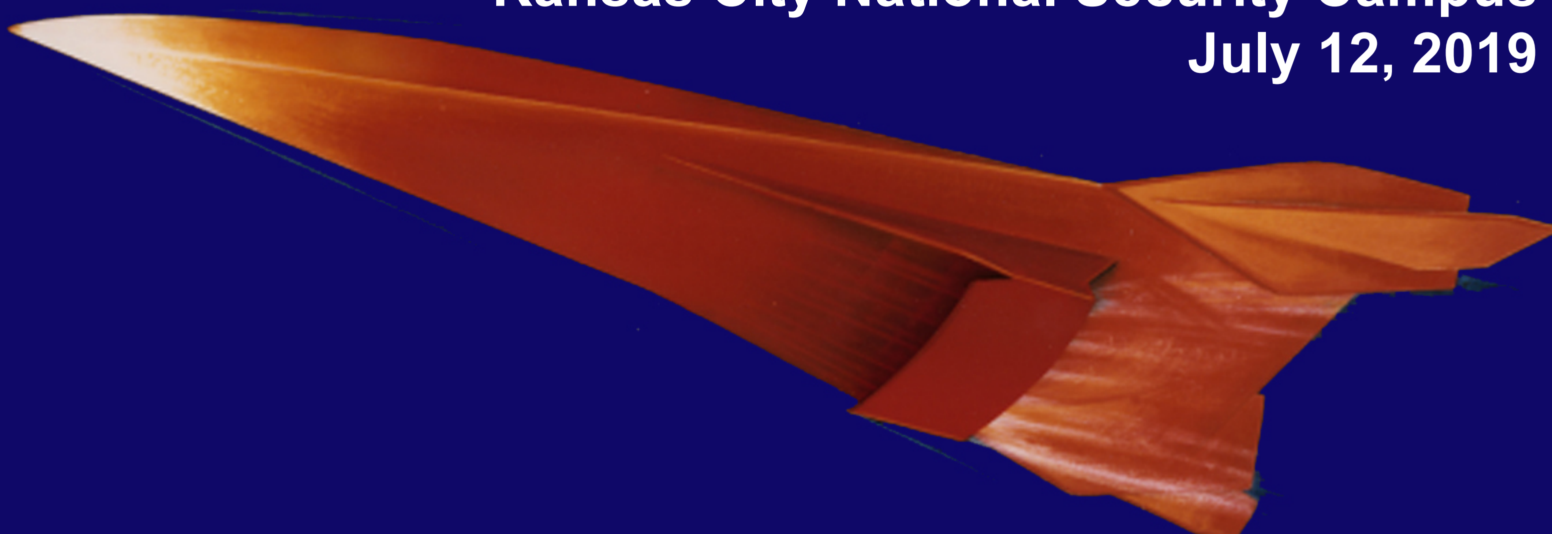
Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles

Kansas City National Security Campus
July 12, 2019



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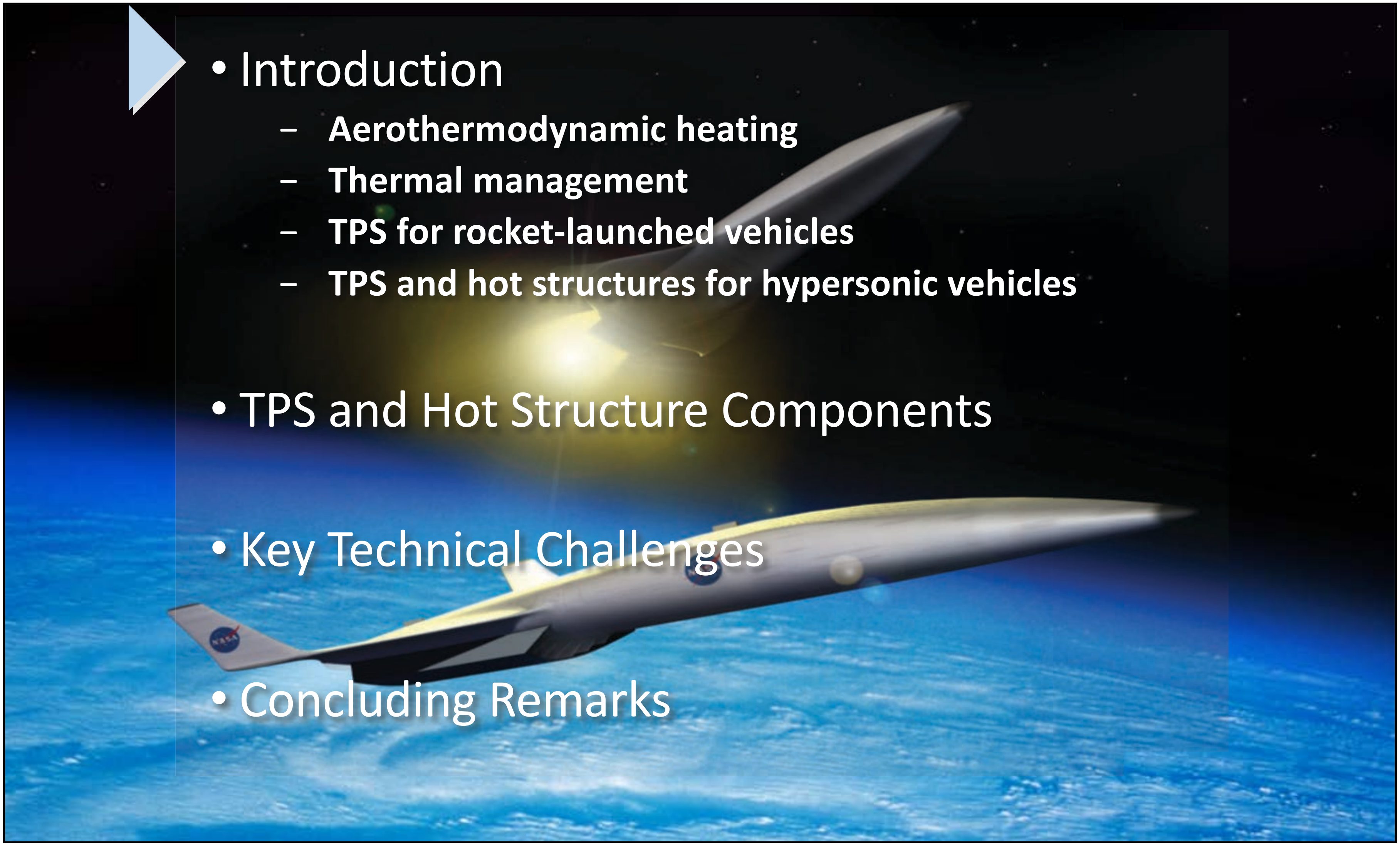
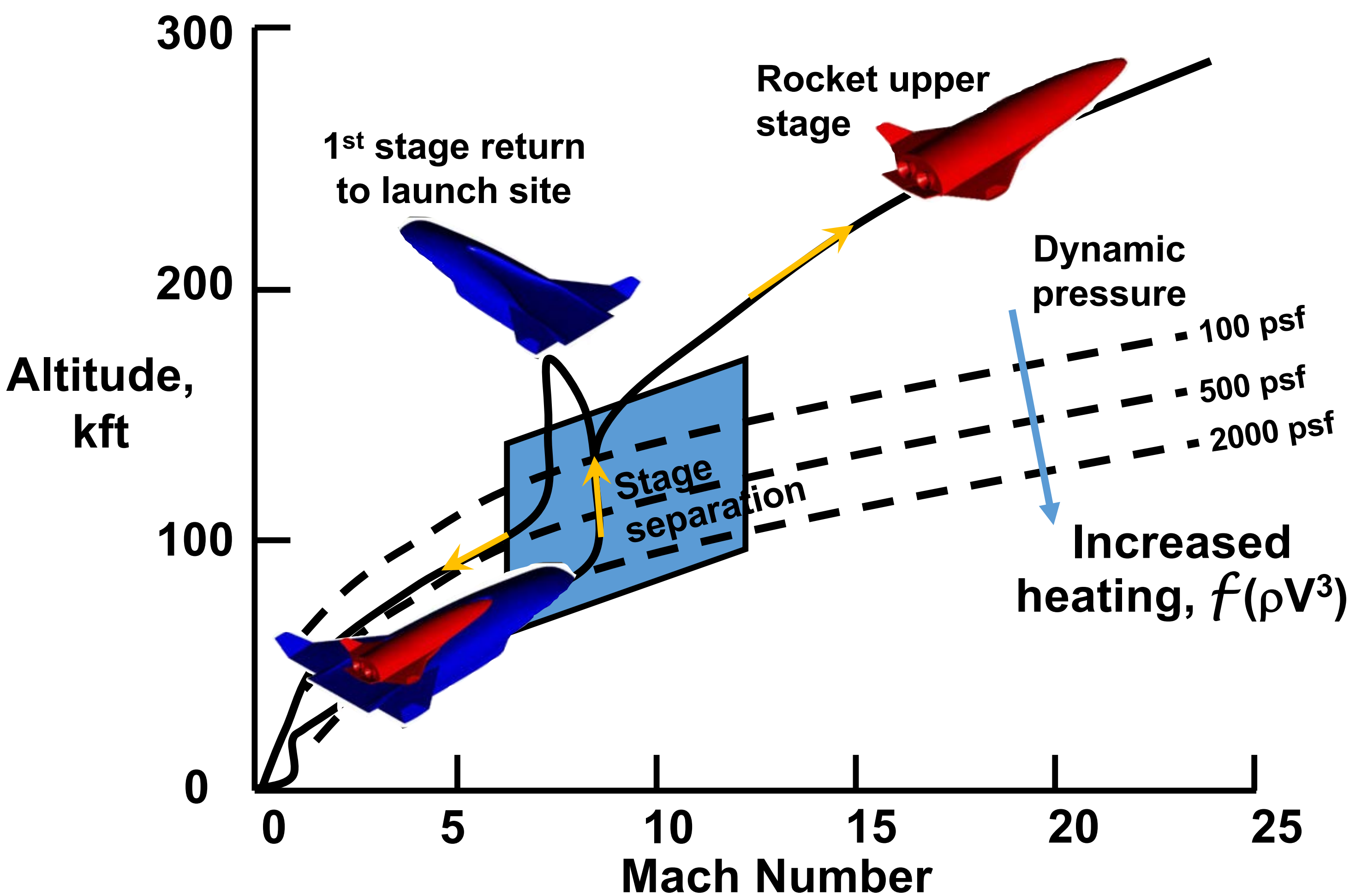
Outline

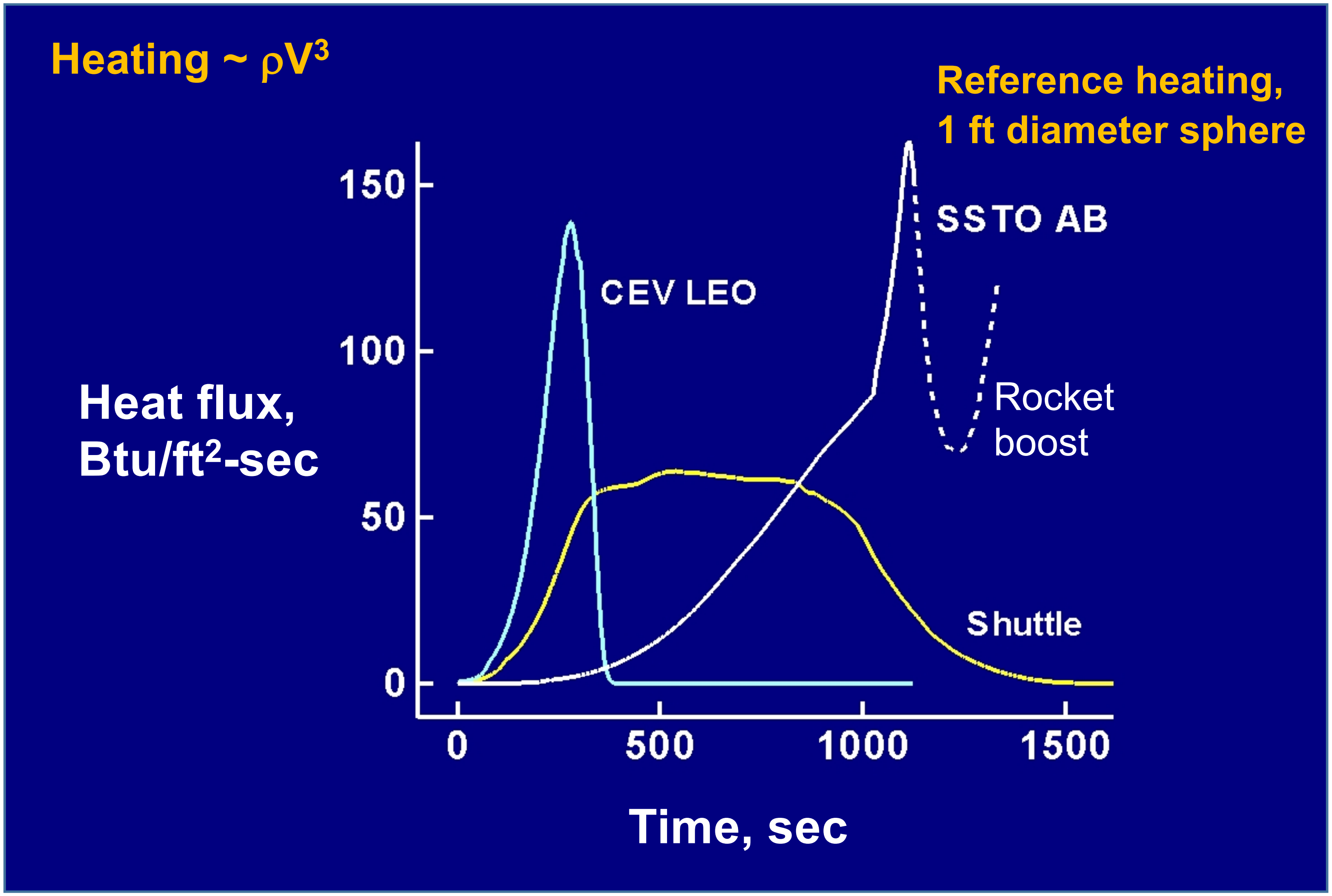


- Introduction
  - Aerothermodynamic heating
  - Thermal management
  - TPS for rocket-launched vehicles
  - TPS and hot structures for hypersonic vehicles
- TPS and Hot Structure Components
- Key Technical Challenges
- Concluding Remarks

Two Stage to Orbit (TSTO) Reference Vehicle



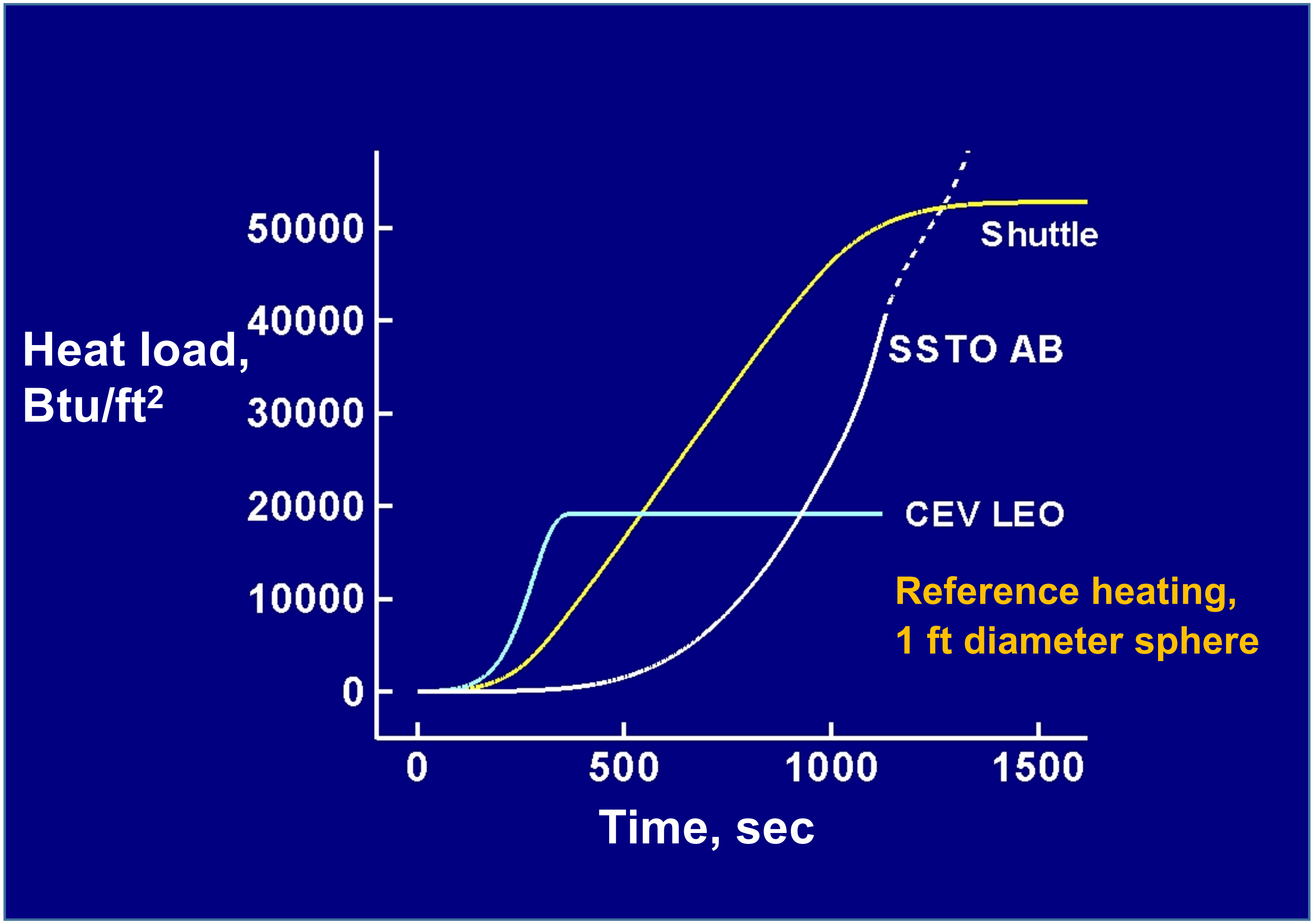
Heat Flux



Crew Exploration Vehicle (CEV) Low Earth Orbit (LEO)
Single Stage to Orbit (SSTO) Airbreather (AB)

Heat Load

$$\text{Heat Load} = \int_{t=0}^{t_{final}} \text{Heat flux} \cdot dt$$



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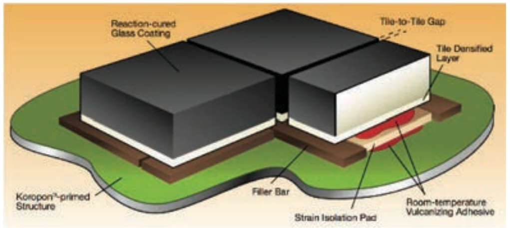
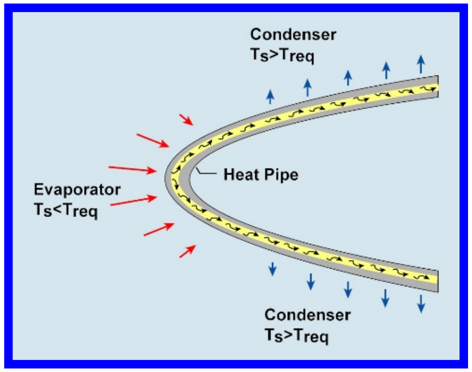
Types of Thermal Management

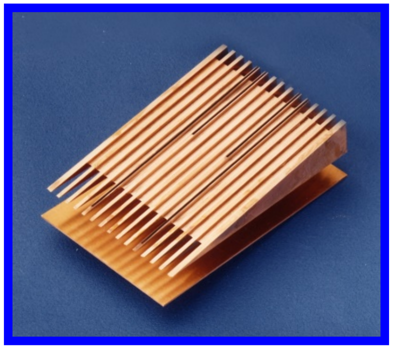
- Passive



- Semi-passive
  - Phase change

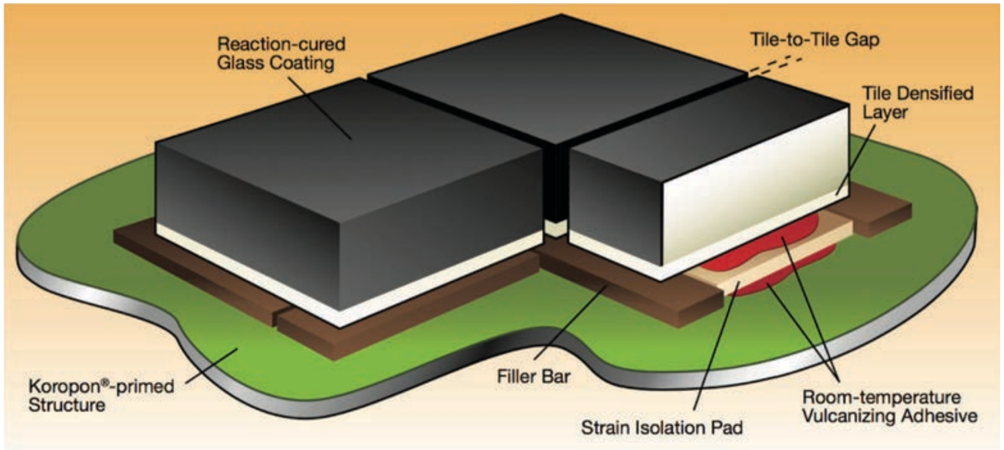


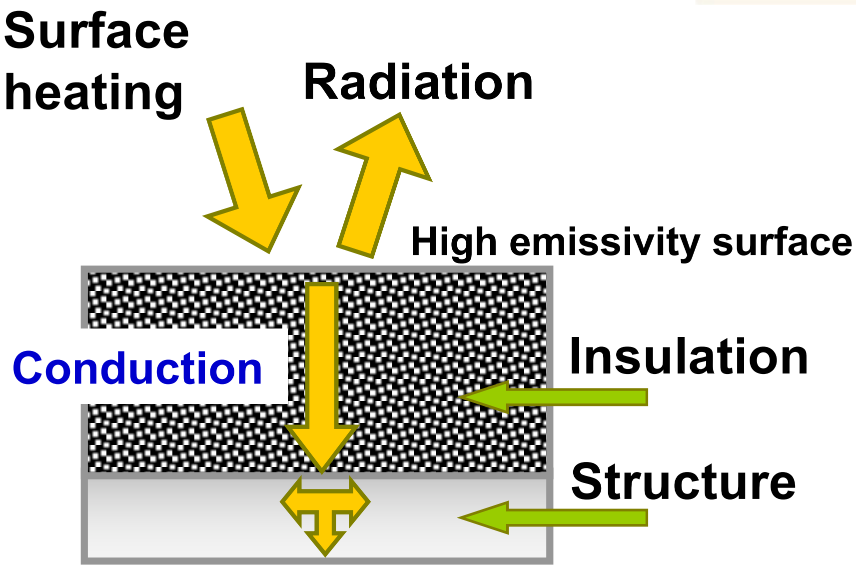
- Active
  - Pumped coolant



Passive: Insulated Structure

Use: Moderate heat flux, short times

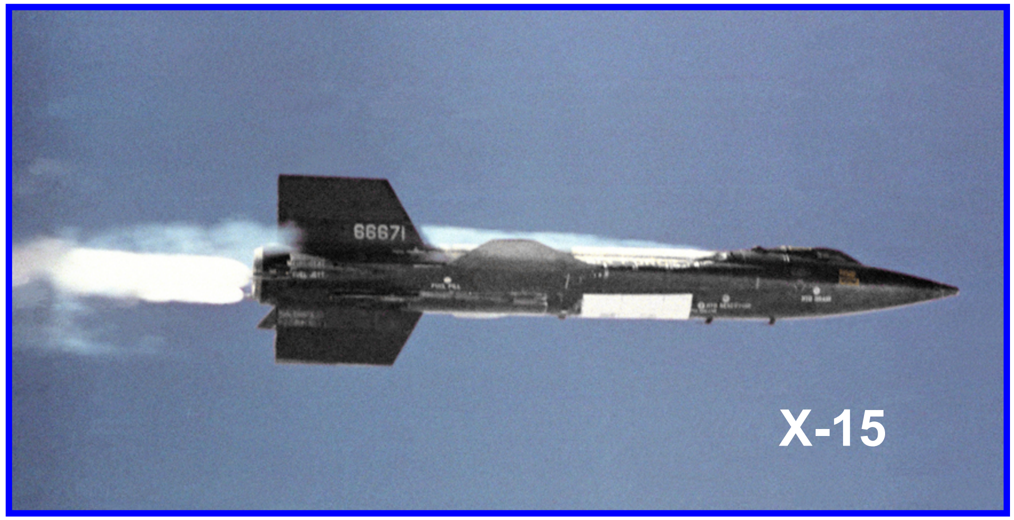


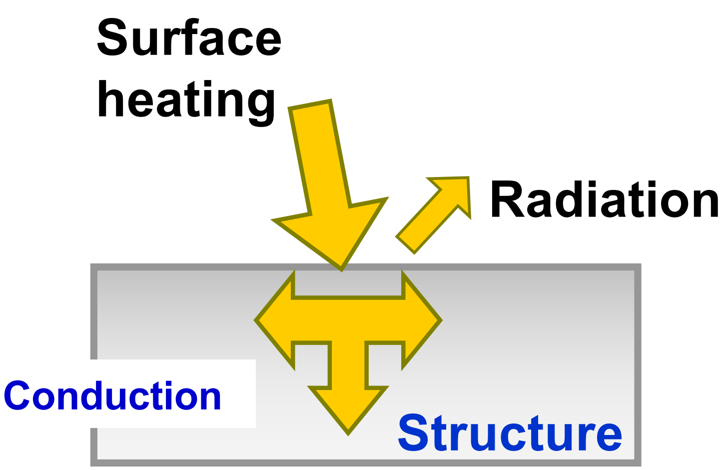


- **Heat radiated away**
  - **Maximize surface emissivity**
- **Minimal heat conducted inward**
- **Structure remains cool**

Passive: Heat Sink Structure

Use: Moderate heat flux, short times (transient)

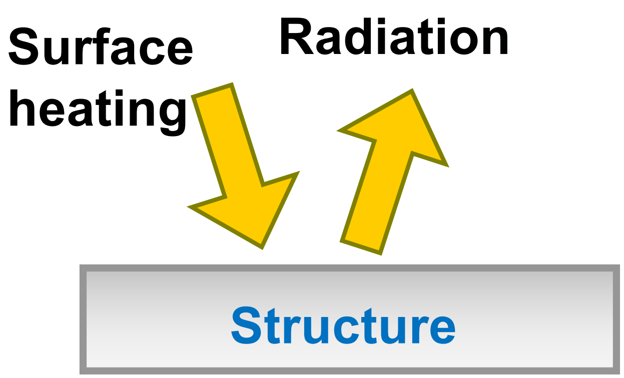




- Heat radiated away
- Heat absorbed by structure

Passive: Hot Structure

Use: Moderate heat flux, long times (steady state conduction)

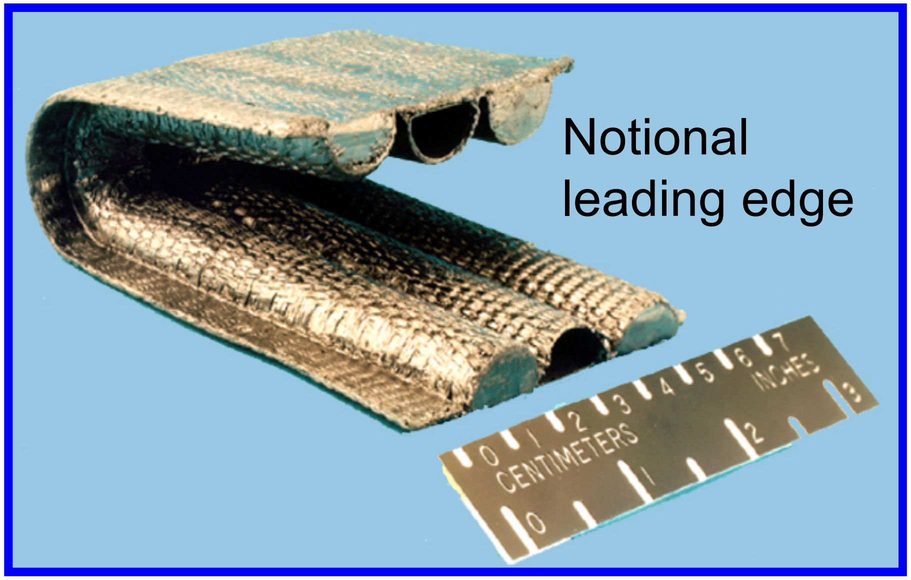


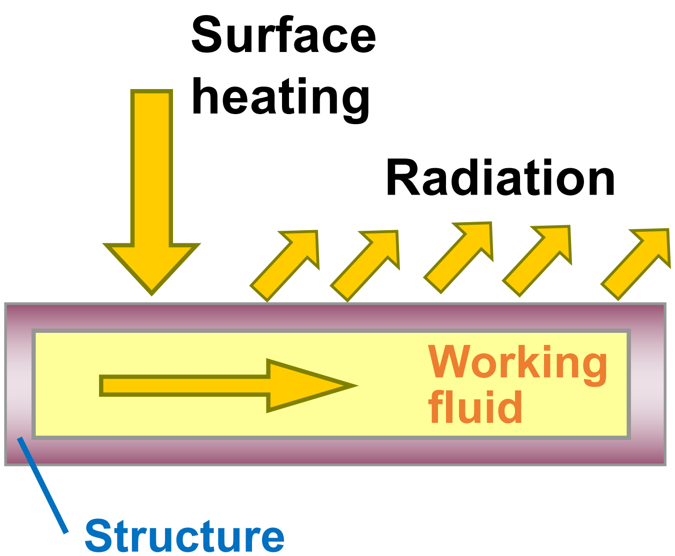
Sub-scale X-37 control surface manufacturing demo

- Heat radiated away
- Heat conducted inward
- Structure operates hot

Semi-Passive: Heat Pipe

Use: High heat flux, long times

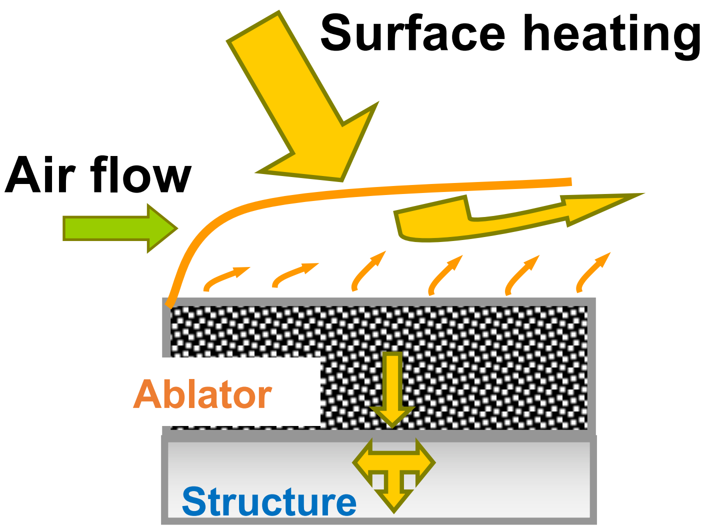




- **Heat transferred by working fluid**
- **Heat radiated away**
- **Structure operates hot**

Semi-Passive: Ablation

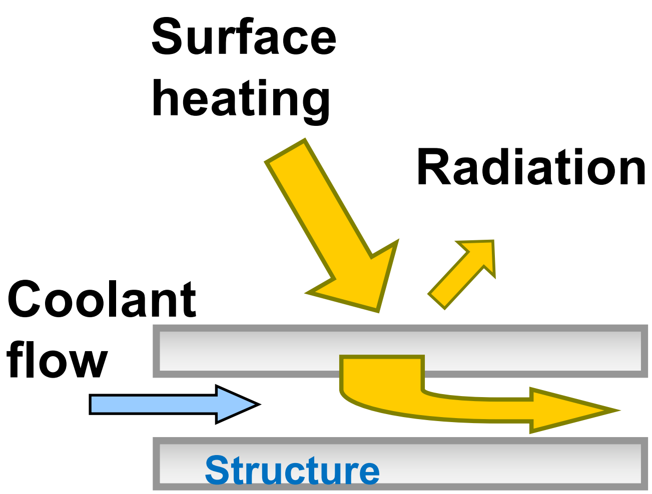
Use: High heat flux, short times, single use



- **Heat blocked by products of ablation (ablator consumed)**
- **Heat absorbed by ablation**
- **Structure remains cool**

Active: Convective Cooling

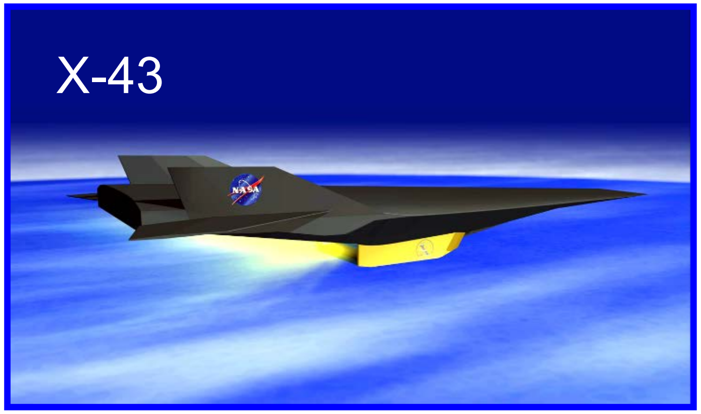
Use: High heat flux, long times

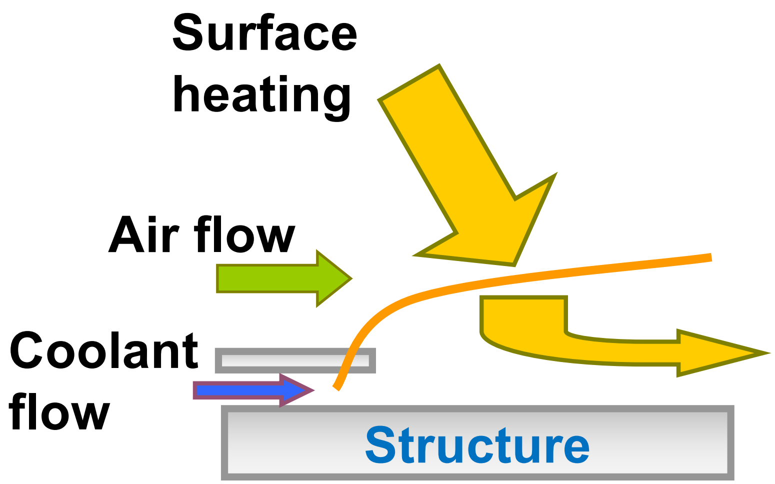


- Heat transferred into coolant
- Coolant heats up and carries heat away
- Structure operates hot

Active: Film Cooling

Use: High heat flux, long times

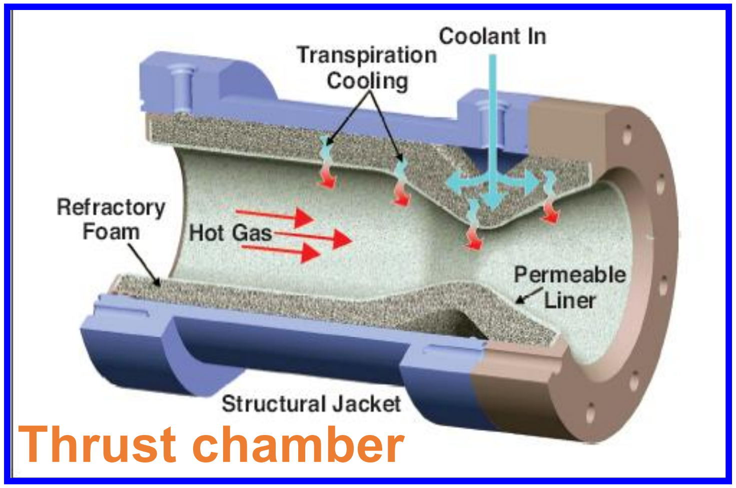


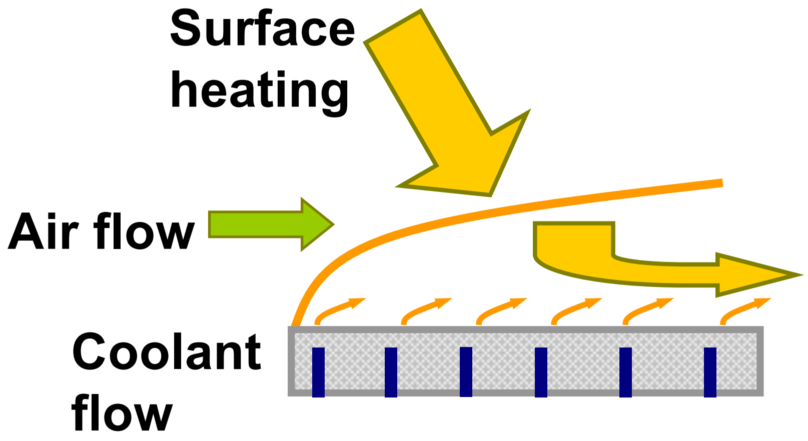


- Coolant injected into flow (upstream)
- Thin, cool, “insulating” blanket
- Structure operates hot

Active: Transpiration Cooling

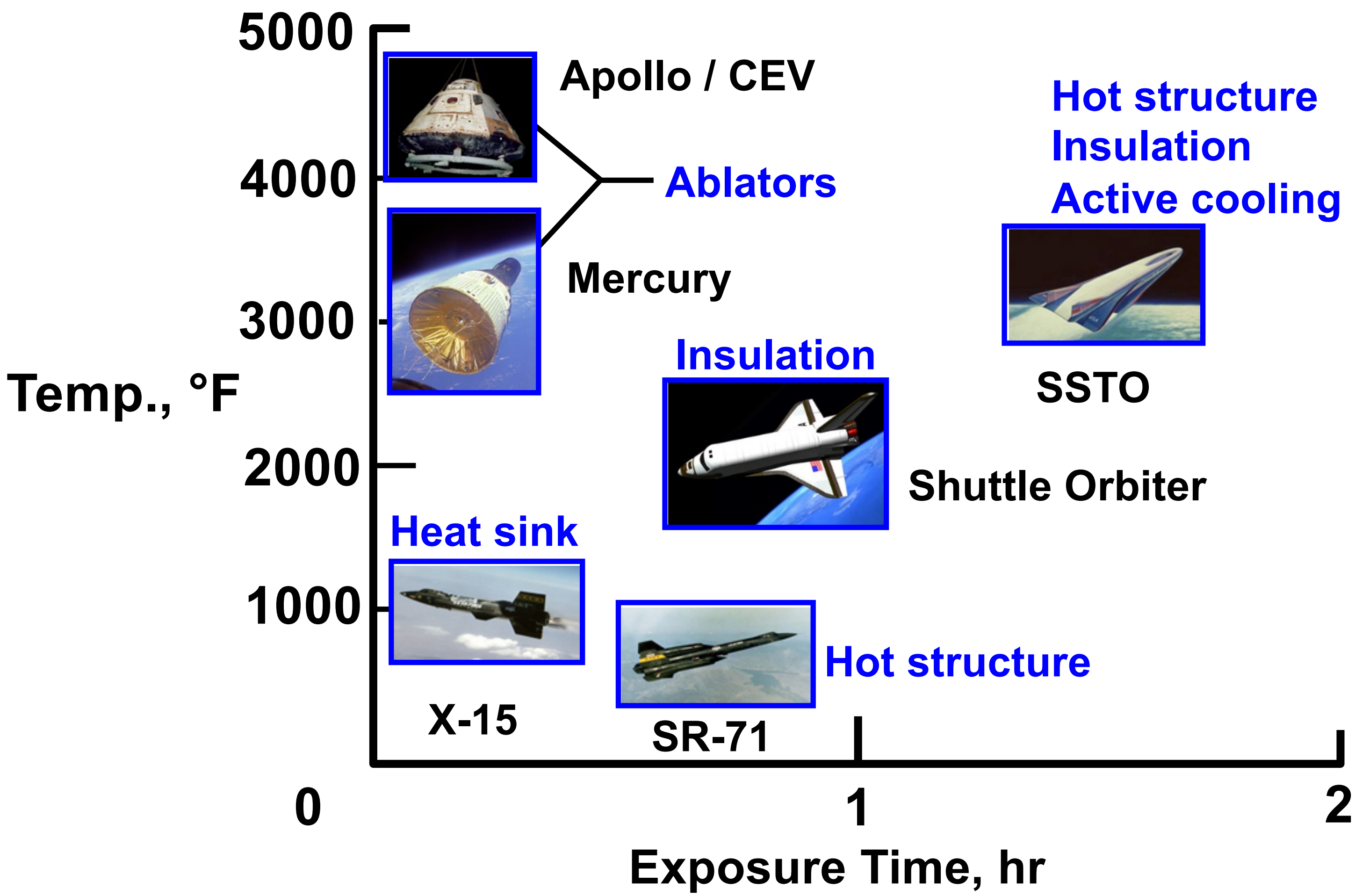
Use: High heat flux, long times





- Coolant injected into flow (porous structure)
- Coolant decreases heat flux to structure
- Structure operates hot

Flight Vehicle Thermal Management



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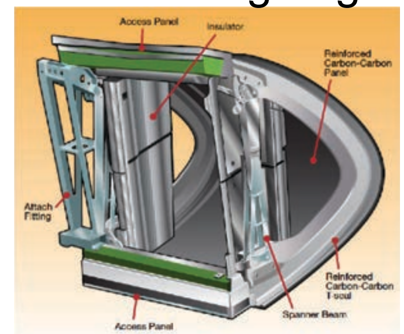
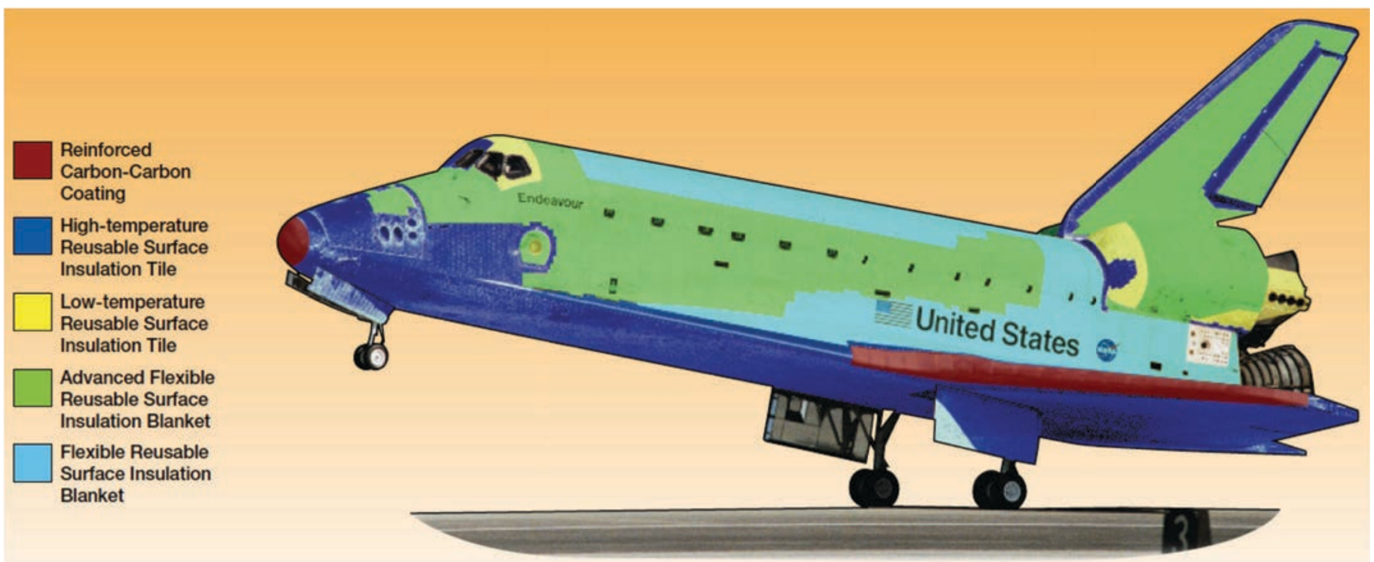
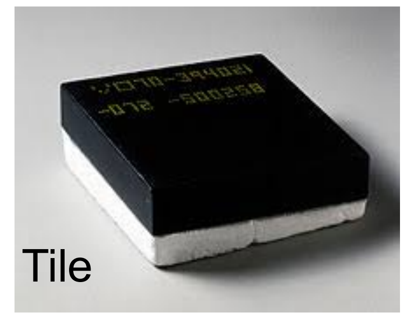
Space Shuttle Orbiter

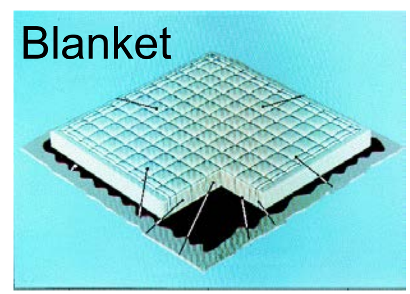
- **Conventional skin-stringer aluminum aircraft structure**
- **Structural temperatures < 350°F**
- **Reusable surface insulation (RSI) tiles**
- **Reusable blankets**
- **Reinforced carbon/carbon (RCC) used for wing leading edges and nose cap, T > 2300°F**

C/C leading edge

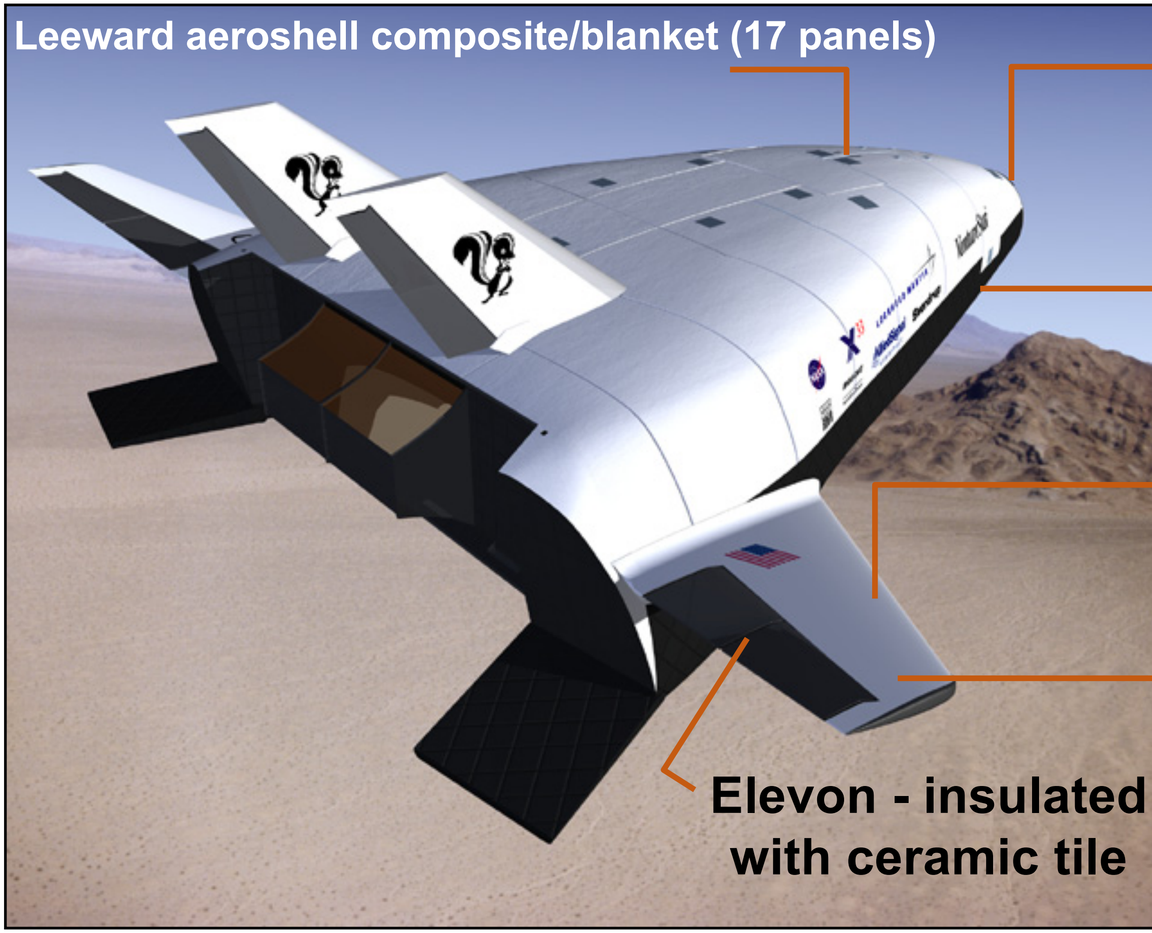








X-33 Thermal Protection System



Carbon/carbon (C/C) nose cap, chin, and skirt

Windward body - Inco 617/MA754 metallic TPS (1333 panels)

C/C leading edge, fillet, and fin tip

Canted fin - metallic (windward) blanket (leeward)

Similar to Orbiter TPS except metallic TPS on windward surface

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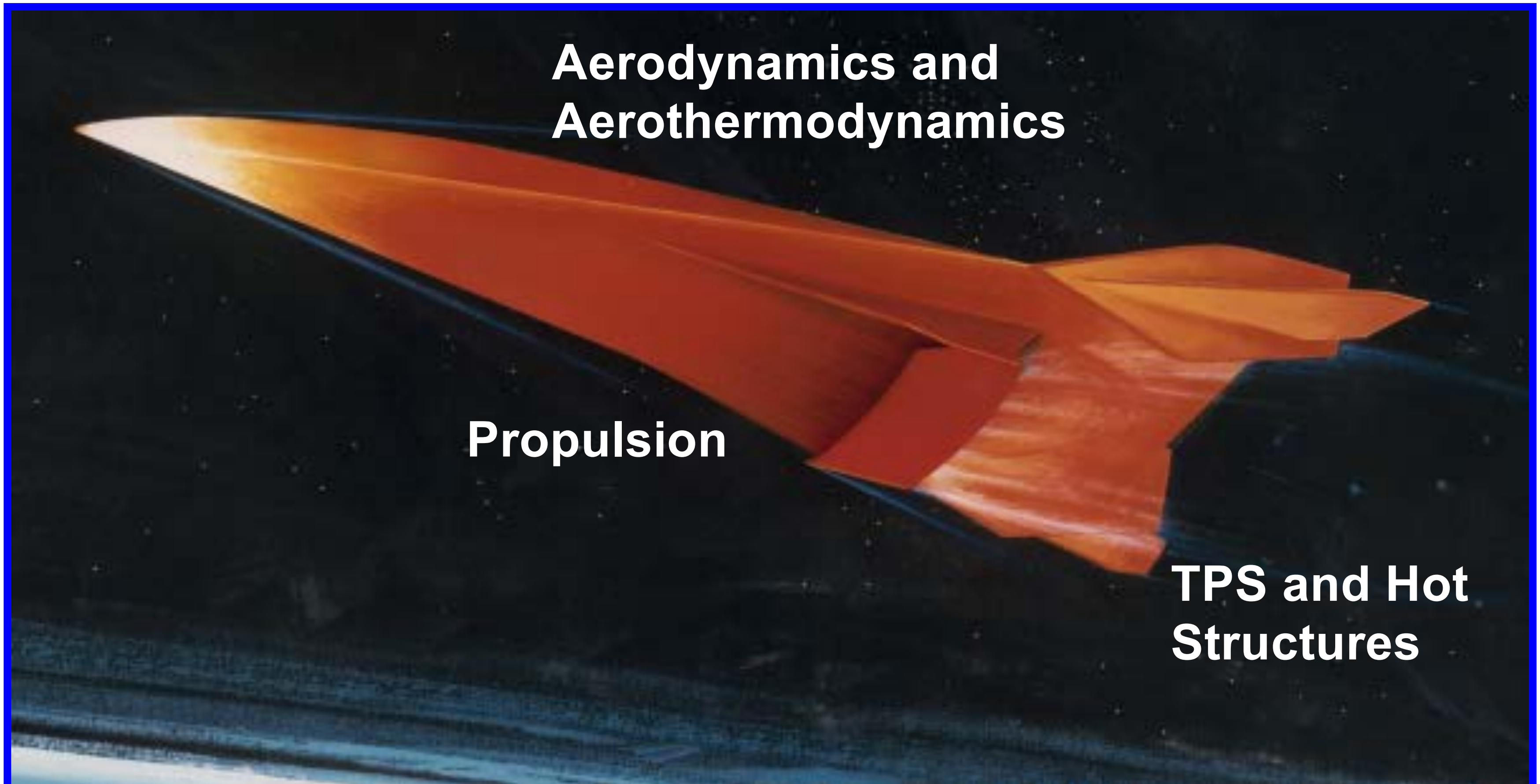
Airbreathing Hypersonic Vehicles



Vehicle propulsion, airframe, and aerothermodynamics are highly integrated

Rocket vs. Airbreather: Flight in Atmosphere

- Accelerate only
- Usually vertical launch
- Get out quick
- Low dynamic pressure

- Accelerate and cruise in atmosphere
- Typically horizontal launch
- High dynamic pressure

Rocket vs. Airbreather: Drag

- High drag not a problem on ascent
- Desirable on descent for deceleration

- Optimize for low drag
- Thin, slender body, low thickness to chord ratio

Key Point: Drag Reduction

- **Reentry vehicles (most of our prior experience) want drag to reduce velocity during reentry**
- **Vehicles flying in the atmosphere must minimize drag during atmospheric flight**
  - Surface and cross-section
- **Hot structure is the preferred approach (rather than TPS over cold structure)**
  - Thin cross sections are required – hot structure is more volumetrically efficient
  - Large, smooth, hot airframe has not been addressed

Rocket vs. Airbreather: Weight and Volume

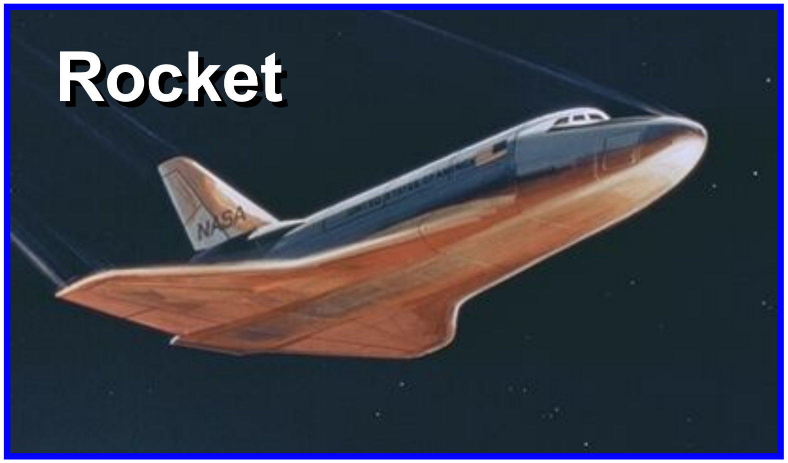
Weight critical

- Structural mass fraction ~10% of gross take off weight (GTOW)

Volume critical

- Volume impacts drag
- Structural mass fraction ~30% of GTOW

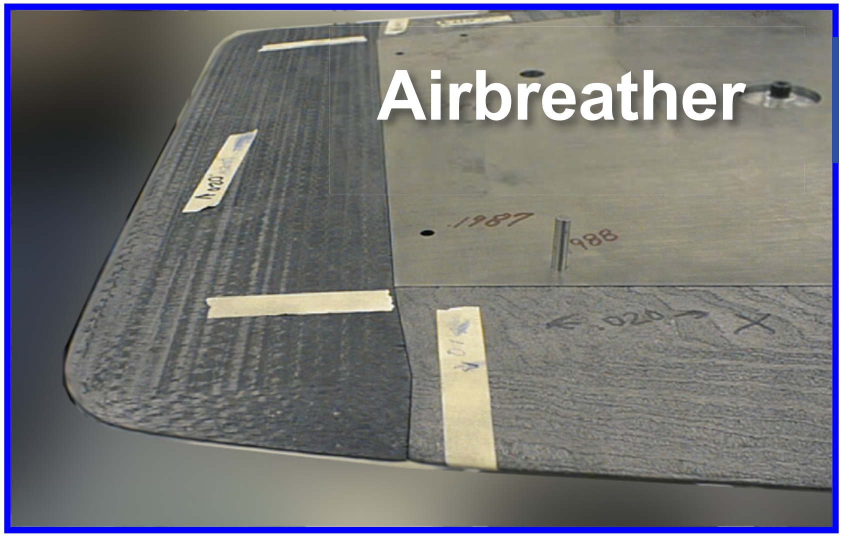
Rocket vs. Airbreather: TPS



- Driven by descent
- Low ascent heat load due to short ascent time and trajectory

- Driven by ascent, descent, and cruise
- High heat load due to long ascent and cruise time

Rocket vs. Airbreather: Leading Edges



- Blunt, due to desire for high descent drag and low heat flux

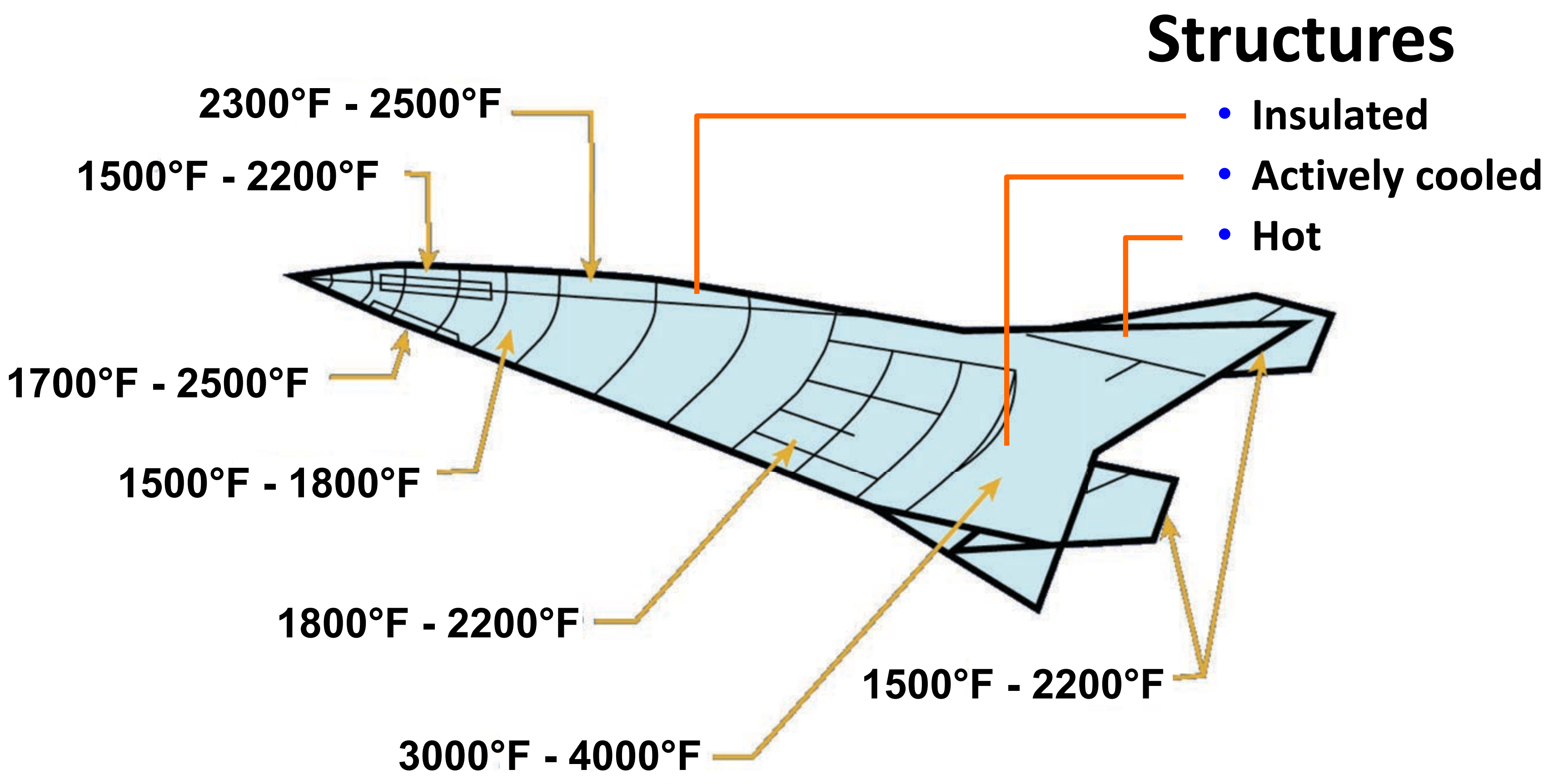
- Sharp, due to low drag, low thickness to chord ratio
- High heat flux

Rocket vs. Airbreather: Structures

- Propulsion and airframe not highly integrated

- Propulsion and airframe highly integrated
- Hot wings and control surfaces due to thin cross sections and high heat flux and heat load

Airbreathing Hypersonic Vehicle Temperatures

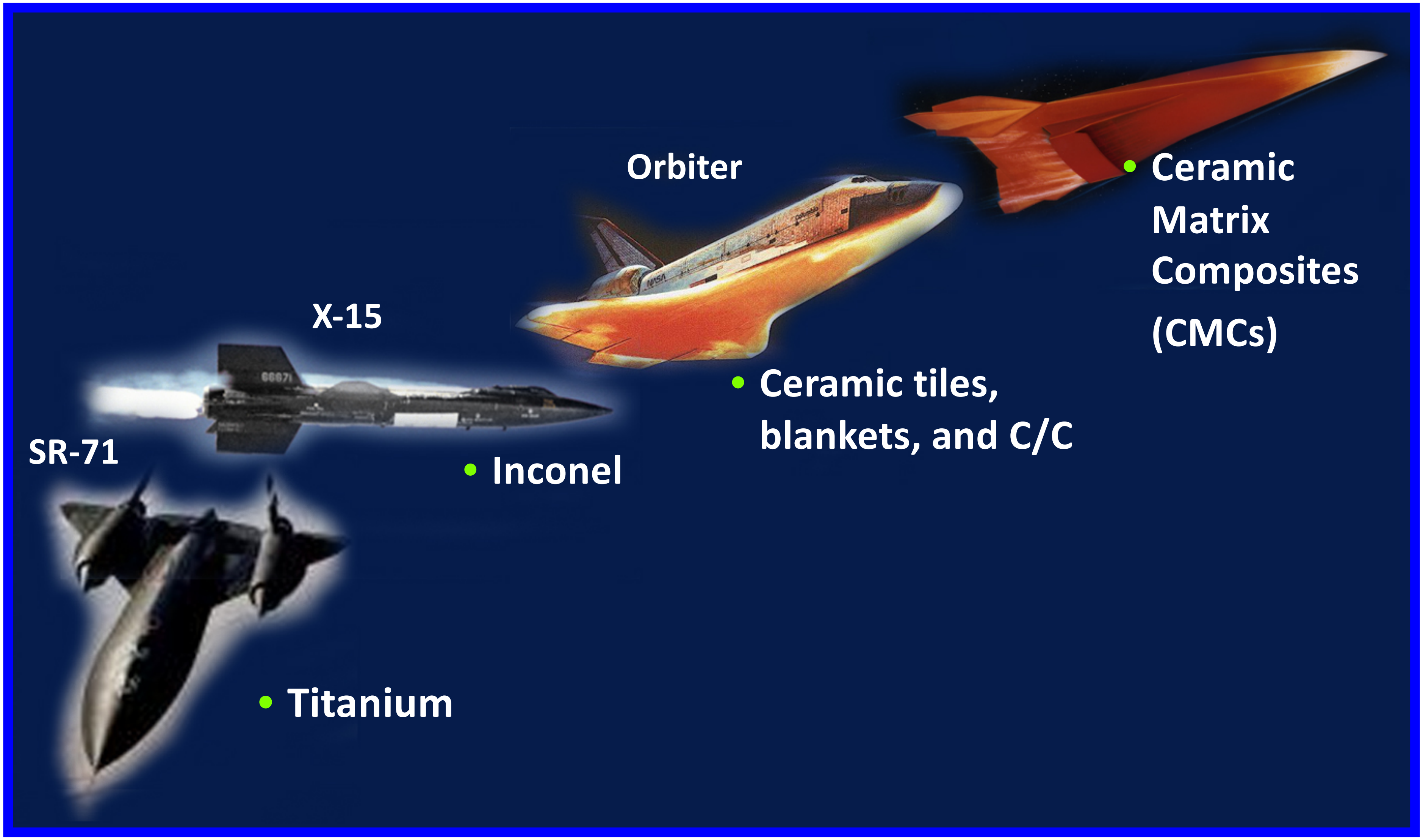


National Aerospace Plane (X-30)

Thermal-Structural Challenges

- Large thermal gradients
  - Tank / outer surface
  - Control surfaces / actuators
- Thin cross sections at high mechanical loads
- High mechanical loads at elevated temperatures
- Stability of the OML shape
  - Performance
  - Leading edge not ablate
  - Steps and gaps (sneak flow and heating)
- Thermal expansion of the propulsion system
- Long times, elevated temperatures, oxidizing environment

History Shows New Material Systems Help Enable the Vehicle

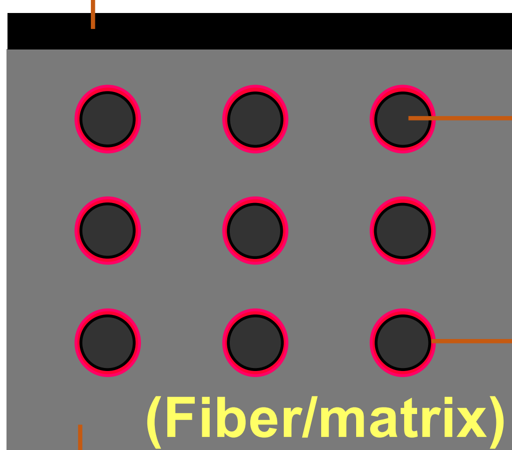


Required Material Attributes (CMC)

- High temperature (2000°F to 4000°F) capability
- Environmental durability
- High toughness
- High strength at temperature
- Lightweight

Ceramic Matrix Composite (CMC)

Environmental Barrier Coating: Protects the materials from oxidation

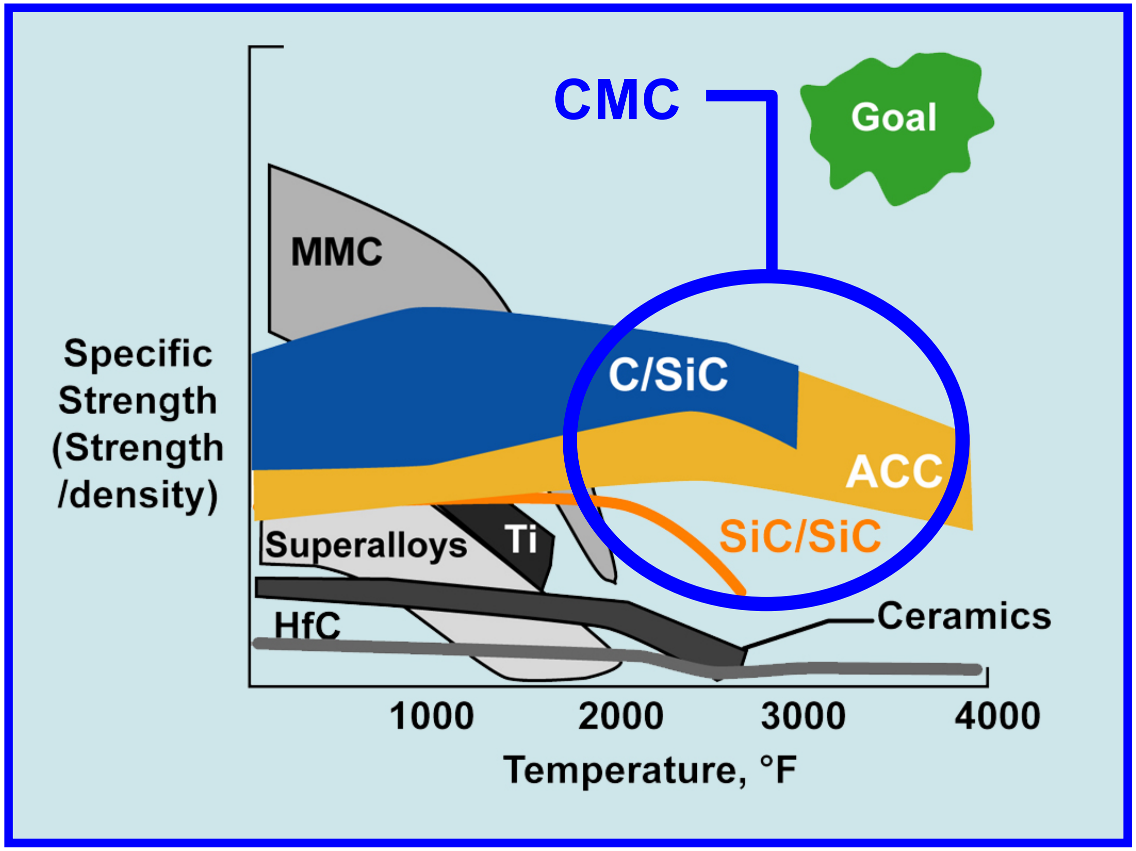


Fiber: Carries the load

Fiber/Matrix Interface Coating: Weak mechanical interface for increased toughness and graceful failure

Matrix: Transfers the load

Material Specific Strength



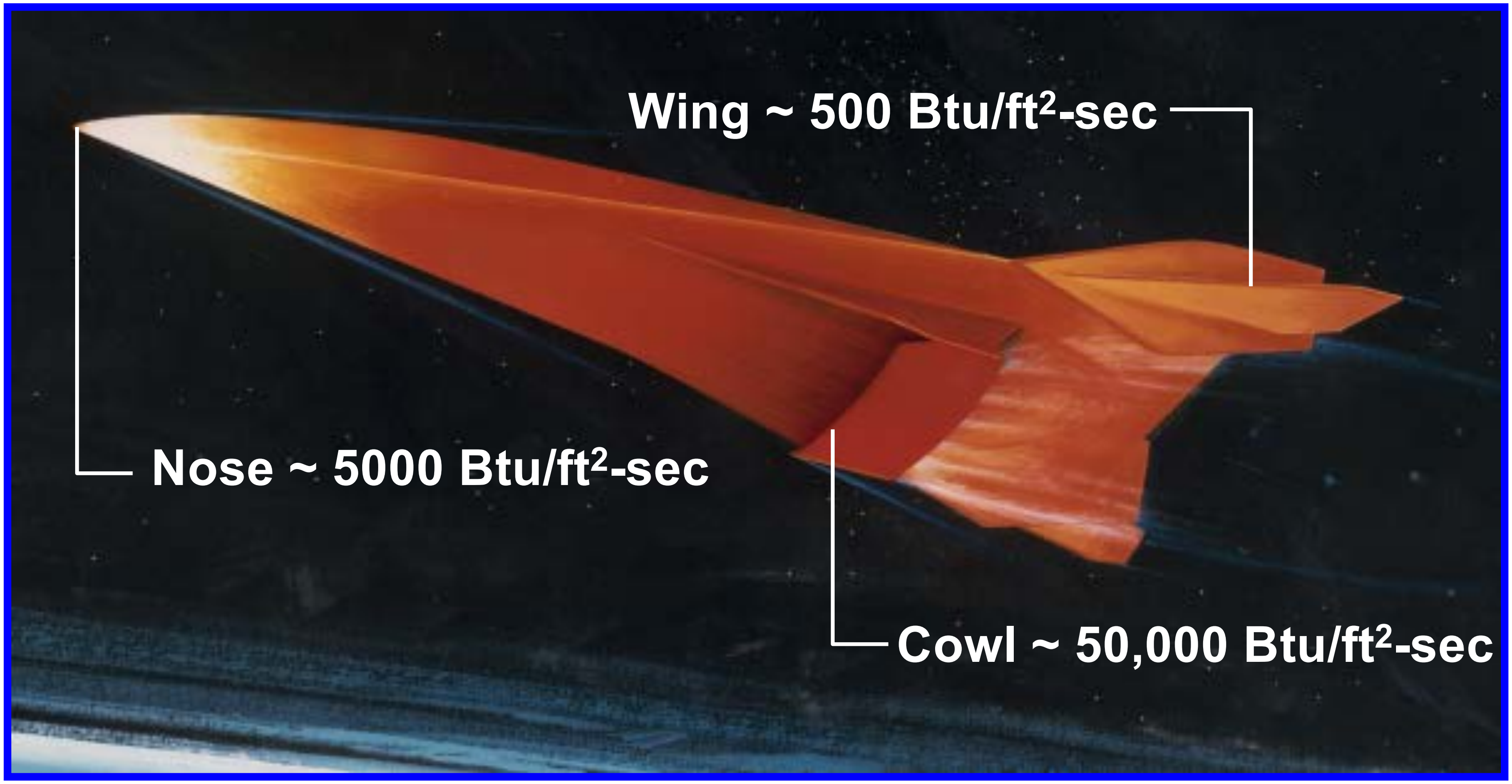
ACC: Advanced carbon/carbon
CMC : Ceramic matrix composite
MMC: Metal matrix composite
HfC: Hafnium carbide
Ti: Titanium

CMCs are the material system that will provide the required strength at elevated temperature

Outline

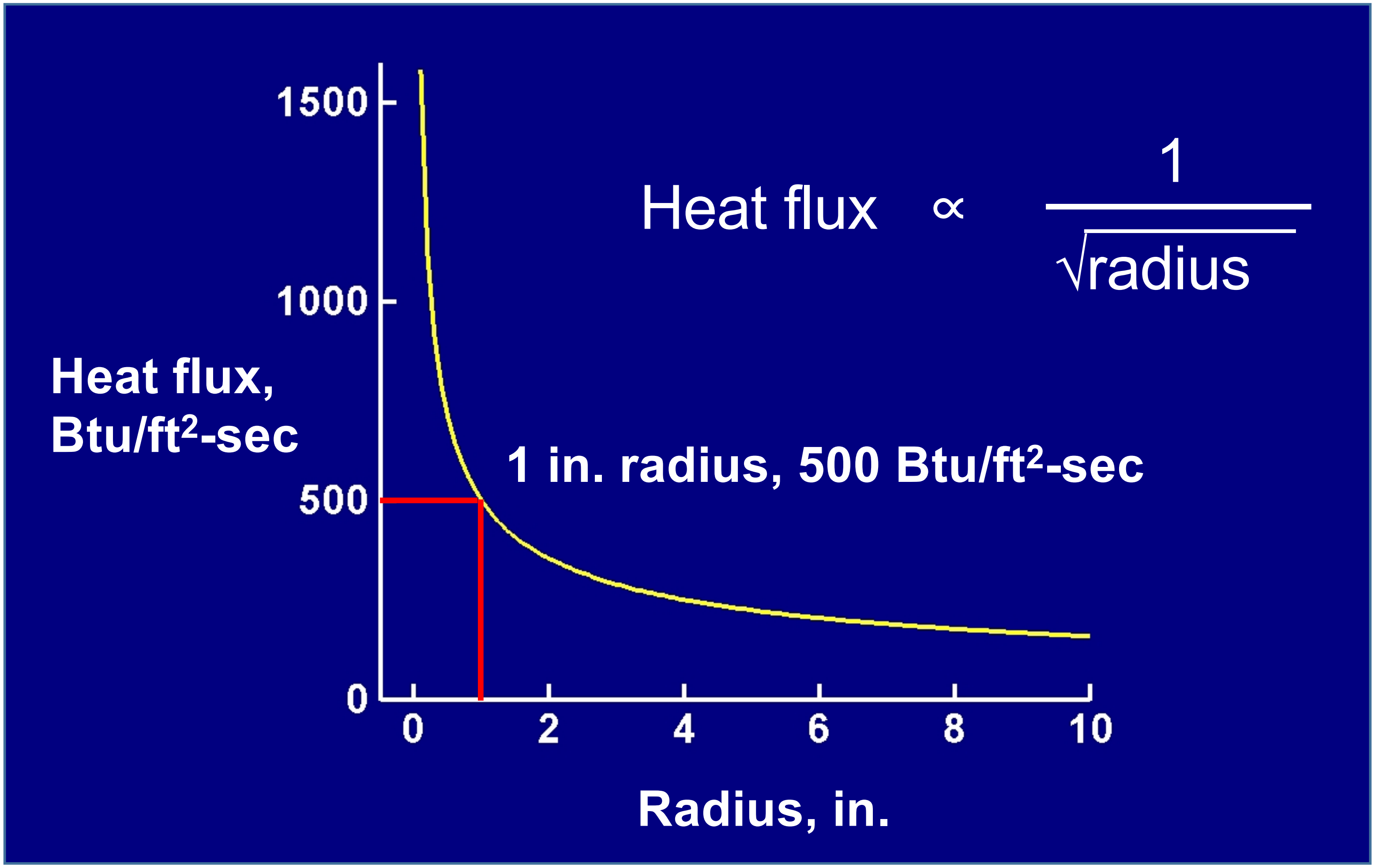
- Introduction
- TPS and Hot Structures Components
  - **Leading Edges**
  - **Acreage TPS / Aeroshell**
- Key Technical Challenges
- Concluding Remarks

Typical Ascent Leading-Edge Heat Flux for SSTO

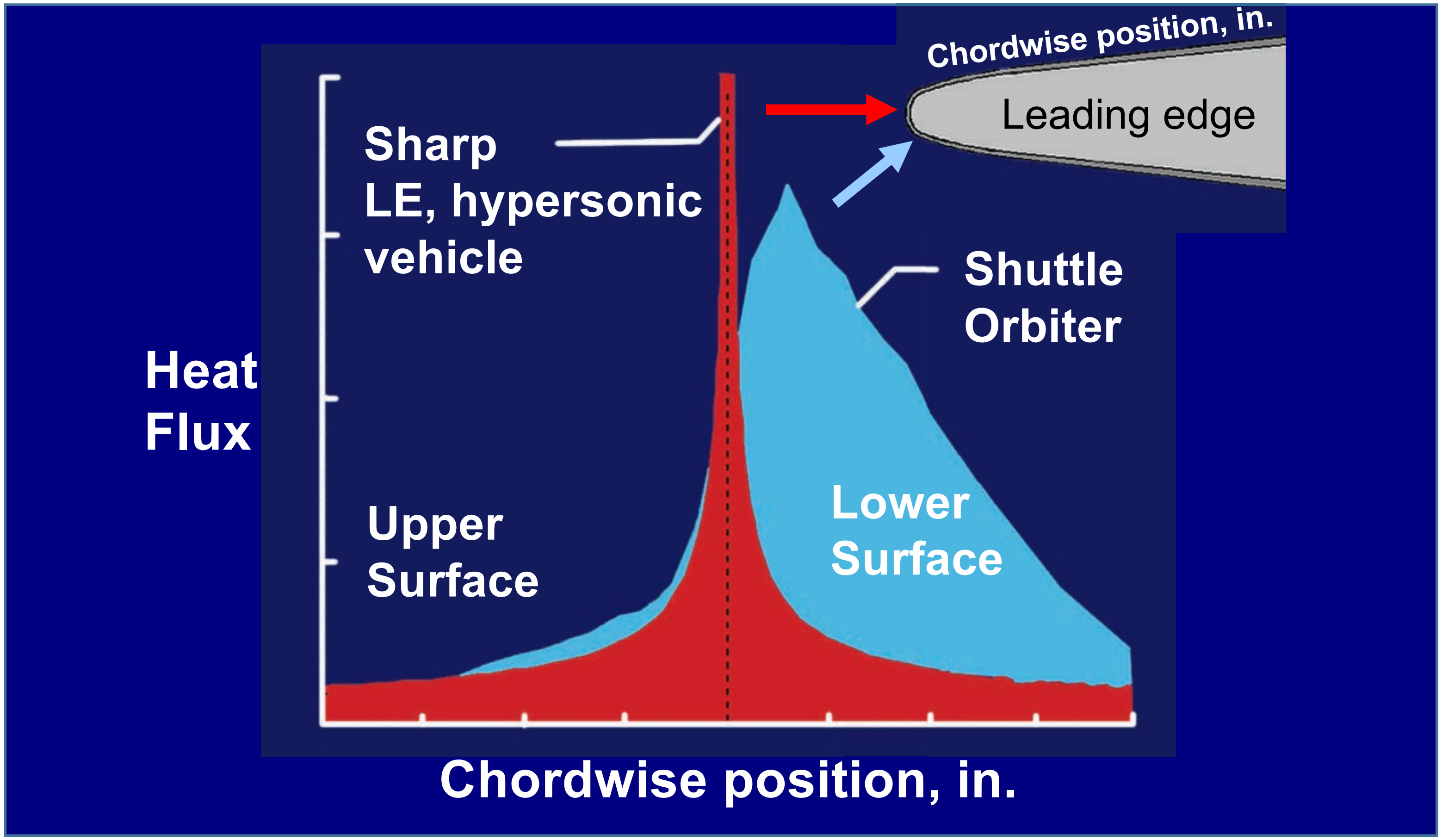


In comparison, Shuttle Orbiter leading edge ~ 70 Btu/ft^2-sec, CEV ~ 700 Btu/ft^2-sec

Leading-Edge Radius Effect on Heat Flux

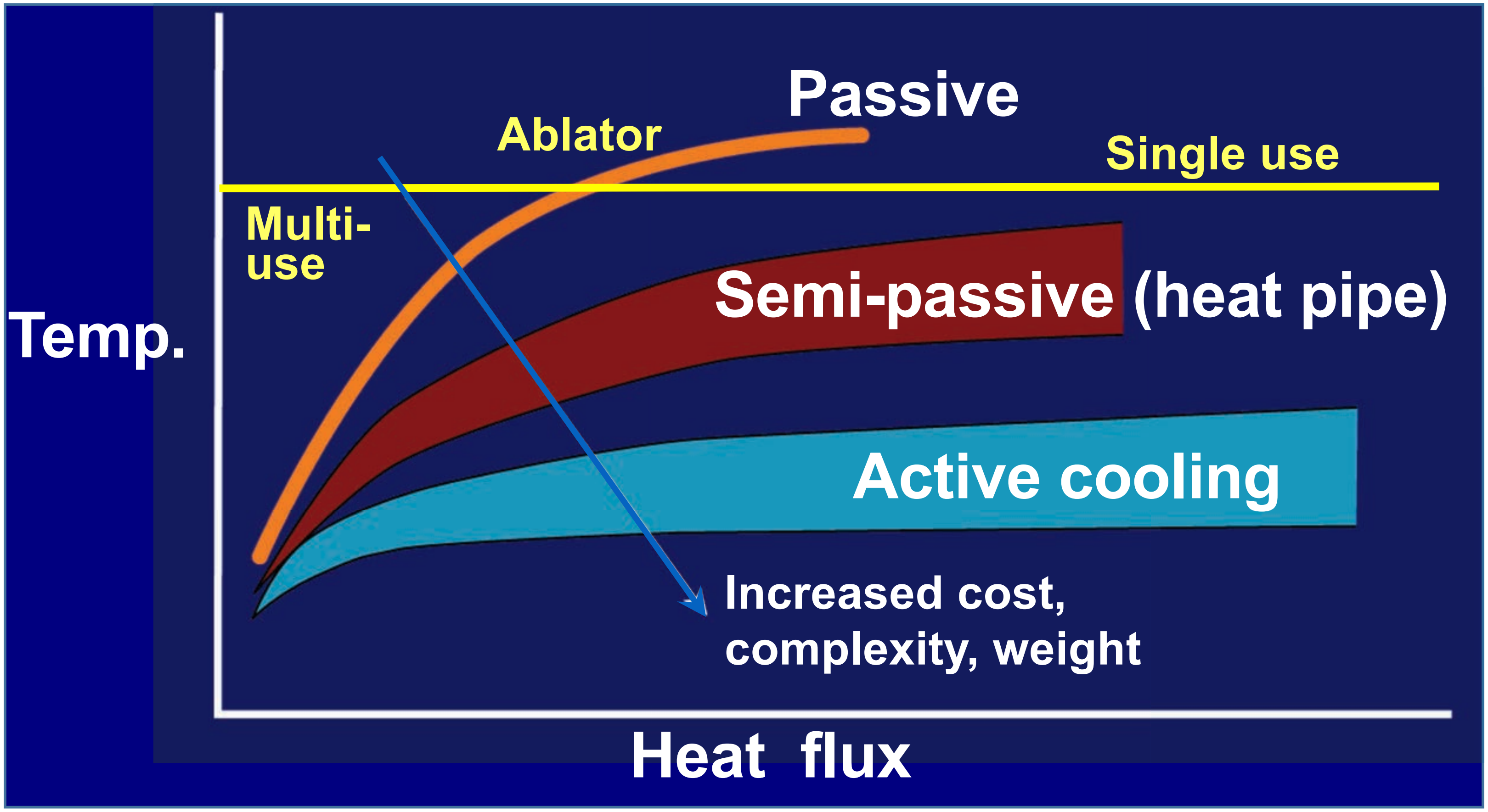


Leading-Edge Heating



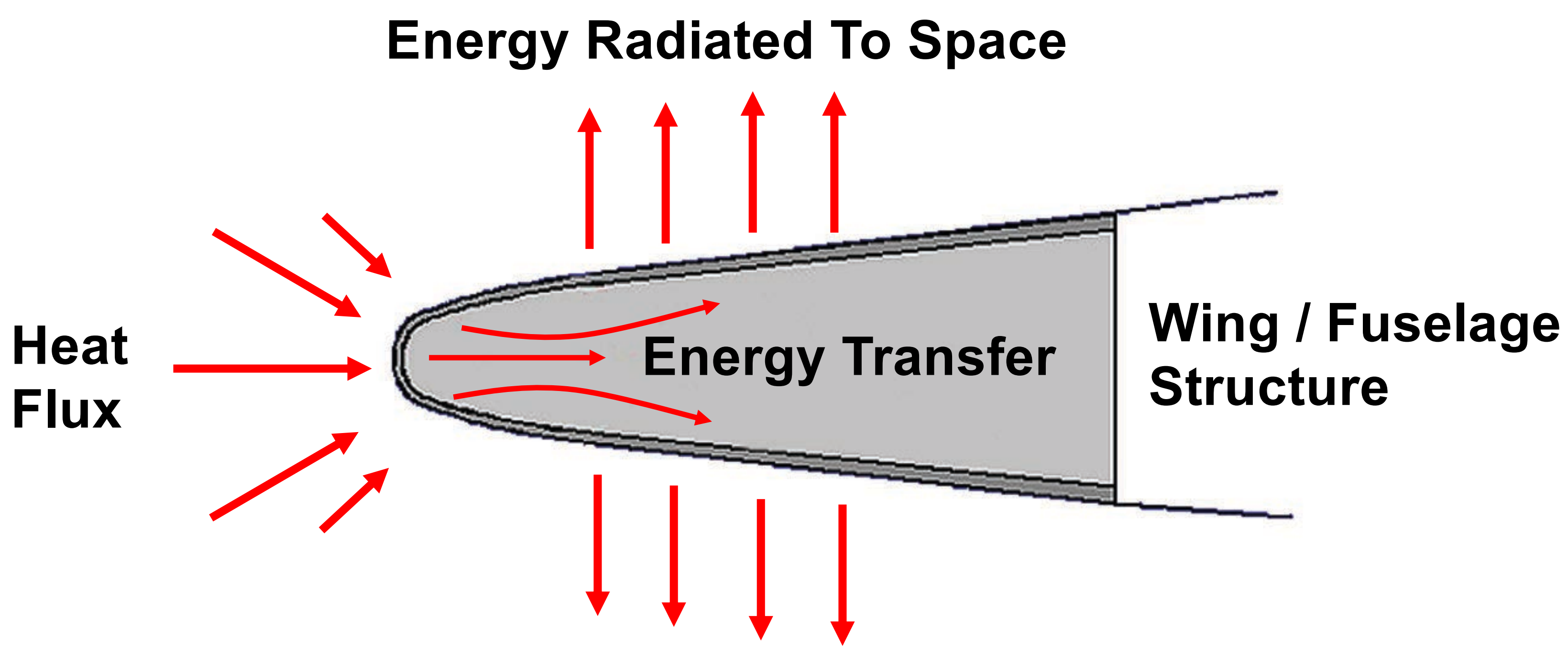
Sharp leading edges produce intense, localized heating

Leading-Edge Thermal Management Options



There are multiple options to manage the intense heating on sharp leading edges

Passive Leading Edges

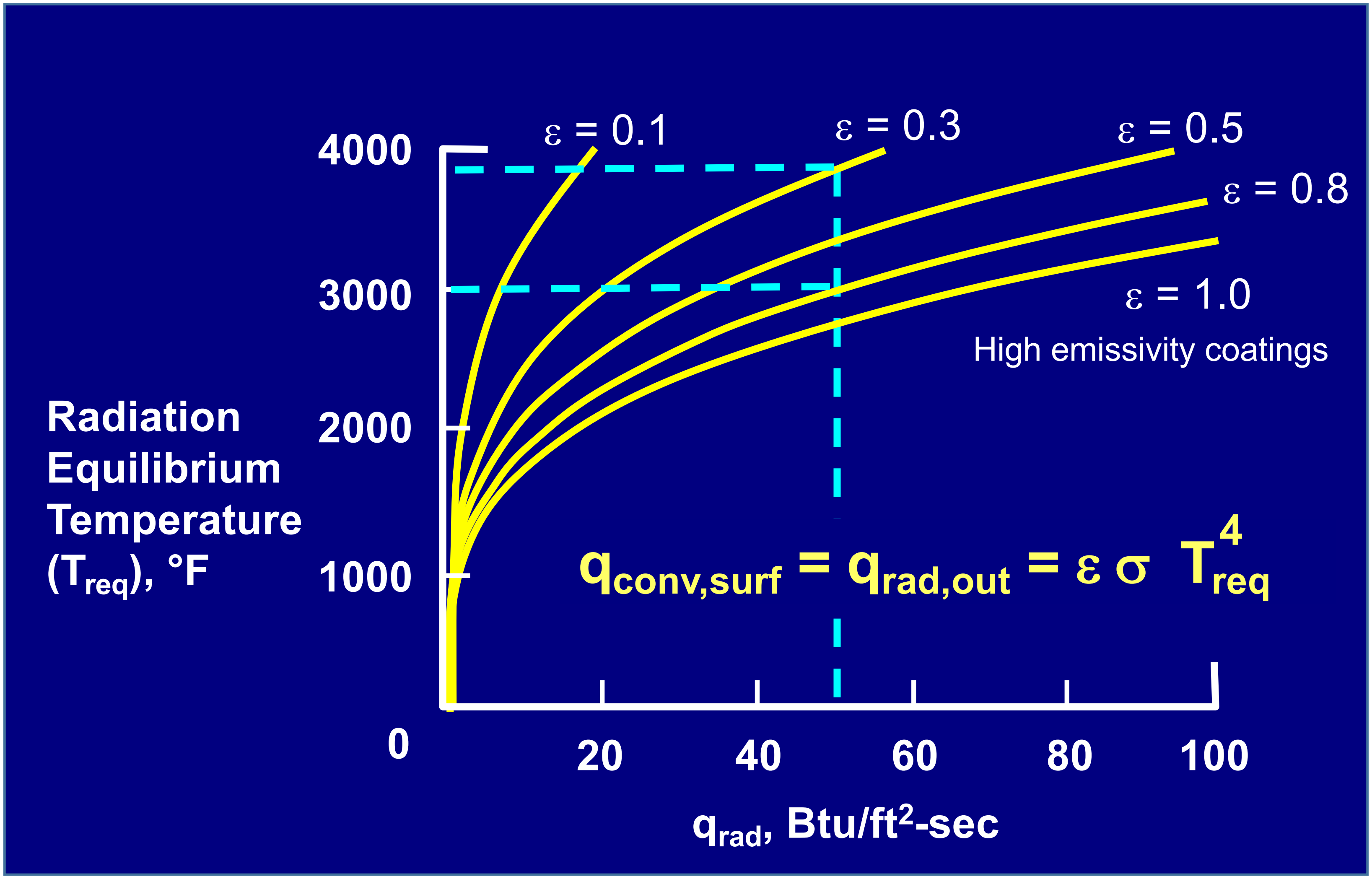


- High-temperature materials to increase capability
- Thermal properties to reduce temperatures

High-Temperature Materials / Coatings

- SiC-based coatings as on Shuttle Orbiter leading edges are good to ~ 3000°F
- Above ~ 3000°F, different class of materials required
  - Carbides, oxides, and diborides of hafnium (Hf) and zirconium (Zr)
- Some of these materials can be used as a matrix, some are more appropriate as a coating
- Thermal properties can have a significant impact on the surface temperatures
  - Emissivity
  - Recombination efficiency

Property: Emissivity (ε)



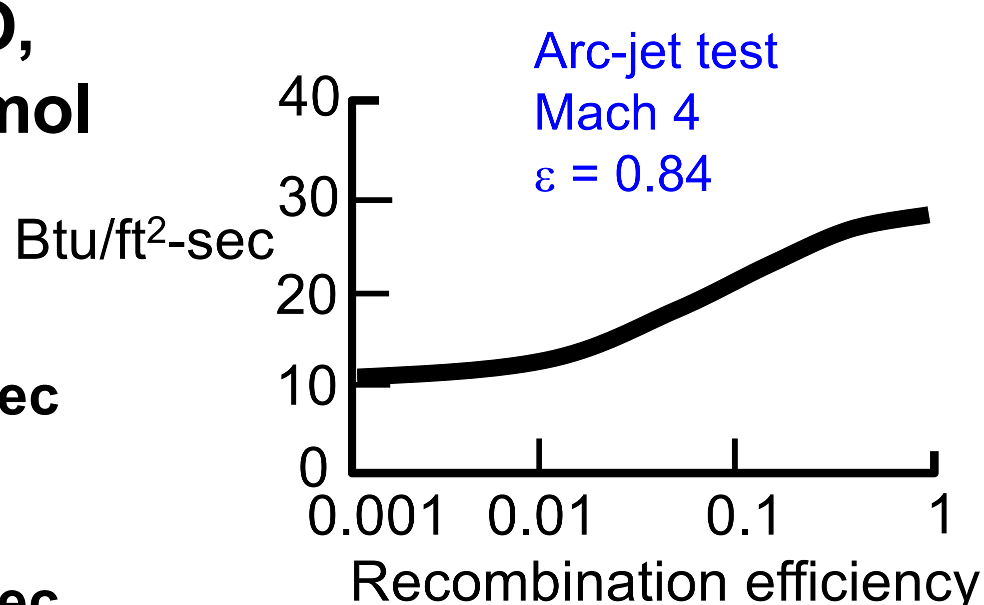
High emissivity coatings are very important to keep temperatures down

Property: Recombination (Catalytic) Efficiency

- **Dissociated species in hypersonic flow**
- **Recombination**
  - **Includes flow and surface**
  - **Can be exothermic**
  - **$Si_{(g)} + O \Leftrightarrow SiO$,**
    $\Delta H = -605$ Btu/mol

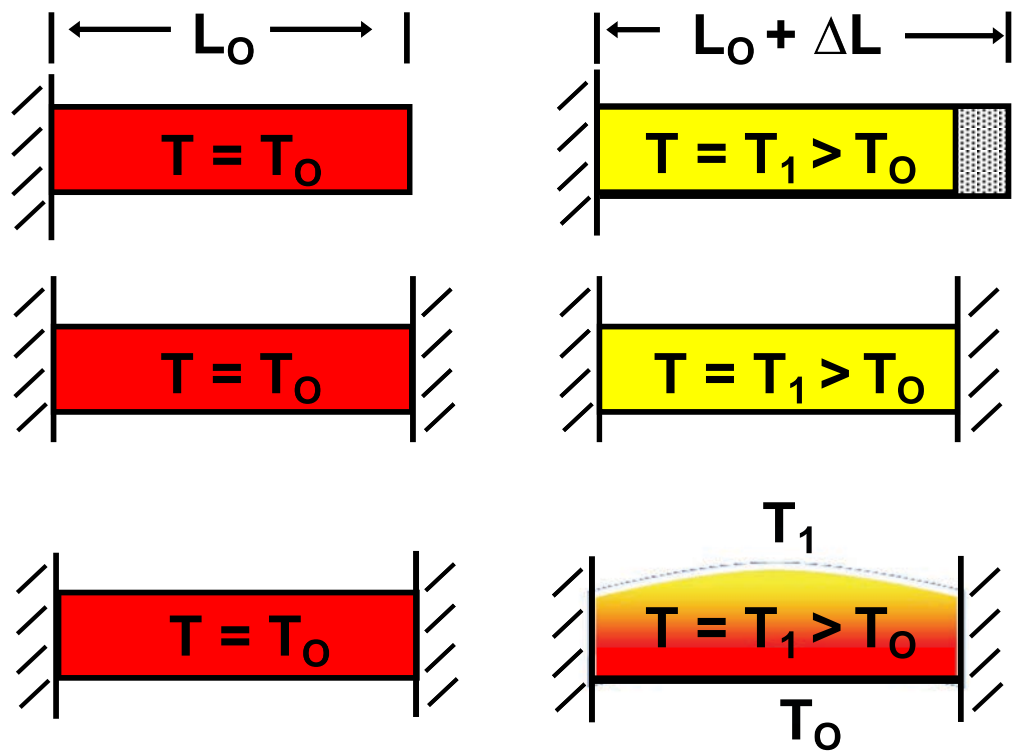
Non-catalytic
q = 10.1 Btu/ft²-sec

Catalytic
q = 28.3 Btu/ft²-sec



Low catalycity coatings are very important to keep temperatures down

Property: Thermal Expansion (α)



$\varepsilon = \dfrac{\Delta L}{L_O}, \sigma = 0$

$\varepsilon = 0, \sigma = E\,\alpha\,\Delta T$

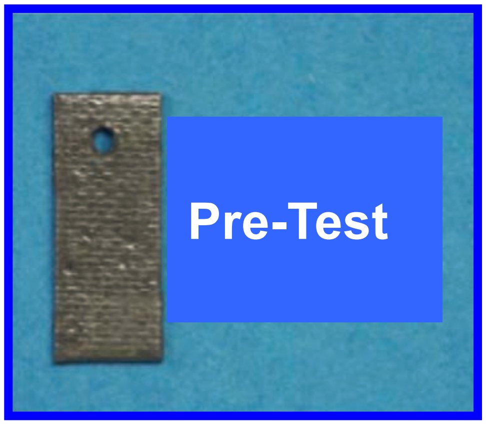
$\varepsilon \neq 0, \sigma \neq 0$

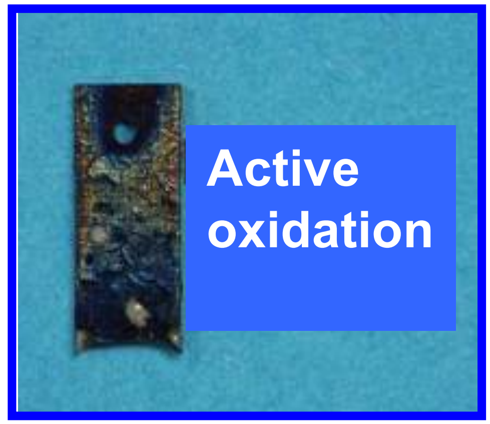
Thermal stress is generated due to a material's thermal expansion, a temperature differential, and structural or mechanical restraint of thermal growth.

Oxidation of SiC Coatings

- Passive oxidation (low temperature / high pressure)
  - $SiC_{(s)} + 2\ O_{2(g)} \rightarrow SiO_{2(s)} + CO_{2(g)}$

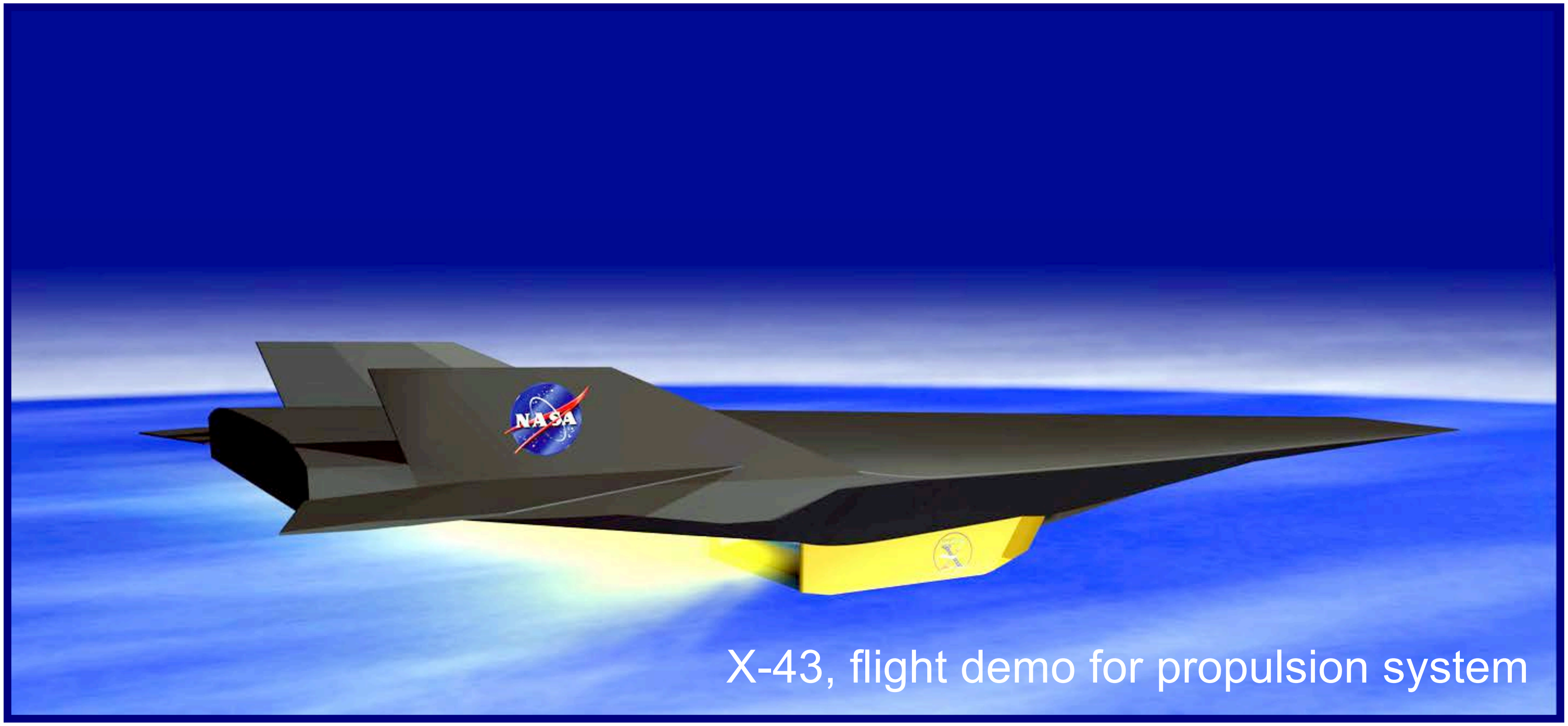
- Active oxidation (high temperature / low pressure)
  - $SiC_{(s)} + 1.5\ O_{2(g)} \rightarrow SiO_{(g)} + CO_{2(g)}$





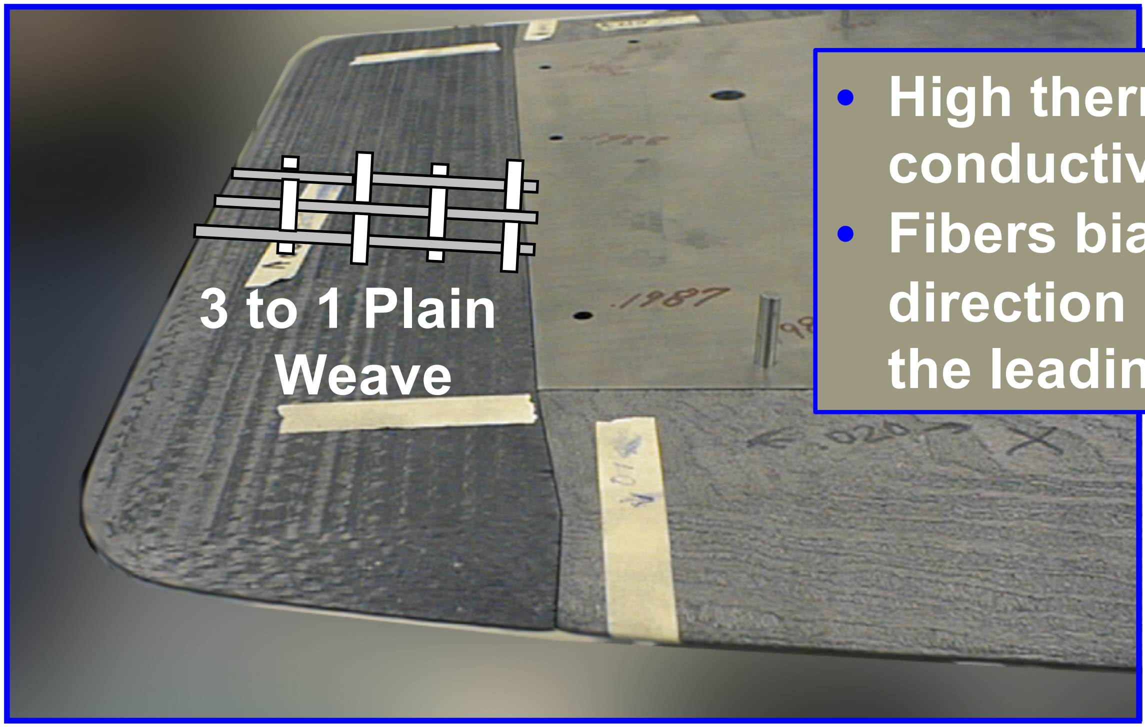
Transition between passive and active oxidation regimes depends on temperature and partial pressure of oxygen

X-43 (Hyper-X) Passive Leading Edges



Hyper-X (Mach 10 vehicle) nose leading edge was designed to reach nearly 4000°F during the 130 s flight

High Thermal Conductivity Leading Edge on X-43



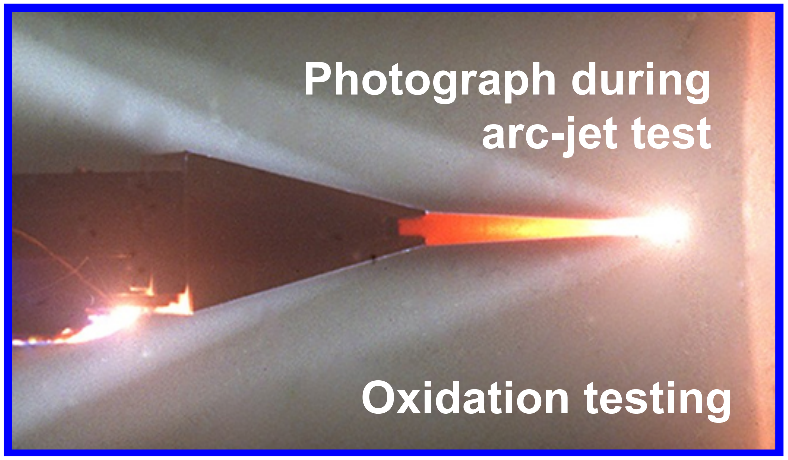
- High thermal conductivity fibers
- Fibers biased in the direction normal to the leading edge

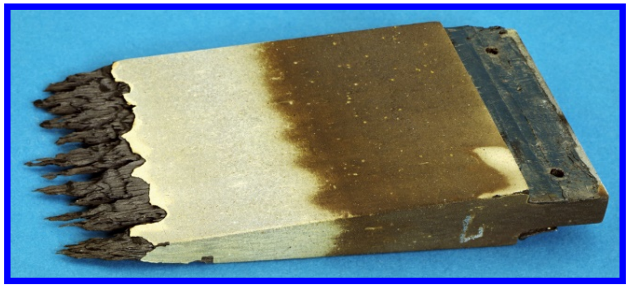
Coating Evaluation of X-43 Leading Edges

Flight conditions simulated during arc-jet test

- Mach 10, 105,000 ft
- Nose radius = 0.03 in.
- q ~ 1300 Btu/ft^2-sec
- 130 sec

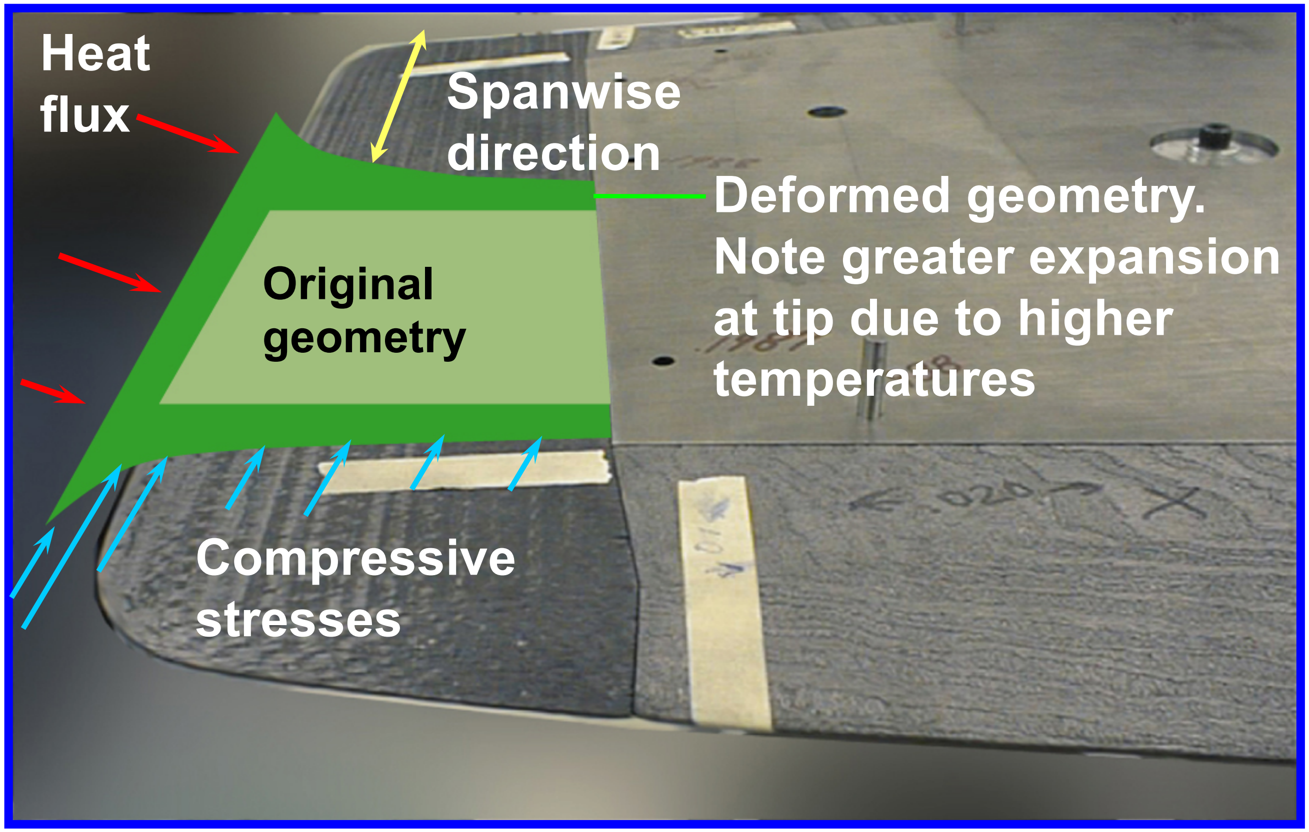
Successful test article





Failed test article

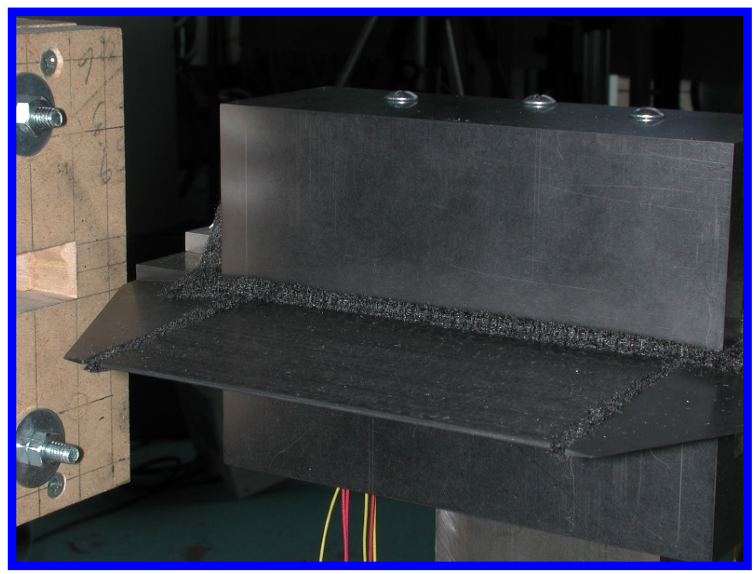
Spanwise Compressive Thermal Stresses



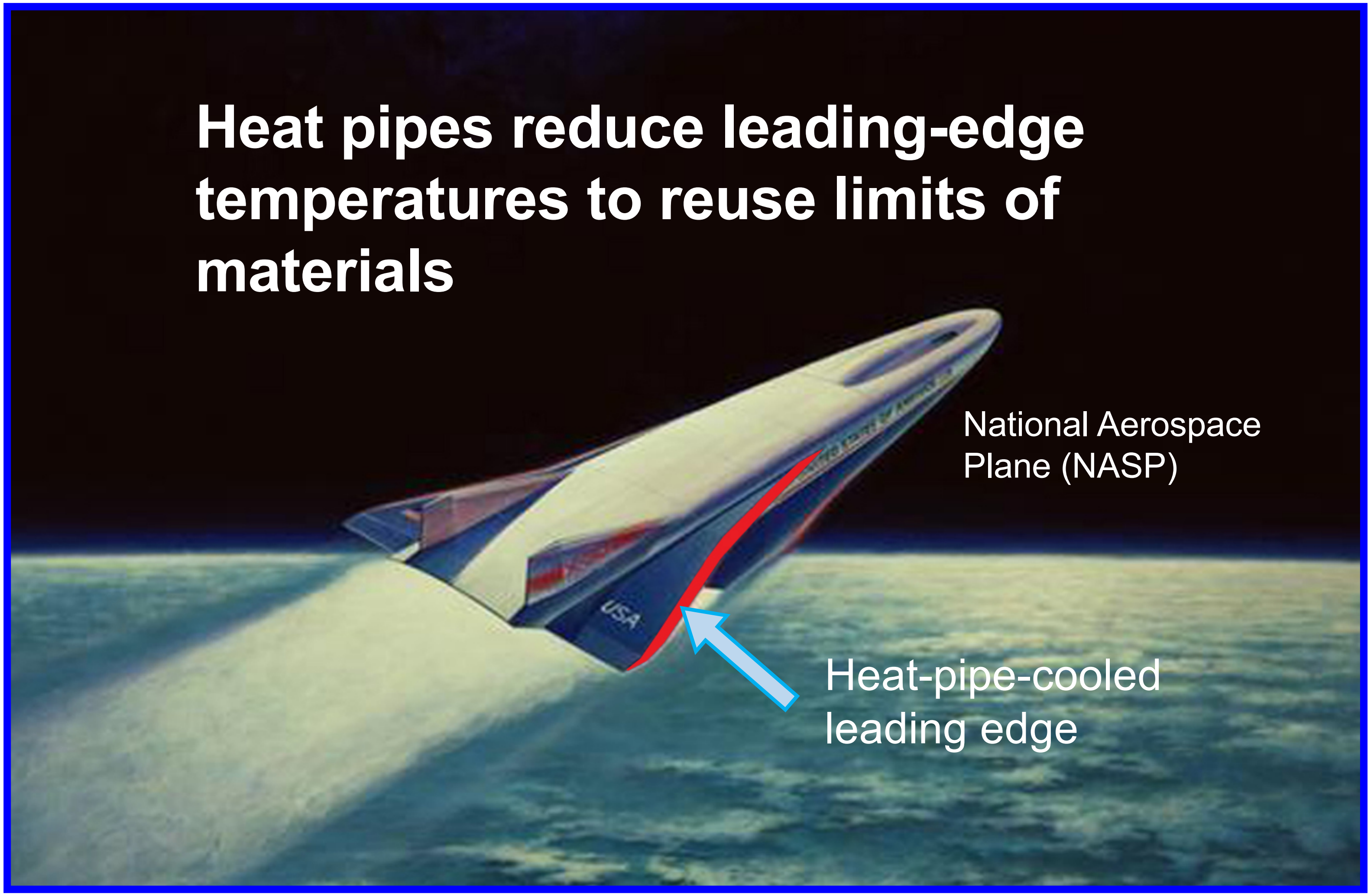
Thermal stresses due to constraint of thermal expansion

X-43 Leading Edge Spanwise Compressive Stresses

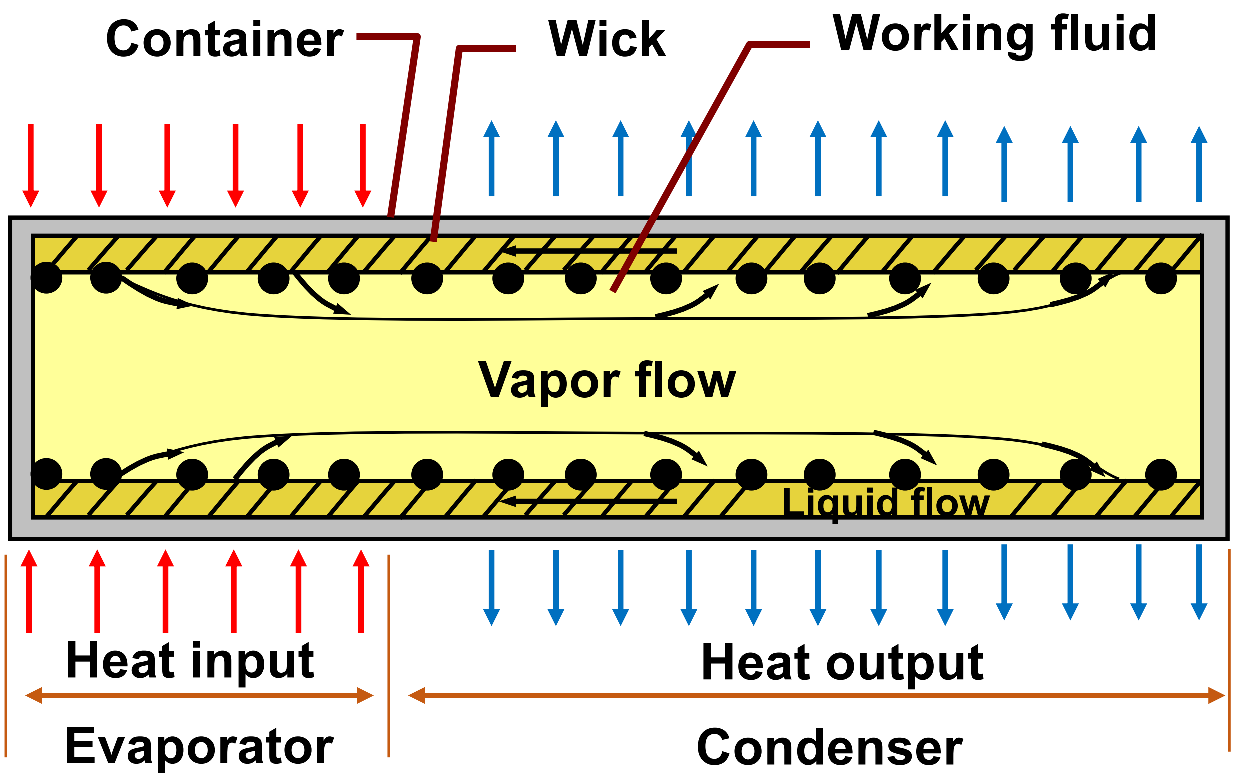
- Compressive thermal stresses exceeded the material allowables
  - Would the substrate fail due to high thermal stresses?
  - Would the coating buckle and spall?
  - If slotting required, what spacing?
  - Would slotting prevent spalling?
- Testing was performed to validate survival of leading edge
- Survived flight



Heat-Pipe-Cooled (Semi-Passive) Leading Edge

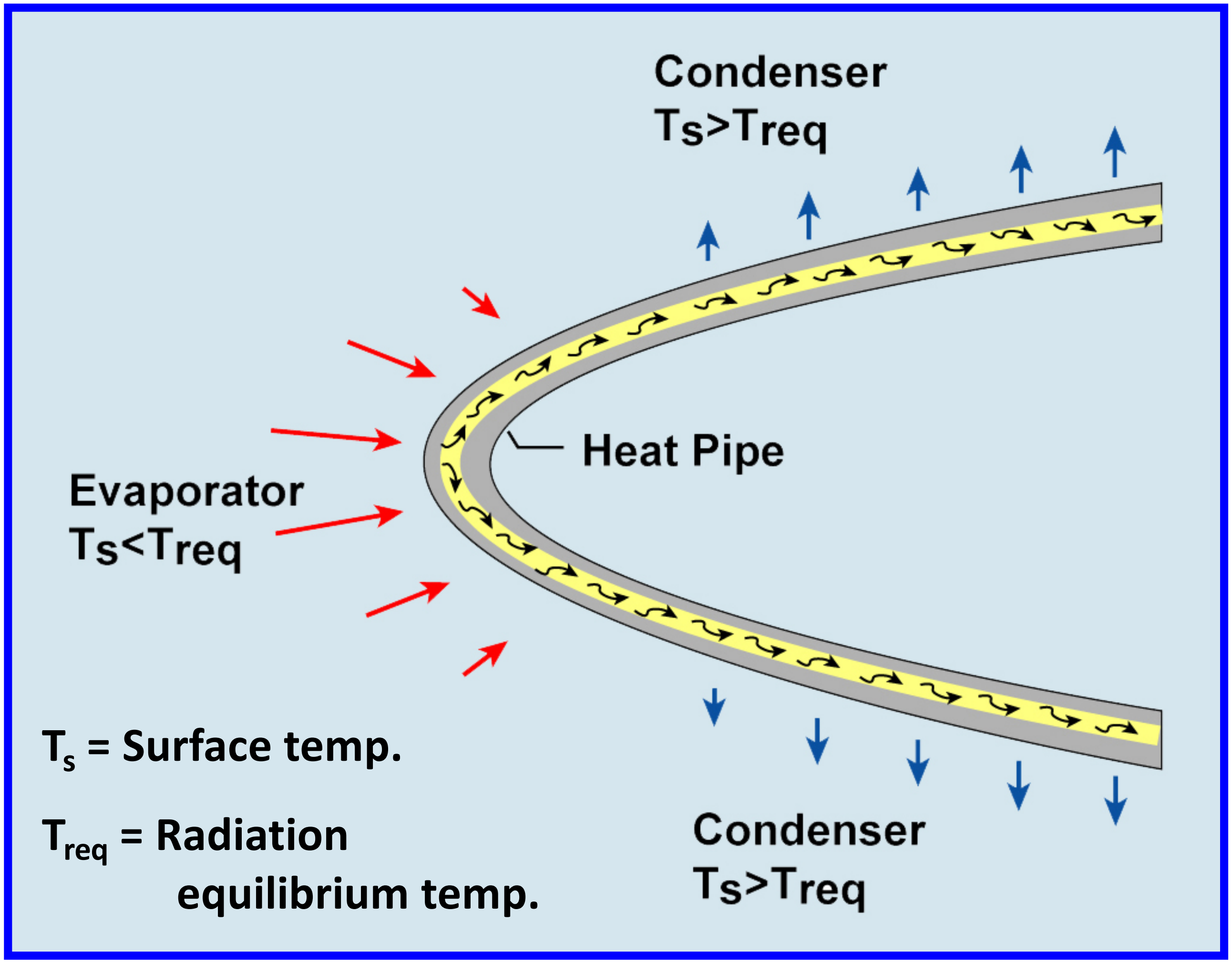


Heat-Pipe Operation



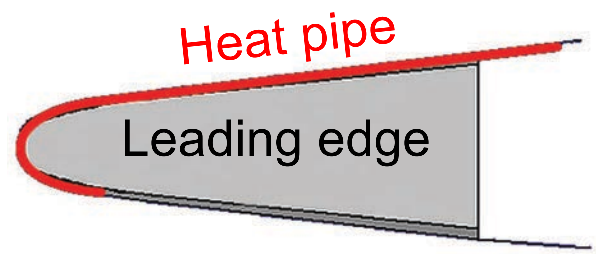
Heat pipes transfer heat isothermally by the evaporation and condensation of a working fluid

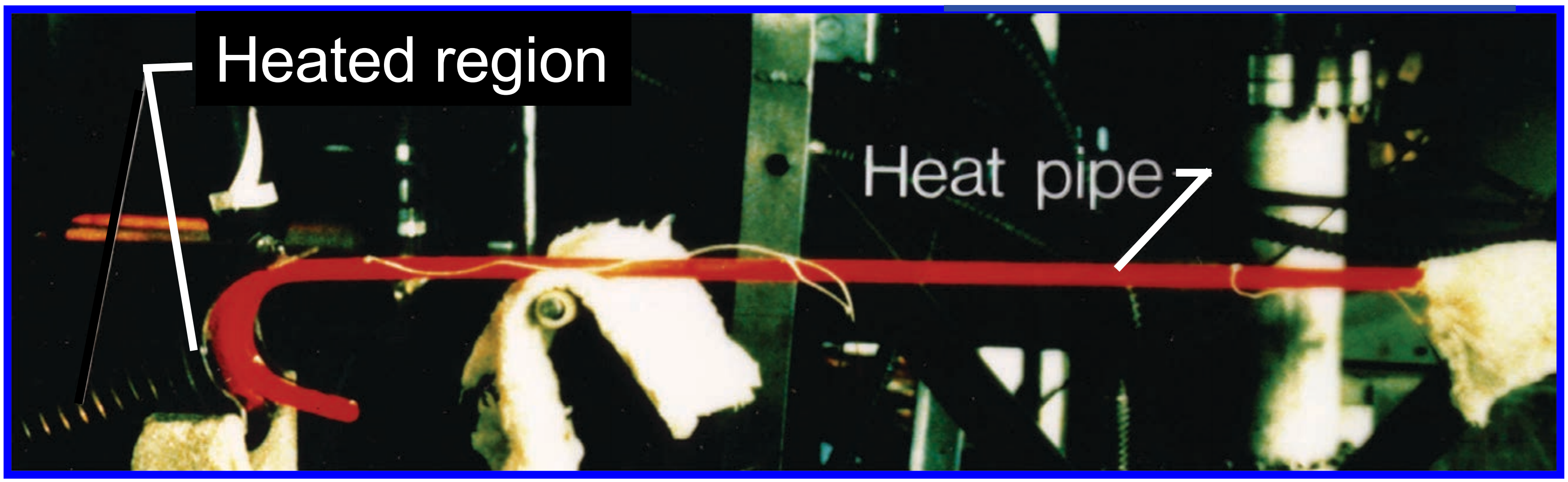
Leading-Edge Heat-Pipe Operation



Leading-Edge-Shaped Heat Pipe

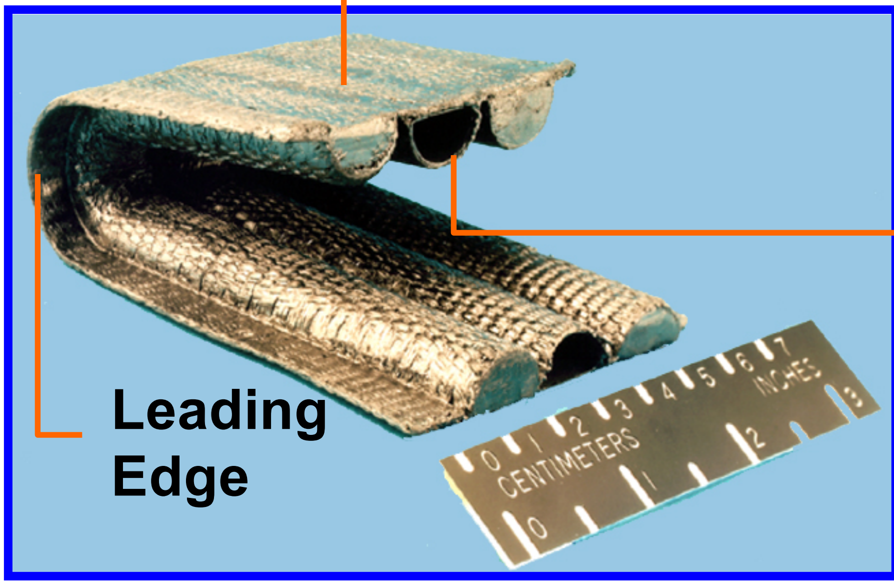
- **Hastelloy-X container**
- **Sodium (Na) working fluid**





Heat pipe results in an isothermal leading edge

NASP Heat-Pipe-Cooled Wing Leading Edge

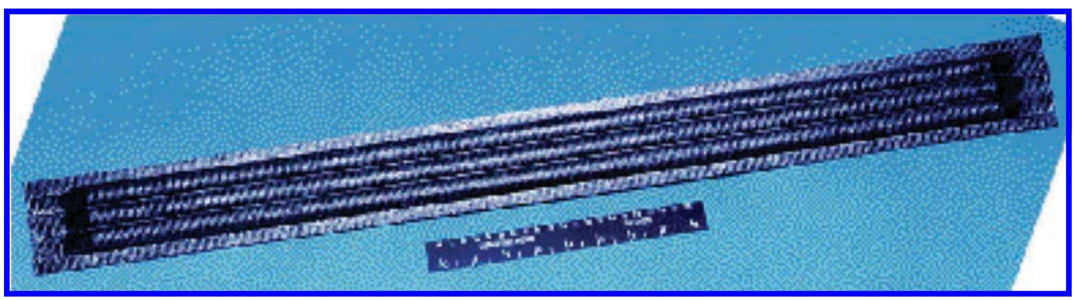


Carbon/carbon (C/C) structure

Mo-Re (molybdenum-rhenium) container

Challenges

- **Material compatibility**
- **Thermal stresses**

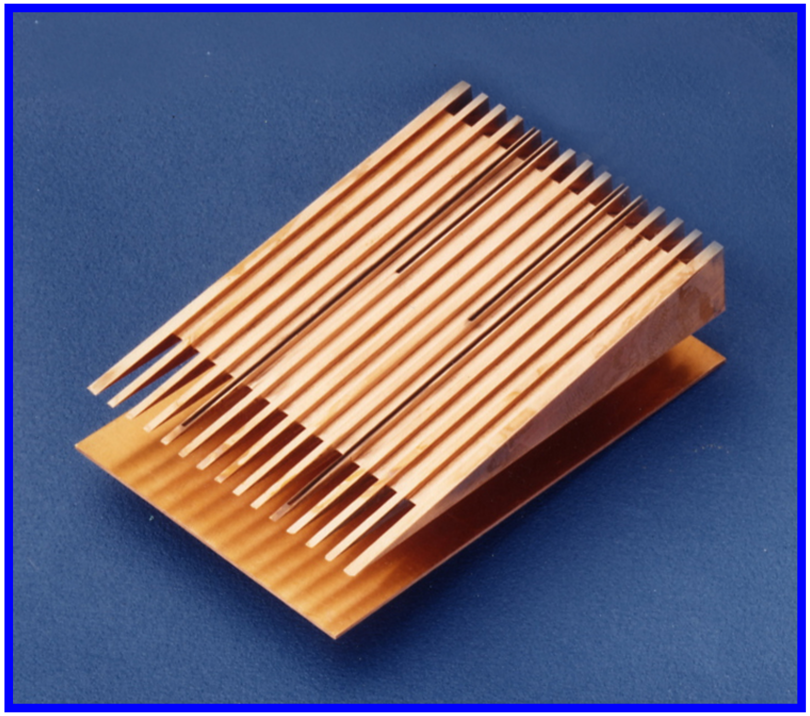


- **Mo-Re embedded in C/C**
- **Lithium working fluid**
- **D-shaped heat pipes**

Actively Cooled Leading Edges

- For highest heat fluxes, active cooling is required

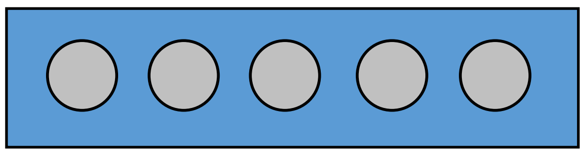
- Metallic actively-cooled leading edge challenges include
  - Hydrogen interaction
  - Multi-cycle life



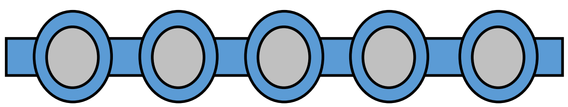
Actively Cooled Composites

- Materials
  - Superalloy and refractory metal tubes
  - CMC structures

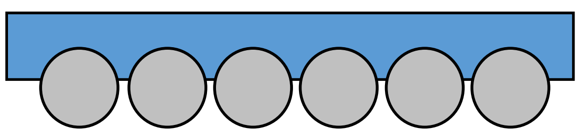
- Concepts



Inserted metal tubes in composite

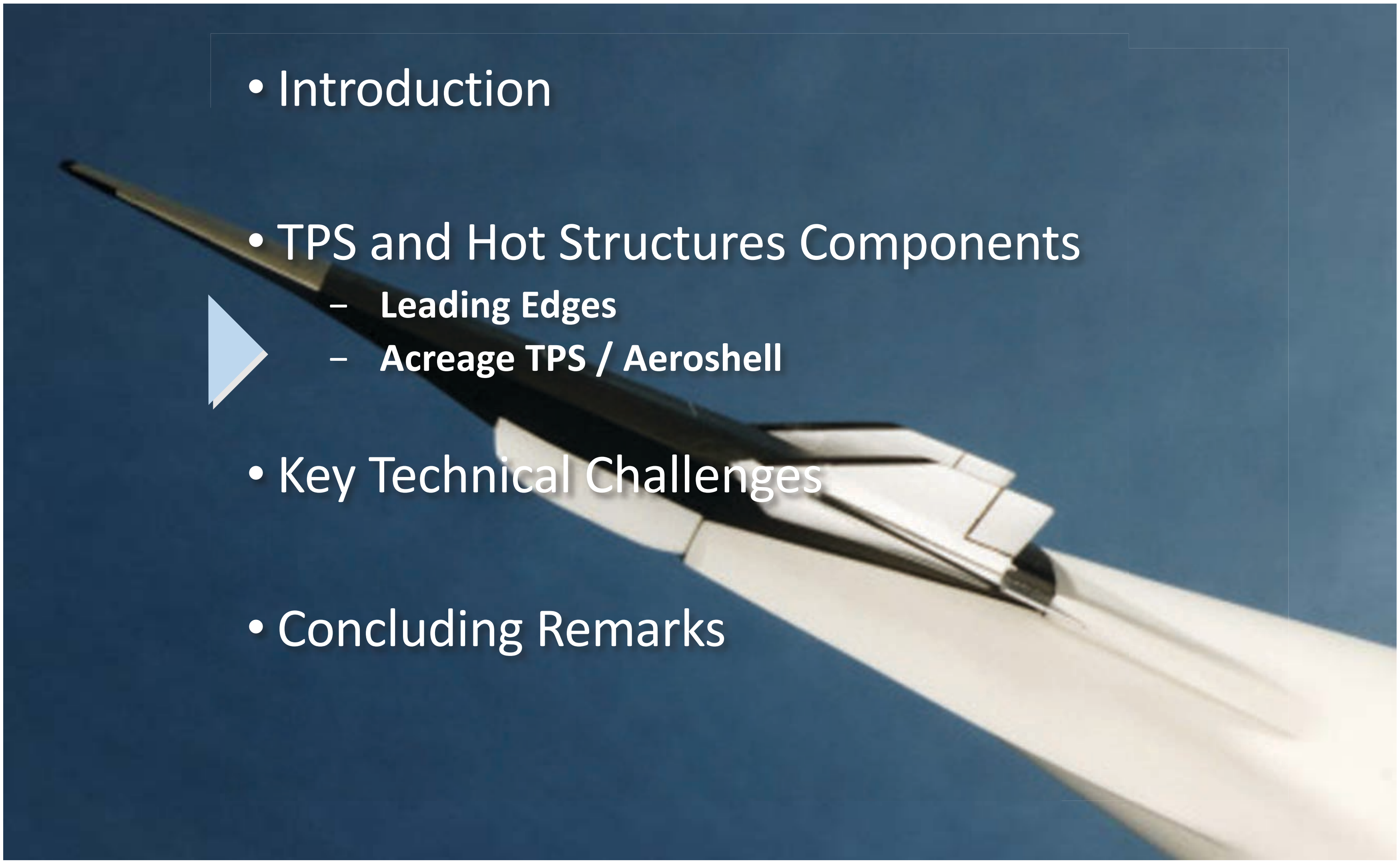


Co-processed metallic tubes



Intimate contact metallic tubes

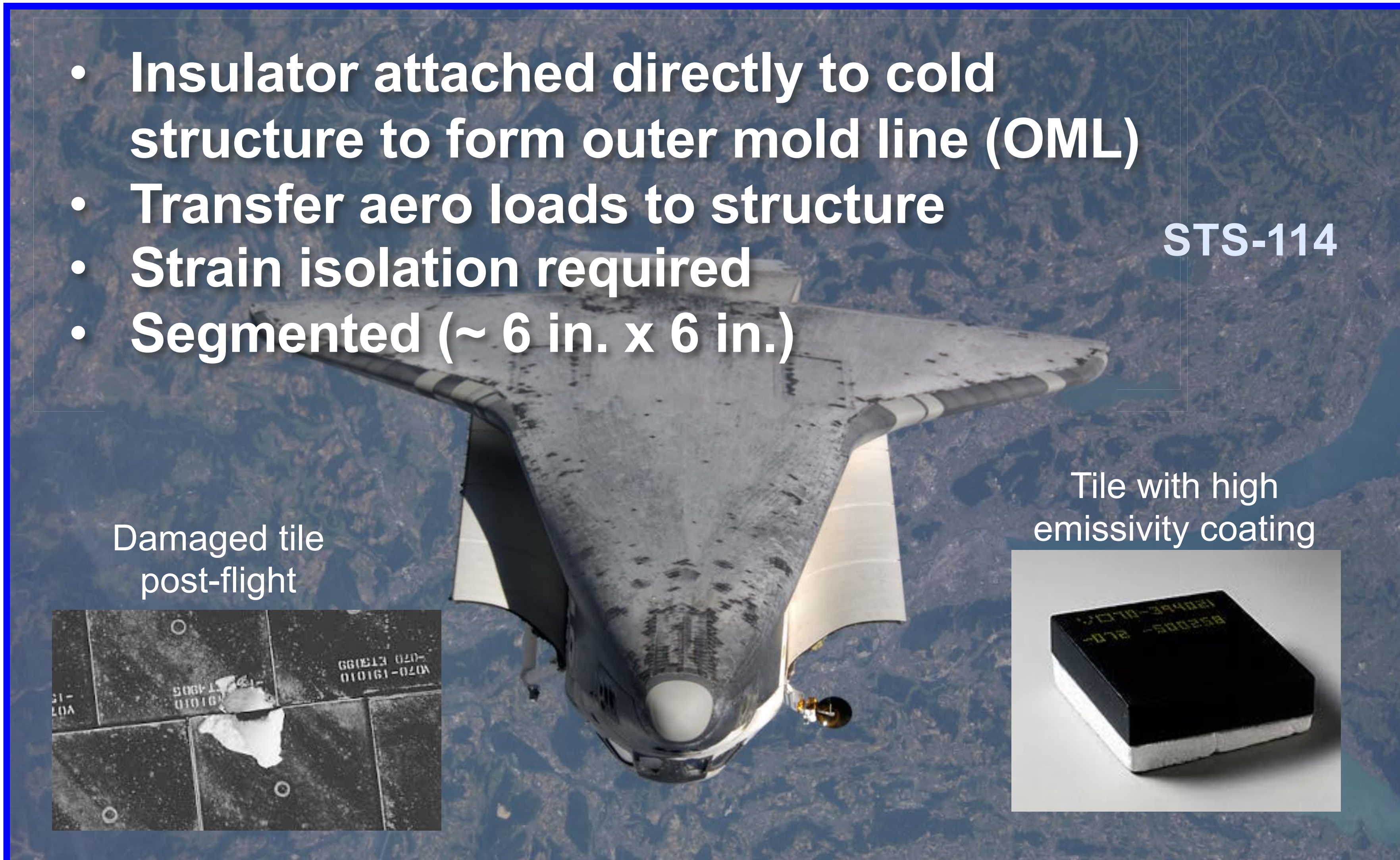
Outline



- Introduction
- TPS and Hot Structures Components
  - Leading Edges
  - Acreage TPS / Aeroshell
- Key Technical Challenges
- Concluding Remarks

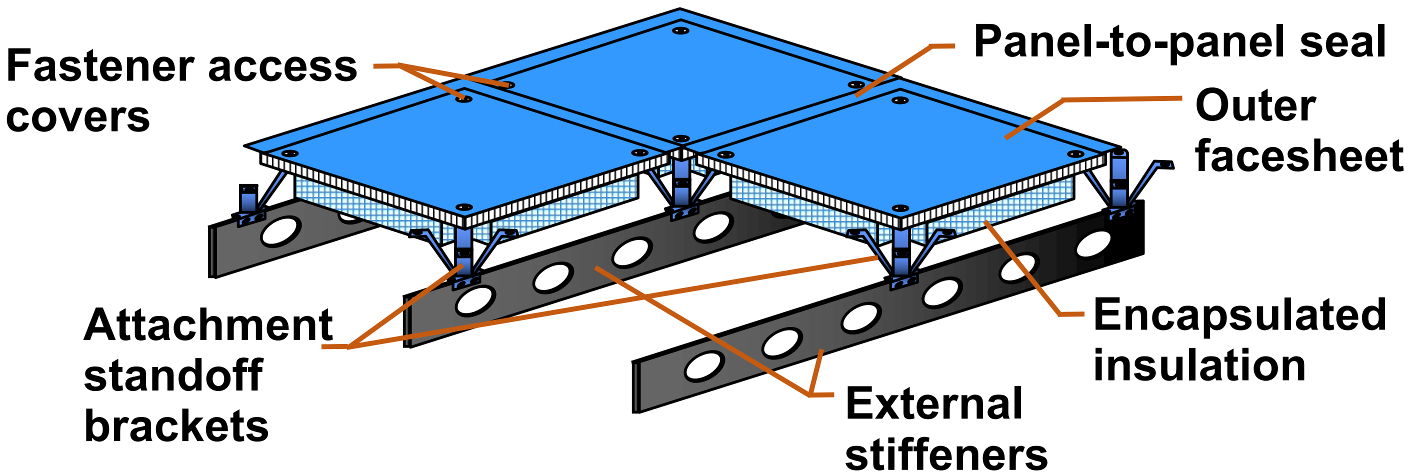
Insulated Structure

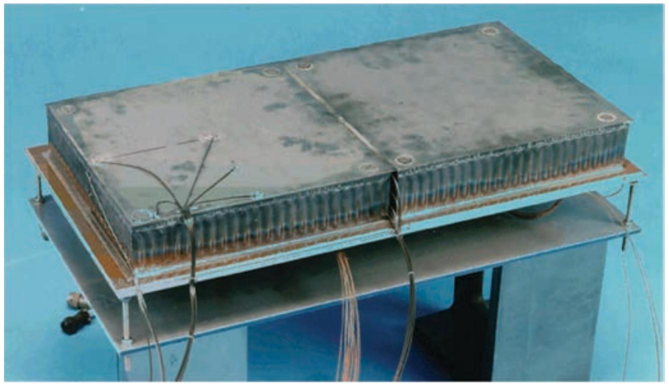
- Insulator attached directly to cold structure to form outer mold line (OML)
- Transfer aero loads to structure
- Strain isolation required
- Segmented (~ 6 in. x 6 in.)



Standoff Thermal Protection System (TPS)

- Cold/warm structure
- Panels attached to standoffs to create aeroshell
- Transfer aero but not thermal loads to structure
- Segmented

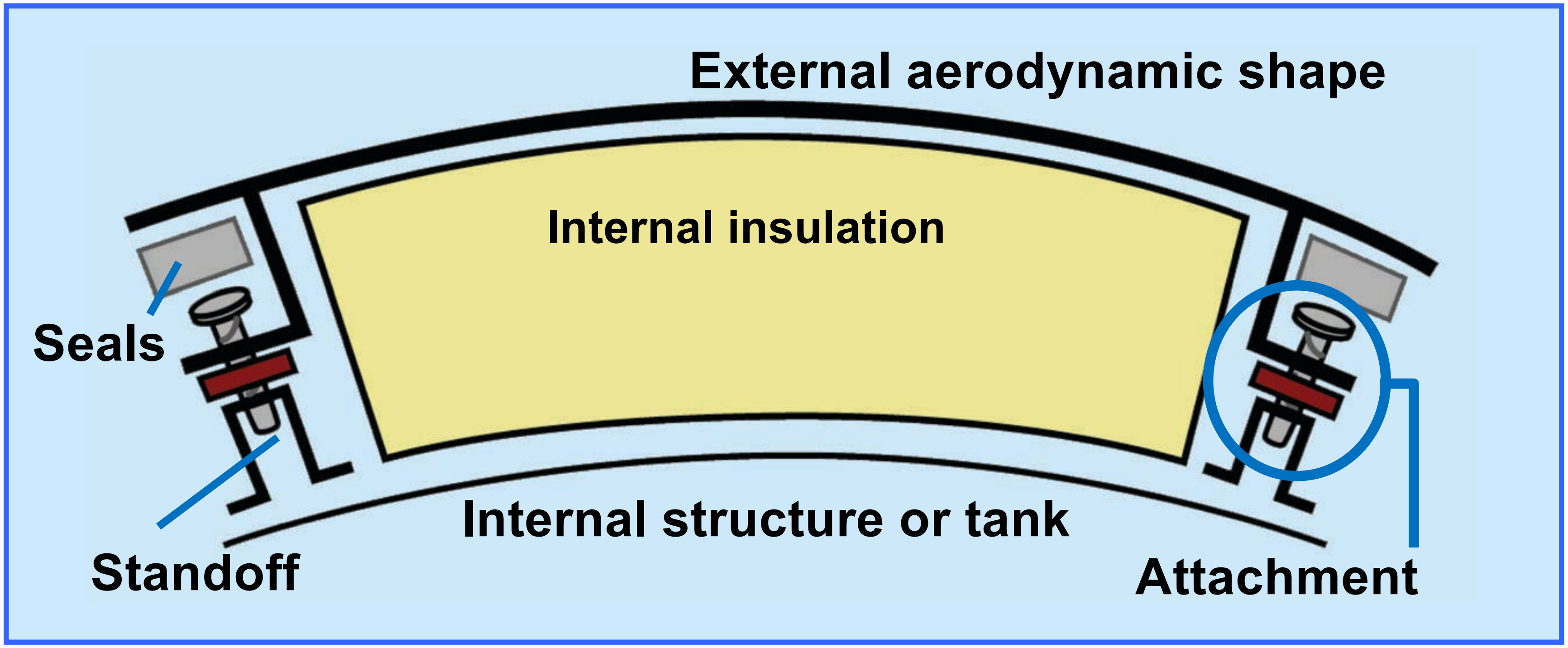




Metallic TPS test article

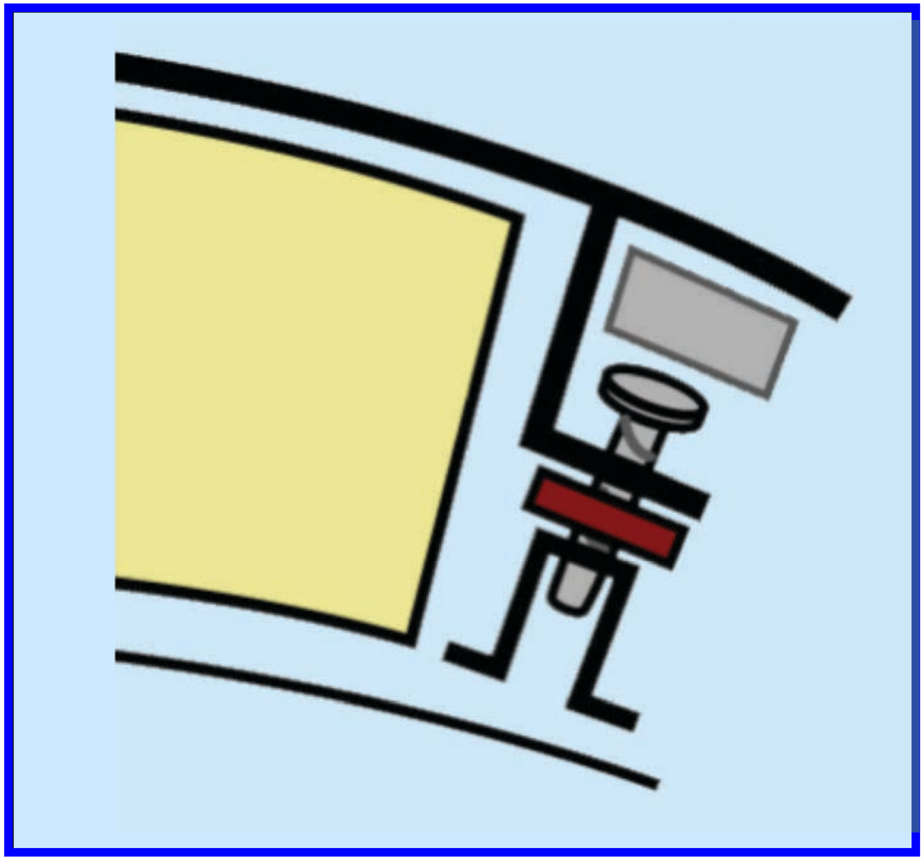
CMC Standoff TPS

- External CMC panel with oxidation protection
- Internal insulation
- High-temperature seals
- Attachment for external CMC and internal structure



Standoff TPS Attachment Challenge

- Attaching the external CMC panel to the substructure is one of the key challenges
- Must transfer aero loads, but not thermal loads



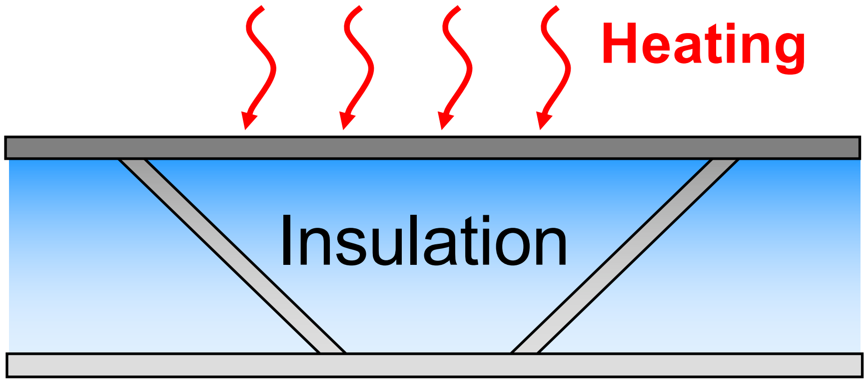
Load Bearing Aeroshell

- Aeroshell carries aero and vehicle axial loads
- Insulation incorporated or separate
- Potential for reduced weight

Structurally Integrated TPS

- **Thermally integrated**
- **Higher efficiency, lower maintenance**
- **Outer surface is robust structure**
- **Wall thickness provides stiffness**
- **Eliminate surface steps and gaps**
- **Low part count**

Structural wall carries airframe loads and insulates inner surface



Outline

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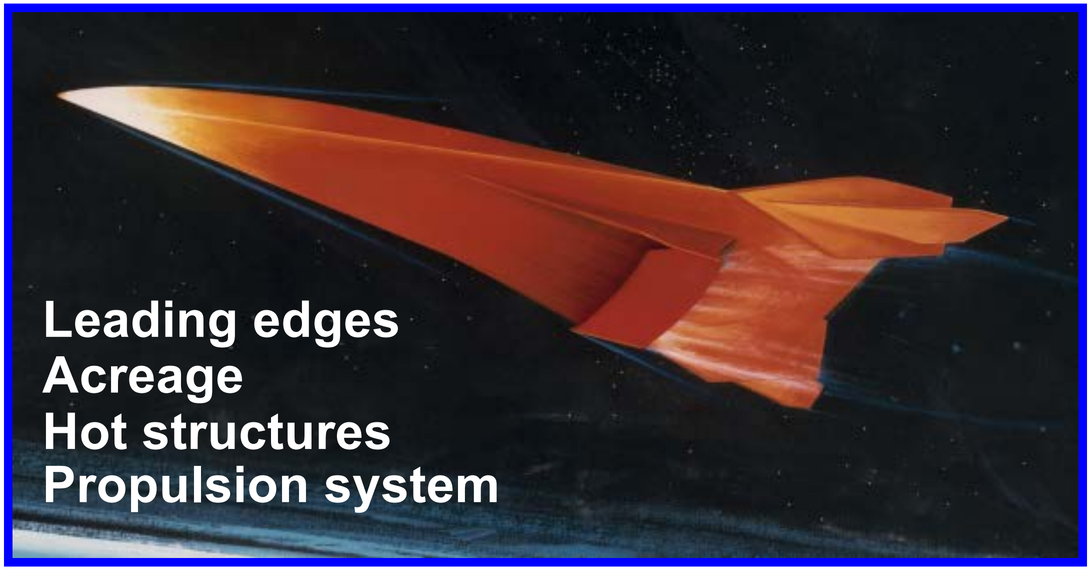
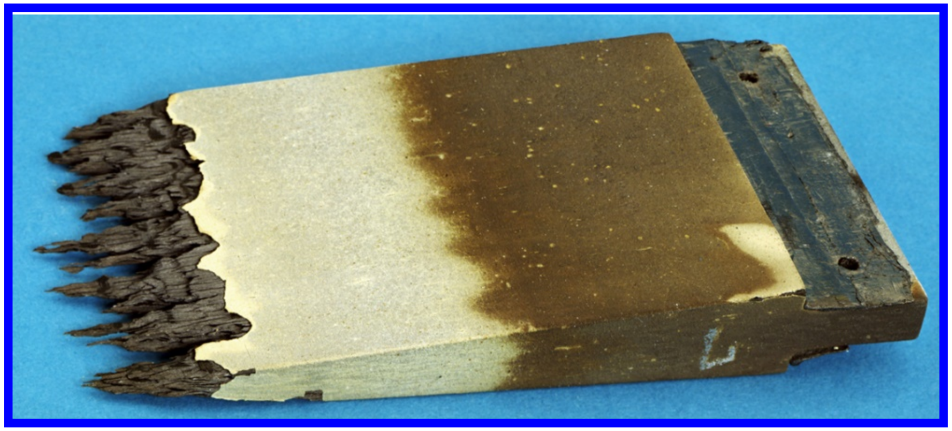
Hypersonic Vehicles

- **CMCs are the family of materials that will enable hypersonic vehicles**



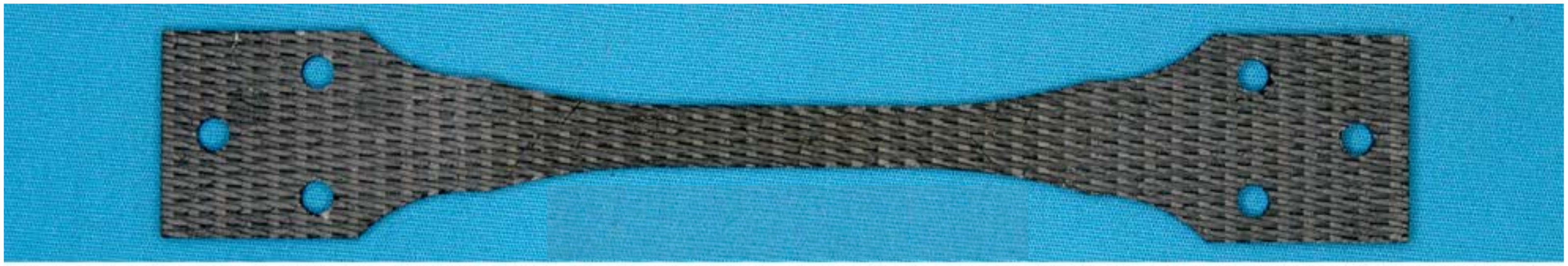
- **For most hypersonic vehicles, there are two key materials and structures technical challenges**

Key Technical Challenge: Environmental Durability



- **Oxidation resistance**
- **Mission life**
  - **Cycles under combined loads**
  - **Inspection**
  - **Repair**
  - **Life prediction**

Hot-Structures Manufacturing



A state-of-the-art material is not the same thing as a state-of-the-art structure

X-38 C/SiC body flaps

Big difference!

Experience is gained through building flight hardware and integrating it into flight vehicles

Fabrication Challenges

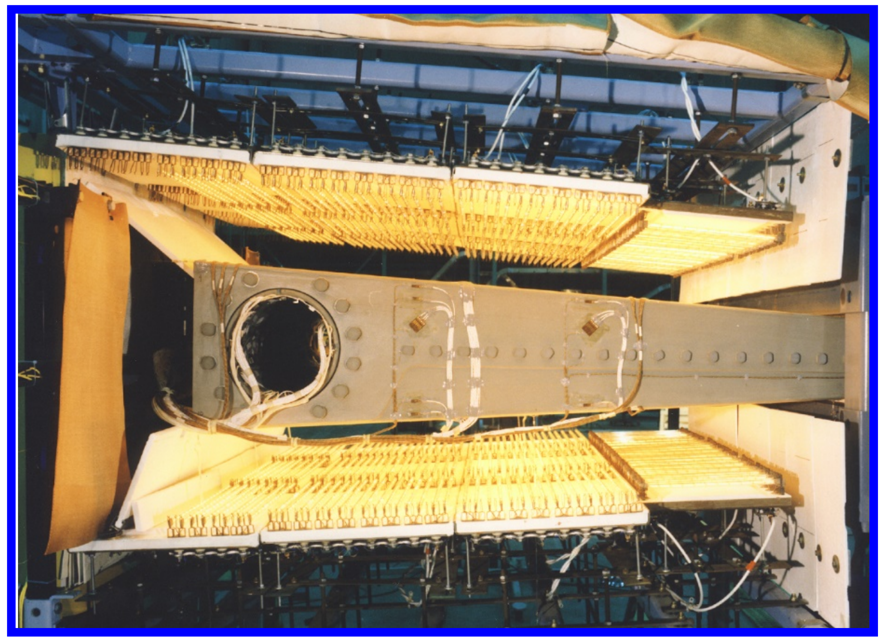
- Thick
- Complex curvature
- Large scale
- Low interlaminar properties
- Delamination
- Critical flaw size
- Non-destructive inspection
- Tooling
- Assembly methods and tolerances
- Reproducibility
- Fabrication modeling
- Design of manufacturable structures
- Affordable (cost and schedule) fabrication techniques

Fabrication challenges are process dependent

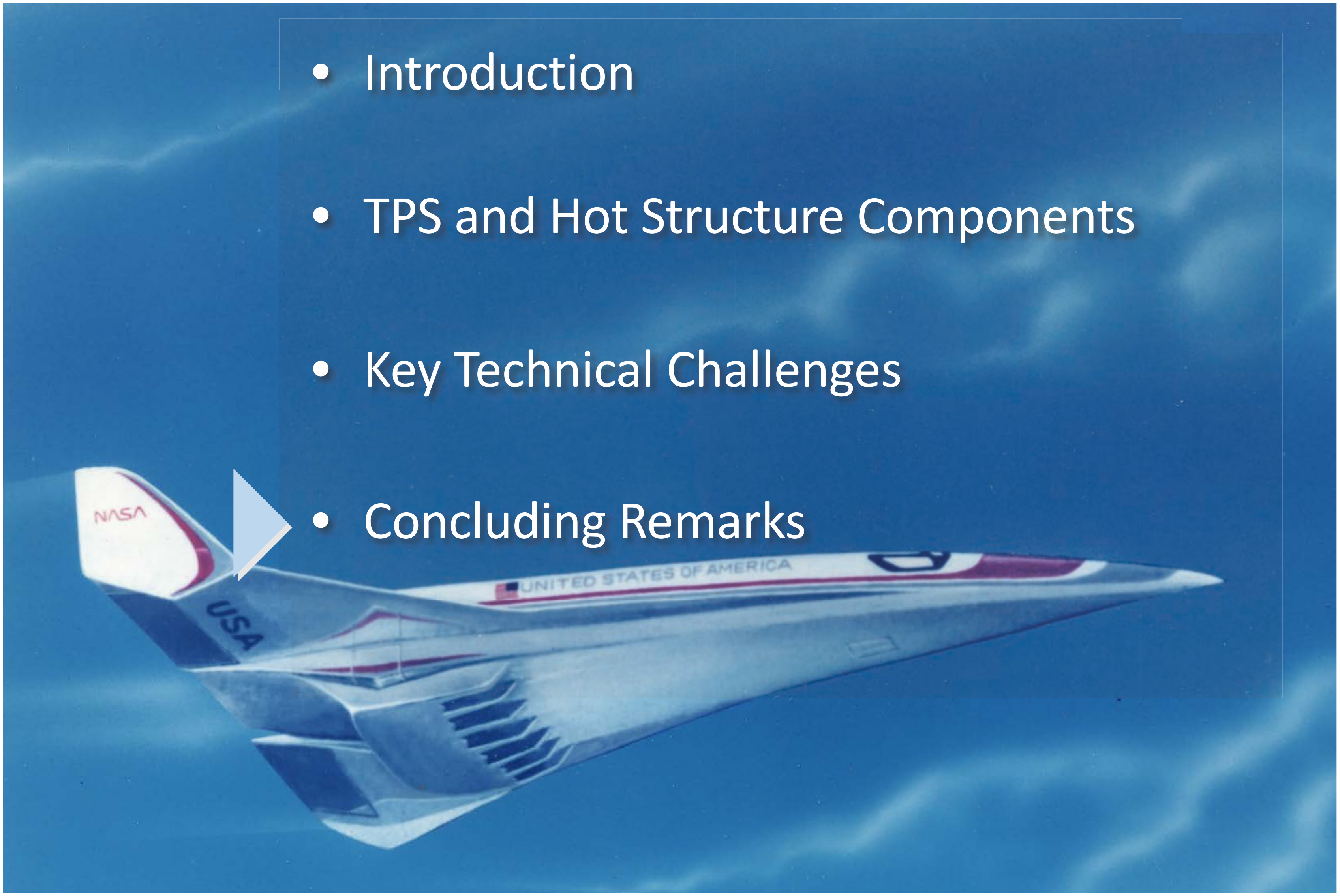
Will Hot Structures Meet Flight Requirements?

Operation has a significant impact on our ability to use these materials as structures on flight vehicles

- Thermal loads
- Thermal gradients
- Mechanical loads
- Acoustic and vibration loads
- Pressure (oxidation)
- Combined loads
- Number of cycles



Outline



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Concluding Remarks

- Hypersonic vehicles will require us to move beyond an insulated aluminum “airplane” to a vehicle with multiple TPS and hot structure approaches

- Our ability to build and fly these vehicles successfully will depend on our ability to utilize multiple types of CMC structures, first having solved the environmental durability and fabrication challenges

Additional details on these topics can be found in AIAA-2008-2682