High-Temperature Materials

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Outline

- **Why High-Temperature Materials?**
  - Industrial Uses
  - Aerospace Vehicles
    - Engines and Motors
    - Hypersonic Thermal Protection
- **Thermal Protection Systems (TPS)**
  - Different Types of TPS
  - Selecting a TPS
- **Historical TPS**
  - Apollo
  - Space Shuttle Orbiter
- **TPS Now – Post-Shuttle**
- **Future TPS**
- **Questions**

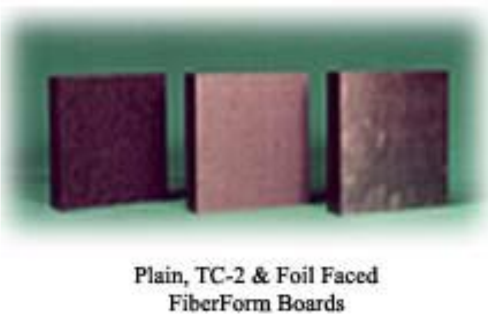
High Temperature Materials: Industrial Uses

High Temperature = Temperatures > ~300 F

- **Energy Production**
- **Fire Protection**
- **Electronics**
- **Material Processing – Ovens**

Inconel 718 Turbine

1300 F (700 C)



Carbon Fiber Boards

>3000 F in vacuum

Alumina Fiber Blankets

2900 F

High Temperature Materials: Aerospace Vehicles

Commercial Aircraft

Titanium – engine compressor and nozzle

Rocket Motors

Carbon cloth phenolic – engine nozzle

Hypersonic Aircraft

Inconel skin
Ti Frames

X-15 Mach 6+

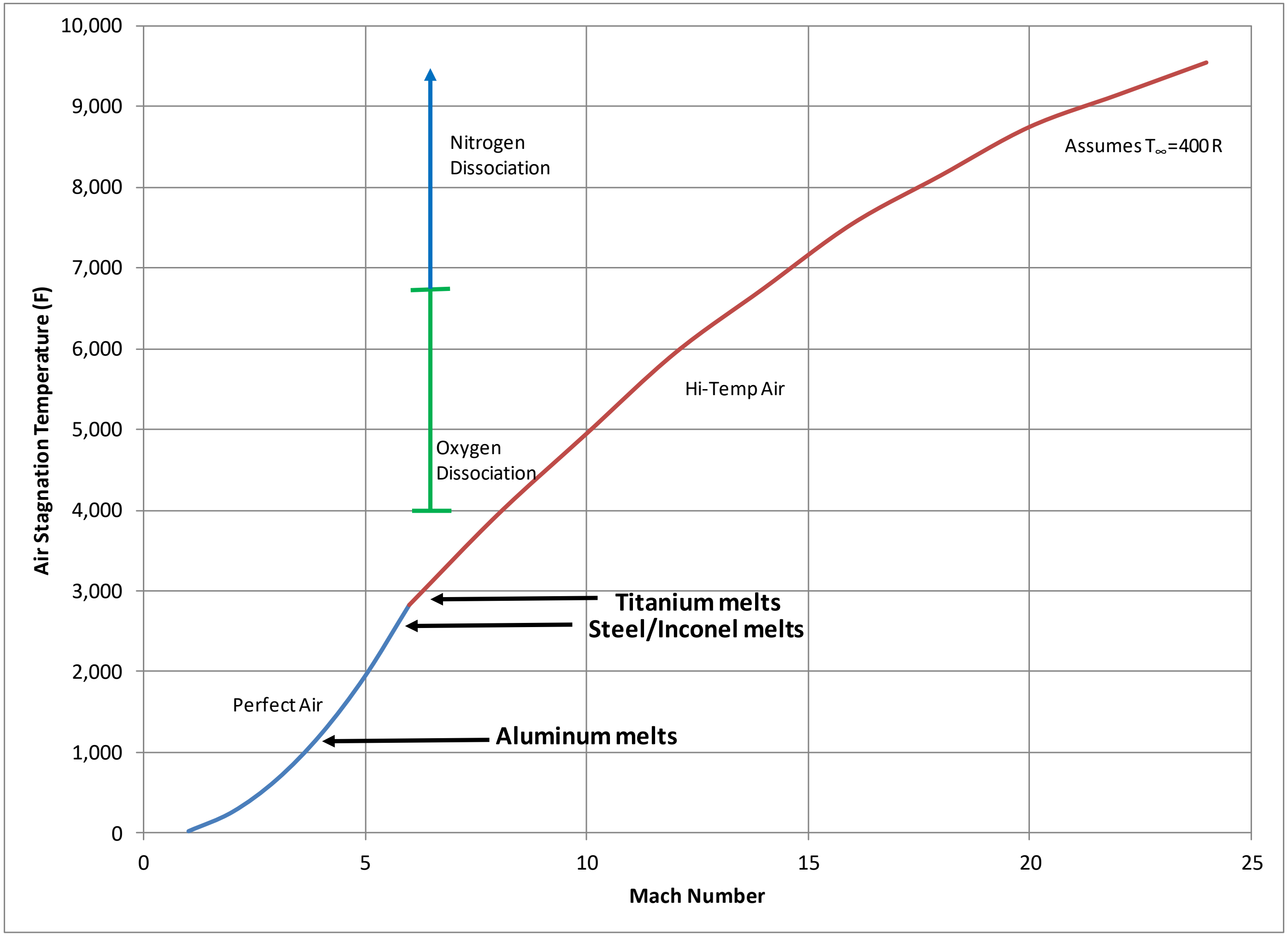
Fibrous Blankets

Carbon-Carbon

Ceramic Tiles

Orbiter Mach 25+

Why Thermal Protection for Hypersonic Vehicles



Above ~Mach 5, the thermal environment drives the need for vehicle thermal protection.

Ref.: Bertin, J.J., 'Hypersonic Aerothermodynamics'

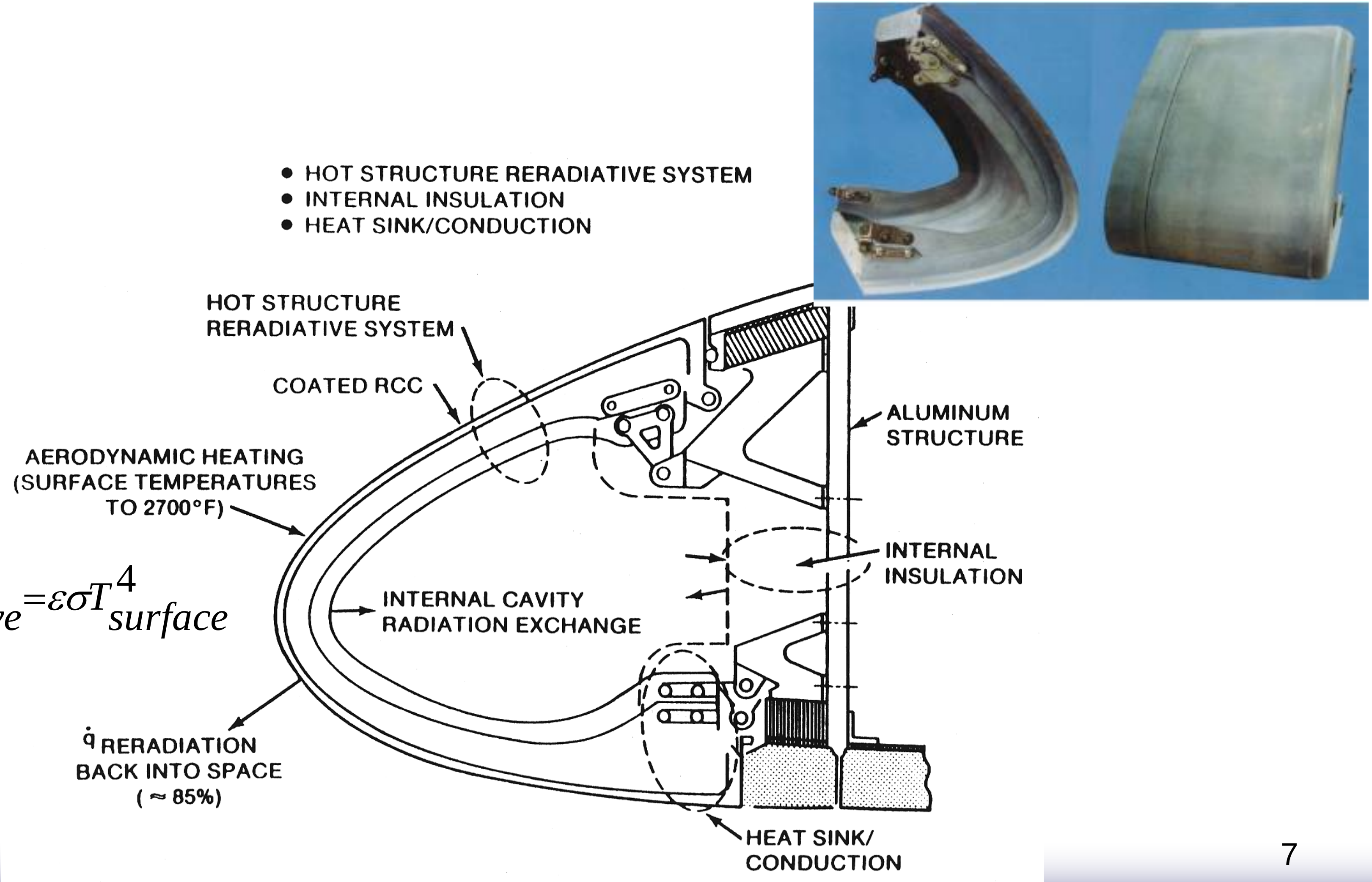
Approaches to Thermal Protection

Ref: 'Entry Thermal Protection,'
NASA SP-8014, Aug. 1968

- **Radiative Systems**
  - Radiate heat away from surface
  - Design implementation: High emittance surface
- **Heat-Sink Systems**
  - Absorb the heat
  - Design implementation: High specific heat
- **Insulation Systems**
  - Slow the heat wave
  - Design implementation: Low thermal conductivity
- **Ablative Systems**
  - Decomposition of material absorbs heat
  - Design implementation: Prefer charring materials
- **Transpiration Systems**
  - Cool the boundary layer
  - Design implementation: Inject fluid into boundary layer from surface
- **Active Cooling Systems**
  - Cool the surface with internal fluid
  - Design implementation: Heat exchanger with cooling fluid

TPS: Radiative Systems

Example: Orbiter Space Shuttle Leading Edge

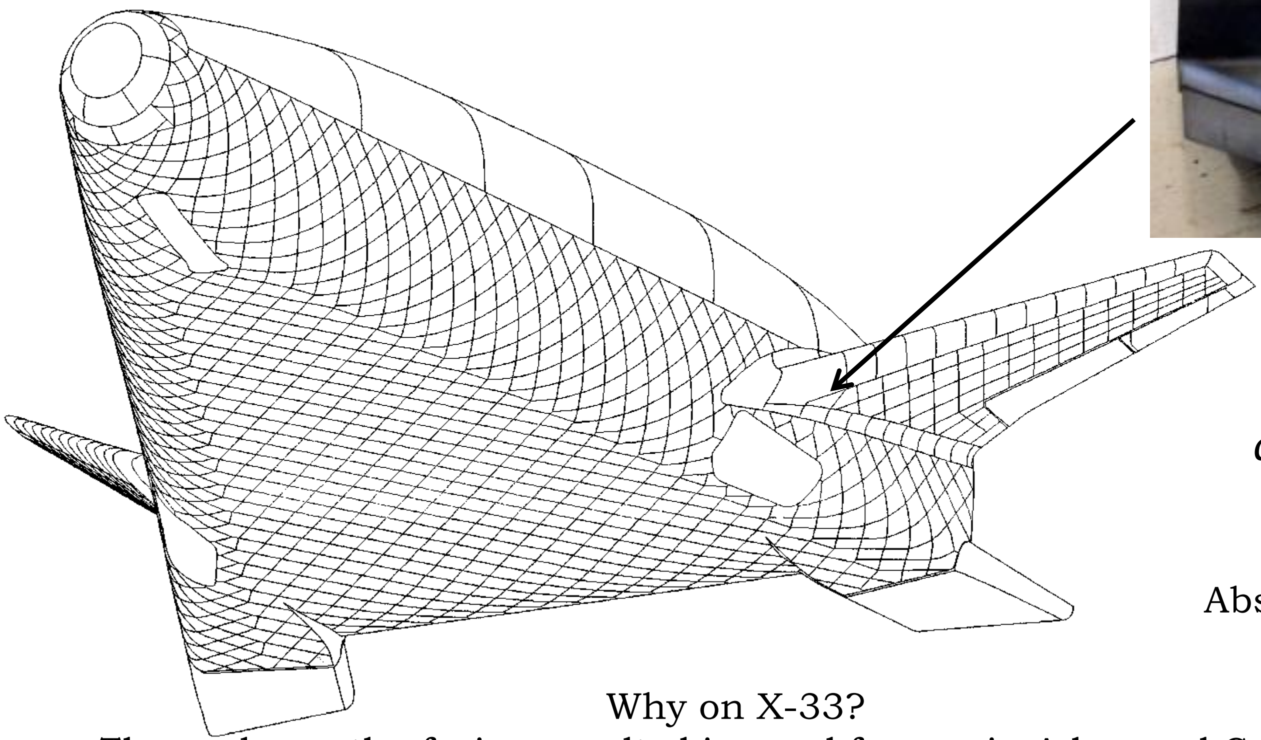


$$q_{convective} = \varepsilon \sigma T^4_{surface}$$

TPS: Heat Sink Systems

Example: X-33 Metallic Fillet

Cast Inconel Metallic Fillet



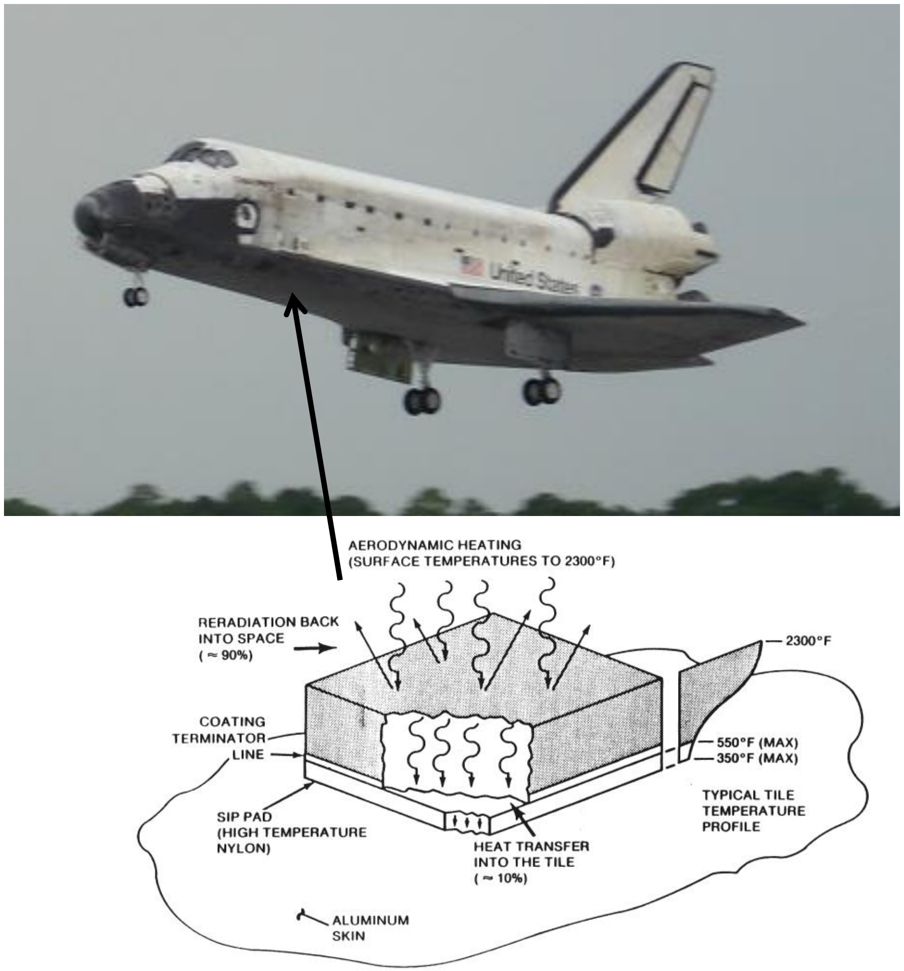
$$q_{convective} = mC_p \frac{\Delta T}{t}$$

Absorb heat into material

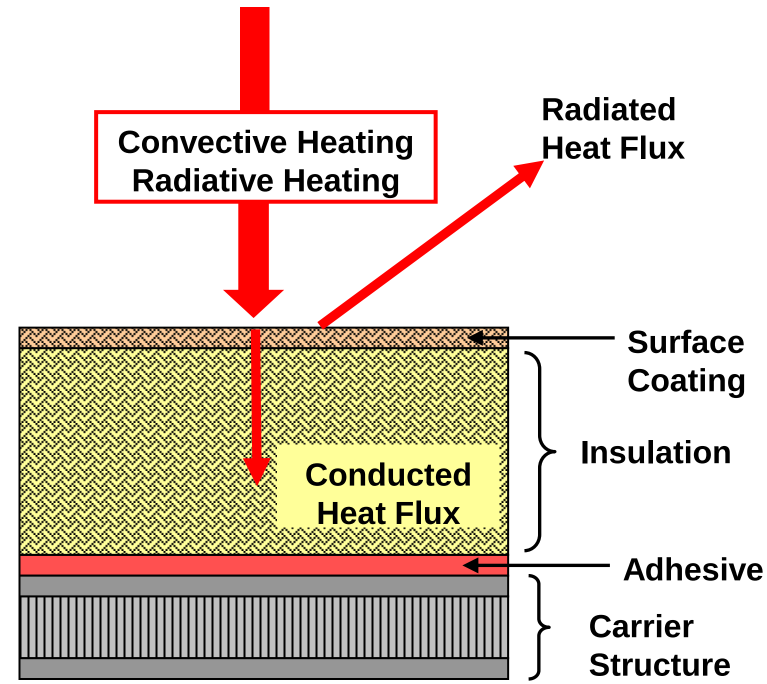
Why on X-33?
Thermal growth of wing resulted in need for gap in Advanced Carbon-Carbon wing leading edge panels. Flow forced into gap was directed to surface by metallic fillet.

TPS: Insulation System

Example: Orbiter Tiles



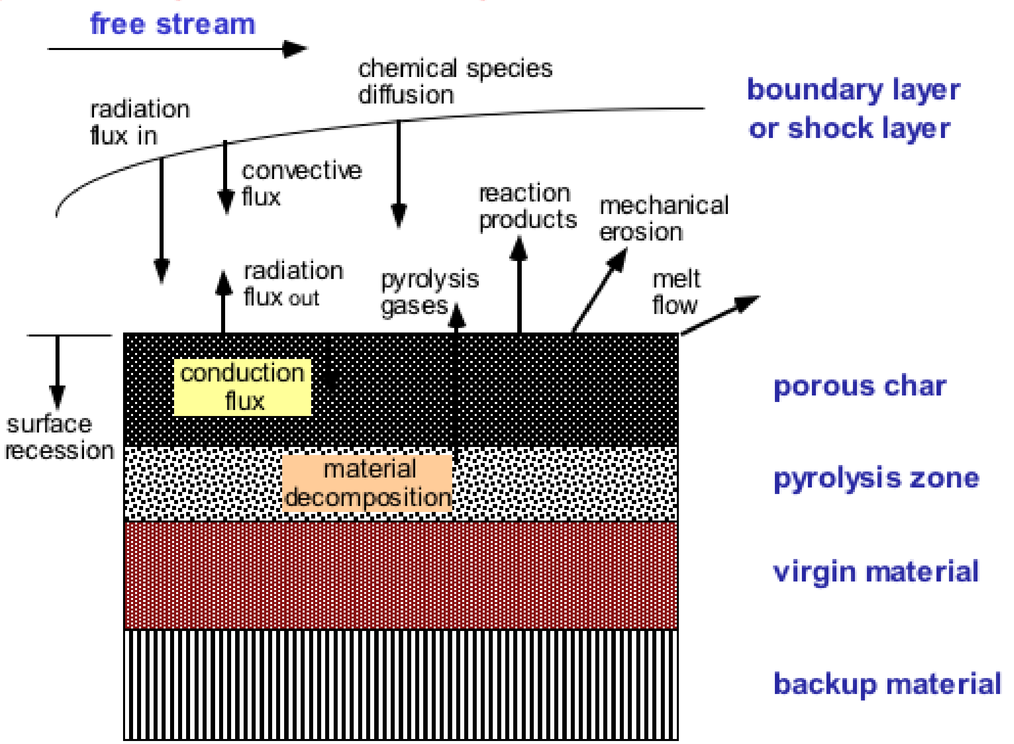
$$-k\frac{\partial T}{\partial x}\bigg|_{x=0} = \dot{q}_{convection} + \dot{q}_{radiation}$$



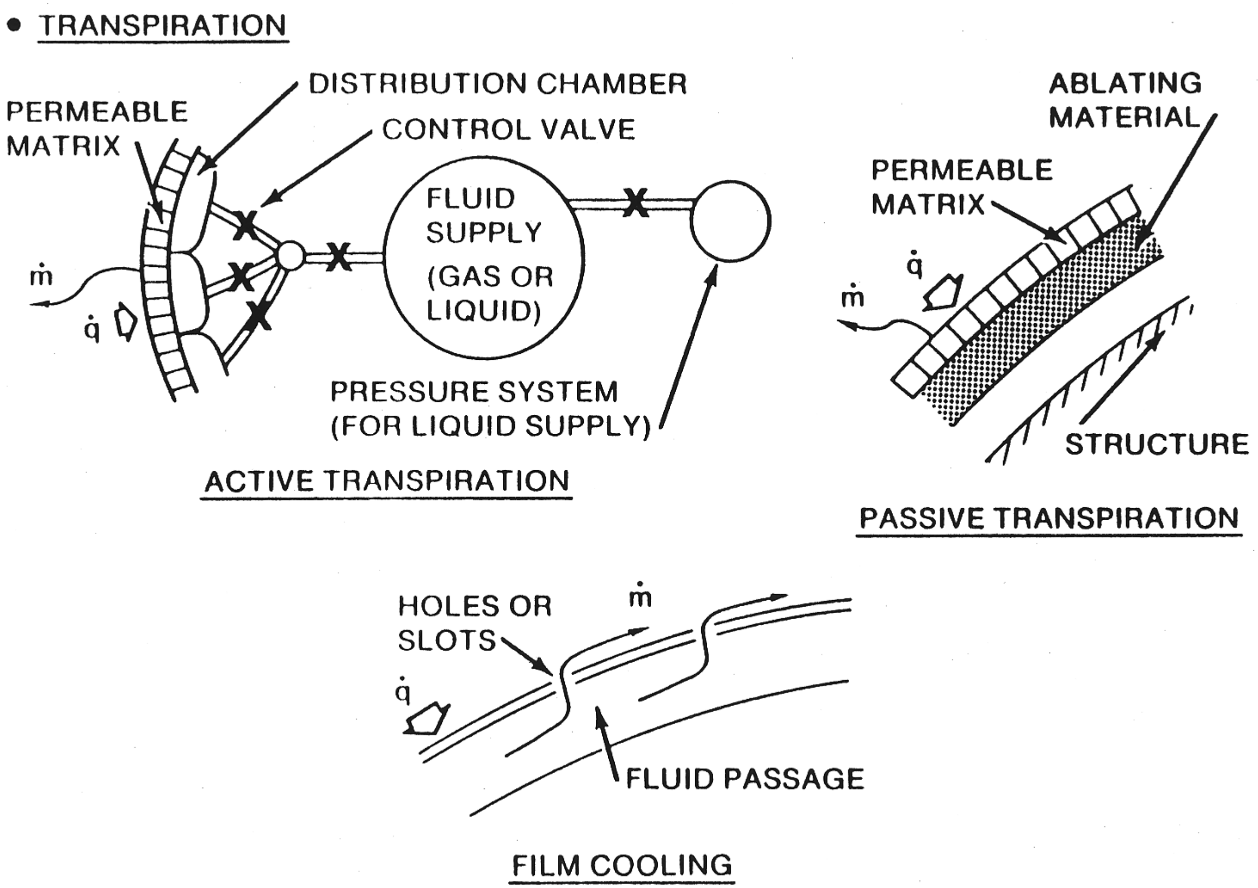
TPS: Ablative Systems

Example: Apollo Heat Shield

Energy management through material consumption

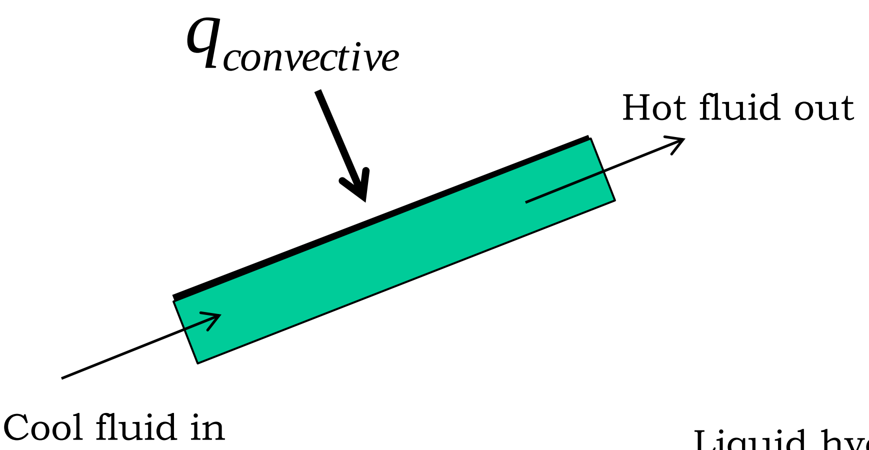


TPS: Transpiration System



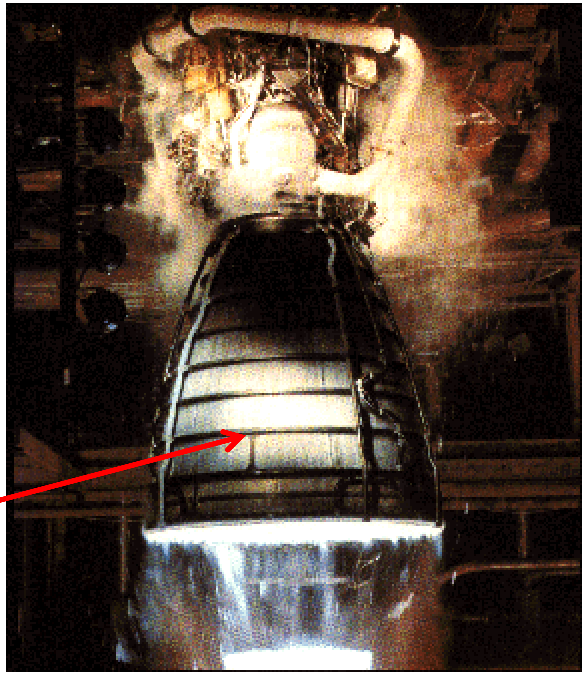
$$\psi\dot{q}_{CONVECTION} + \dot{q}_{COMBUSTION} + \dot{q}_{RADIATION} = \dot{q}_{CONDUCTION} + \dot{q}_{RERADIATION}$$

TPS: Active Cooling



Example: Shuttle Main Engines

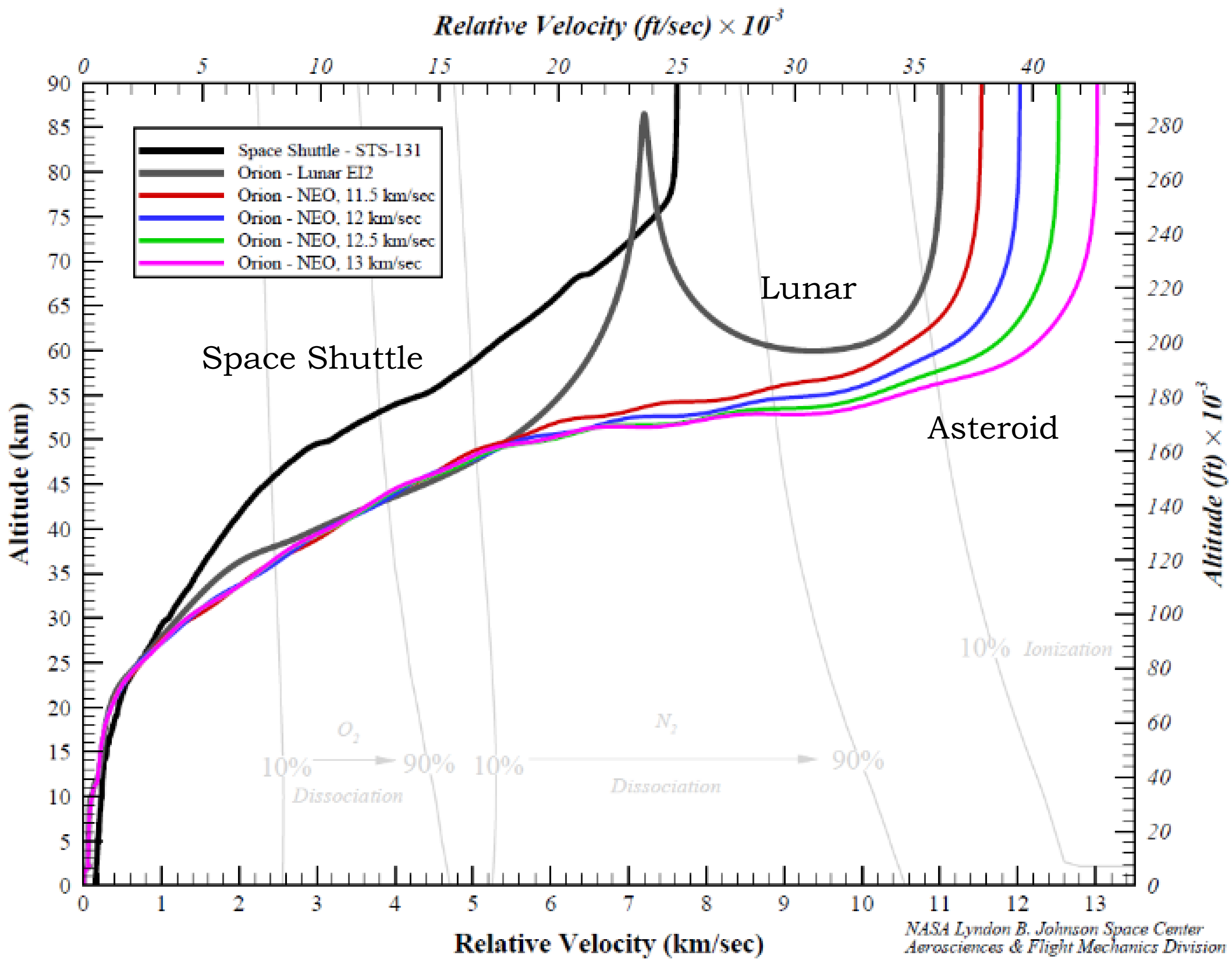
Liquid hydrogen flows thru tubes.
Cools nozzle and preheats hydrogen



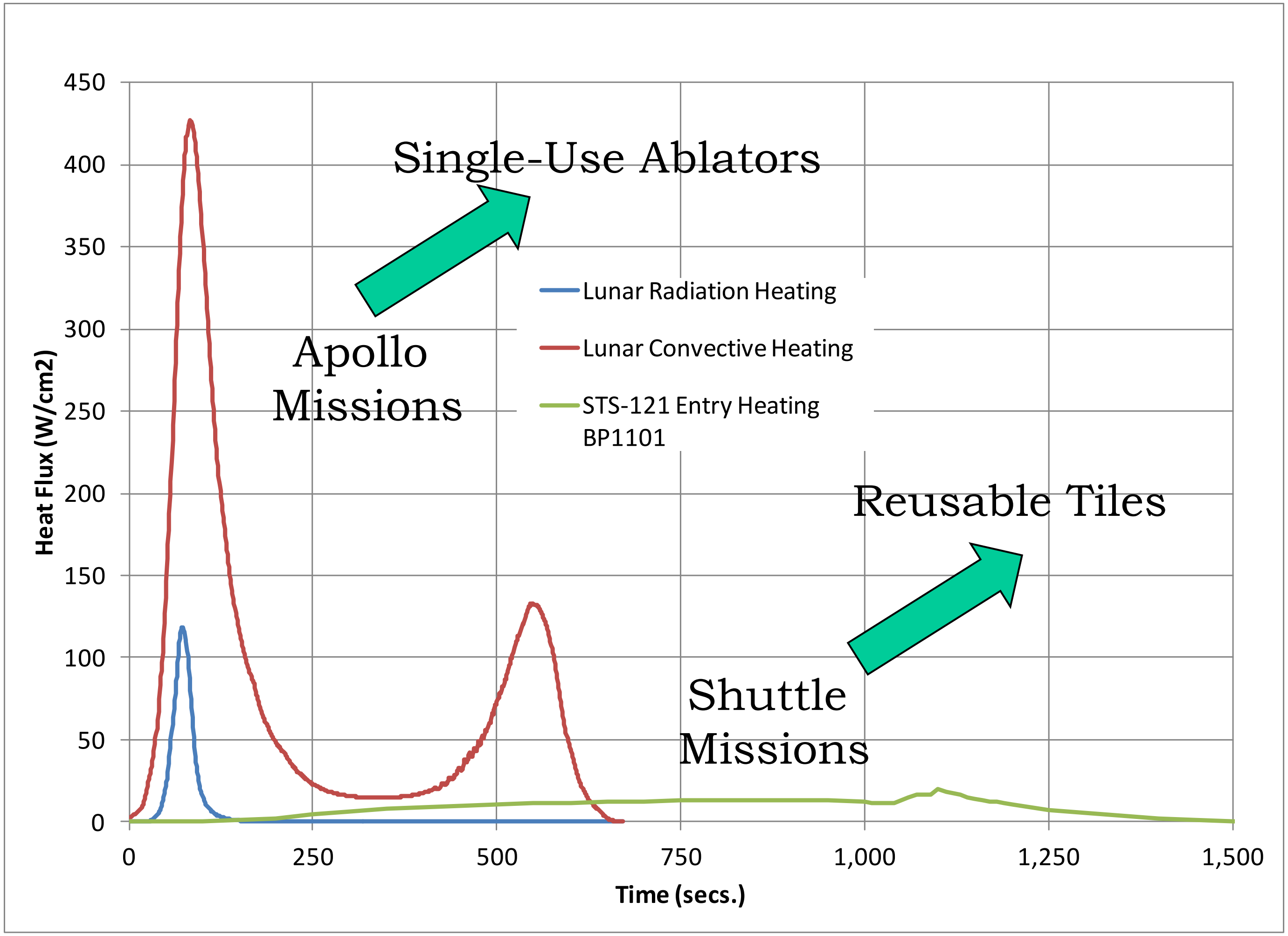
Brazed Stainless Steel Nozzle

How to Select a TPS

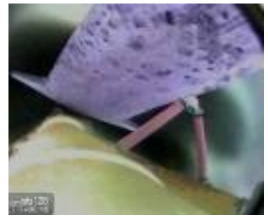
Missions Drive Environments



Reentry Environments Drive TPS Selection



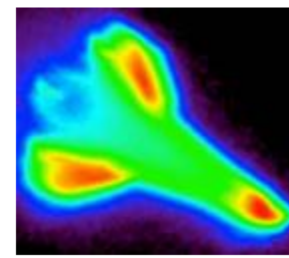
But, It's More Than Reentry Heating



Separation Event
-Pyro shock

On-Orbit
- Temperature Cycles
- Vacuum
- Atomic oxygen
- MMOD impact

Ascent
- Aeroheating
-Rapid pressure decrease
- Plume Heating
- Debris impact



Reentry
- High heating
- Dissociated Air

Launch
-Vibro-acoustic
- Over-pressure
- Debris impact

Mission Sequence of Environments

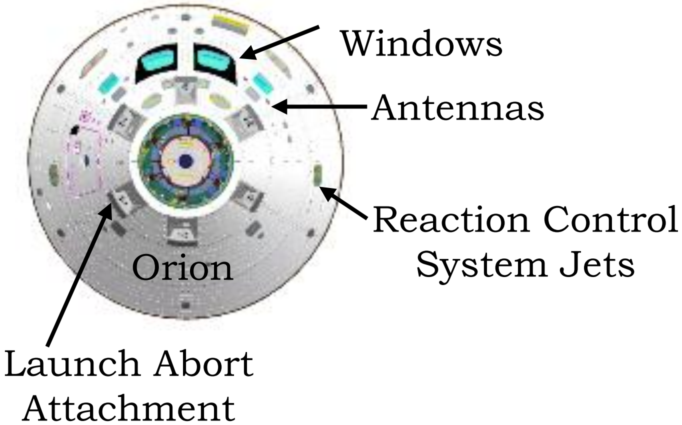
Landing
- Heat shield separation

On the Pad
-Humidity
- Rain
- Lightning

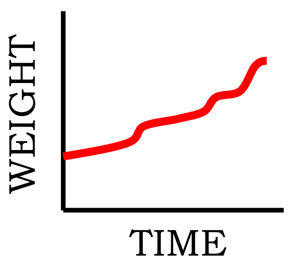
Other Considerations

Penetrations thru TPS

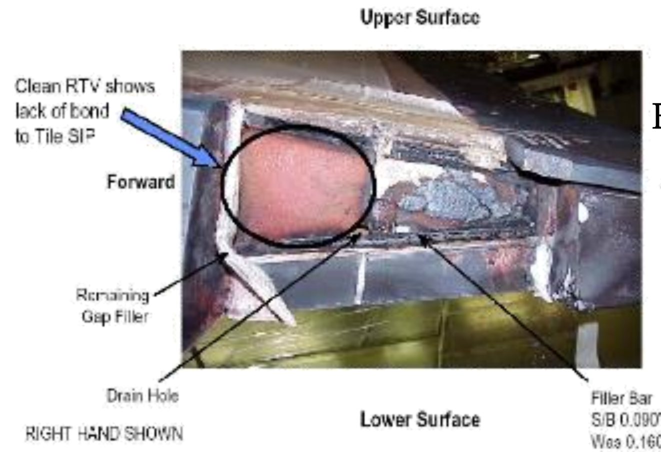
Doors
-ET Umbilical
- Landing gear
- Hatches



TPS Mass

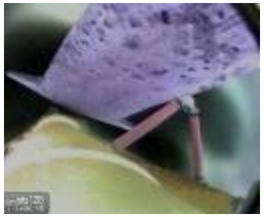


Manufacturing Processes & Supply Chain

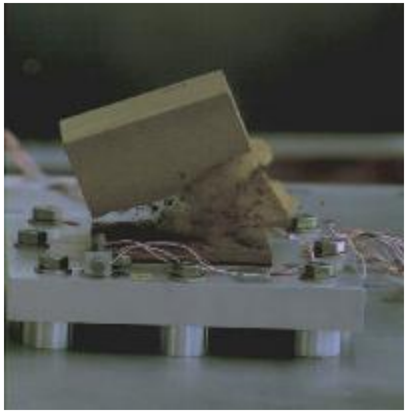


OV-103
Flt 27
Lost
Elevon Tile

Shock Events



ET
Separation



PICA Failure

TPS Testing

Radiant Heat Tests

- Radiant Heating
  - -Variable heat
  - - Variable pressure
- Large Test Articles
  - -TPS assemblies
  - - TPS penetrations
- Thermal Conductivity
- Thermal Model Validation
- Thermal induced deflections

Arc-jet Tests

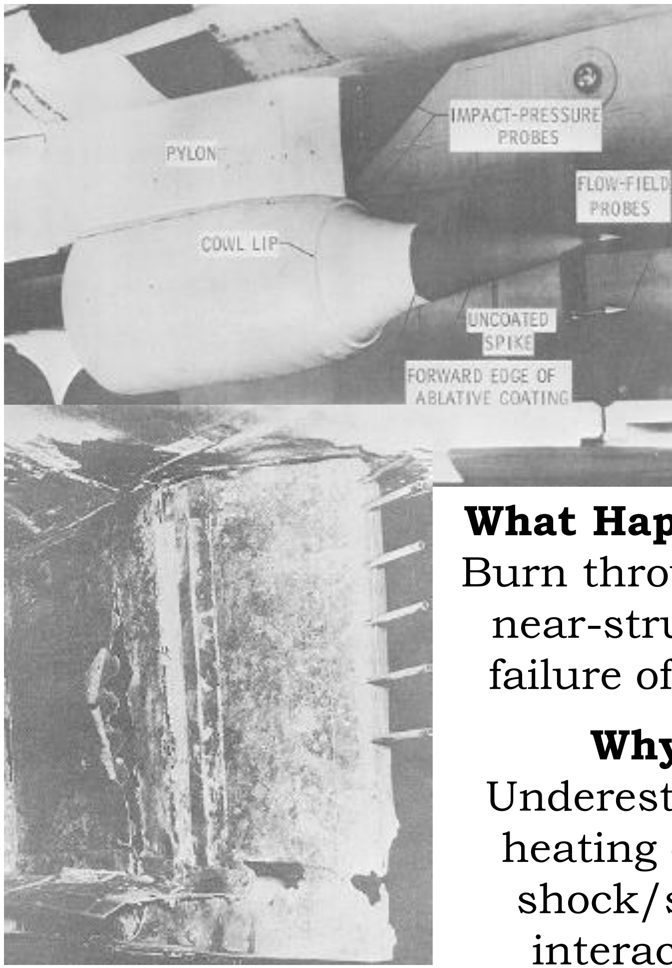
- Reentry Aerothermal Simulation
  - - Dissociated gas
- Small Test Articles
  - -TPS materials
  - - TPS penetrations
- Thermal/chemical behavior
- Thermal Response Model Validation

Structural Tests

- Structural Flexure
- Medium Test Articles
  - -TPS assemblies
  - - TPS penetrations
- Structural Model Validation

Results of Getting It Wrong

X-15 Ramjet Flight Test



What Happened?
Burn through and near-structural failure of pylon.

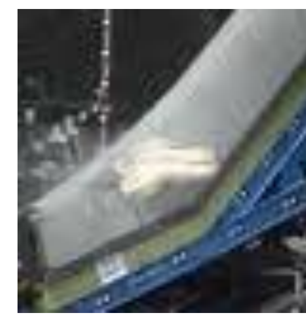
Why?
Underestimated heating due to shock/shock interaction.

http://history.nasa.gov/x15lect/intro.html

Columbia Accident

What Happened?
Loss of vehicle and crew.

Why?
Ascent impact damage to Carbon-carbon leading edge.



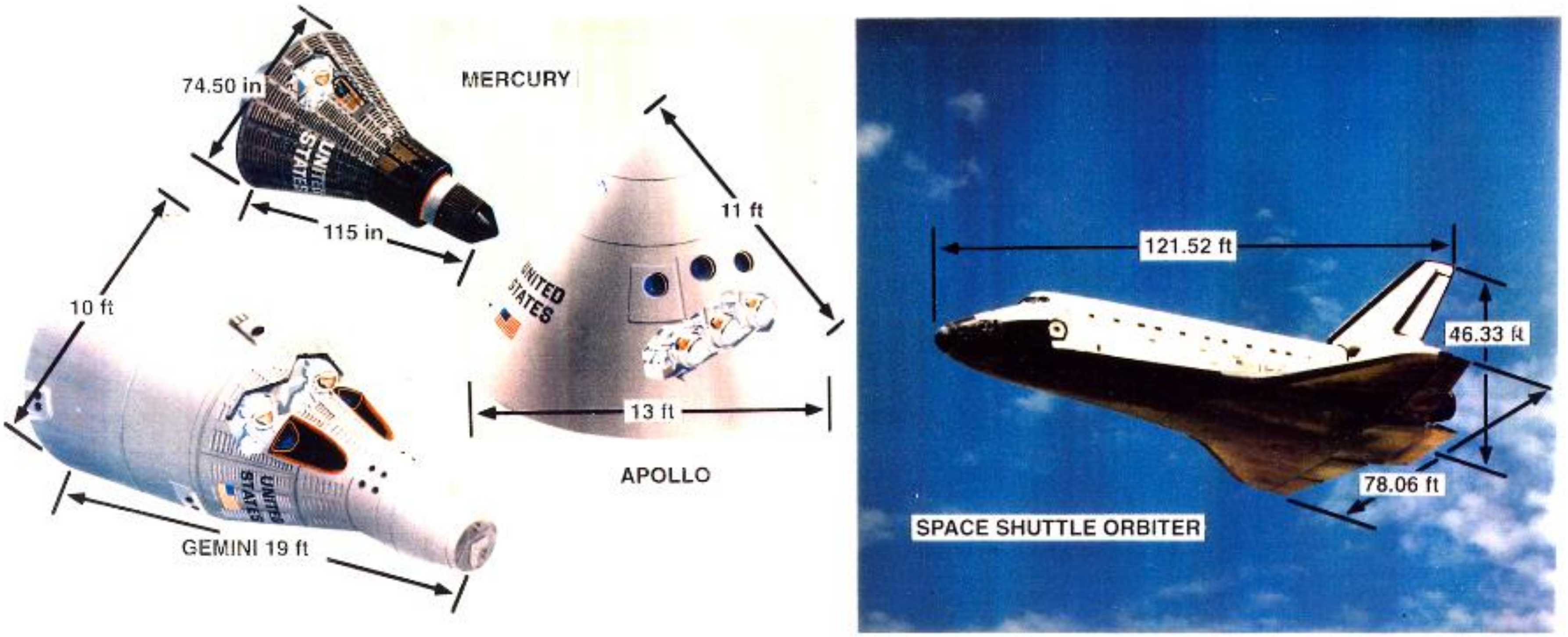
Columbia Accident Investigation Board, Aug. 2003

Historical
Thermal Protection Systems

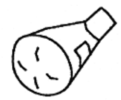
Good Reference

Glass, David E., "Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles;"; 15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Dayton, OH; AIAA-2008-2682; April-May 2008

Manned Spacecraft Entry Vehicles

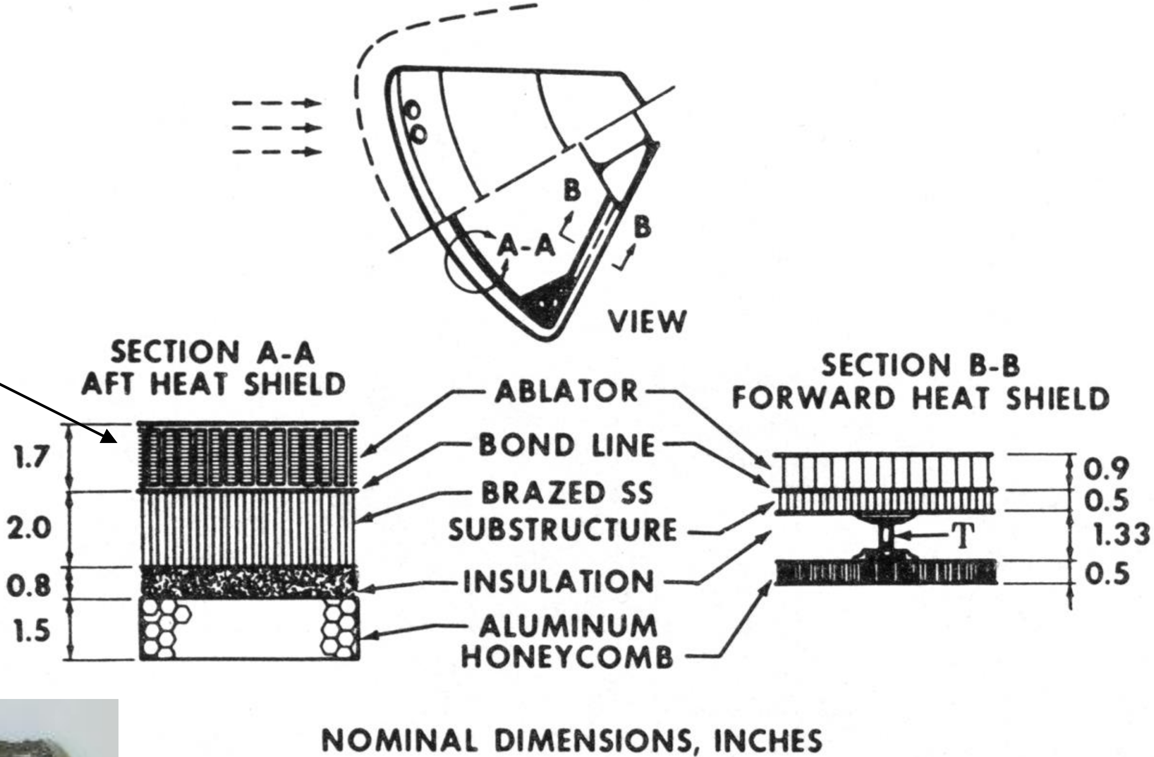


Comparison of Manned Entry TPS

	MERCURY	GEMINI	APOLLO	SHUTTLE
DATE No. of flight	10/7/58 - 5/16/63 6 flights	3/23/65 - 11/15/66 10 flights	10/11/69 - 12/19/72 11 flights	4/12/81 – 7/21/11 135 (133) flights
				
AREA	32 FT^2	45 FT^2	365 FT^2	11 895 FT^2
WEIGHT	315 LB	348 LB	1465 LB	18 904 LB
WT/FT^2	10.2	7.5	3.9	1.7
MATERIAL	ABLATOR (FIBERGLASS-REINFORCED LAMINATED PLASTIC)	ABLATOR (DOW CORNING DC 325)	ABLATOR (AVCO 5026-39)	**Rigidized silica fibers**
DENSITY	114 LB/FT^3	54 LB/FT^3	33 LB/FT^3	**9-22 LB/FT^3**
USAGE	1 FLIGHT	1 FLIGHT	1 FLIGHT	**135 (133) FLIGHTS**

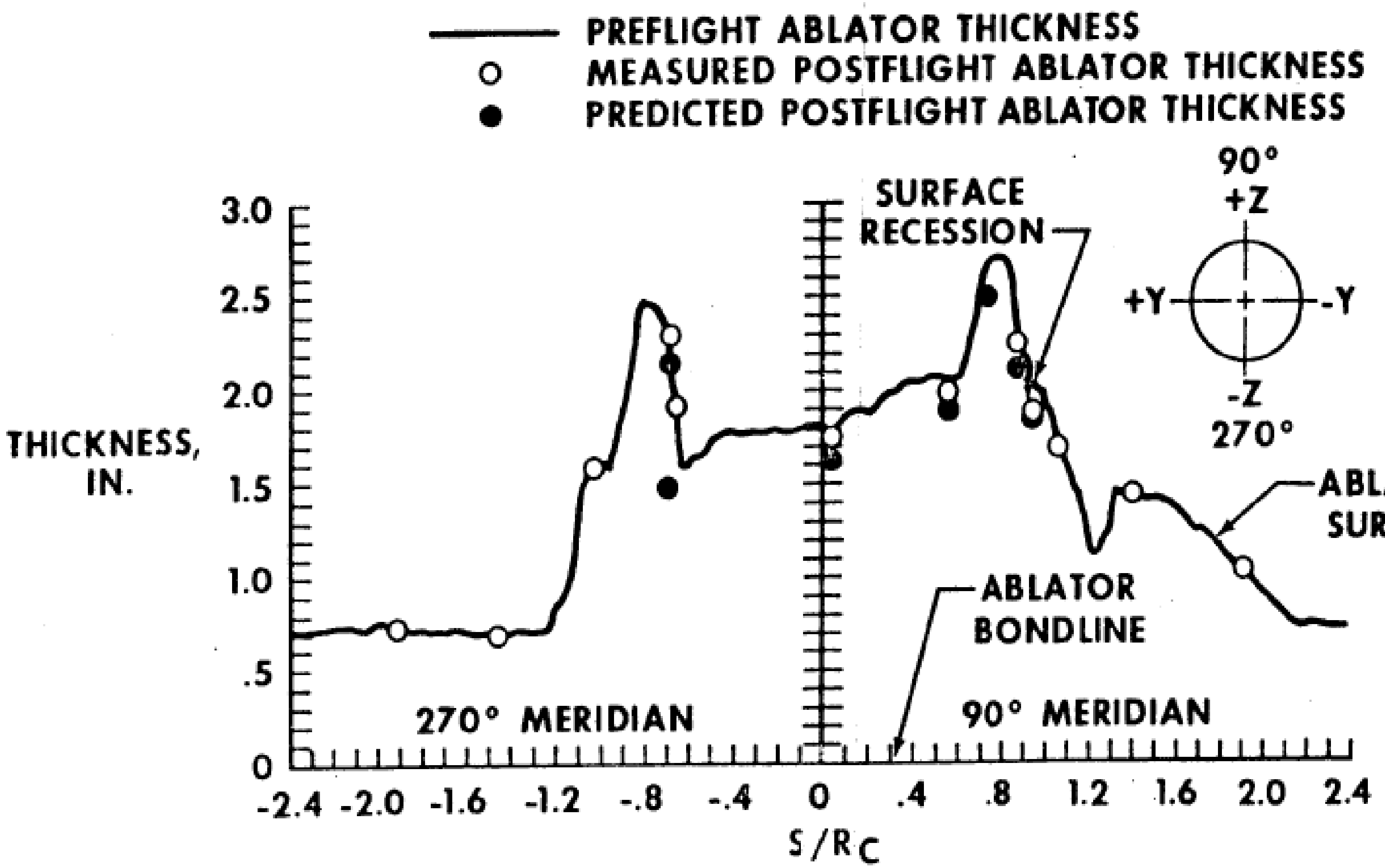
Apollo TPS/Structure Configuration

AVCO 5026-39 HCG
(Filled Epoxy Novalac in Fiberglas-Phenolic Honeycomb)
Now manufactured by Textron

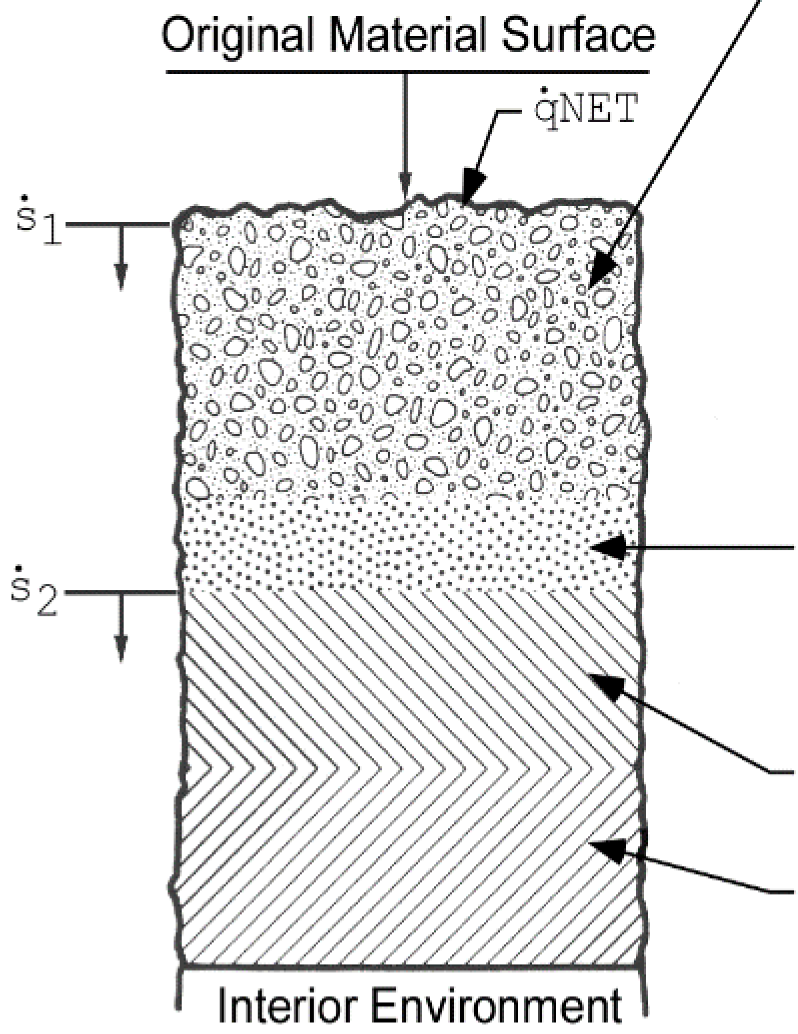


Heat shield Core from Apollo 11

Apollo Ablator Thickness & Surface Recession Distribution



Physical Model of a Charring Ablator



Char Layer Zone

1. Aerodynamic Heating (convective And Radiative)
2. Heat Blockage
3. Ablation Gas Flow
4. Reradiation
5. Surface Recession
6. Combustion
7. Conduction
8. Deposition
9. In-depth Radiation

Reaction Zone

1. Material Degradation
2. Ablation Gas Flow
3. Conduction

Virgin Zone (plastic)

1. Conduction

Backup Structure

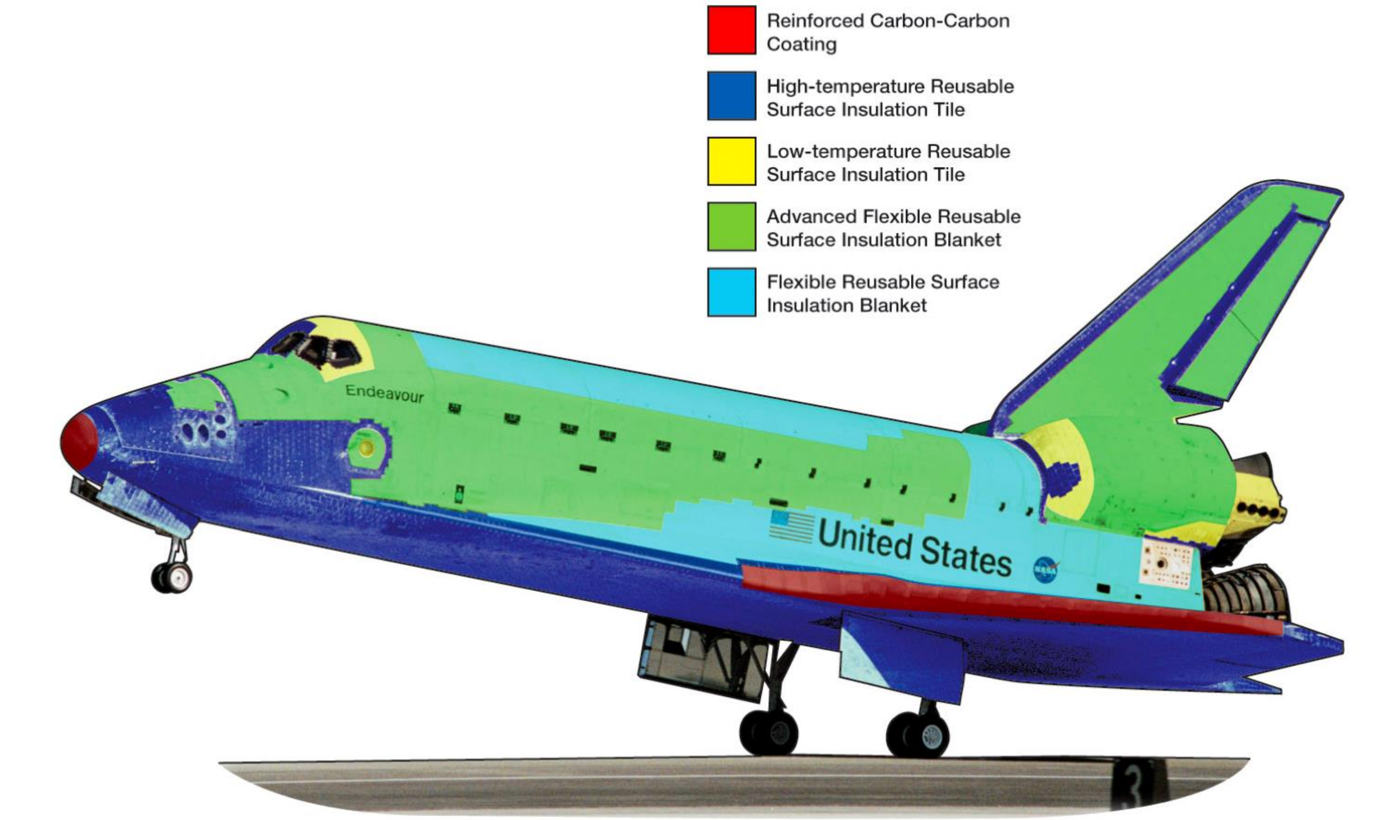
1. Conduction
2. Heat Loss To Cabin Environment

Space Shuttle Orbiter TPS Configuration

- RCC - Reinforced Carbon-Carbon
- HRSI - High-temperature Reusable Surface Insulation
- LRSI - Low-temperature Reusable Surface Insulation

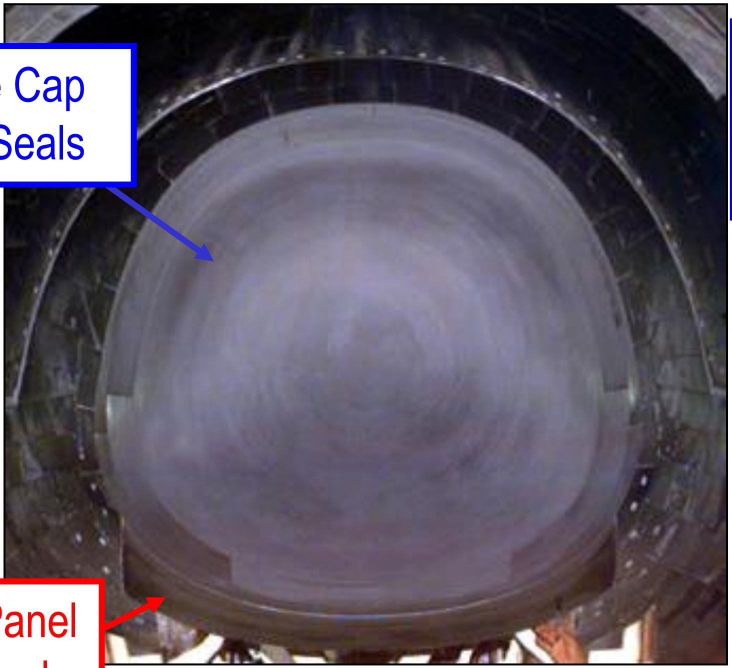
- AFRSI (FIB) - Advanced Flexible Reusable Surface Insulation
- FRSI - Flexible Reusable Surface Insulation
- Penetrations - seals and thermal barriers

Orbiter Tile Placement System Configuration

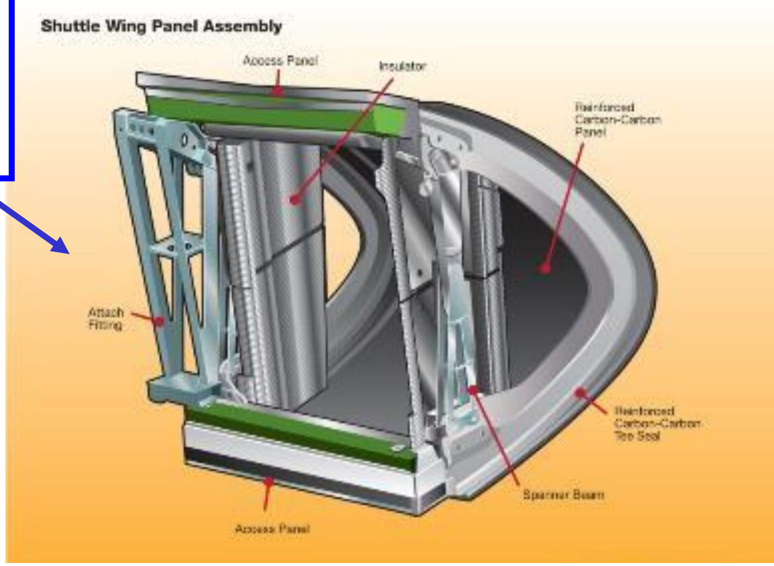


Space Shuttle Orbiter RCC Components

Nose Cap and Seals

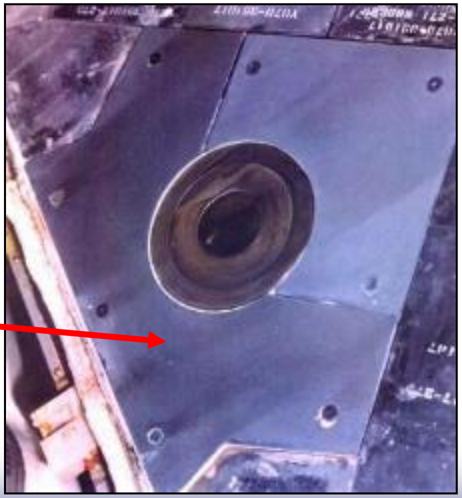


Wing Leading Edge Panel

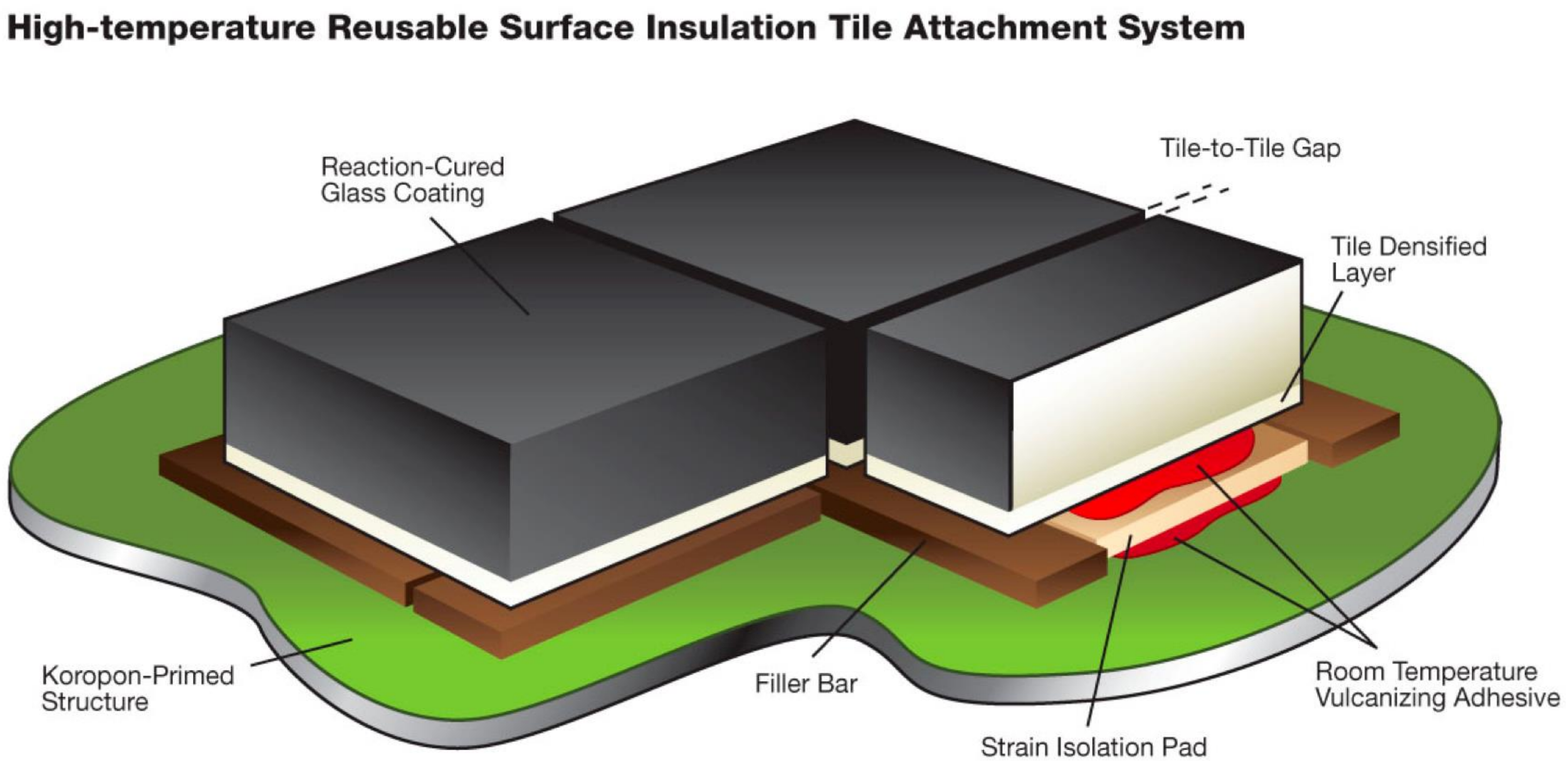


Chin Panel and Seals

Forward ET Attach Point Arrowhead RCC Plates

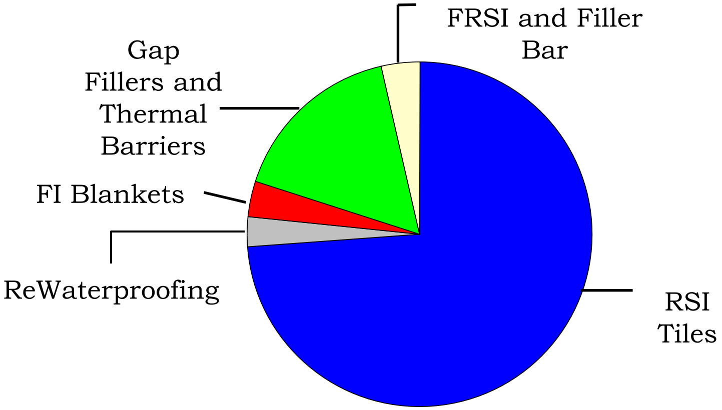


HRSI Tile System



Orbiter TPS: Operational Issues

Flight Processing



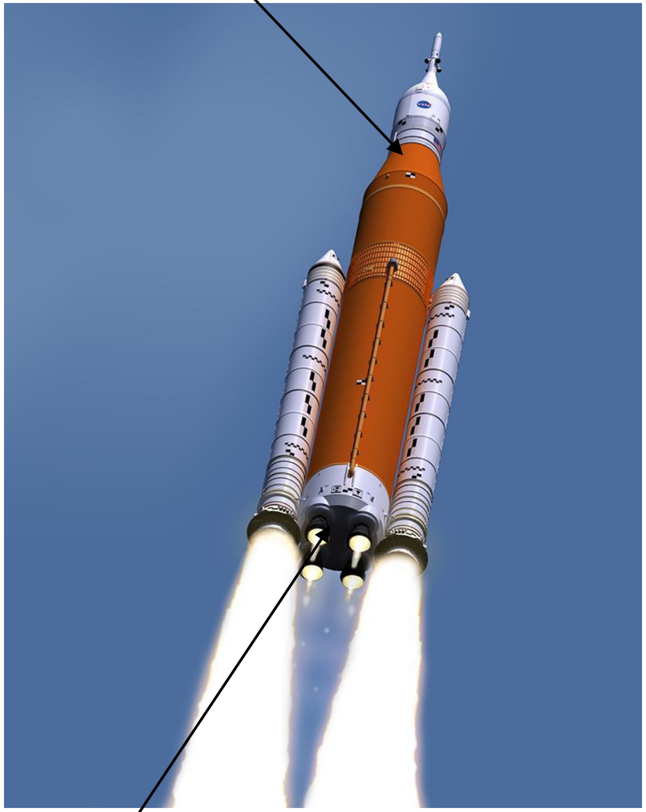
On-Orbit Inspections

Protruding Gap Filler

EVA
During STS-114

Launch Vehicles Need TPS

Aerodynamic Heating Heating



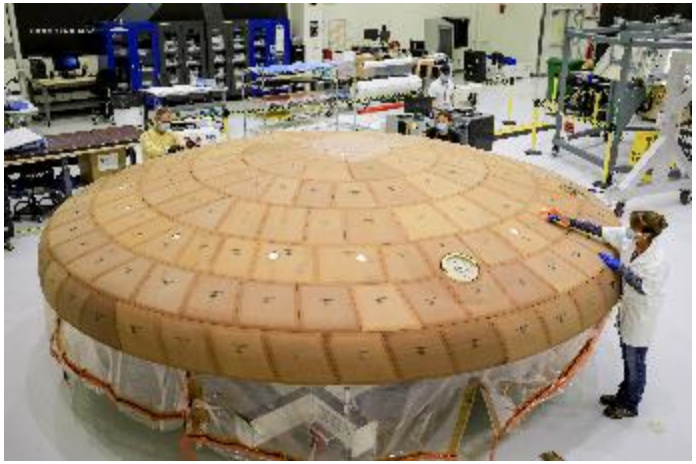
Plume-induced Heating

Space Shuttle
Retired 2011

Space Launch System
1st Launch 2021

Current TPS

Multi-Purpose Crew Vehicle Orion Heat Shield

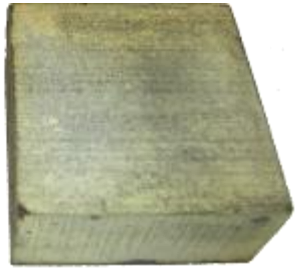


Avcoat (Apollo) but in Block Form

SpaceX Dragon Capsule

Note: SpaceX makes their own PICA.

Phenolic Impregnated Carbon Ablator (PICA)



Mars 2020

TPS in the Future

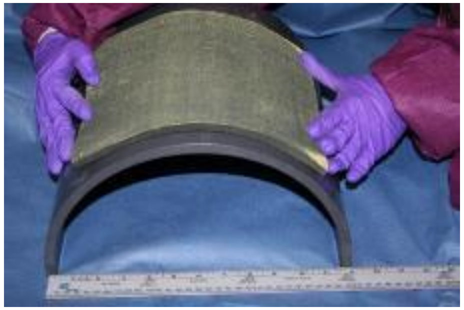
Increase Robustness

3-D Woven Carbon Fibers
Infiltrated with Resin

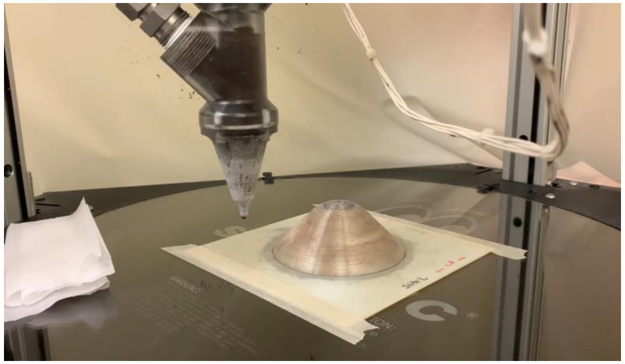
Reduce Weight

Graded Ablator
High Density to Lower Density

Improve Manufacturing/ Reduce Costs



Conformable Ablator
Infiltrated Felts



Let's 3D Print it!

Questions??