Reusable TPS
Past, Present, & Future

EDL Seminar Series

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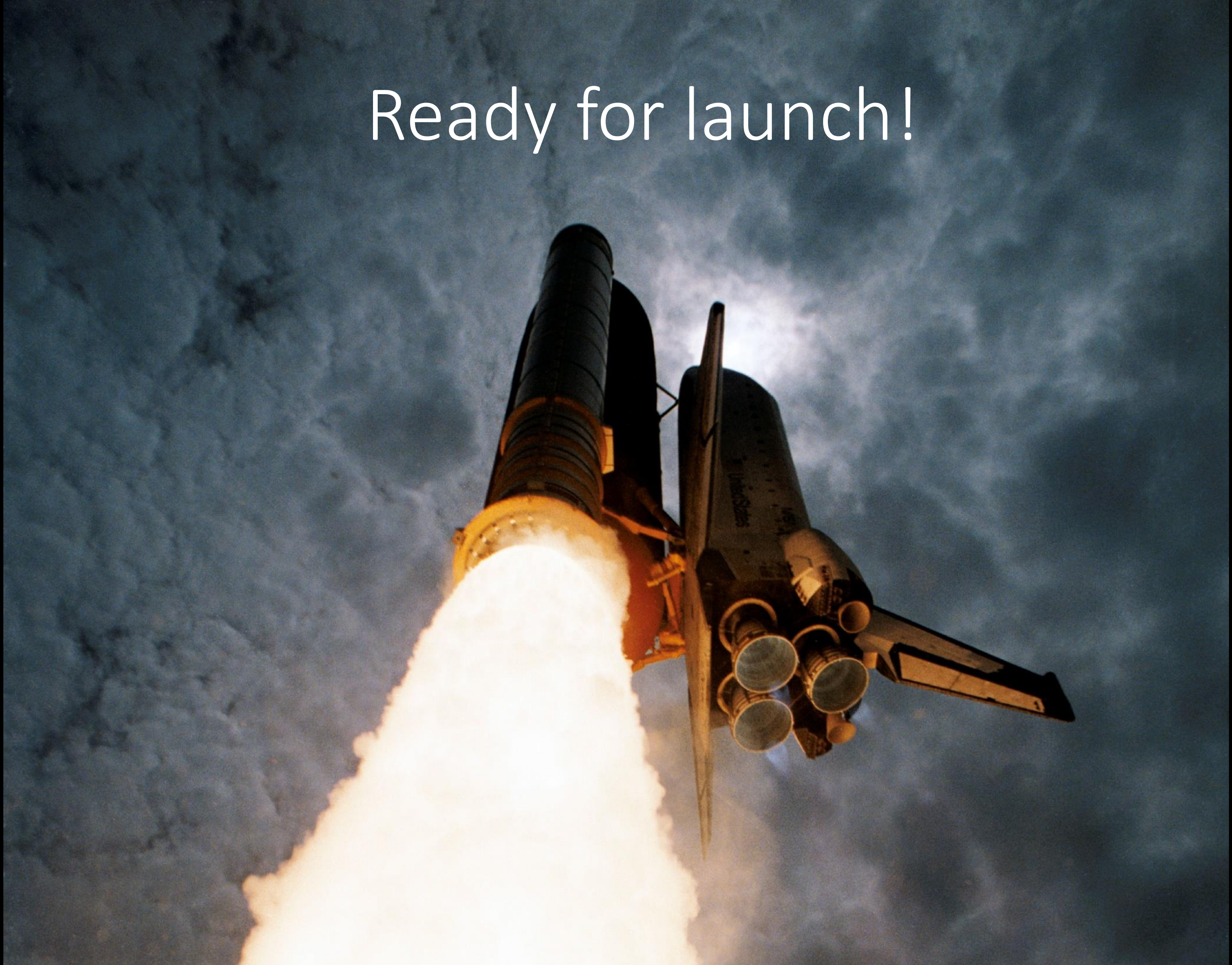
Outline

- Background on re-entry and thermal protection systems
- Past:
  - History of the Space Shuttle Orbiter
  - Orbiter Thermal Protection System (TPS)
- Present:
  - Current State-of-the-Art Reusable TPS
  - Applications
- Future:
  - Research Thrusts for Reusable Materials

Ready for launch!



Aerothermal Heating During Entry

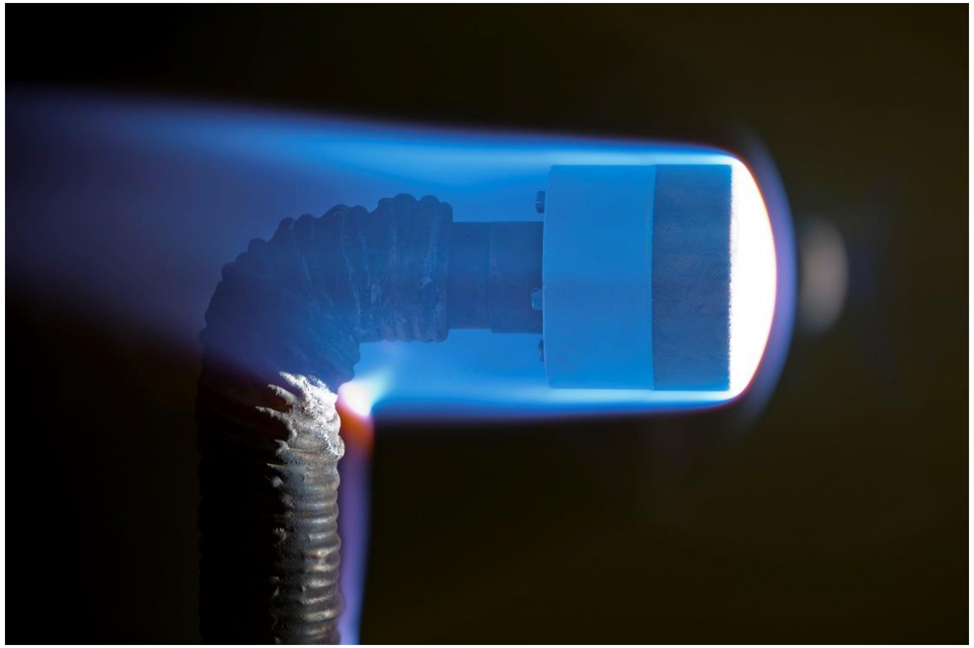
- Convective heating ($\dot{q}_{conv}$) – heat transfer resulting from conduction with the shock layer gasses (typically includes atomic recombination on the surface)
- Radiative heating ($\dot{q}_{rad}$) – radiation from excited atoms and molecules in the shock layer
- Heat flux ($\dot{q}$) [W/cm^2] is dependent on velocity (V), atmospheric density (ρ), and radius of the body (R)

$$\dot{q}_{conv} \propto V^3 \left(\frac{\rho}{R}\right)^{0.5}$$

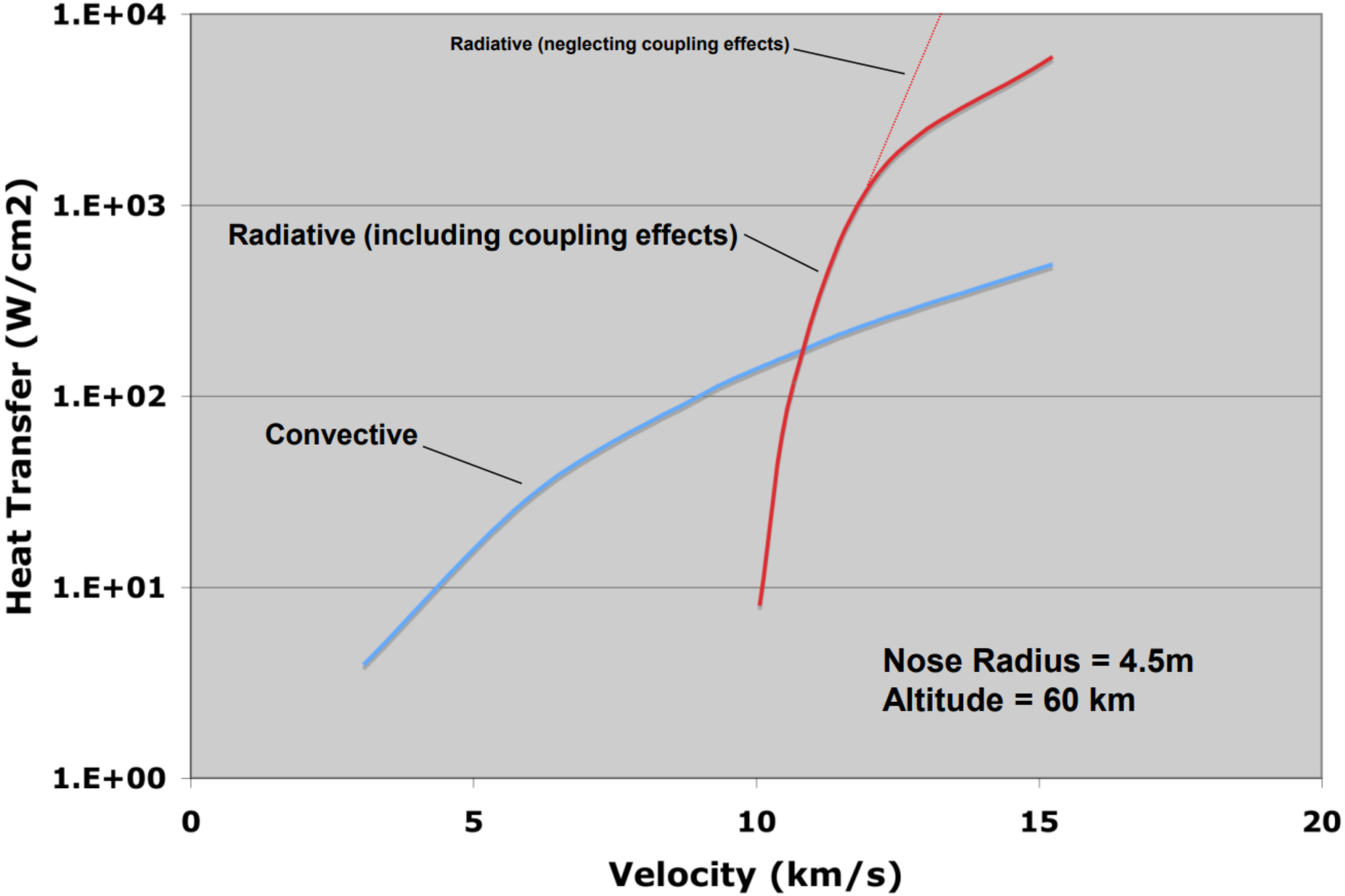
$$\dot{q}_{rad}{}^{*} \propto V^{8.5} \rho^{1.6} R^{1.0}$$

*Exponents for Earth atmosphere

- Heat load (Q) is the integrated heat flux over time [J/cm^2]



Entry Heating

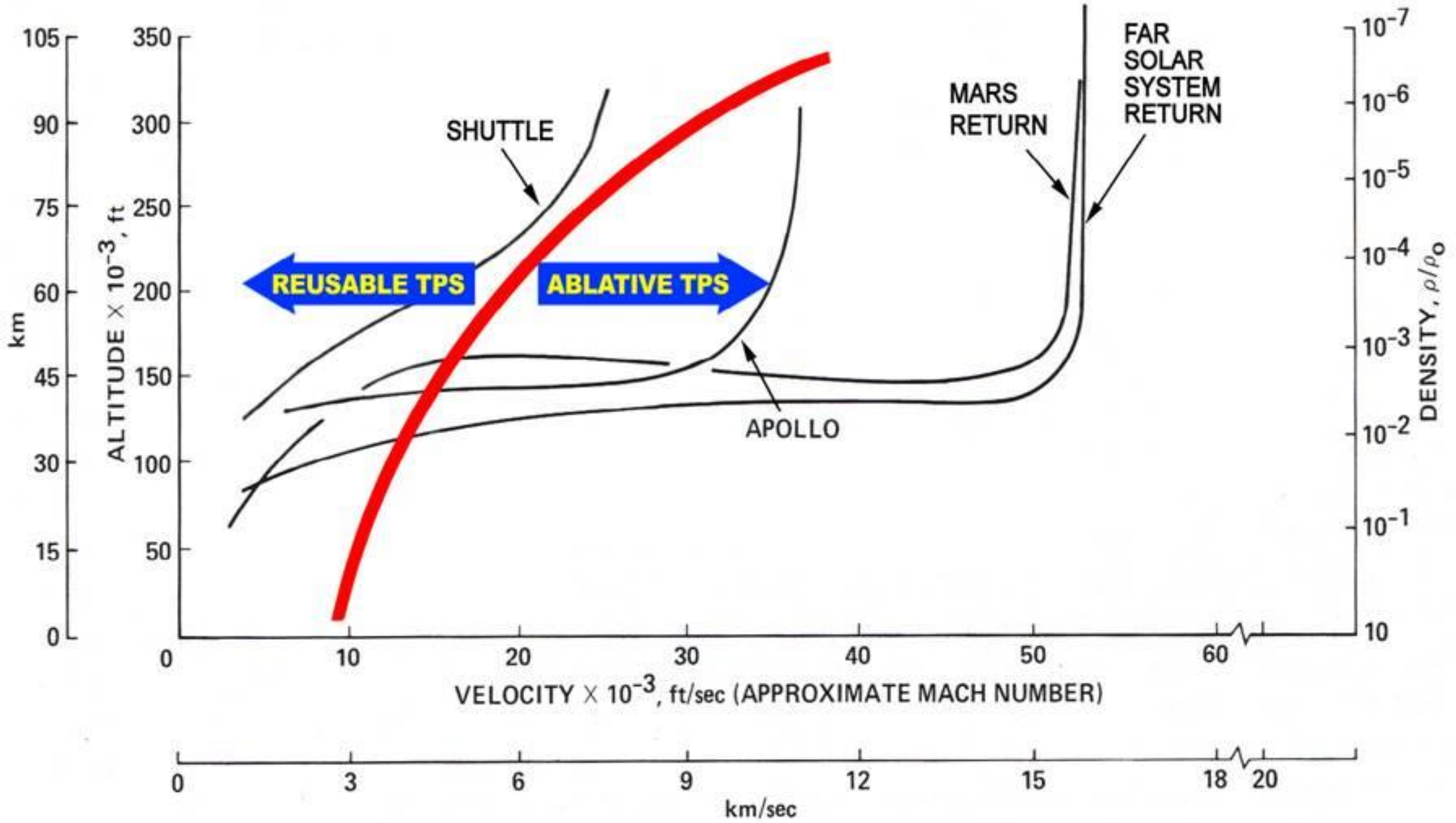


Adapted from Anderson, Hypersonic and High Temperature Gas Dynamics, Fig. 18.10

Thermal Protection System (TPS)

- The TPS insulates vehicles from the extreme heat of entry
- Two main classes of TPS materials:
  - **Ablative** – materials that ablate and decompose during entry to dissipate energy
    - Wide range of densities (0.2 to 1.8 g/cc) but can handle much higher heat fluxes and heat loads
    - Examples – PICA, Avcoat, HEEET, 3MDCP
  - **Reusable** – materials that do not degrade or change during aerothermal heating
    - Low density ceramic fiber-based materials with low thermal conductivity
    - Examples – Shuttle tile (HRSI), AFRSI blanket, TUFROC

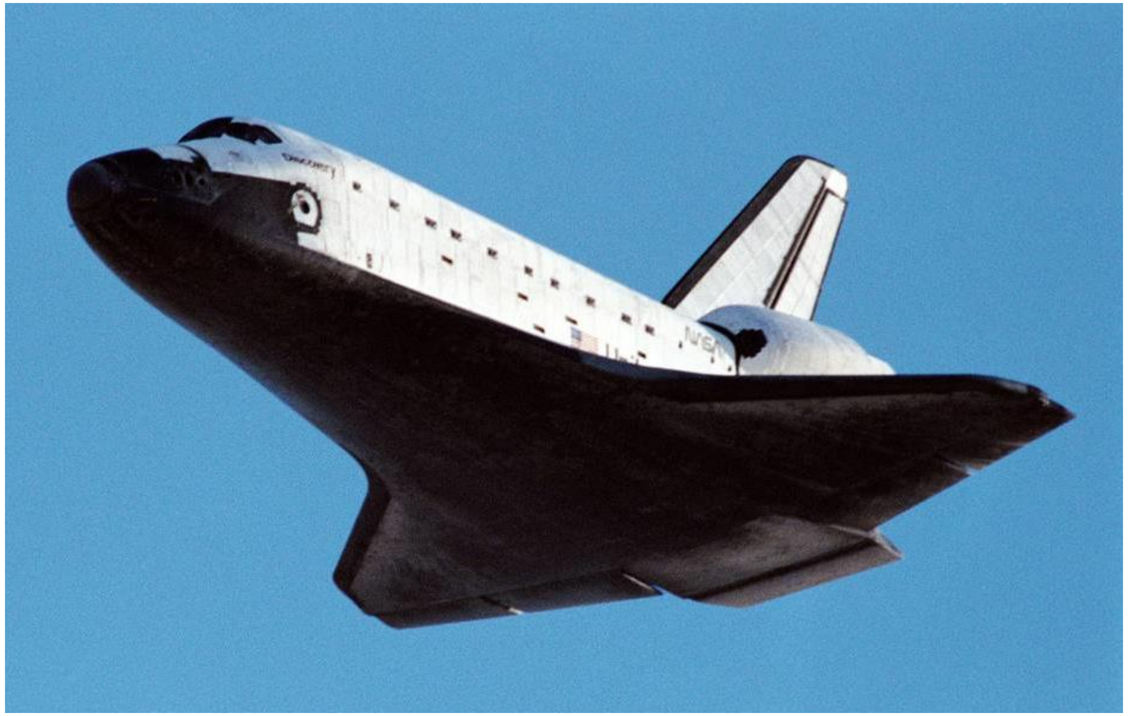
Re-entry Heating



Adapted from John Howe, "Hypervelocity Atmospheric Flight: Real Gas Flow Fields," NASA TM 101055, 1989

Space Shuttle Orbiter

- Shuttle program was started in 1972 as a Space Truck to ferry astronautes and satellites to and from low-earth orbit
- Required the development of reusable thermal protection materials for the Orbiter Vehicle (OV)
- Fleet
  - Challenger (OV-099)
  - Enterprise (OV-101)
  - Columbia (OV-102)
  - Discovery (OV-102)
  - Atlantis (OV-104)
  - Endeavour (OV-105)



Space Shuttle Discovery approaches for landing on a concrete runway at Edwards Air Force Base

Space Shuttle Orbiter

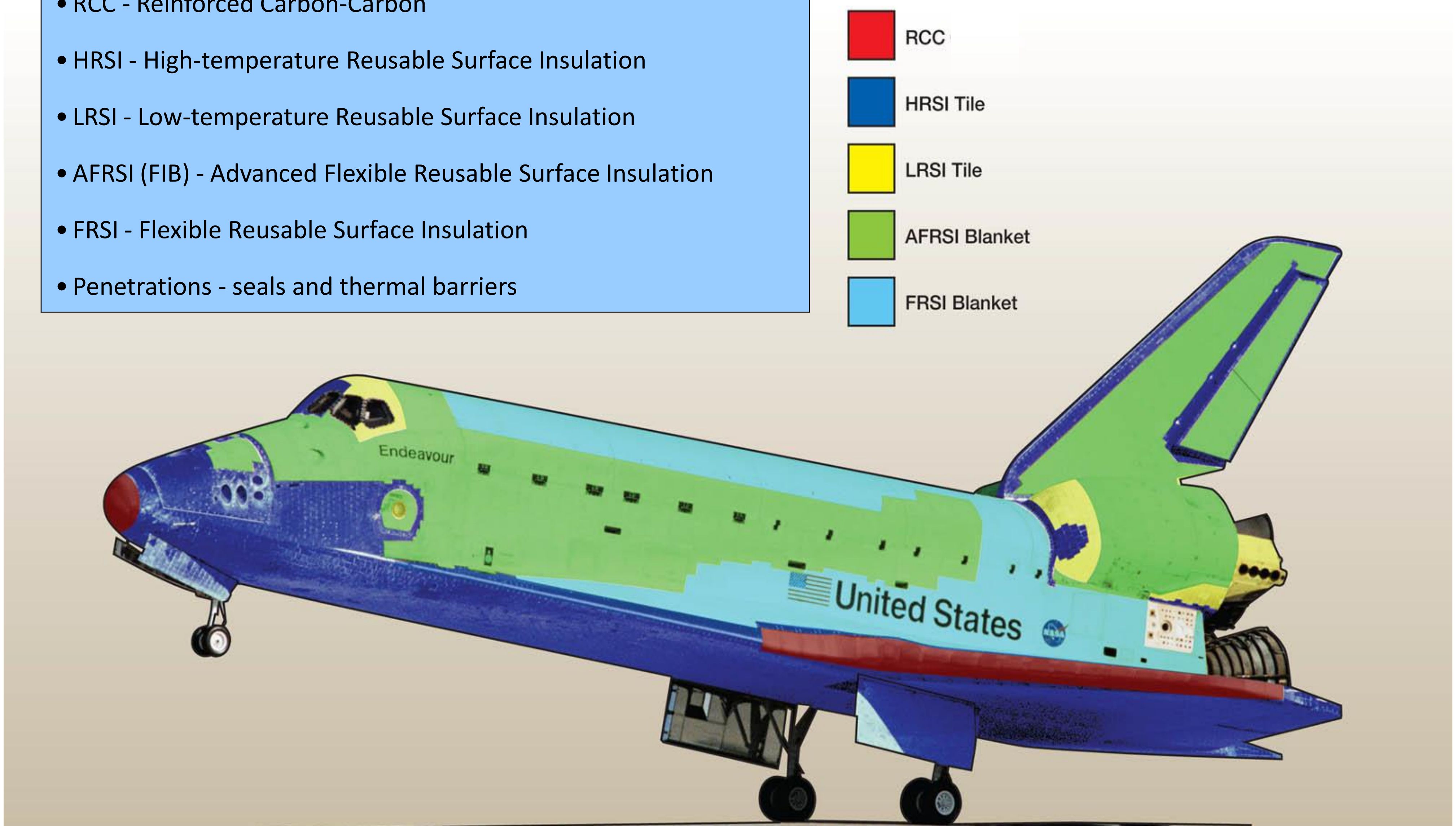
Interesting Facts

- The fleet completed **135 missions** from April 1981 to July 2011
- TPS had ~**22,000 tiles** that were installed by hand
- Orbiter cost: $1.7 billion
- Average cost per mission was $450 million

Space shuttle Endeavour, mission STS-123, view from the ISS

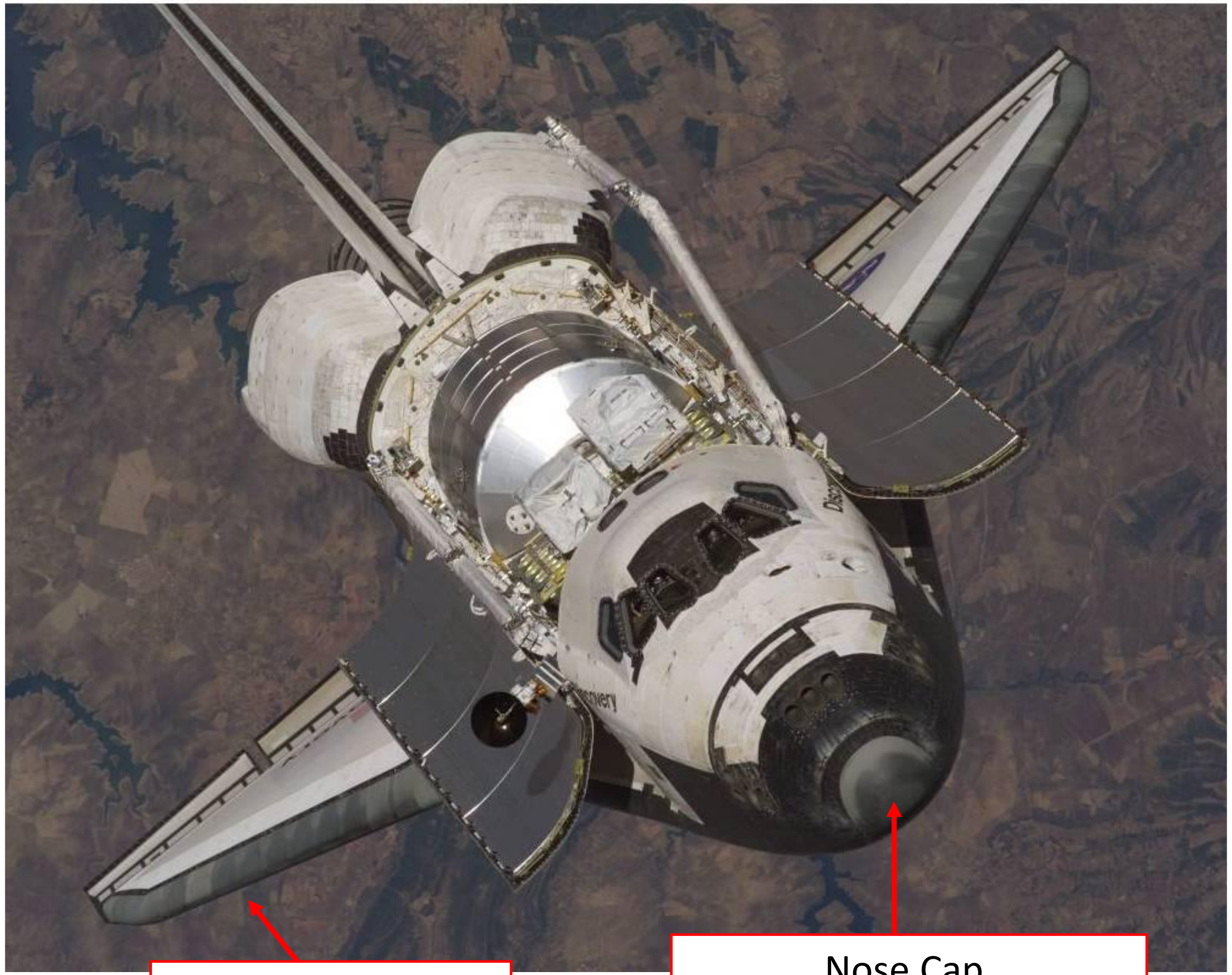
Shuttle Orbiter TSP Configuration

- 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



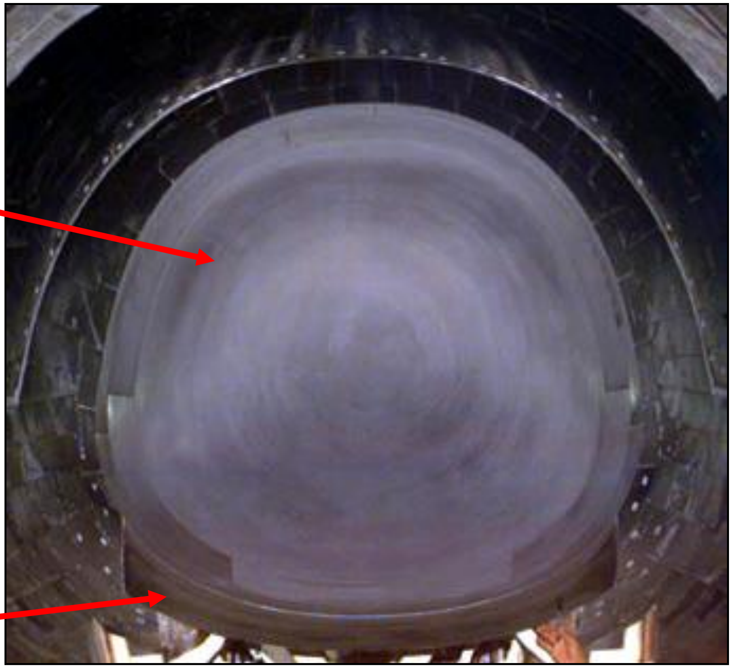
Reinforced Carbon/Carbon (RCC)

- Thermal Protection
  - Multi/Single 3000 °F / 3,220 °F
  - **Hot structure** requiring internal insulation
- Aerodynamic Shape
  - Maintain airfoil shape for flight
  - Roughness & waviness critical
- Load Distribution
  - Aerodynamic **load transmission**
- Impact Resistance
  - Minimal Ground Handling Resistance



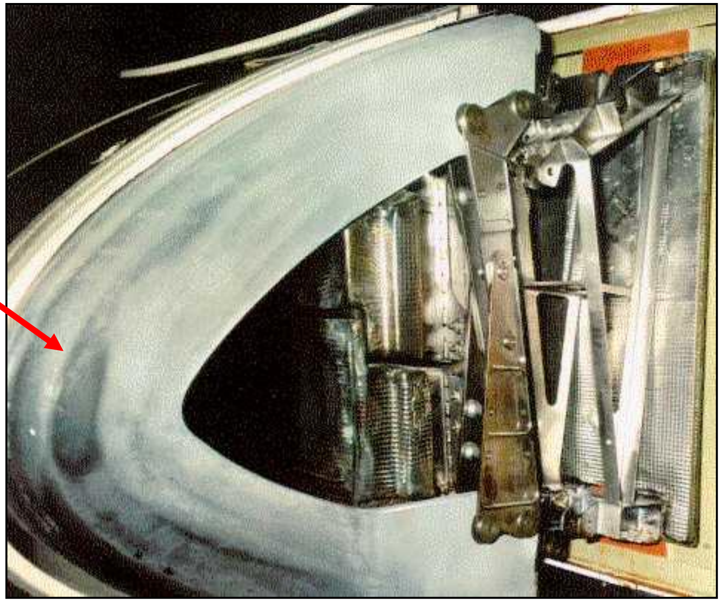
RCC Components

Nose Cap and Seals

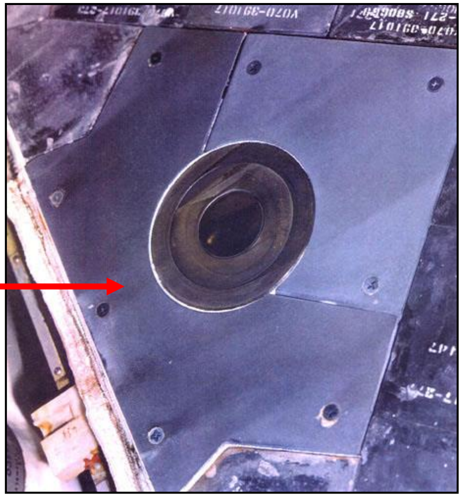


Chin Panel and Seals

Wing Leading Edge Panel



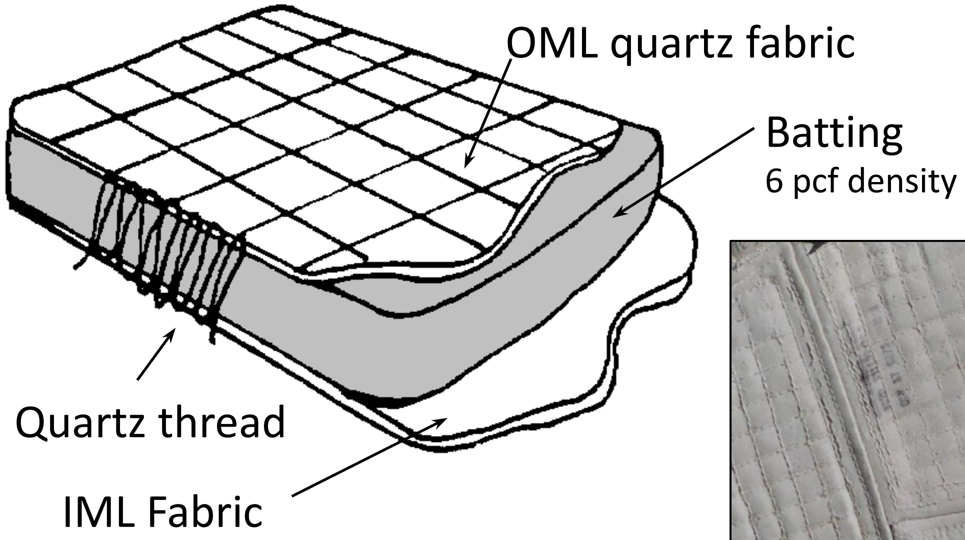
Forward ET Attach Point Arrowhead RCC Plates



Blanket Materials

Advanced Flexible Reusable Surface Insulation (AFRSI)

- Glass fabric outer cover
- Q-felt batting
- Stitched with glass thread

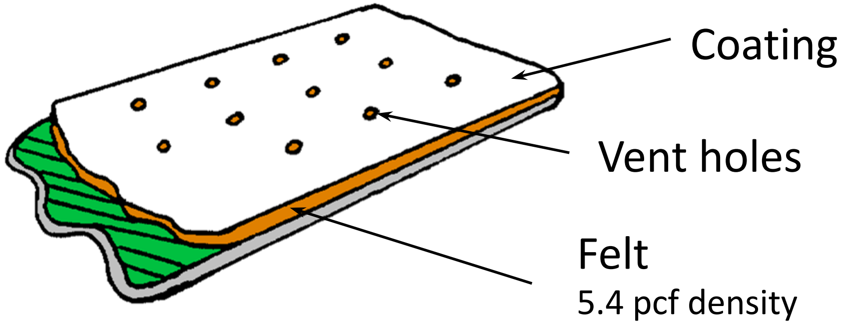


Multi-use Temperature < 1500 °F

Currently not readily available commercially

Flexible Reusable Surface Insulation (FRSI)

- Needled Nomex felt
- Silicone coating
- Can be made multi-layer



Multi-use Temperature < 700 °F

Potentially available commercially

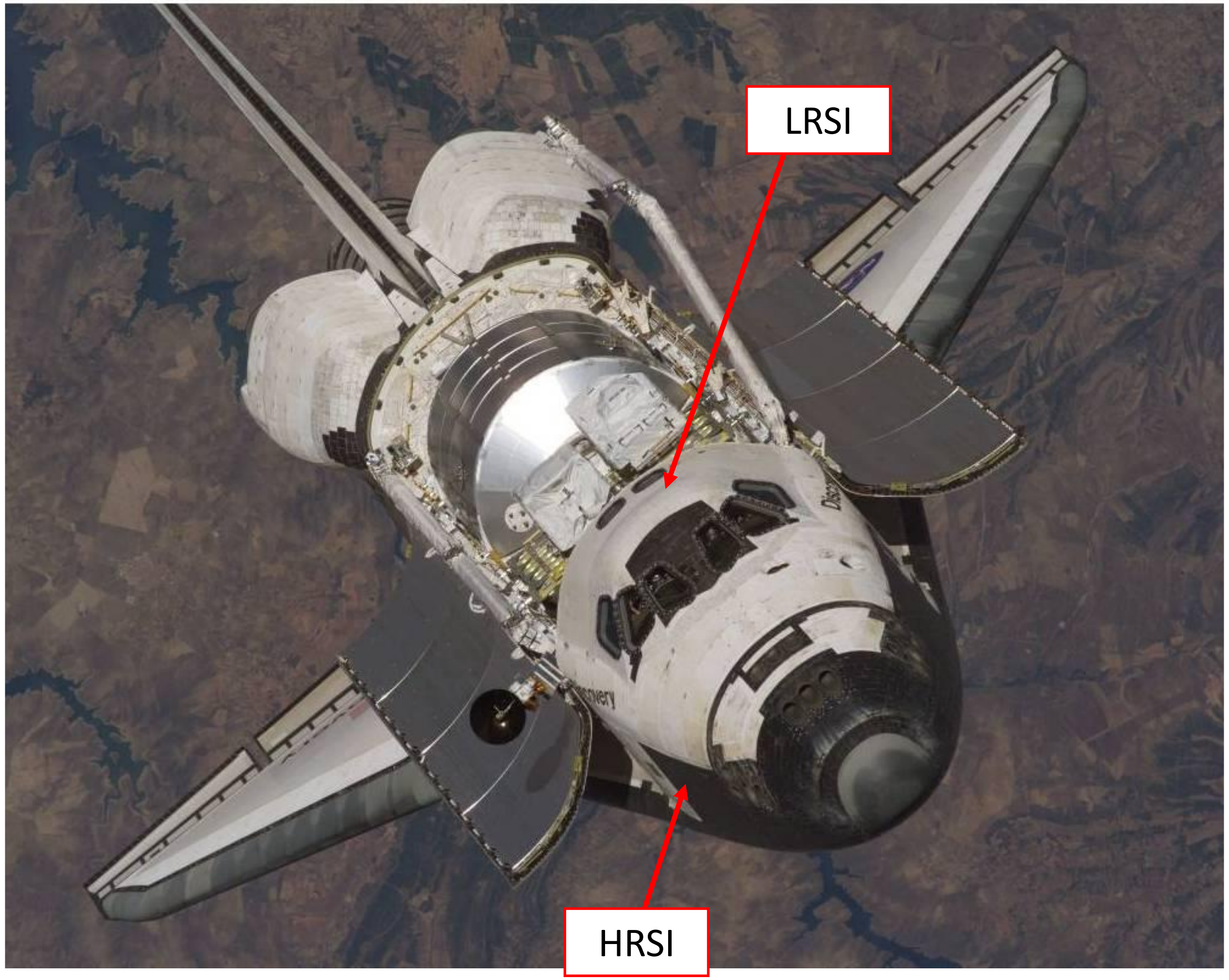
Tile Materials

HRSI - "High-temperature Reusable Surface Insulation"

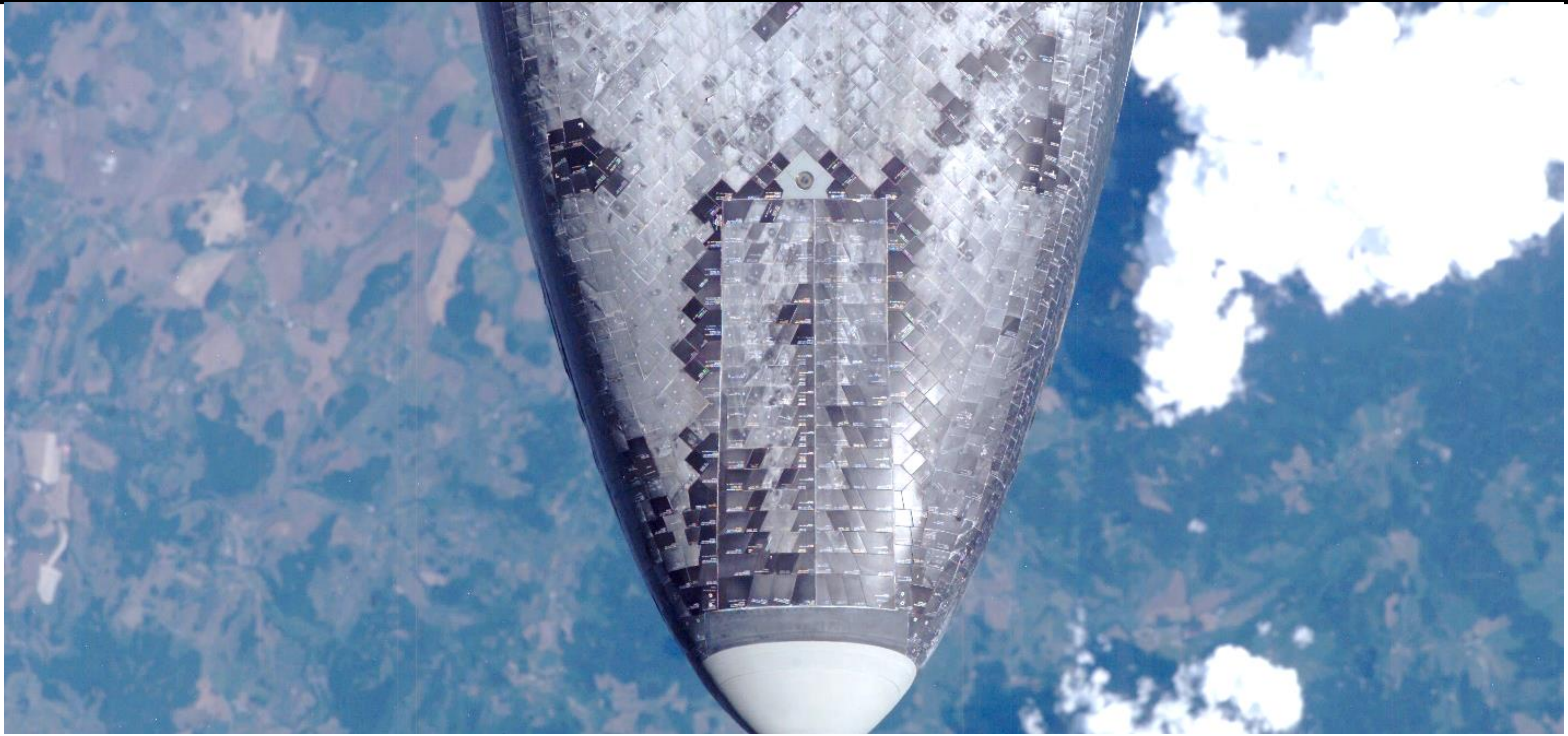
- Black glass coating with high emissivity for heat rejection during re-entry
- Multi-use temperature ~ 2300 - 2700^{o}F

LRSI - "Low-temperature Reusable Surface Insulation"

- White glass coating with high reflectivity to reflect sunlight
- Multi-use temperature – 1200^{o}F



Space Shuttle Orbiter



Space shuttle Discovery as viewed from the ISS for inspection of the heat shield

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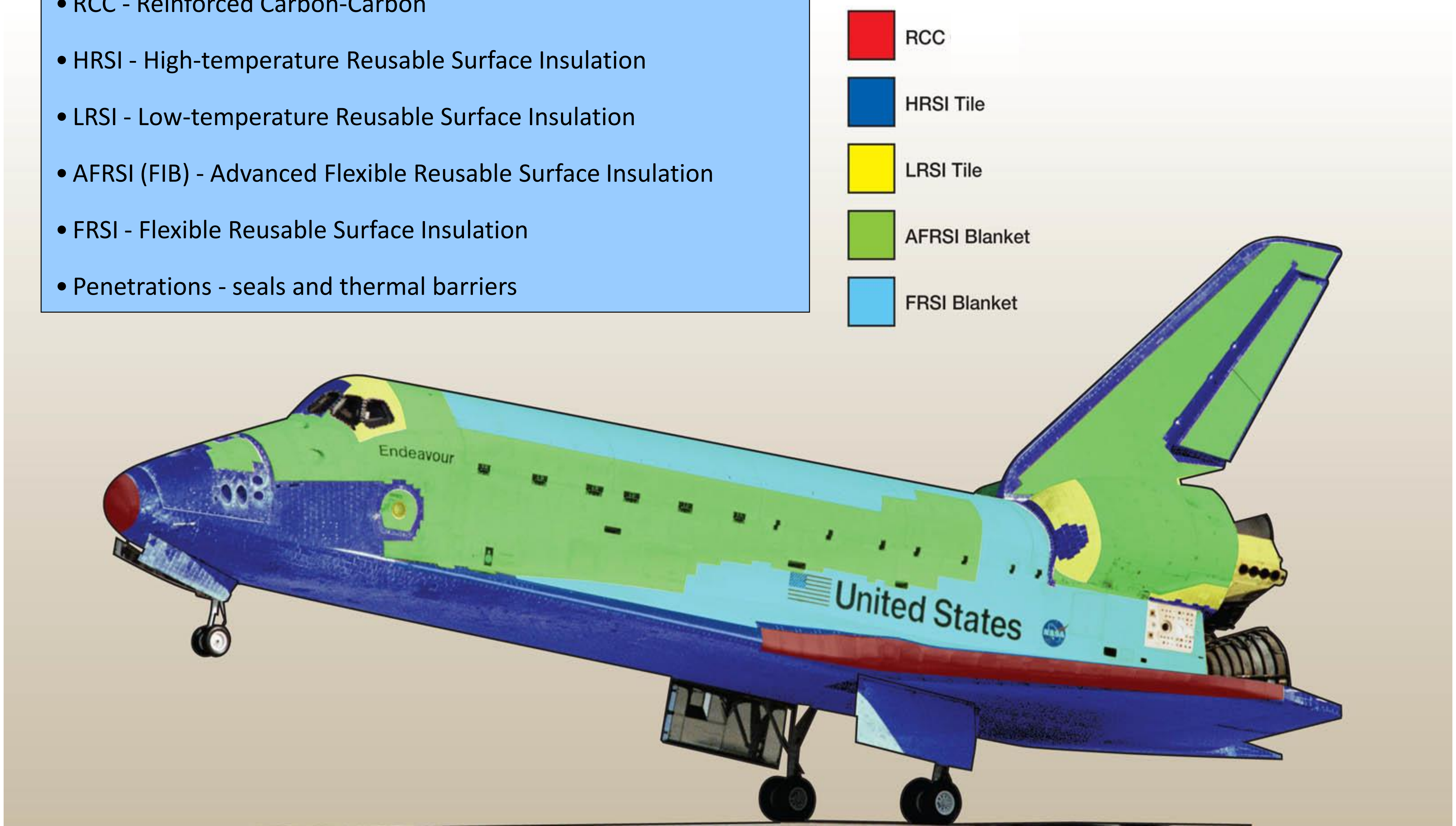


HRSI Tile System

- HRSI tiles are made from ceramic fibers and have very low densities
- HRSI tiles utilize a black coating, called reaction cured class (RCG), for high emittance on entry

<u>Materials</u>:
- LI-900
- LI-2200
- FRCI-12
- AETB-8
- BRI-18

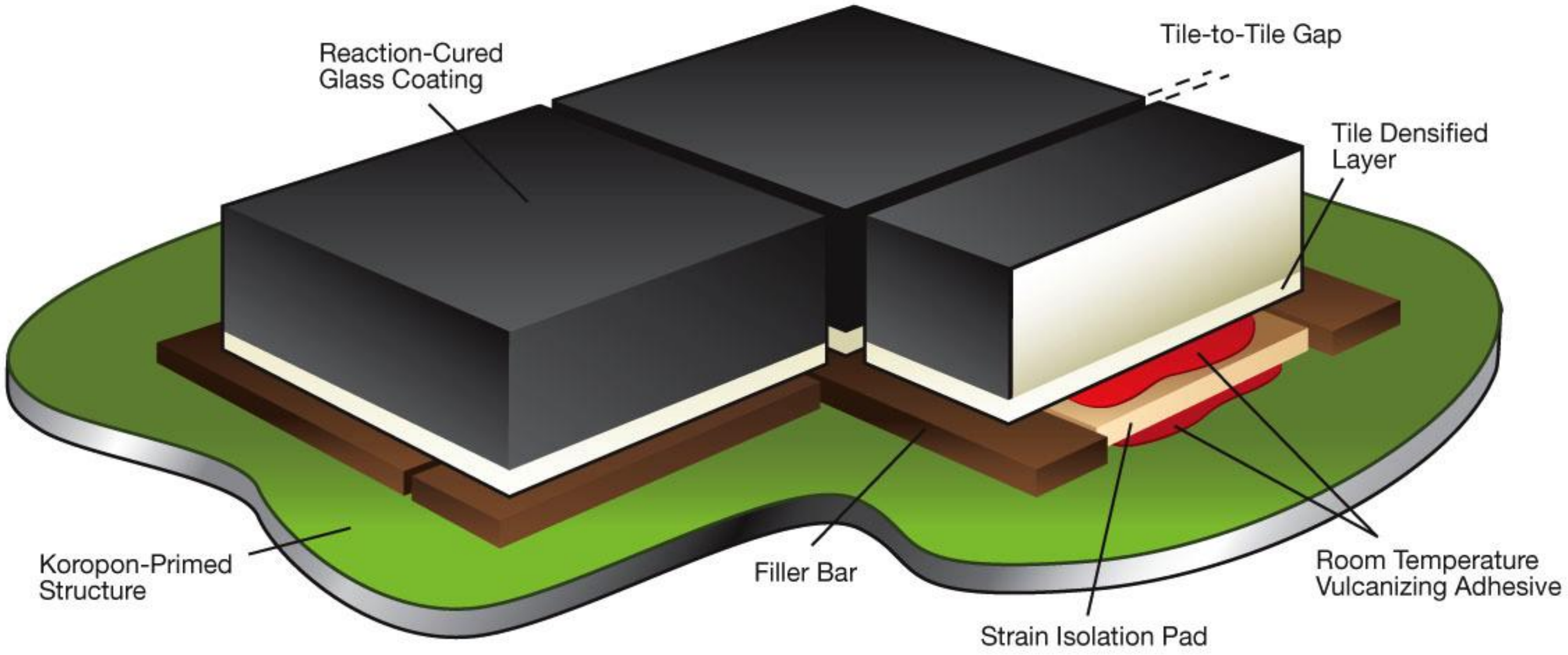
essentially obsolete

modern materials

<u>Multi-use temperature range#:</u>

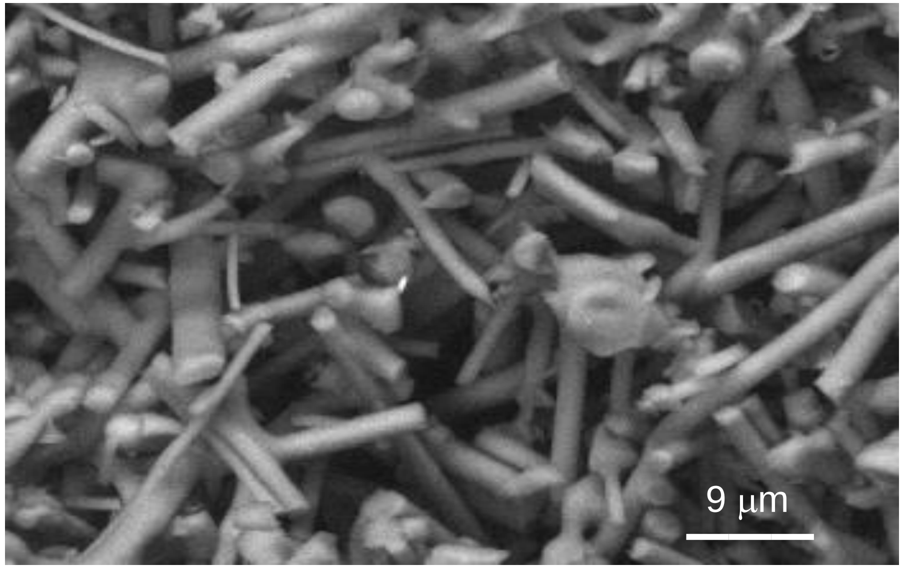
~2300 - 2700 °F

#dependent on material & exposure duration



LI-900/LI-2200 Tile

- Tile composed of high purity (99.9%) silica fiber
- Developed for the Shuttle Orbiter by Lockheed Martin
- LI-900
  - Low density of 9 pcf (0.14 g/cc)
  - Used widely through the space shuttle for its low thermal conductivity and mass
- LI-2200
  - Higher density of 22 pcf (0.35 g/cc)
  - Better mechanical properties at the cost of higher thermal conductivity and mass



FRCI-12 Tile

- "Fibrous Refractory Composite Insulation"
- Developed in 1979 at NASA Ames
- Consists of silica fibers and aluminoborosilicate fibers
- Density of 12 pcf (0.19 g/cc)
- Lower density than LI-2200 with higher tensile strength
- FRCI replaced HRSI tiles where damage had been an issue

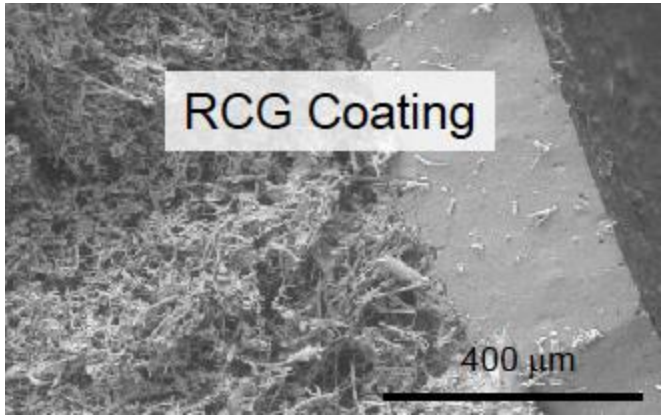
Virgin FRCI tile surrounded by LI-900

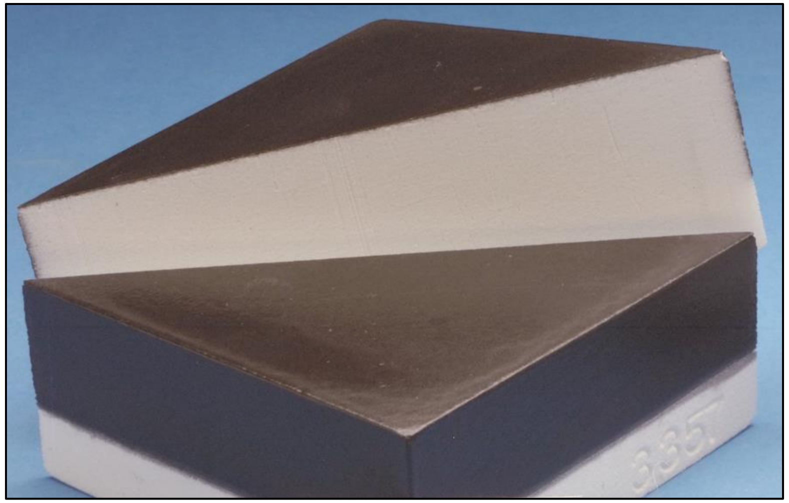
Tile Materials

Type	Name Density	Composition	Tensile Strength (Min)	Material Limit
1st Generation Pure Silica	**LI-900** 9 lb / cu ft	Silica	13 psi	2300 °F (100 Flt) 2600 °F (Single)
	LI-2200 22 lb / cu ft	Silica Silicon Carbide	35 psi	2300 °F (100 Flt) 2900 °F (Single)
2nd Generation Composite	**FRCI-12** 12 lb / cu ft	Silica Aluminaborosilicate Silicon Carbide	52 psi	2300 - 2500 °F (100 Flt) 2700 °F (Single)

Reaction Cured Glass (RCG) Coating

- Consists of borosilicate glass (B_2O_3/SiO_2) and silicon boride (SiB_x)
- Applied to tile by spray coating as a wet slurry and fired to sinter
- The high emissivity of the black coating rejects heat from the hot surfaces during re-entry





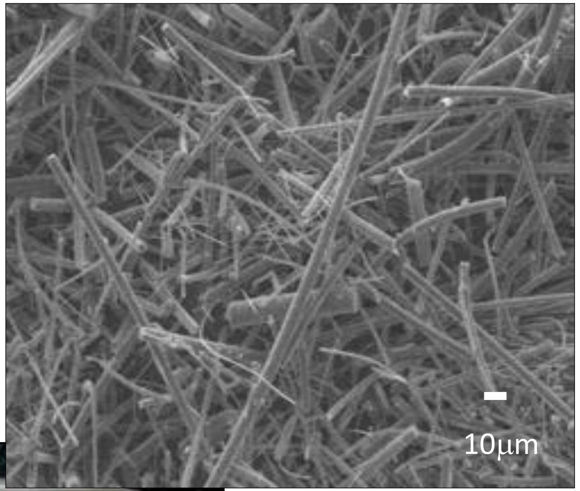
Present

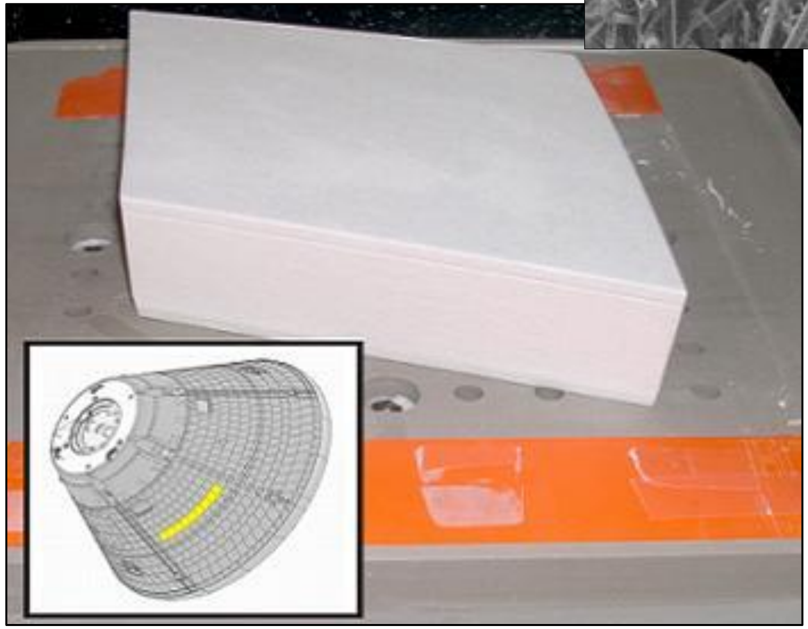
- State-of-the-art reusable TPS today consists of:
  - Alumina Enhanced Thermal Barrier (**AETB**) tile
  - Toughened Uni-Piece Fibrous Insulation (**TUFI**) coating
  - Toughened Uni-piece Fibrous Reinforced Oxidation-Resistant Composite (**TUFROC**)

Alumina Enhanced Thermal Barrier (AETB)

AETB-8, -12, -17, -20 (pcf)

- <u>Substrate has ~95% porosity</u>
- Density ranges from 0.13 to 0.32 g/cc
- Consists of aluminoborsilicate fibers, alumina fibers, silica fibers, & silicon carbide
- <u>Best dimensional stability of the tile materials</u>
- <u>Use up to ~2800 °F (single use)</u>





AETB-8 fabricated for Orion backshell

Tile Materials

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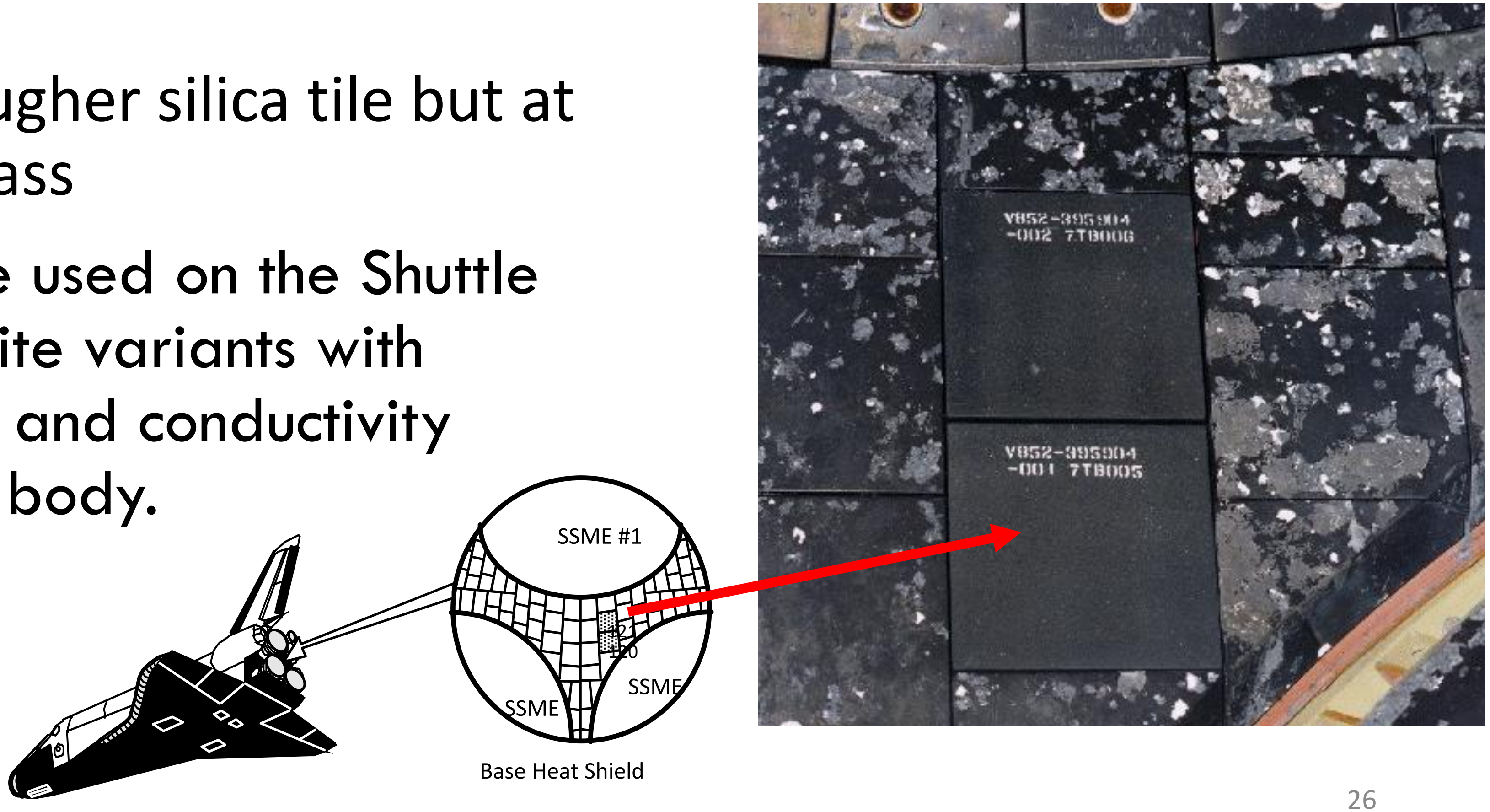
2nd Generation Composite	FRCI-12 12 lb / cu ft	Silica Aluminaborosilicate Silicon Carbide	52 psi	2300 - 2500 °F (100 Flt) 2700 °F (Single)
3rd Generation Advanced Composite	AETB-8, -12, -17, -20 8 to 20 lb / cu ft	Silica Alumina Aluminaborosilicate Silicon Carbide	40 psi (AETB-8) 100 psi (AETB-20)	2300 - 2600 °F (100 Flt) 2800 °F (Single)

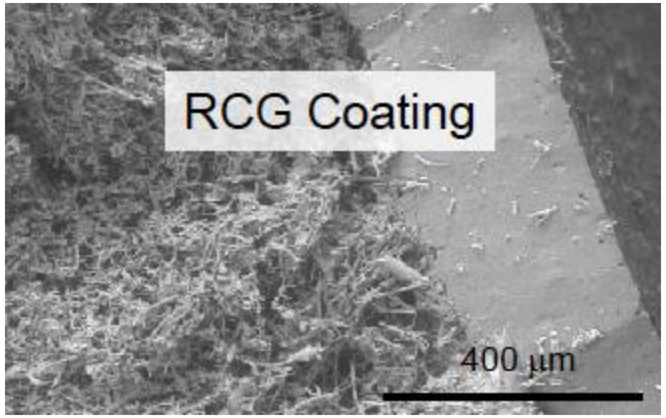
Toughened Uni-Piece Fibrous Insulation (TUFI)

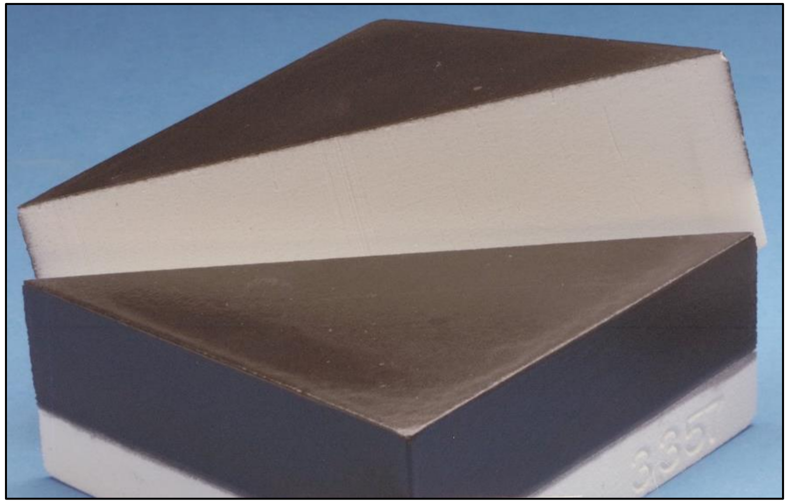
- Consists of borosilicate glass (B_2O_3/SiO_2), silicon boride (SiB_x), and molybdenum disilicide ($MoSi_2$)
- Produces a stronger, tougher silica tile but at the cost of increased mass
- Standard TUFI tiles were used on the Shuttle Orbiter's underside. White variants with higher impact resistance and conductivity were used on the upper body.

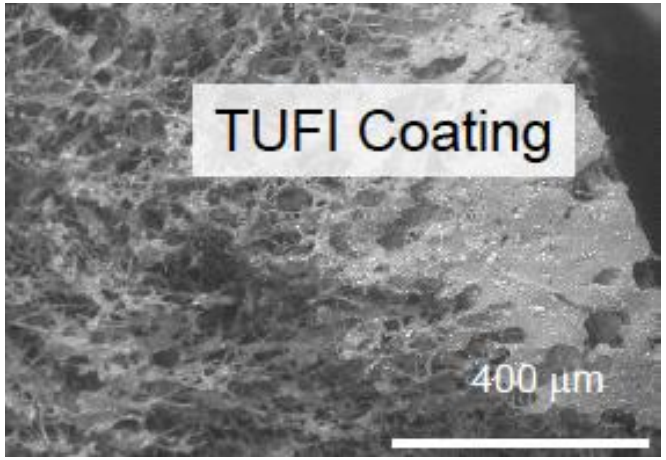


Coatings

- RCG coatings sit on top of the substrate & partially seal surface
- TUFI surface treatments penetrate the substrate (~ 0.1”) & add toughness
- Coatings & surface treatments share some goals:
  - high temp. stability
  - high emissivity (≥0.9)
  - low catalycity (exothermic atom recombination)
  - mechanically stable as part of the system (e.g., no thermal expansion mismatch)

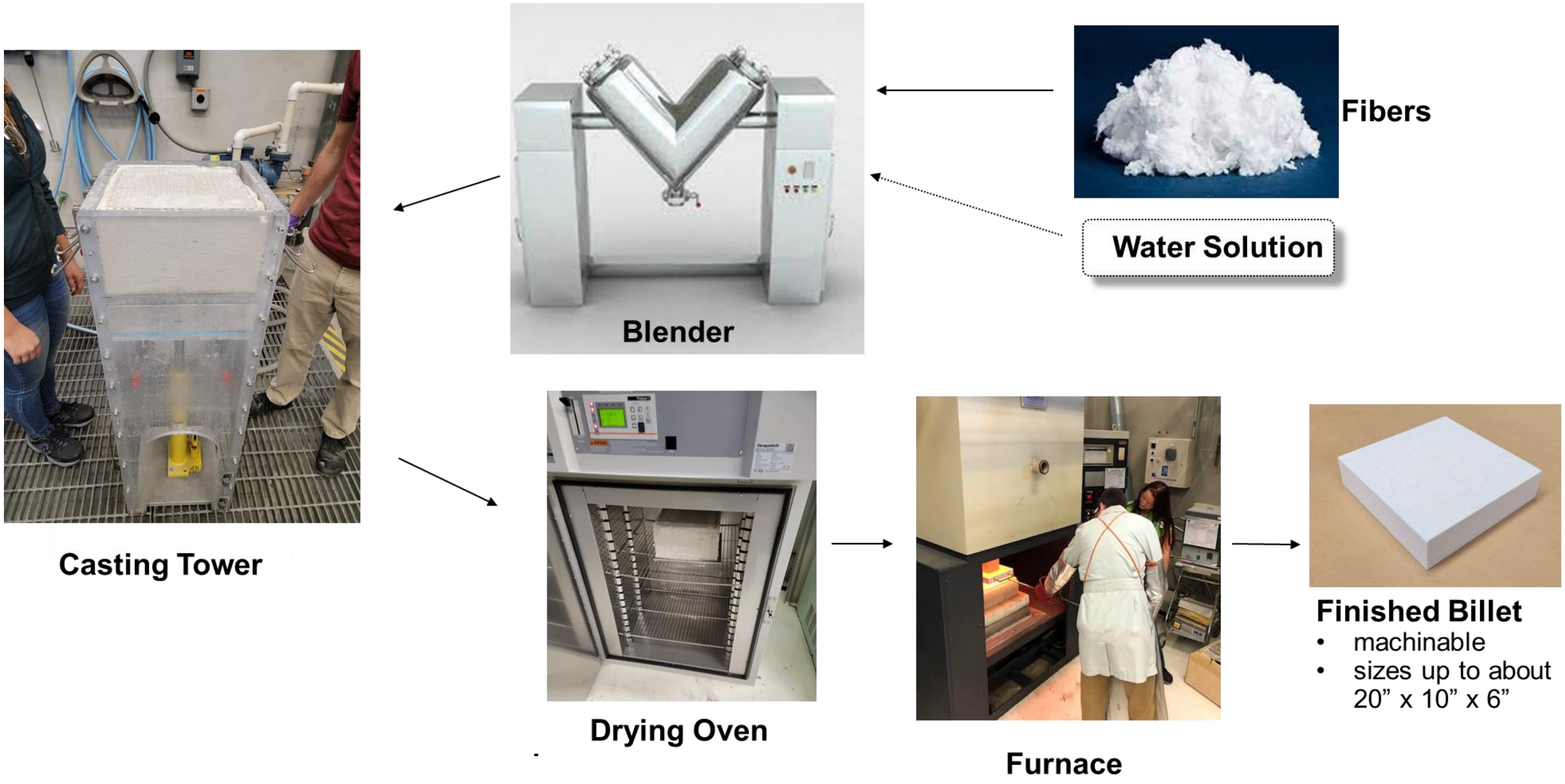






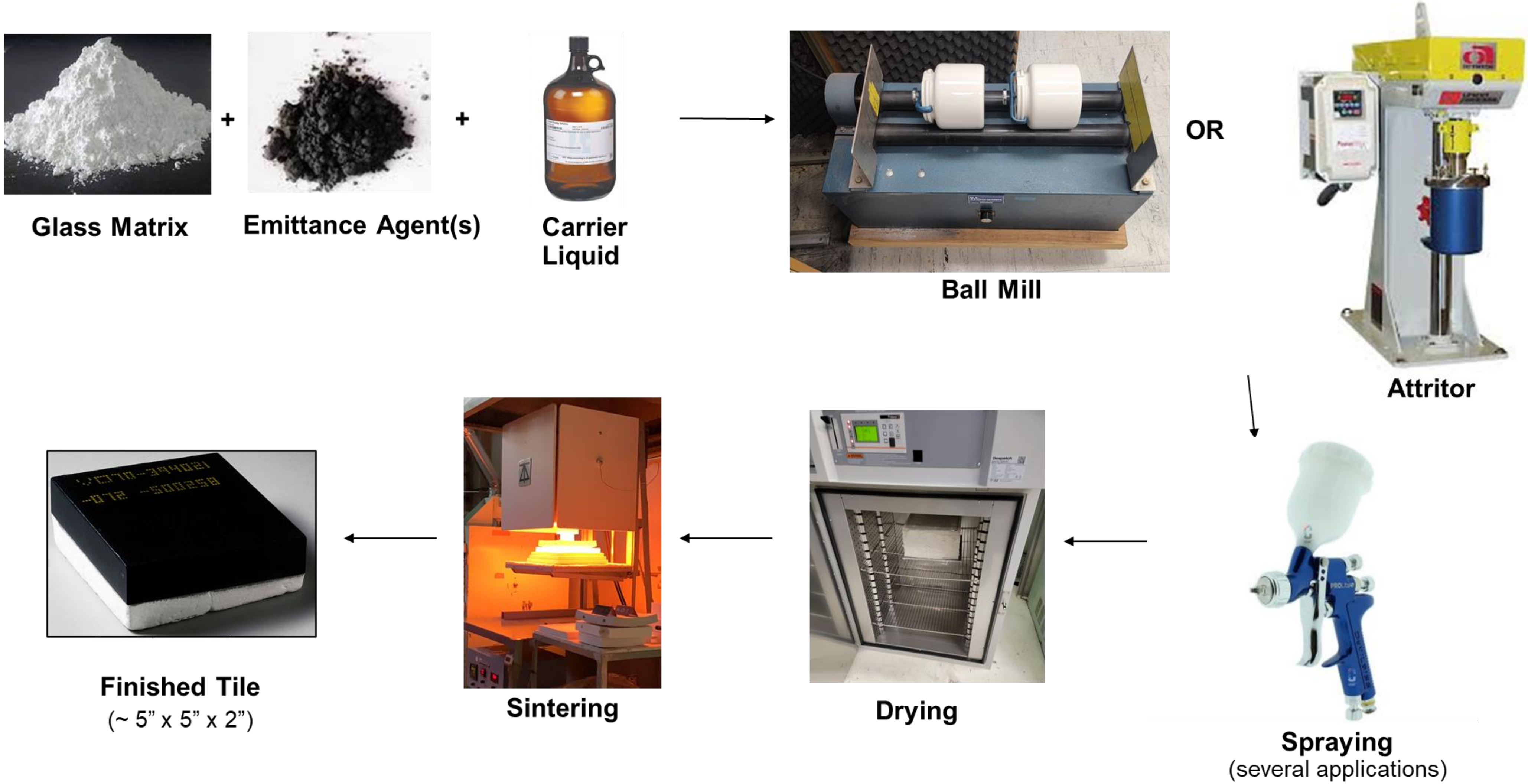
Tile Production Process

Tile Process Schematic



Tile Coating Process

Coating & Surface Treatment Fabrication Process



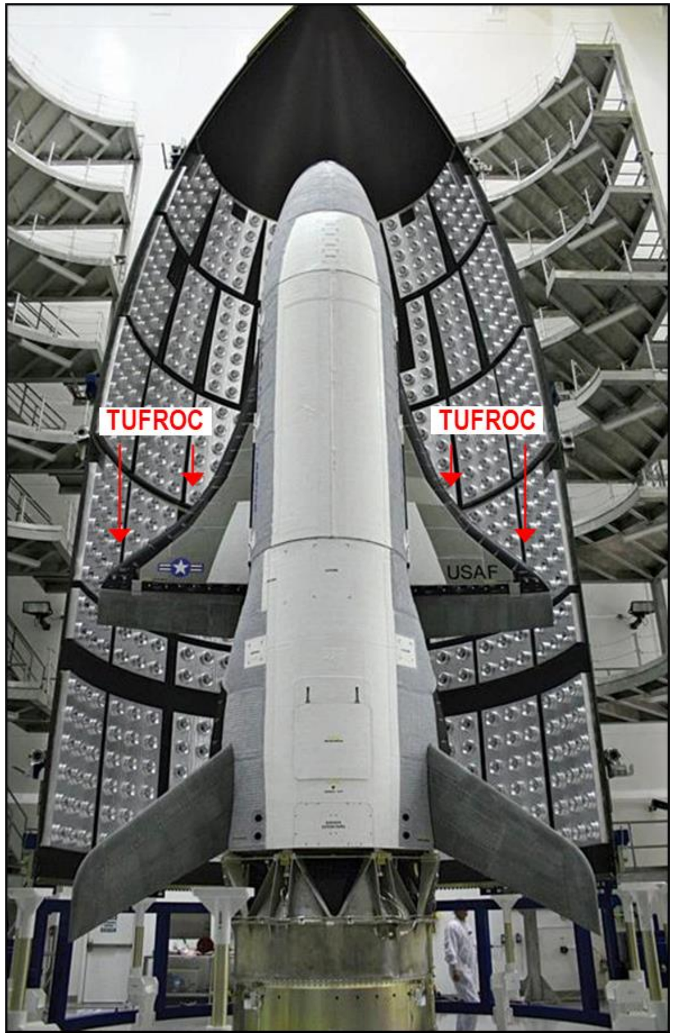
Current Efforts

- Coated AETB tile is made with **heritage raw materials** using processes and equipment that have **not been updated since invention** and are no longer available for purchase
- Current efforts focus on **modernization** of legacy processes using heritage materials to make contemporary versions of AETB tile with TUFI and RCG coating

TUFROC

- "Toughened Uni-piece Fibrous Reinforced Oxidation-Resistant Composite"
- A multi-component tiled TPS system that is the state-of-the-art reusable material system used on the leading edges of X-37B
- Features (vs. C/C or C/SiC)
  - Low cost (10x cheaper than C/C)
  - Light weight (~0.3 g/cm^3)
  - Insulative
  - Reusable temperature 2900°F (≥3, 5min exposures)
  - Single-use temperature exceeding 3100°F

X-37B preparing for 1st launch, 2010



Commercial Space Application

- Resurgence in **demand for reusable thermal protective systems** in driving renewed research and development
- Commercial flight systems under development for low-earth orbit (LEO) re-entry or hypersonic flight
  - Space X (Starship)
  - Blue Origin (New Glenn)
  - Sierra Space (Dream Chaser)
  - Stratolaunch (Talon-A)
  - Relativity (Terran R)
  - Radian (Radian One)
  - Rocket Lab (Neutron)
  - Venus Aerospace (Stargazer)

Future

- Further developments in reusable TPS will address concerns identified by NASA and commercial partners:
  - Raw material cost
  - Reducing manufacturing and certification cost
  - Supply chain issues
  - Ease of integration, inspection, and refurbishment

Acknowledgments

The content in these slides was from previous efforts and talks as well as contributed efforts from many researchers at NASA

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- Matt Switzer

Space shuttle Discovery, mission STS-105, landing at NASA's Kennedy Space Center

Questions?

National Aeronautics and Space Administration

Ames Research Center
Entry Systems and Technology Division