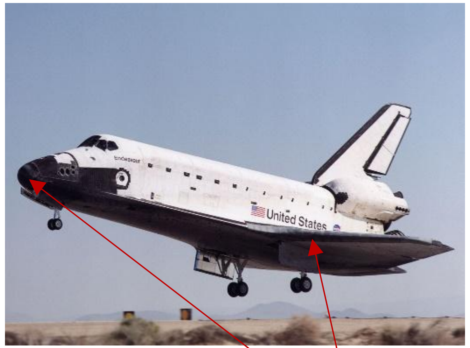




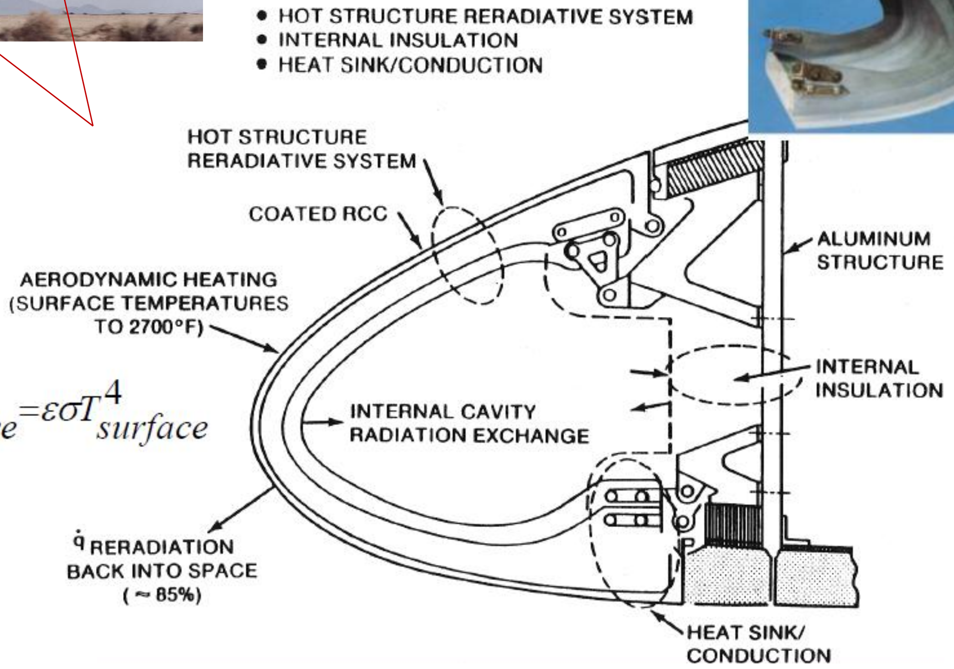
RCG = Reaction Cured Glass
TUFI = Toughened Unipiece Fibrous Insulation

Hot structures serve as the spacecraft structure and thermal protection

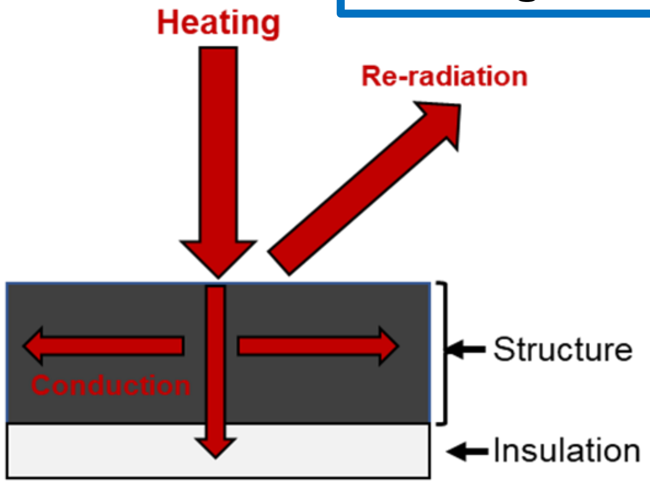
Energy management through re-radiation.



RCC (Reinforced Carbon Carbon)



$$q_{convective} = \varepsilon \sigma T^4_{surface}$$



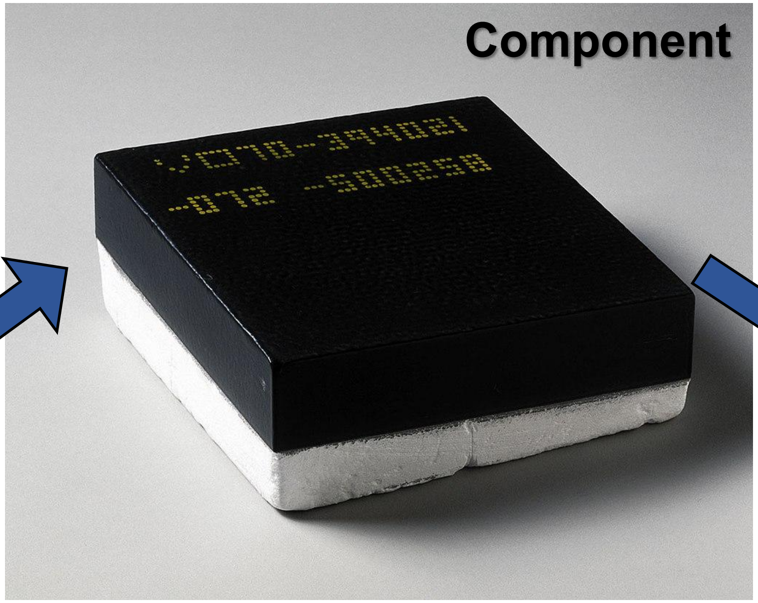
The hot structure *serves two roles*: thermal protection and spacecraft structure. The primary heat rejection mechanism is re-radiation.

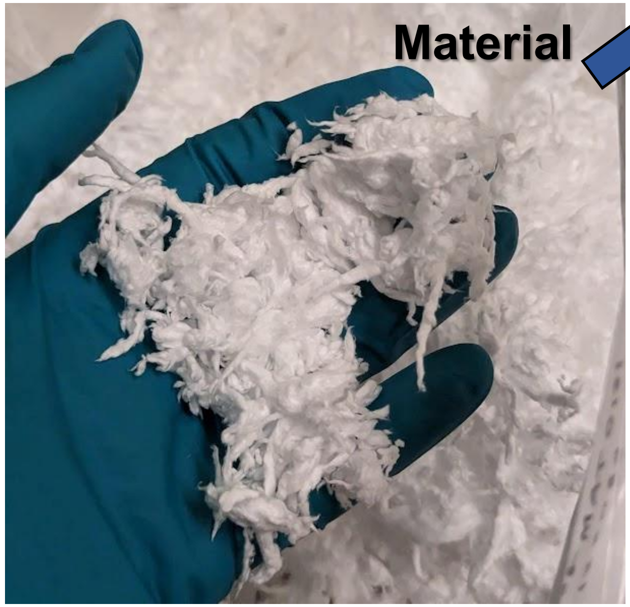
Offers reduced mass, reduced complexity (eliminates need to integrate TPS), and reusability.

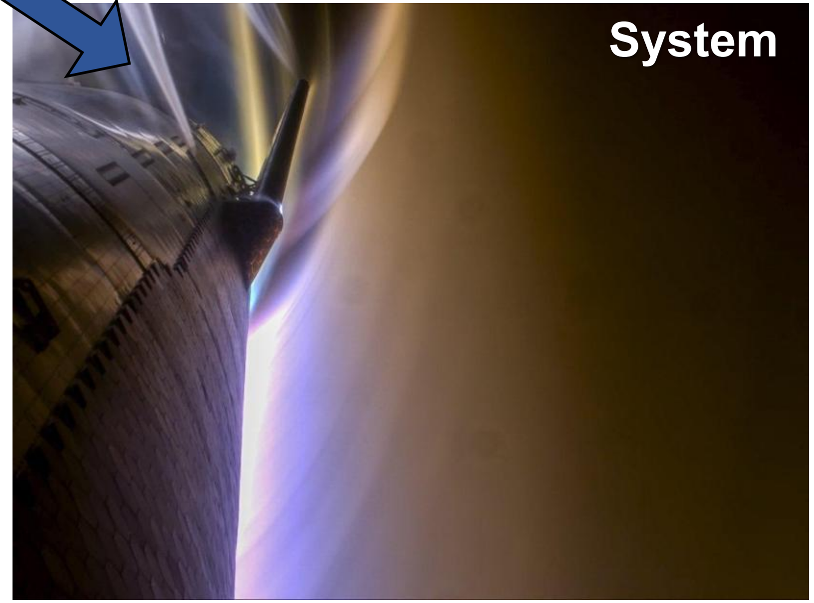
Materials = C/C, CMCs, refractory metals

"High-Temperature Materials Overview-2021RevA.pdf" by Stan Bouslog
Glass, David. *AIAA international space planes and hypersonic systems and technologies conference*. 2008.

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



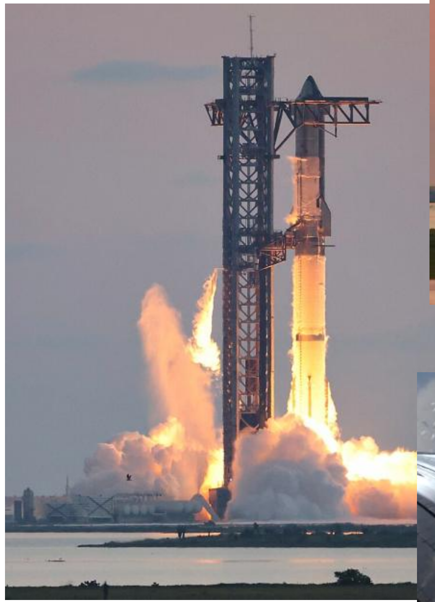


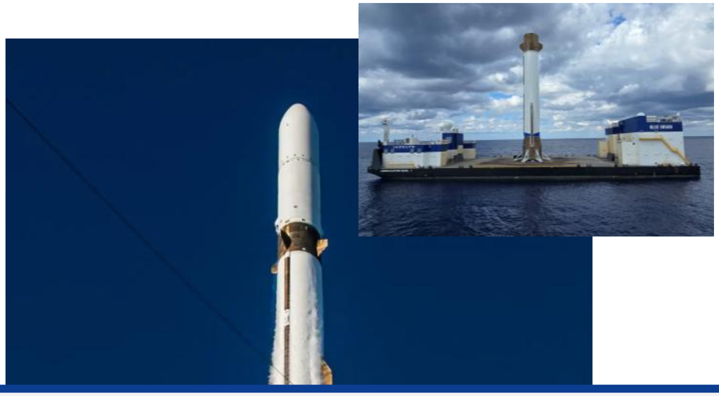


From material to component to system
(and everything in between)
with a focus on reusable ceramic TPS

Starship re-entry image from SpaceX

Reusable TPS crucial for success in paradigm of reusable spacecraft & launch vehicles





Achieving rapid reusability for routine hypersonic flight, LEO transportation, and Lunar exploration will require development of new reusable TPS technologies.