Entry Systems and Technology Division
Ames Research Center

National Aeronautics and
Space Administration

Reusable Thermal Protection Material Development

Aerospace Materials Manufacturing Digital Summit by SAE International

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May 13, 2025

Outline

- Introduction
- Motivation for Reusable Thermal Protection Systems (RTPS) Development
- Background on Entry and RTPS
- Current State-of-the-Art
- Development Efforts
- Summary

Introduction

Dr. Adam Caldwell

Material Scientist/ Engineer in the Thermal Protection Branch (TSM) at NASA Ames Research Center

Serve as the Deputy Manager for the High Temperature Reusable Materials (HTRM) Program and the Deputy Lead for Materials and Processing for the Artemis Orion Project

Research focused on thermal protection material development and investigating processing/property/performance of heritage materials

Ground Testing ADEPT's Spiderweave Material Tested at NASA ARC's Arc Jet Facilities

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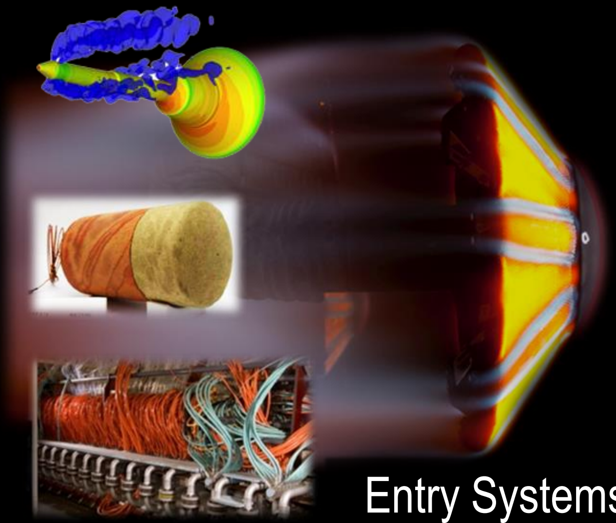
NASA Centers and Installations

Core Competencies at Ames Today

Air Traffic Management

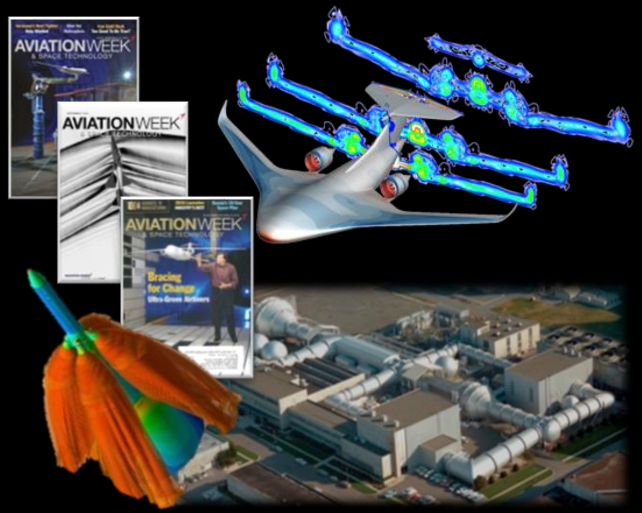


Entry Systems

Advanced Computing
& IT Systems

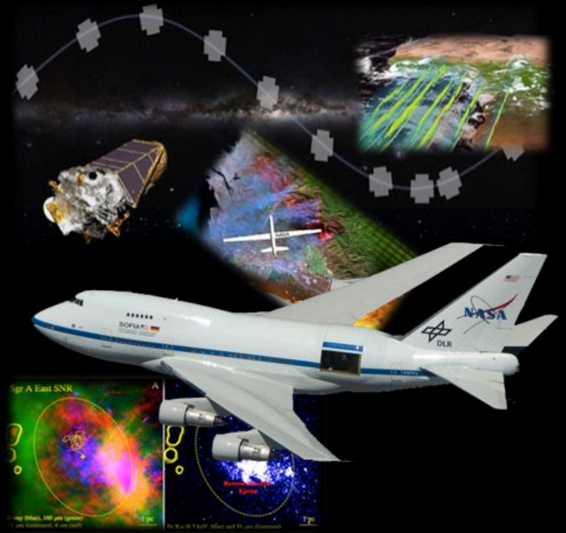
Intelligent/ Adaptive Systems

Cost-Effective Space Missions



Aerosciences

Astrobiology and Life Science

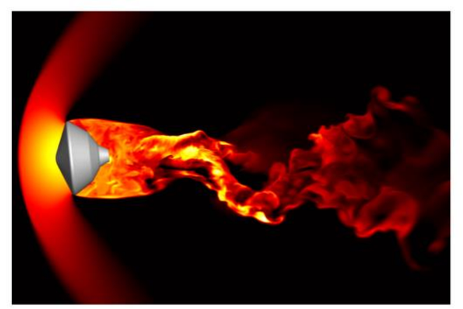
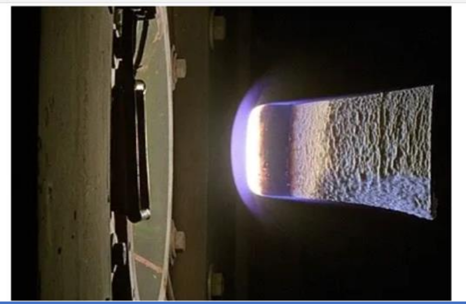
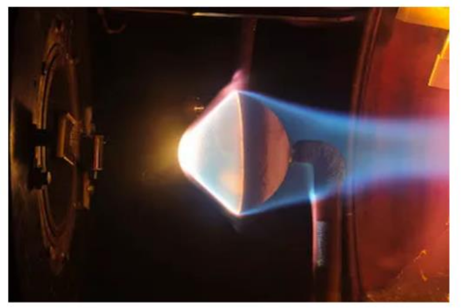


Space and Earth Sciences

NASA Ames Research Center

Exploration Technology Directorate

Entry Systems and Technology Division

Aerothermodynamics	Thermal Protection Materials	Thermophysics Facilities	Entry Systems and Vehicle Development
			

Conceives, develops, and infuses innovative entry system technologies into NASA human exploration and planetary science missions. Operates high enthalpy testing facilities including the arc jet complex, hypervelocity free flight facility, and electric arc shock tube. Develops advanced entry systems modeling, thermal protection materials, and engineering science instrumentation. Assists in the advancement of commercial space endeavors by providing entry systems insight and expertise.

Motivation

- Resurgence in **demand for reusable thermal protective systems** is driving renewed research and development
- Many commercial flight systems are under development for low-earth orbit (LEO) re-entry or hypersonic flight including:
  - 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)
- The Space Shuttle Orbiter's thermal protection systems (TPS's) are the flight proven starting point for reusable entry systems
- Gap between the Shuttle efforts and now:
  - Loss of personnel, know-how, supply chains, and equipment
  - Reusable insulating TPS were produced using raw materials from lifetime purchases by NASA for the Shuttle Program in the 1990's - called "heritage"
  - This NASA stockpile will be depleted during planned Artemis Orion missions

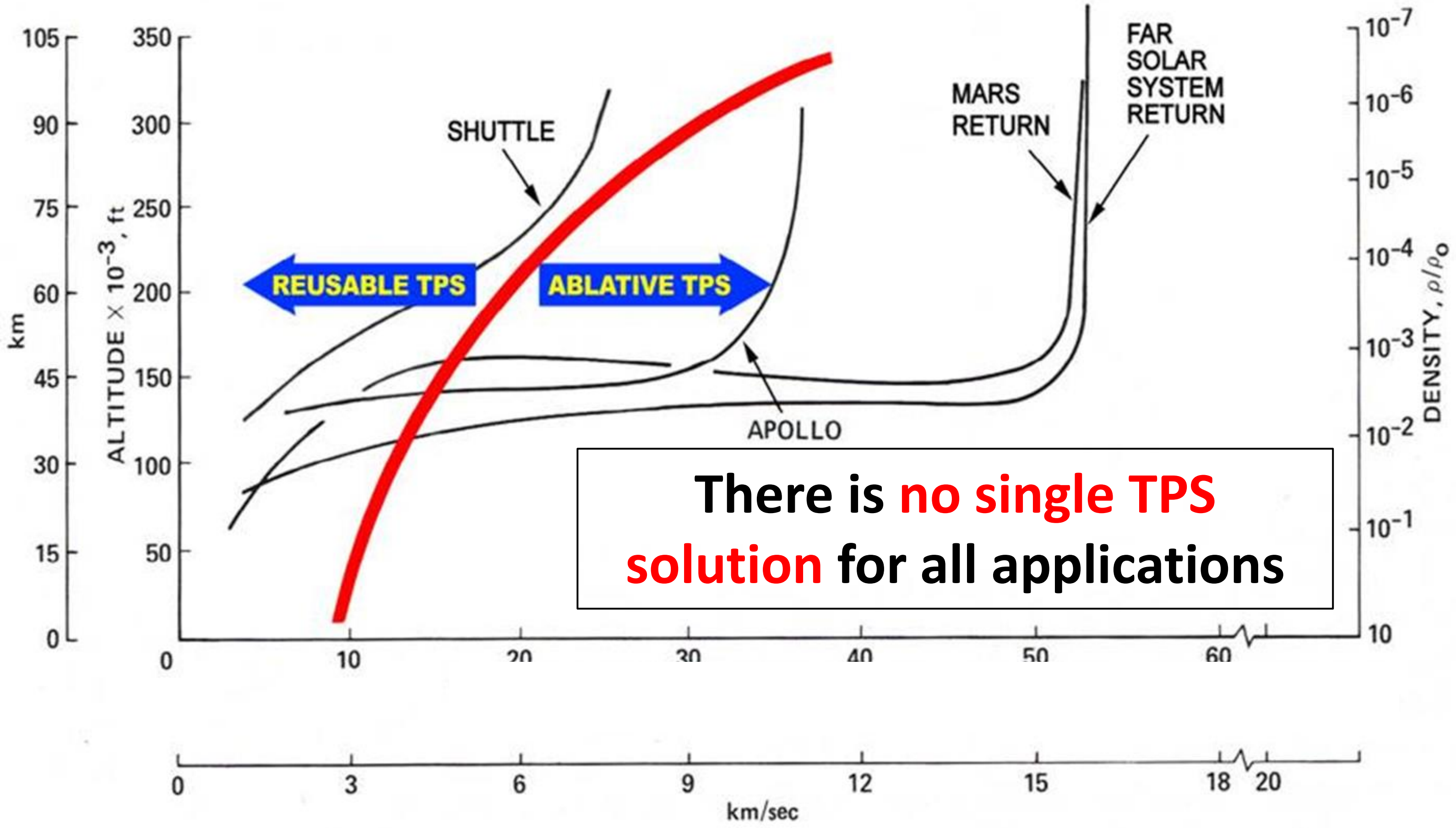
Thermal Protection System (TPS)

- The TPS insulates vehicles from the extreme heat of entry
- Two main classes of TPS materials:
  - **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
  - **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 relatively higher heat fluxes and heat loads
    - Examples – PICA, Avcoat, HEEET, 3MDCP (3D-wovens)

Space Shuttle Orbiter

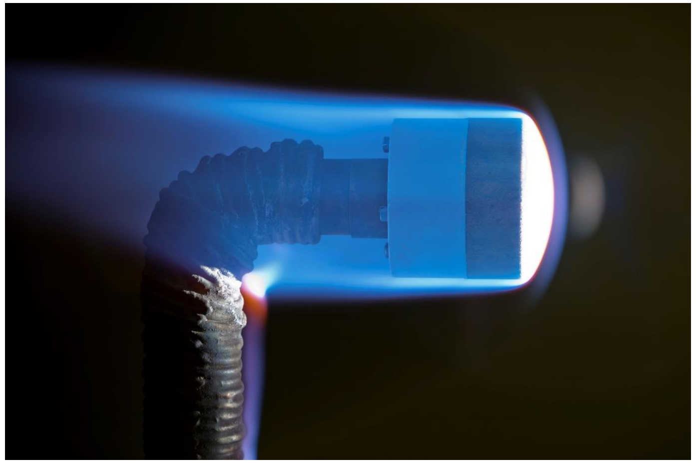
Mar Exploration Rover Capsule

Aerothermal Heating



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

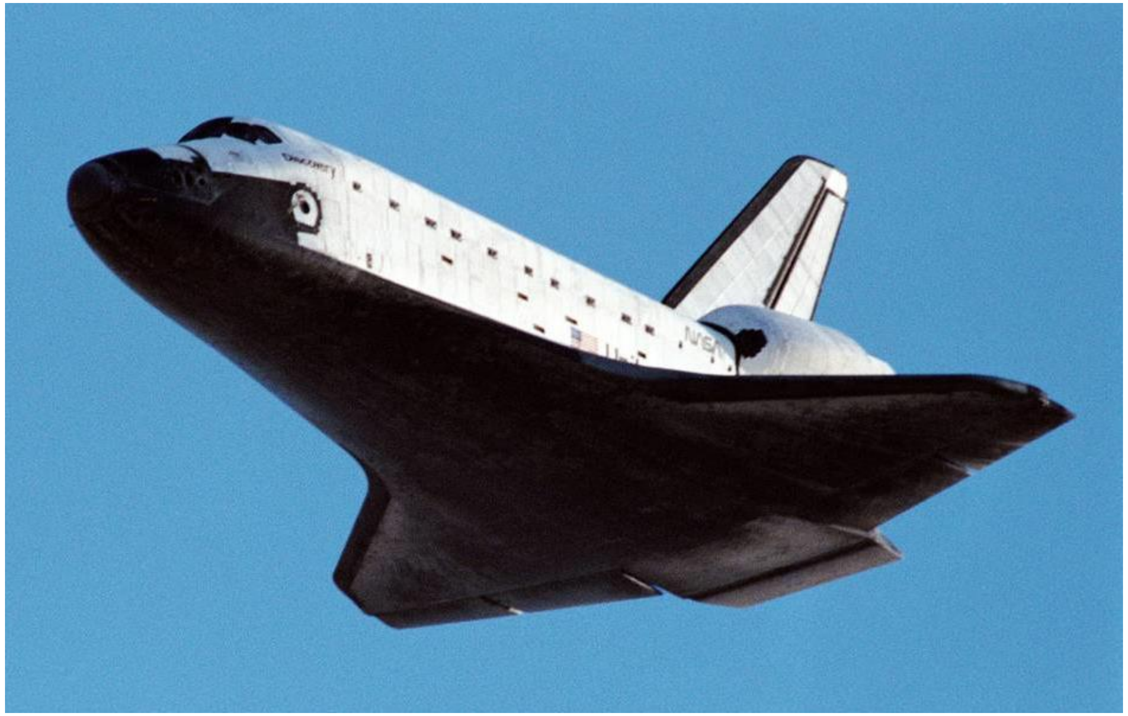
- Atmospheric entry causes heating by gasses that are compressed in front of the vehicle
- A thermal protection system (TPS) is needed to protect the vehicle
- Atmospheric entry profile (trajectory), vehicle geometry, and TPS are designed in concert



Ground testing at ARC's Arc Jet Facilities

Space Shuttle Orbiter

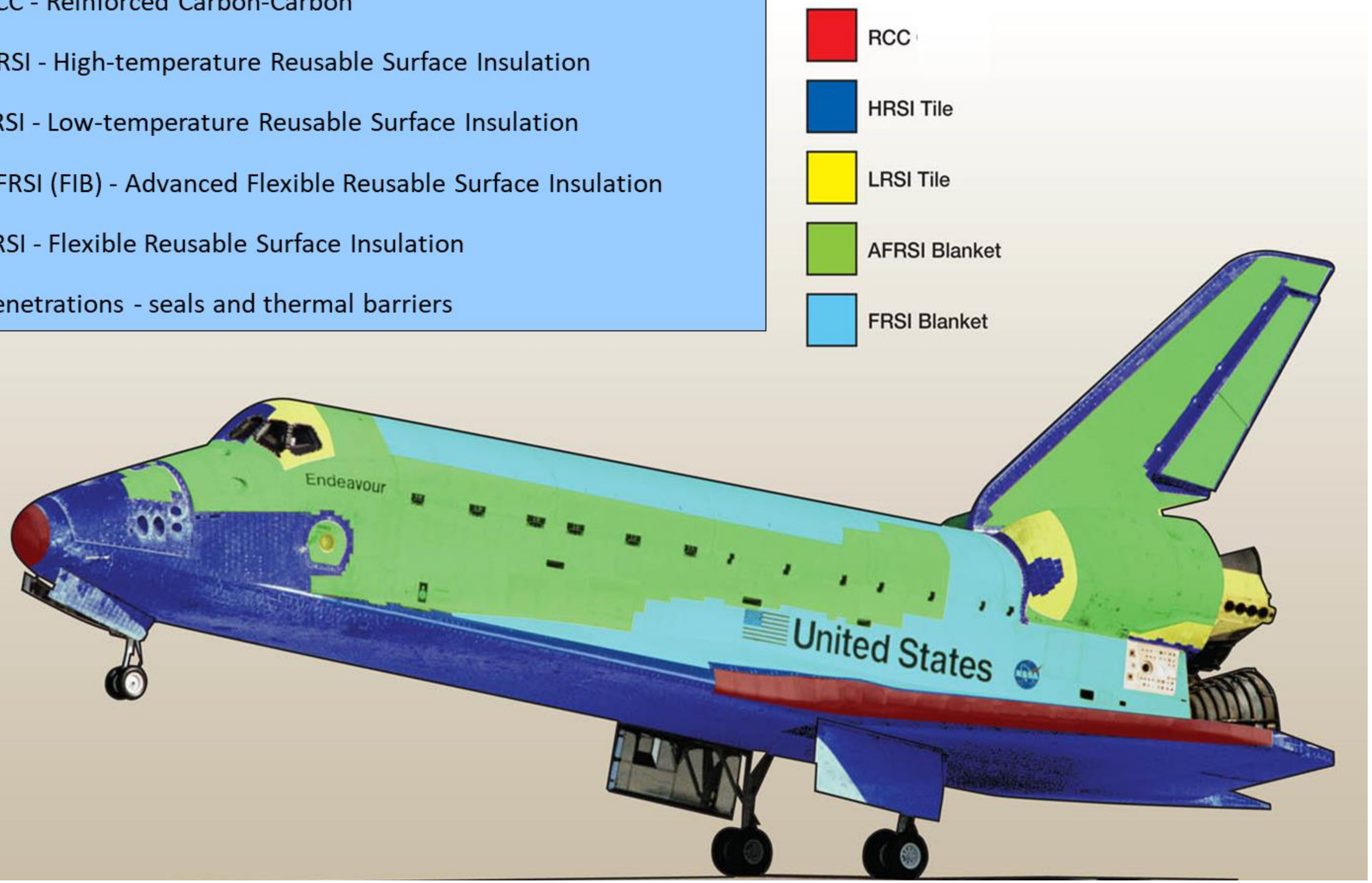
- Shuttle program was started in 1972 as a Space Truck to ferry astronauts and satellites to and from low-earth orbit
- Reusable thermal protection materials were invented to enable the Orbiter Vehicle (OV)
- Fleet
  - Challenger (OV-099)
  - Enterprise (OV-101)
  - Columbia (OV-102)
  - Discovery (OV-102)
  - Atlantis (OV-104)
  - Endeavour (OV-105)



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

Shuttle Orbiter TPS Configuration

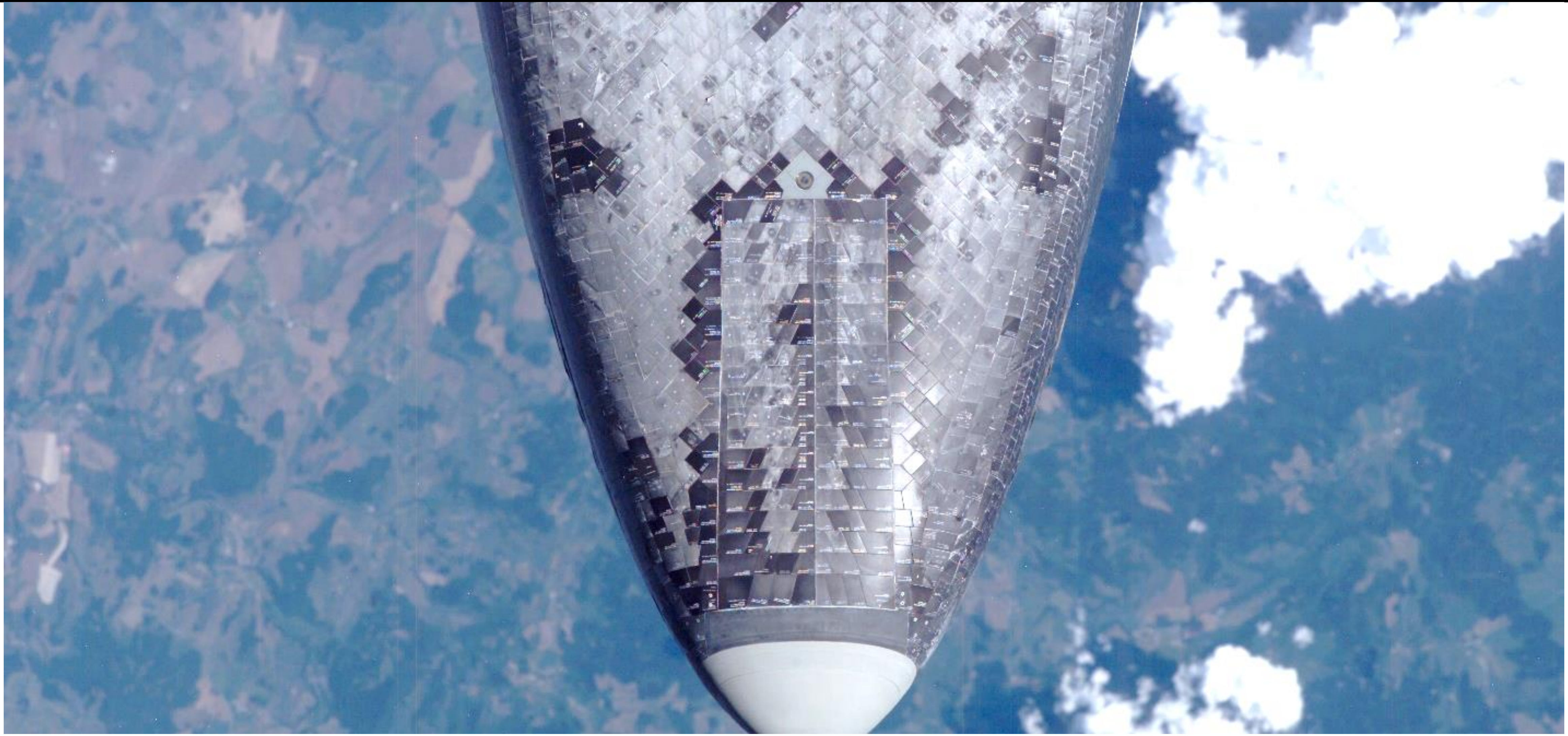
- RCC - Reinforced Carbon-Carbon
- HRSI - High-temperature Reusable Surface Insulation
- LRSI - Low-temperature Reusable Surface Insulation
- AFRSI (FIB) - Advanced Flexible Reusable Surface Insulation
- FRSI - Flexible Reusable Surface Insulation
- Penetrations - seals and thermal barriers



A variety of RTPS were used on shuttle that were tailored for the specific requirements for each area

- Higher condition regions required greater thermomechanical stability which resulted in higher densities and complexity (RCC/HRSI Tile)
- Lower condition regions allowed for flexible materials that could be lower density and easier to integrate (AFRSI/FRSI)

Space Shuttle Orbiter

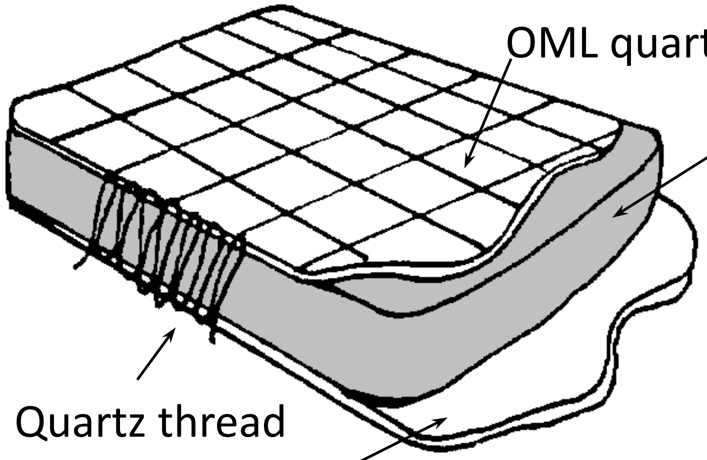


Space shuttle Discovery as viewed from the International Space Station for inspection of the heat shield

Flexible Blanket Materials

Advanced Flexible Reusable Surface Insulation (AFRSI)

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

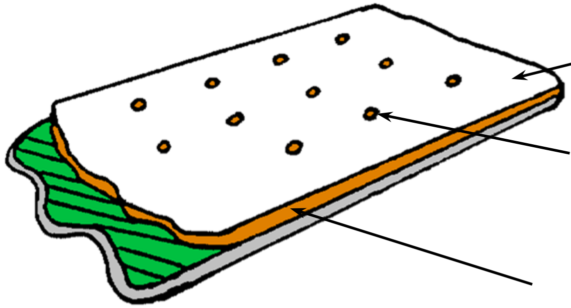


Multi-use Temperature < 1500 °F

Currently not readily available commercially

Flexible Reusable Surface Insulation (FRSI)

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

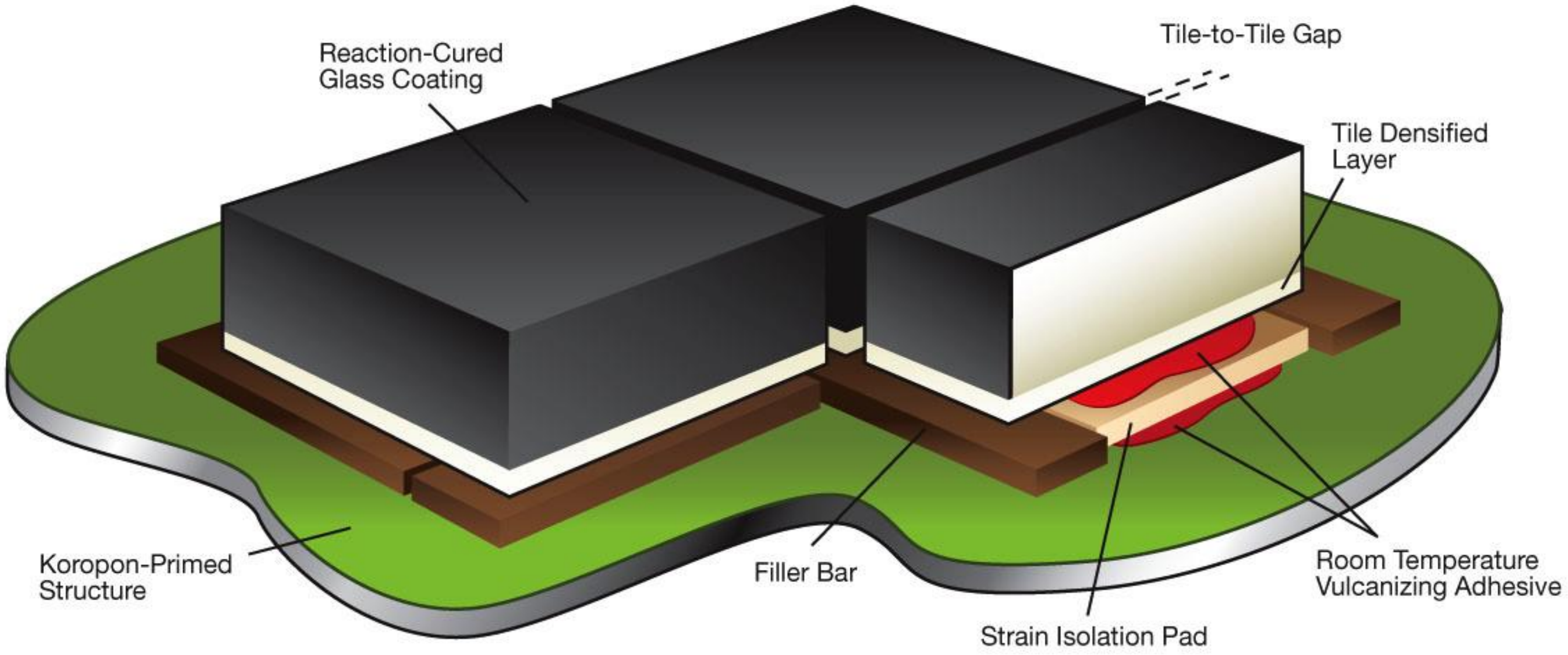


Multi-use Temperature < 700 °F

Available commercially with supply chain risk

HRSI Tile System

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



<u>Materials</u>:
- LI-900
- LI-2200
- FRCI-12

essentially obsolete

- AETB-8
- BRI-18

modern materials

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

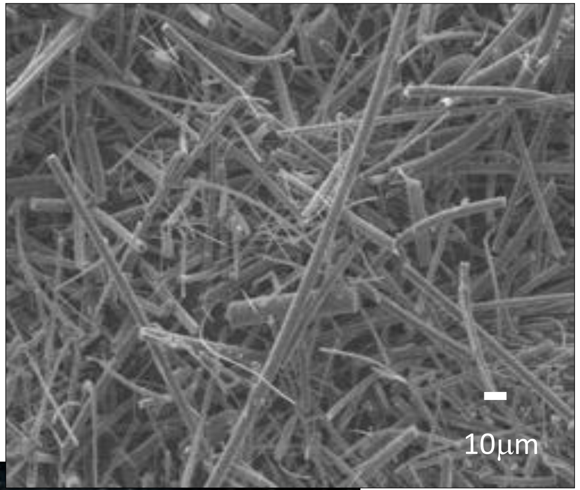
~2300 - 2700 °F

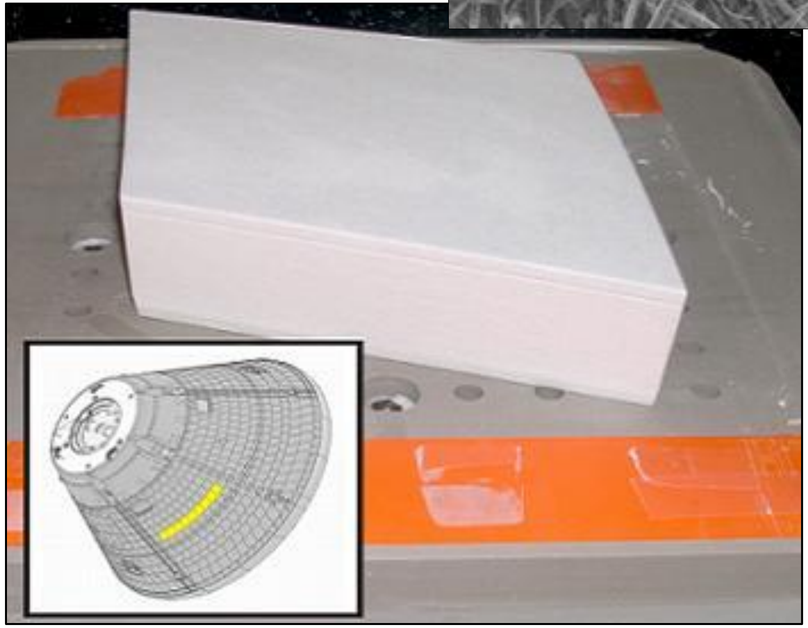
#dependent on material & exposure duration

Alumina Enhanced Thermal Barrier (AETB)

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

- Substrate has ~95% porosity
- Density ranges from 0.13 to 0.32 g/cc
- Consists of aluminoborsilicate fibers, alumina fibers, silica fibers, & silicon carbide
  - Relatively expensive with limited supply chain
- Best dimensional stability of the tile materials
- Rated for use up to 2800 °F (single use) and 2600 °F (multi-use)





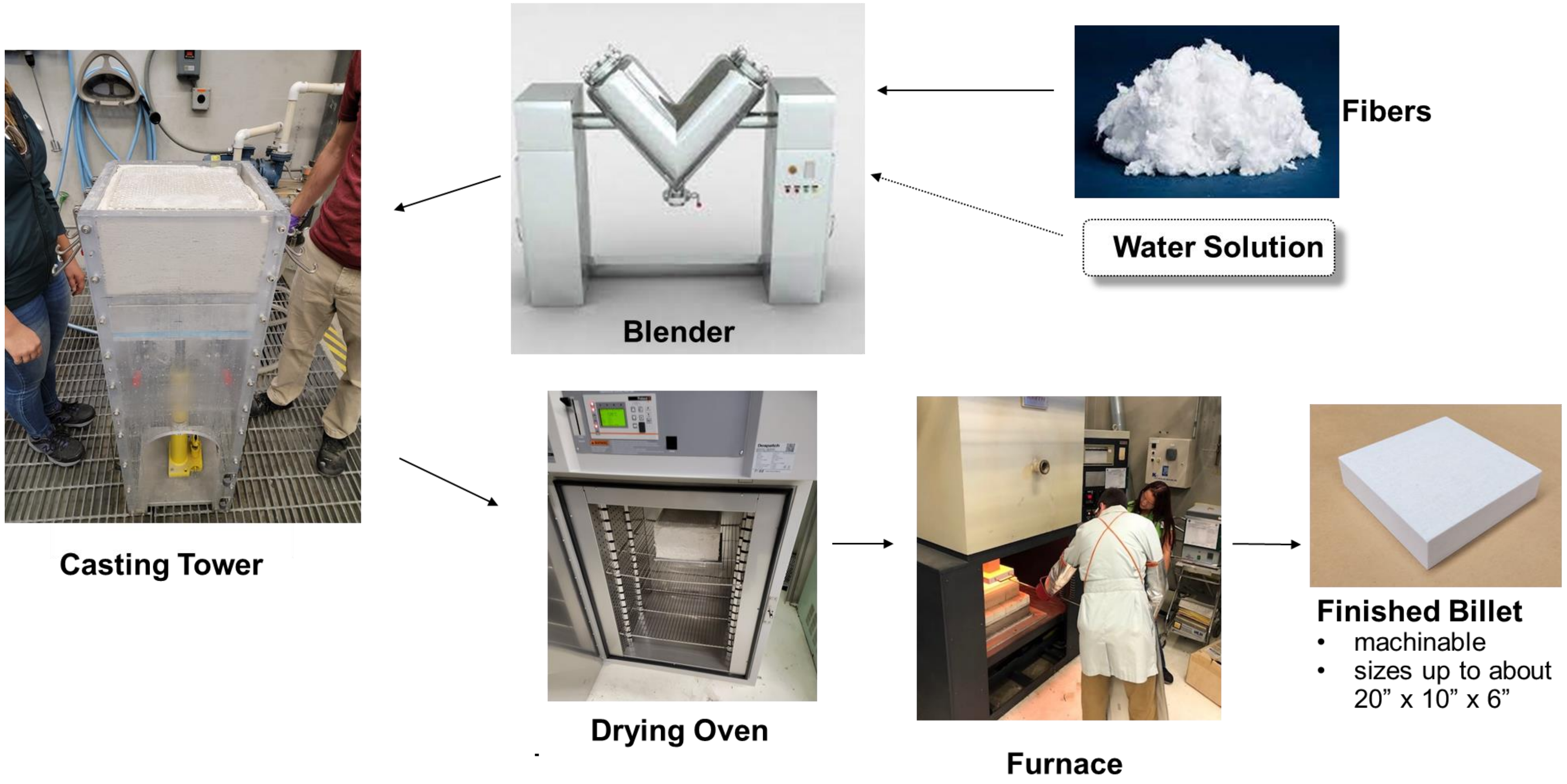
AETB-8 fabricated for Orion backshell

Development Efforts

- NASA stockpile of raw materials (from the 90's) will be depleted during planned Artemis Orion missions requiring transition to modern variants for future NASA missions or commercial space
- We have found marked difference between processing modern raw materials vs heritage resulting in reduced material properties of AETB
- This kicked off modernization efforts to investigate tile processing and allow for utilization of these modern variants while maintaining heritage quality
- Looking beyond to next generation tiles for tailored properties for commercial application

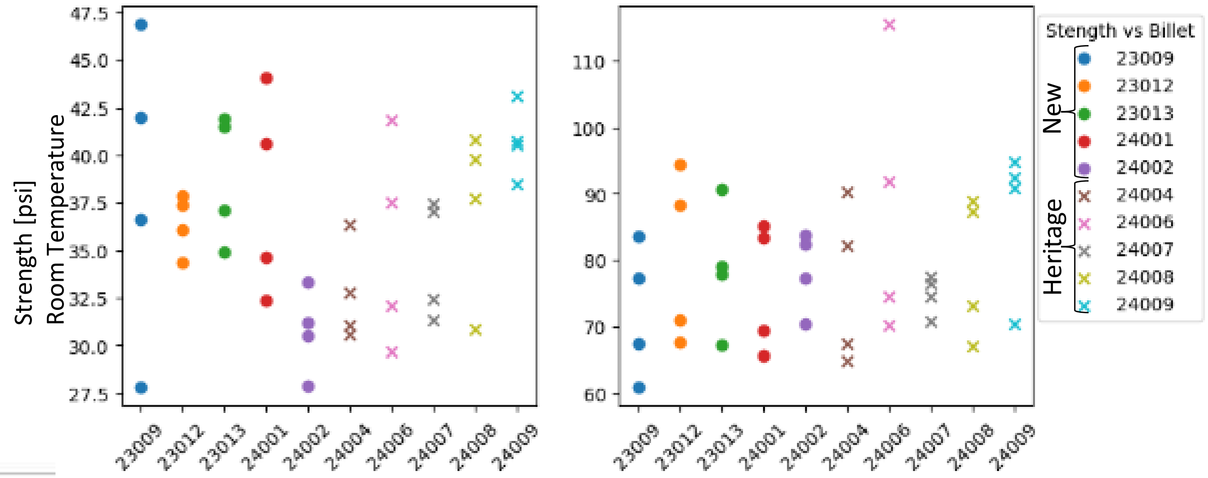
Tile Production Process

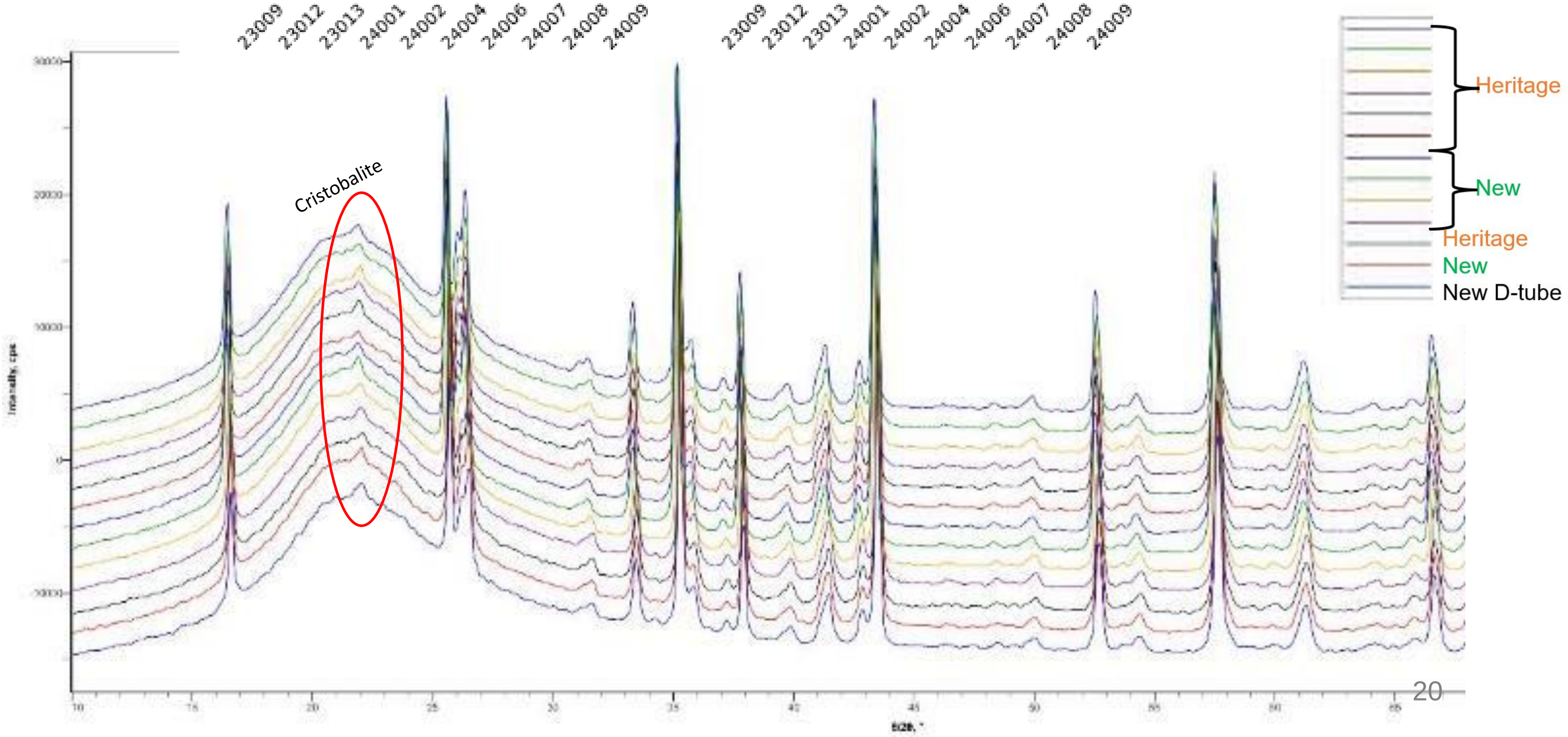
Tile Process Schematic



AETB Traditional Characterization

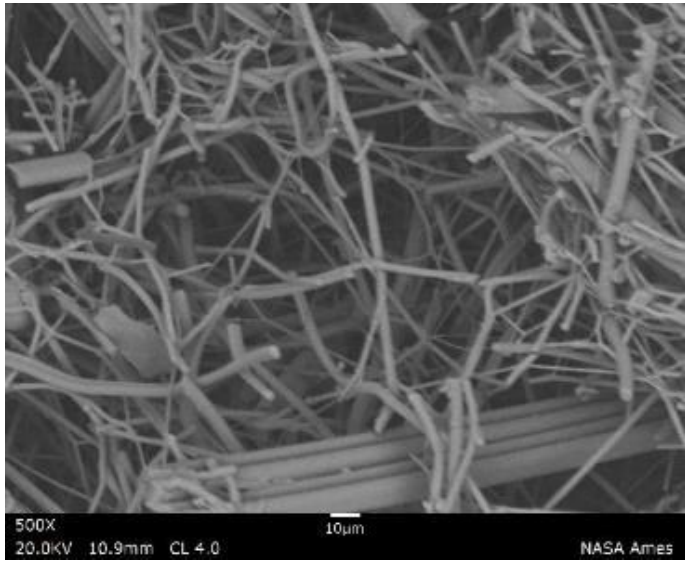
- Most AETB characterization and specification has been on bulk properties
- Ongoing effort to resolve new vs Shuttle heritage fiber has focused on tensile strength and bulk composition (XRD)
- However, sample to sample variation and additional processing studies do not correlate with bulk composition

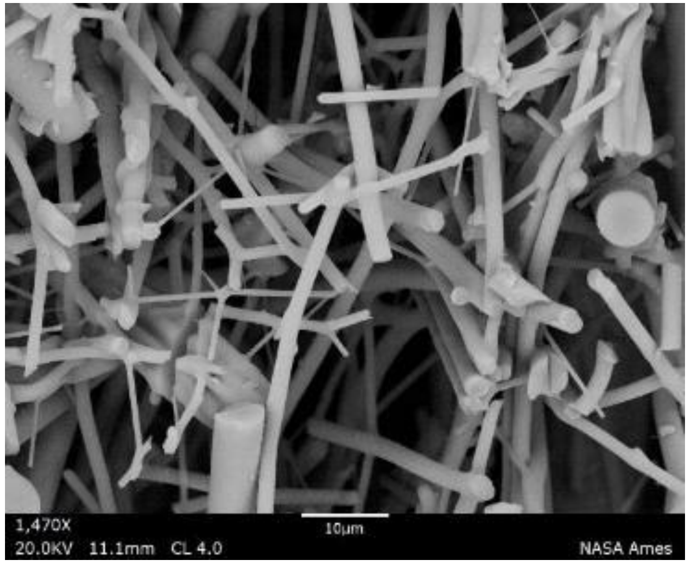




AETB Structure Defects - Properties

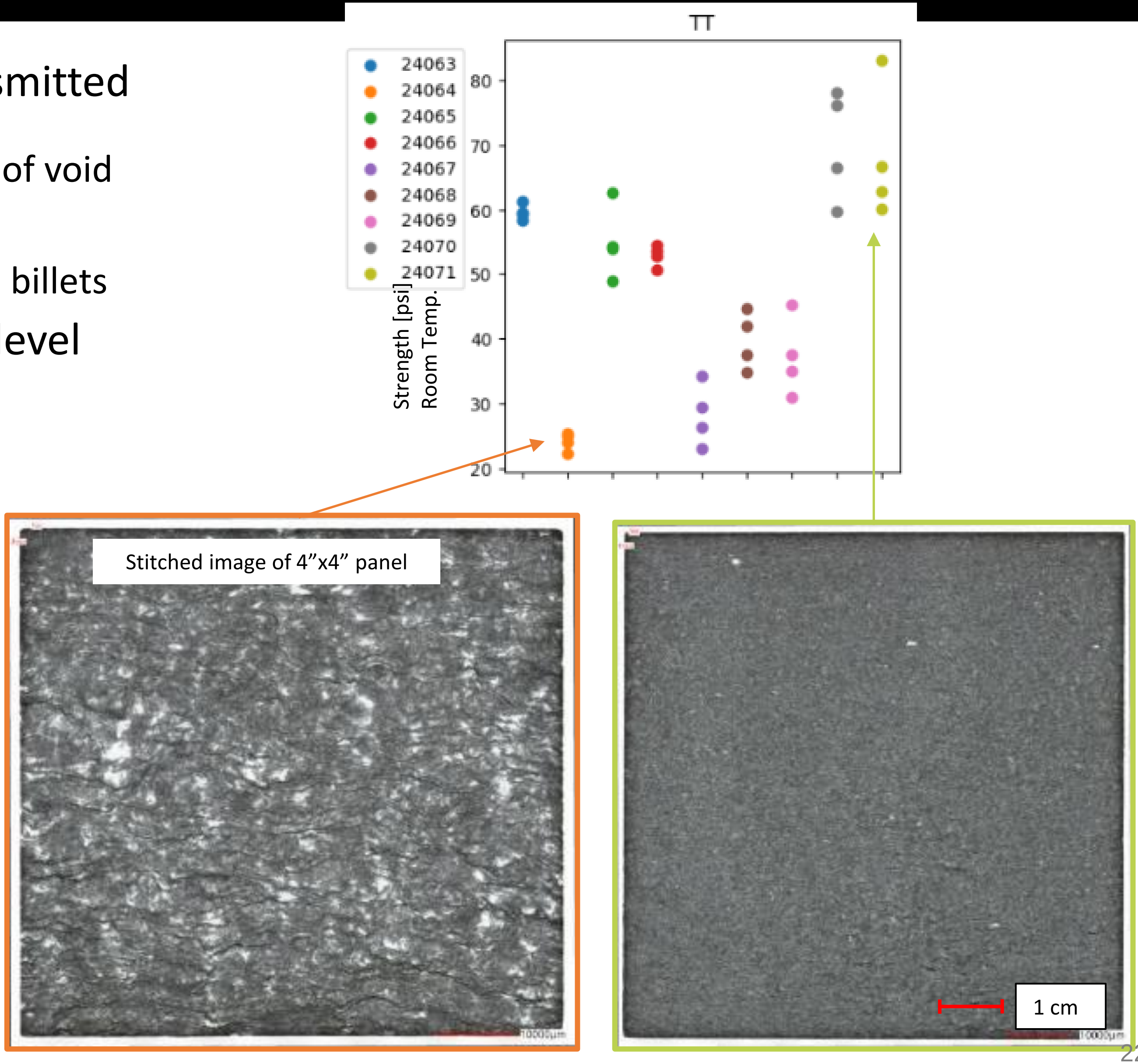
- Microscale structural defects
  - Non-fused fiber junctions – mechanically weak leading to stress concentrations
  - Cristobalite formation and growth – fracturing of silica fibers from thermal cycling
- Mesoscale structural defects
  - Voids (~100µm and larger)
    - Stress concentrations
    - Translate to defects in coatings and attachment
  - Alumina fiber clusters
    - Collapse elsewhere due to lack of alumina
  - Nextel fiber clusters
    - Locally low mechanical strength and regional devitrification



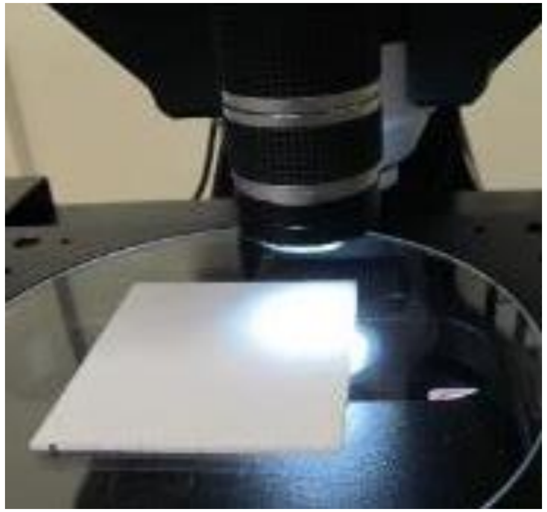


AETB Micro/Mesostructure Characterization

- Initial characterization of coarse structure by transmitted light microscopy
  - 4mm thick slices approximately the scale of large end of void distribution
  - "Particle" size analysis on bright (voids) and dark (SiC segregation) correlates to highest and lowest strength billets
- Does not capture true microstructure at the fiber level
- Ongoing project to utilize µCT scanning

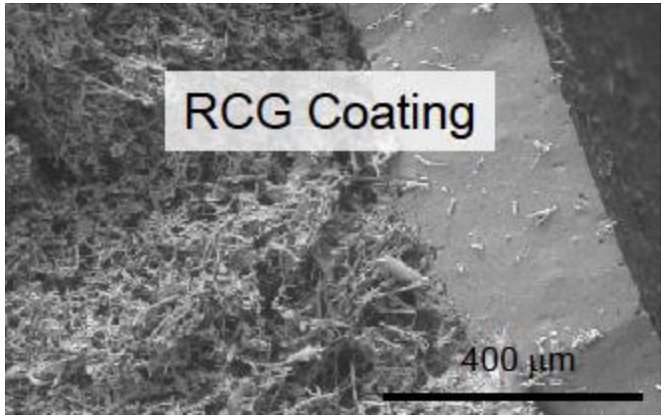


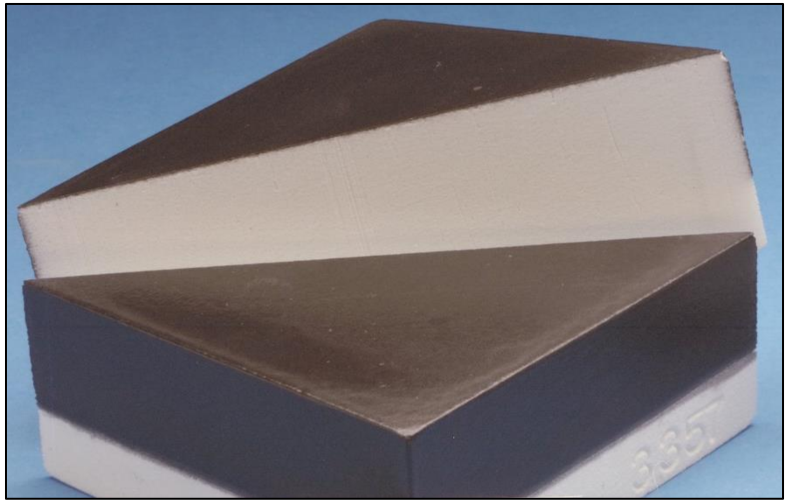
Optical Microscope Set-Up

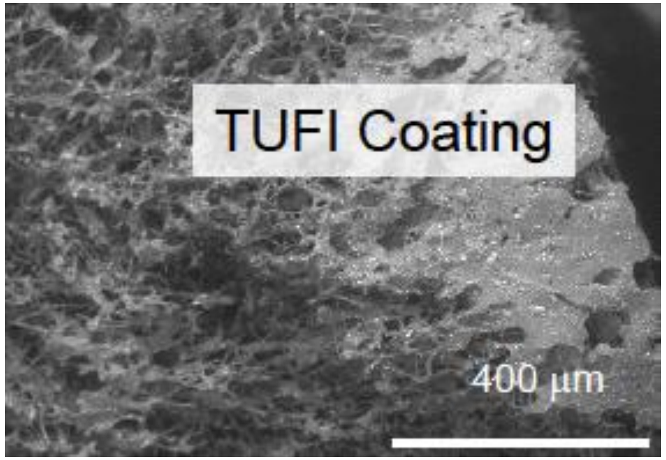


Coatings

- Reaction Cured Glass (RCG)
  - Coatings sit on top of the substrate & partially seal surface
  - Consists of borosilicate glass (B_2O_3/SiO_2) and silicon boride (SiB_x)
- Toughened Uni-Piece Fibrous Insulation (TUFI) is
  - 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)
- Same issue with the raw material supply concerns as the fiber

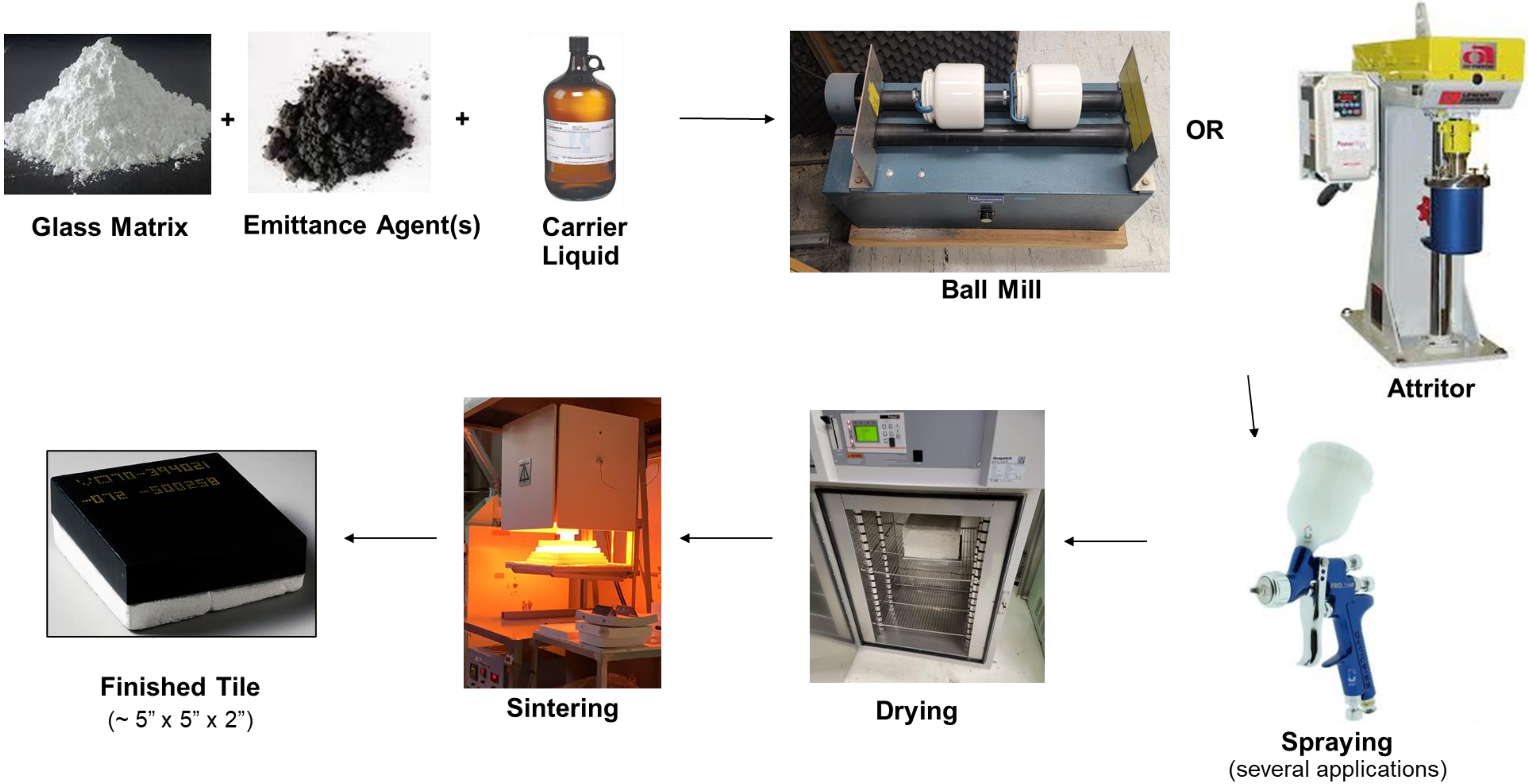






Tile Coating Process

Coating & Surface Treatment Fabrication Process



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

Summary

- Motivation
  - Supply chain concerns for raw materials to produce heritage quality RTPS
  - Increasing commercial space demand for low cost -> reusability
- Background on Entry and Reusable Thermal Protection Systems (RTPS)
- Current State-of-the-Art RTPS
- Development Efforts
  - Modernization to utilize contemporary raw materials

Acknowledgments

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

HTRM Research group:

- Audrey Turcotte
- Dan Leiser
- Jay Feldman
- Jose Chavez-Garcia
- Kyle Hendrickson
- Kristina Skokova
- Marc Rezin
- Matt Switzer
- Peter Marshall

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

Questions?

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National Aeronautics and Space Administration

Ames Research Center
Entry Systems and Technology Division

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

Aerothermal Heating During Entry

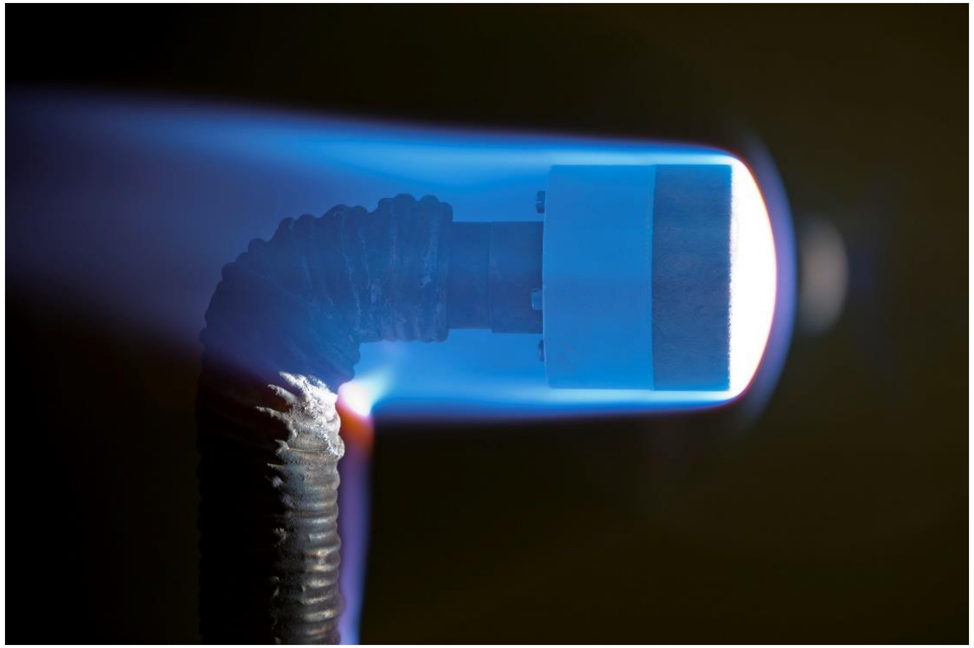
- Convective heating ($\dot{q}_{conv}$) – heat transfer resulting from conduction with the shock layer gasses (typically includes atomic recombination on the surface)
- Radiative heating ($\dot{q}_{rad}$) – radiation from excited atoms and molecules in the shock layer

- 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]

Shuttle Orbiter TSP Configuration

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- HRSI - High-temperature Reusable Surface Insulation
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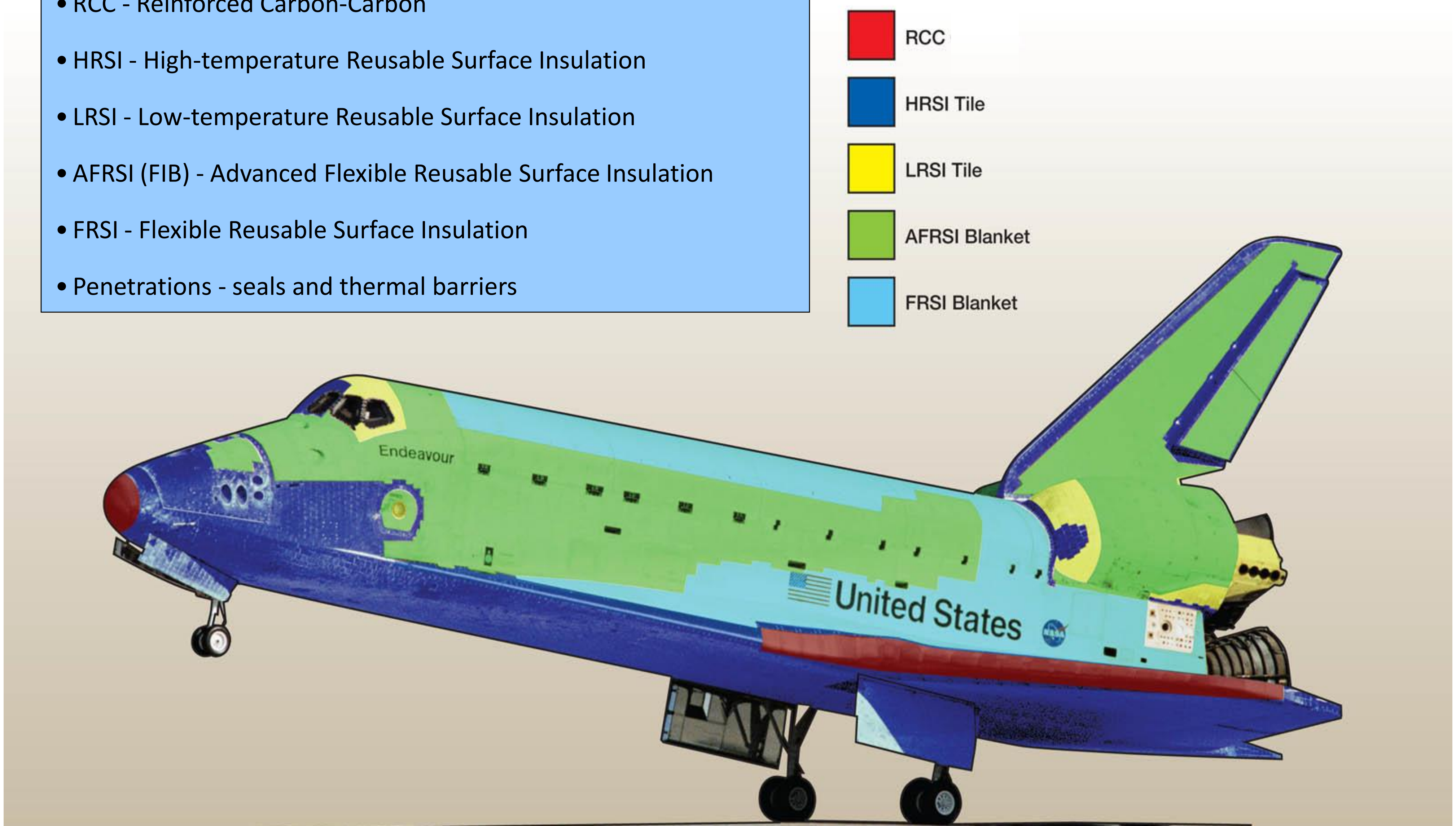
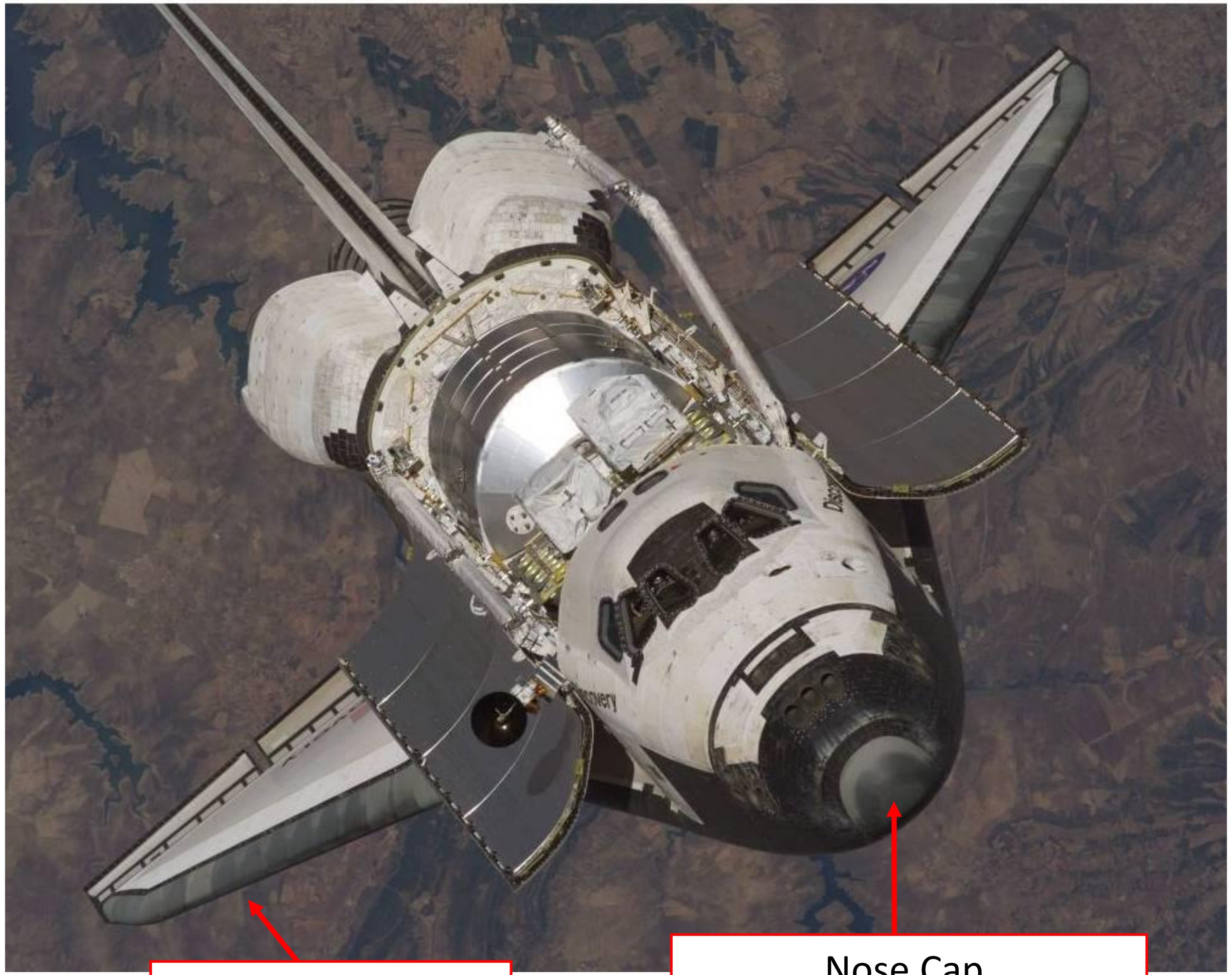


Reinforced Carbon/Carbon (RCC)

- 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
- Cost and lead time concerns

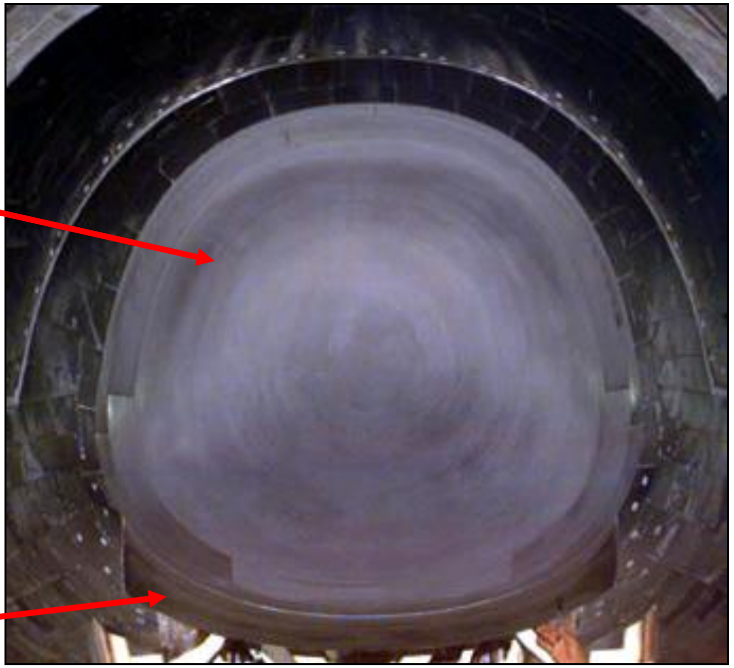


Wing Leading Edge Panels and Seals

Nose Cap, Chin Panel, ET Arrowhead Attach Plate, and Seals

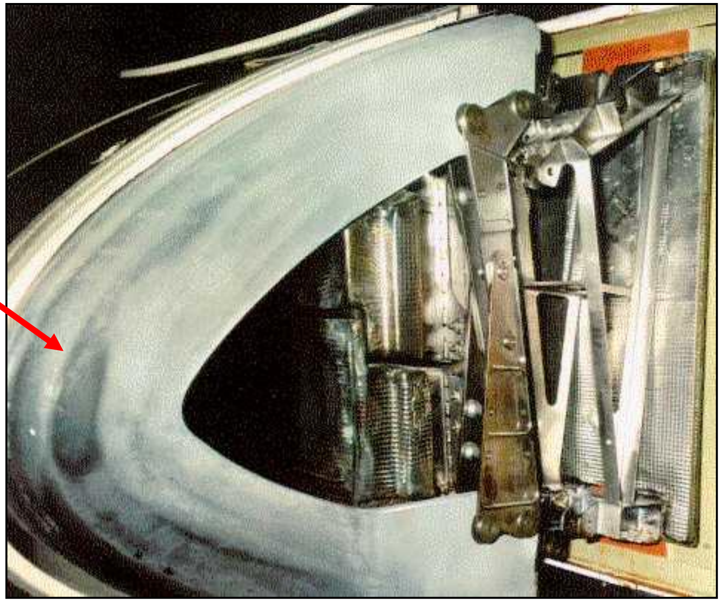
RCC Components

Nose Cap and Seals

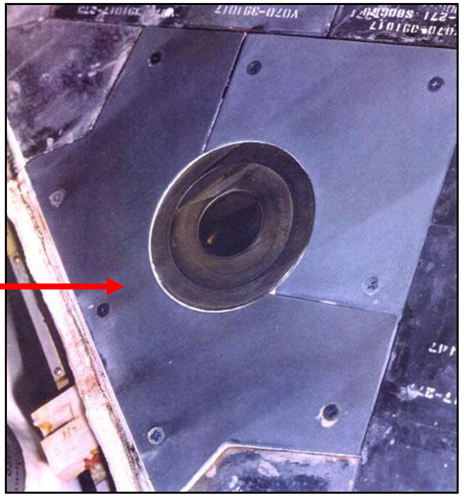


Chin Panel and Seals

Wing Leading Edge Panel



Forward ET Attach Point Arrowhead RCC Plates



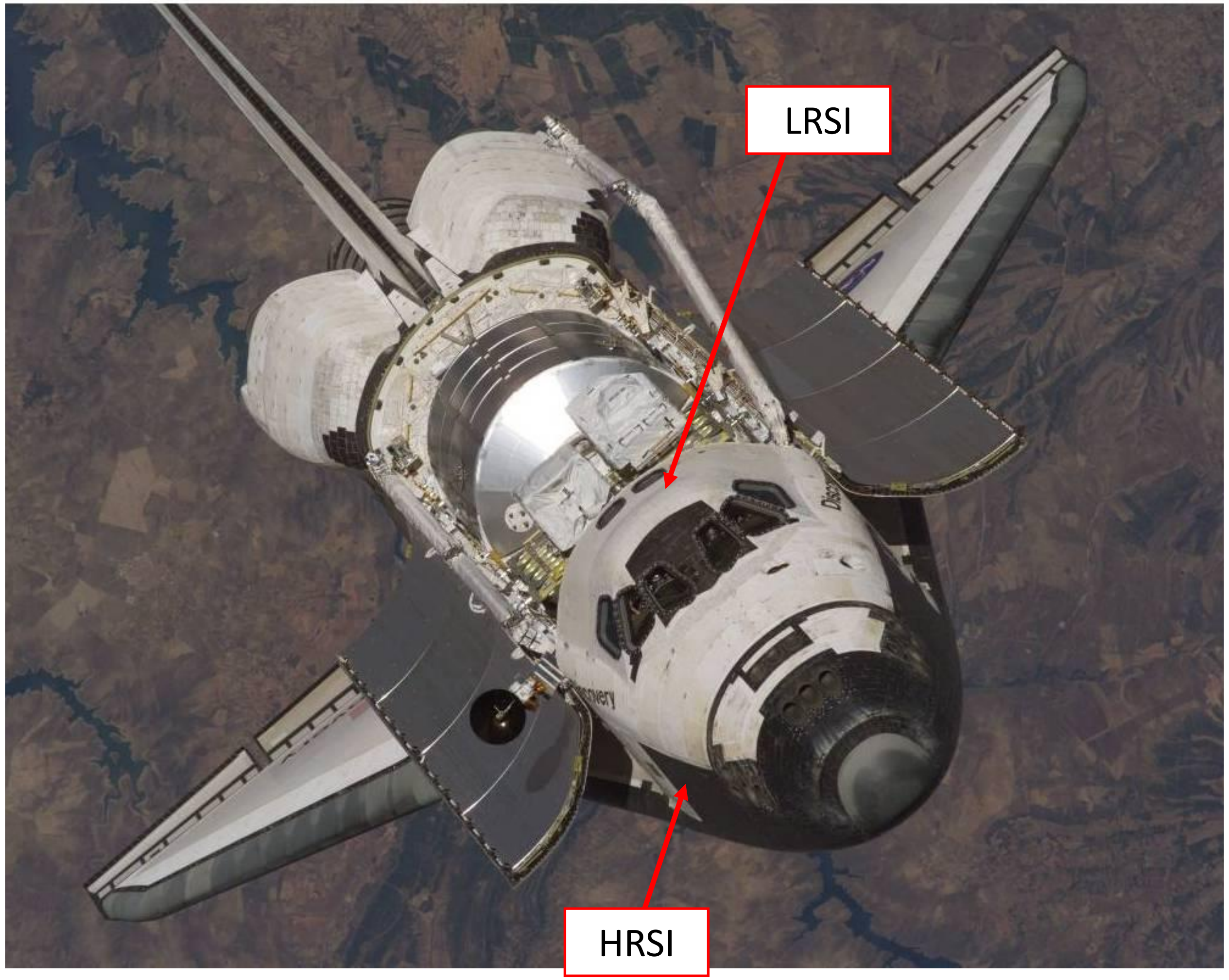
Tile Materials

HRSI - "High-temperature Reusable Surface Insulation"

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

LRSI - "Low-temperature Reusable Surface Insulation"

- White glass coating with high reflectivity to reflect sunlight
- Multi-use temperature – 1200°F

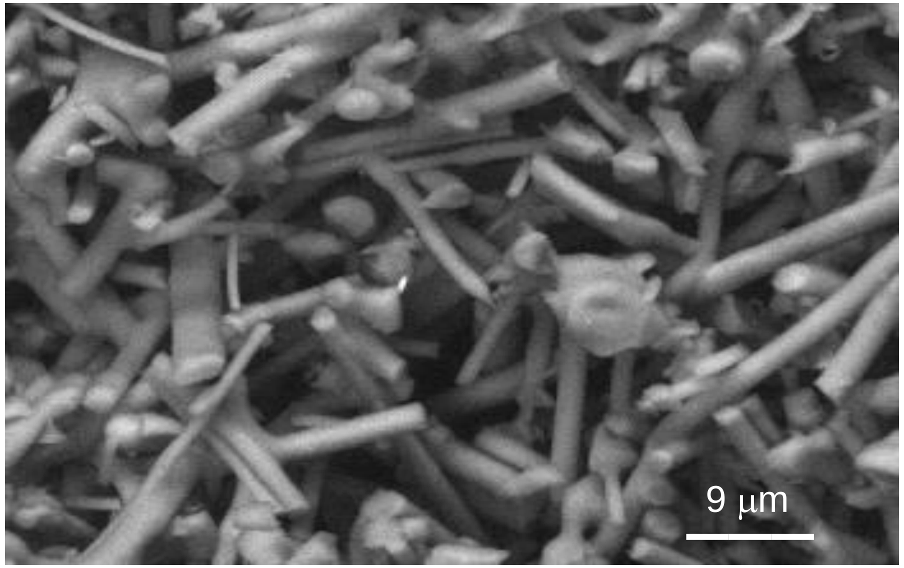


Tile Materials

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)
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)

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

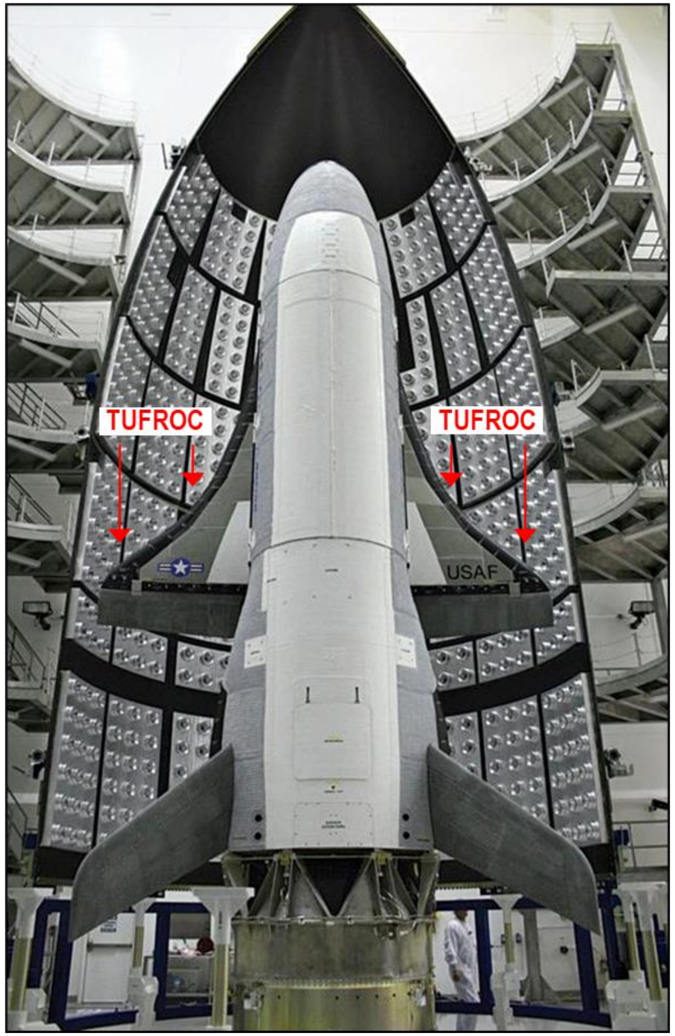
- “Fibrous Refractory Composite Insulation”
- Developed in 1979 at NASA Ames
- Consists of silica fibers and aluminoborosilicate fibers
- Density of 12 pcf (0.19 g/cc)
- Lower density than LI-2200 with higher tensile strength
- FRCI replaced HRSI tiles where damage had been an issue

Virgin FRCI tile surrounded by LI-900

TUFROC

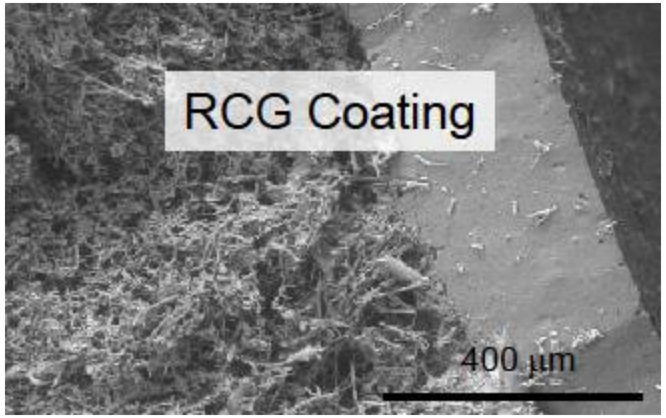
- "Toughened Uni-piece Fibrous Reinforced Oxidation-Resistant Composite"
- A multi-component tiled TPS system that is the state-of-the-art reusable material system used on the leading edges of X-37B
- Features (vs. C/C or C/SiC)
  - Low cost (10x cheaper than C/C)
  - Light weight (~0.3 g/cm^3)
  - Insulative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

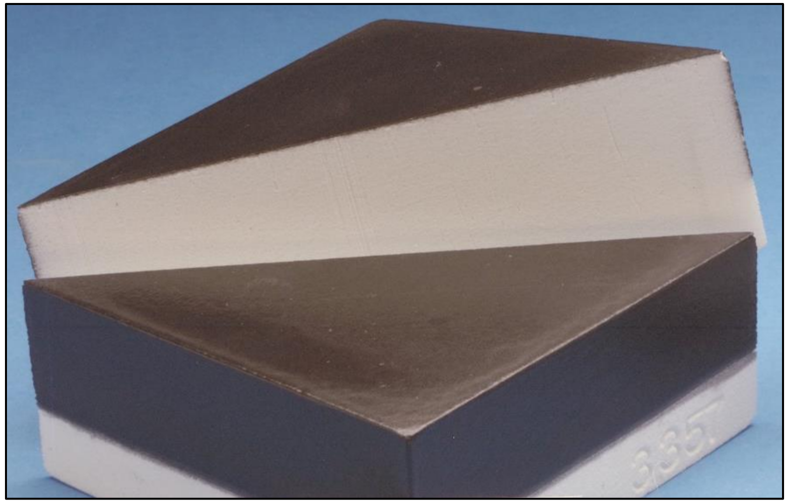
X-37B preparing for 1st launch, 2010



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





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.