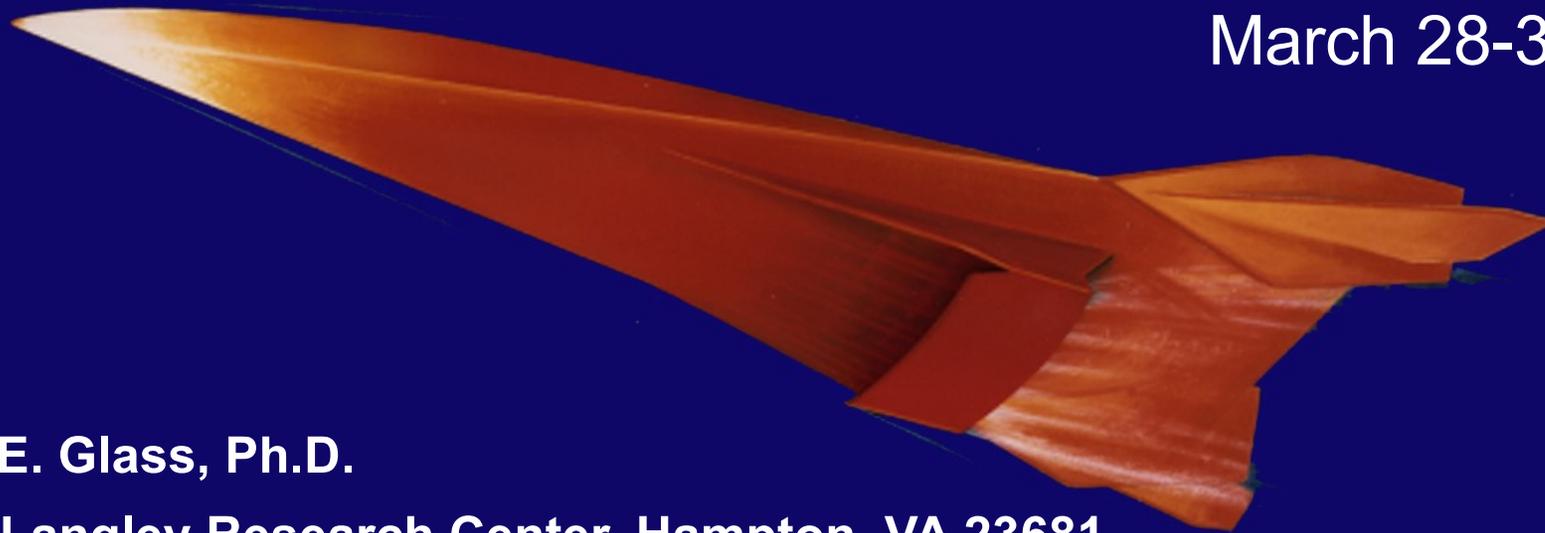


Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles

**Additive Manufacturing Thermal Protection System Workshop
NASA Johnson Space Center
March 28-30, 2022**



David E. Glass, Ph.D.

NASA Langley Research Center, Hampton, VA 23681

Craig A. Stephens

NASA Armstrong Research Center, Edwards, CA 93523

Approved for Public Release

AIAA-2008-2682

Outline



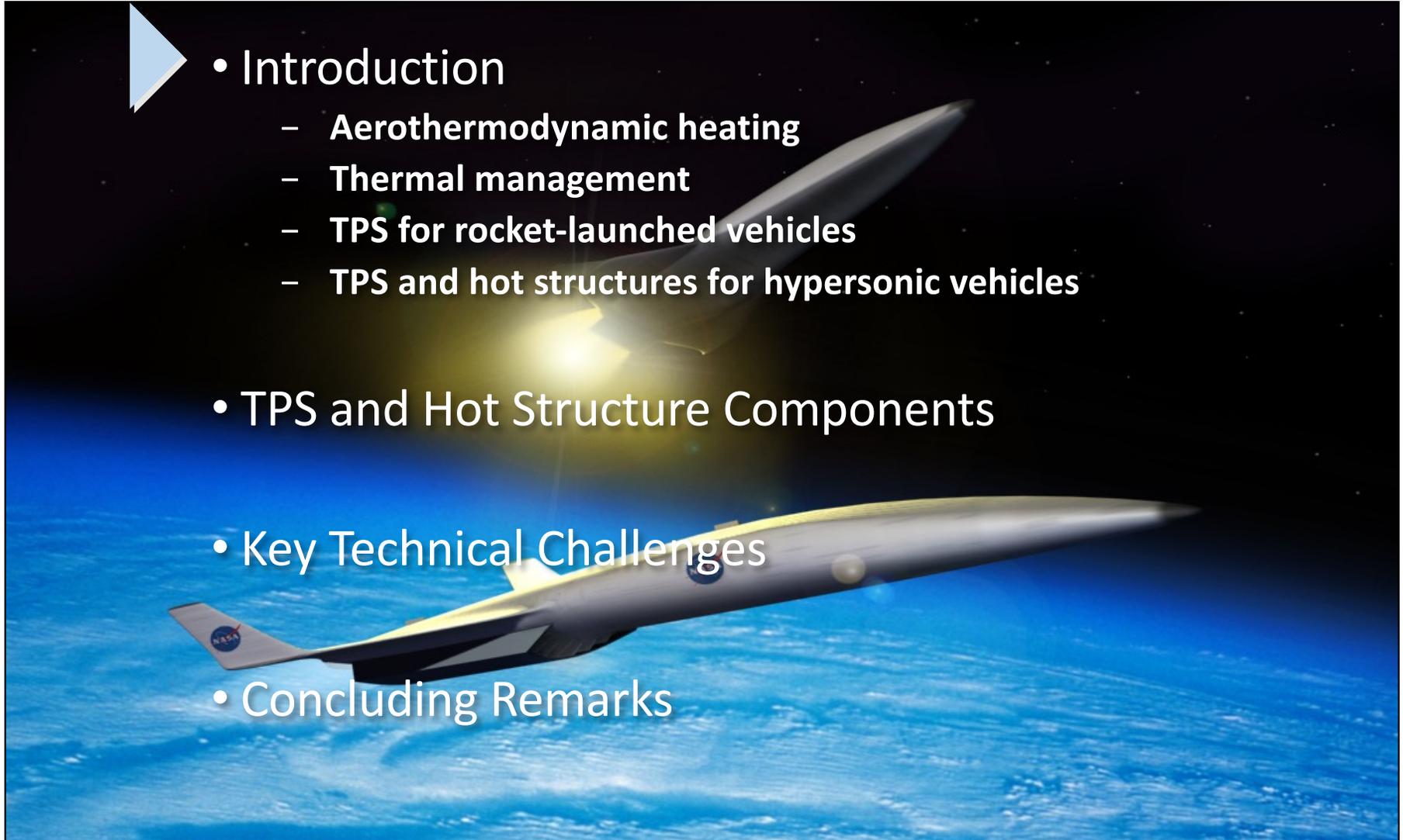
- Introduction

- Aerothermodynamic heating
- Thermal management
- TPS for rocket-launched vehicles
- TPS and hot structures for hypersonic vehicles

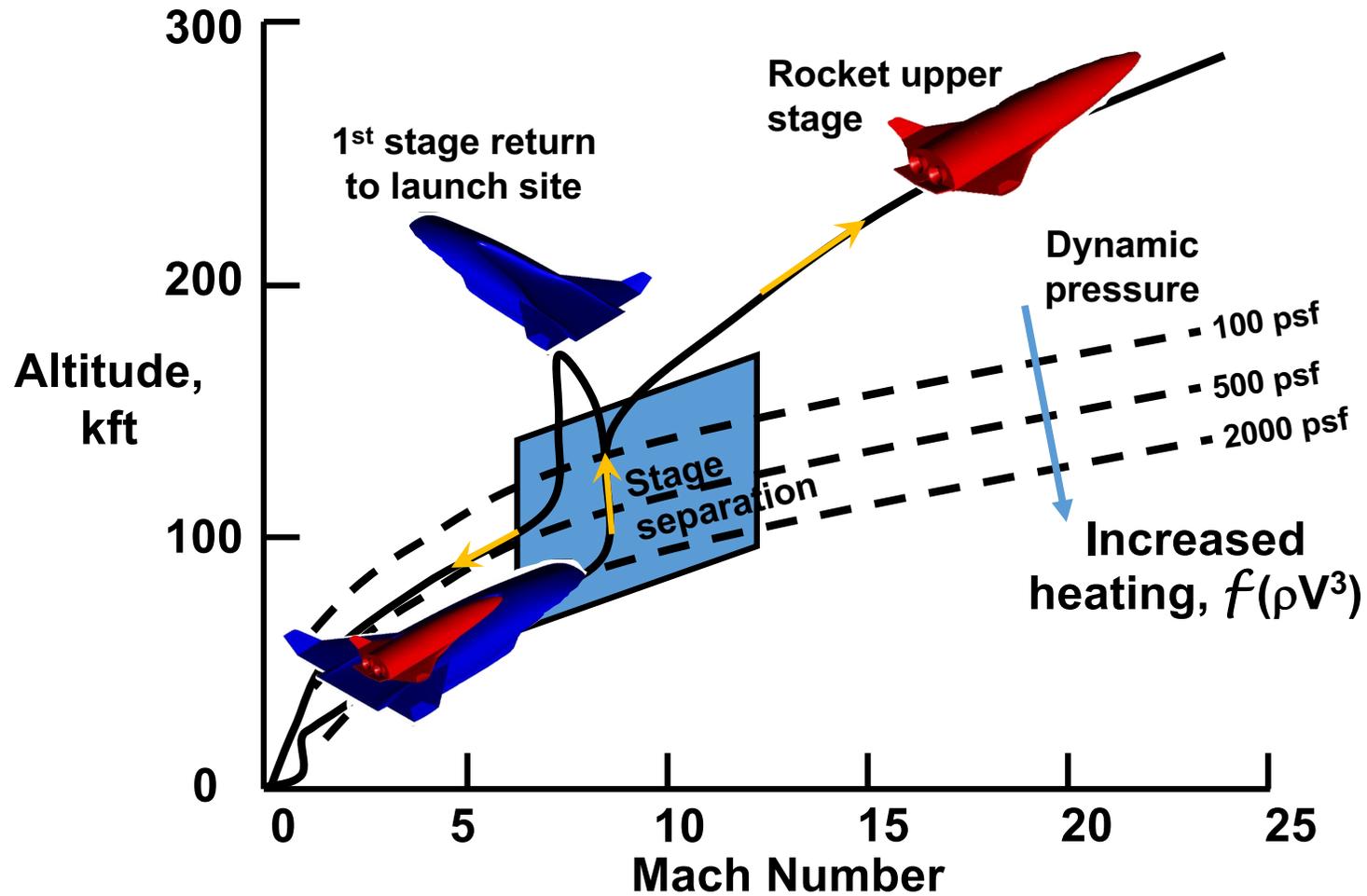
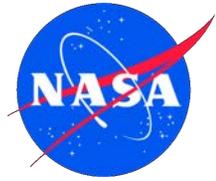
- TPS and Hot Structure Components

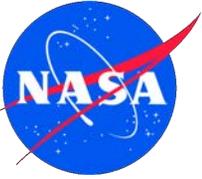
- Key Technical Challenges

- Concluding Remarks

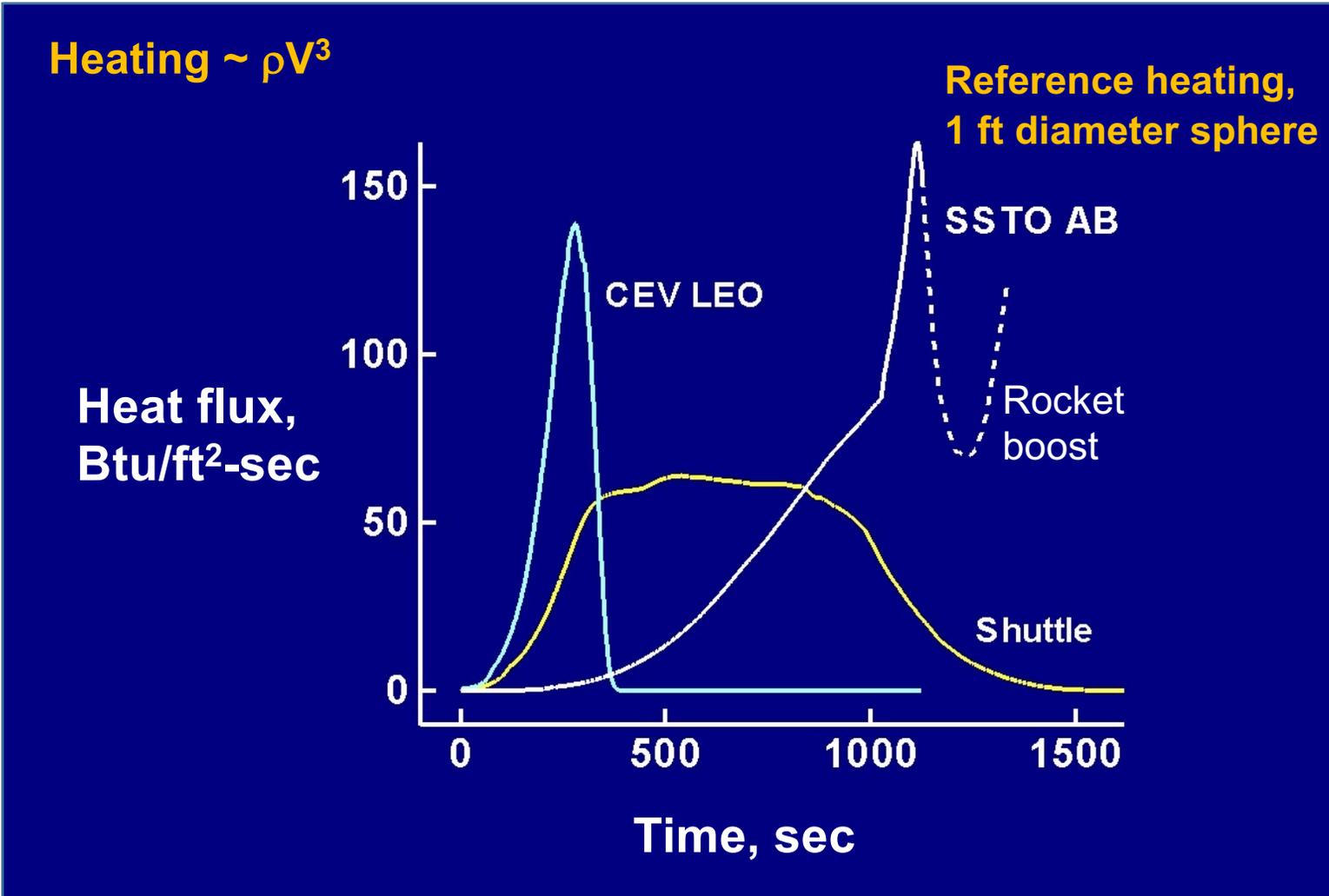


Two Stage to Orbit (TSTO) Reference Vehicle

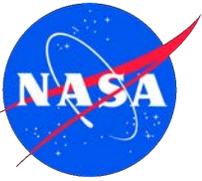




Heat Flux

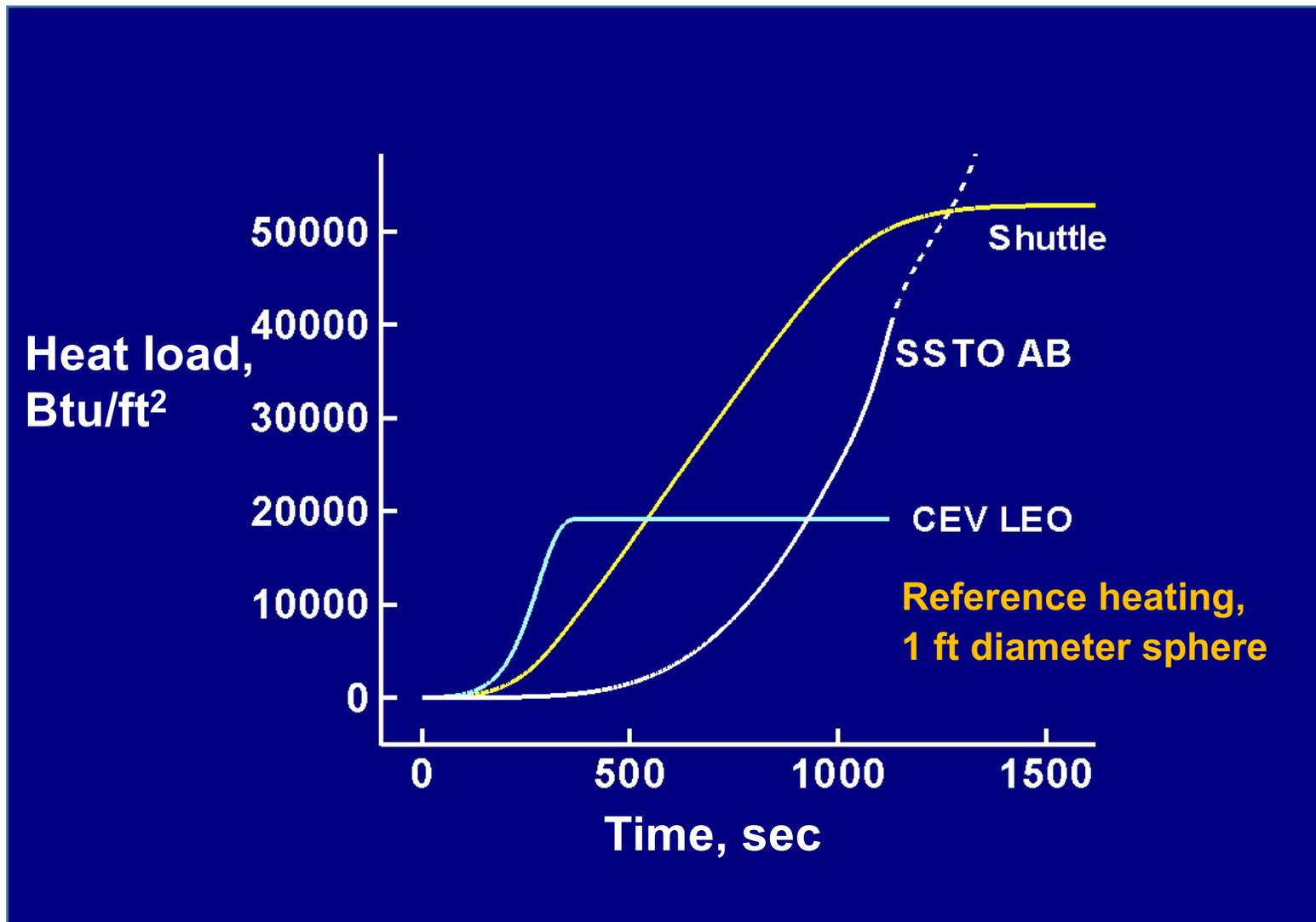


Crew Exploration Vehicle (CEV) Low Earth Orbit (LEO)
Single Stage to Orbit (SSTO) Airbreather (AB)



Heat Load

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

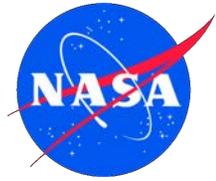


Outline



- 
- A 3D rendering of the X-43 hypersonic aircraft in flight, viewed from a low angle. The aircraft is white with black markings and a NASA logo. It is flying over a blue and white Earth background. The text of the outline is overlaid on the image.
- 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

TPS & Hot Structures



- In the US, the term “TPS” (thermal protection systems) is used to include:
 - Acreage TPS such as tiles, blankets, and ablators
 - Insulation
 - Hot structures such as leading edges, nose caps, control surfaces, and aeroshells
 - Multi-functional structure that carries load at operating temperatures
- Europe uses the term “TPS & Hot Structures”

Post-flight photo of European Intermediate eXperimental Vehicle (IXV)

Utilized both TPS & hot structures

The US needs to increase understanding of hot structures by separating it from TPS

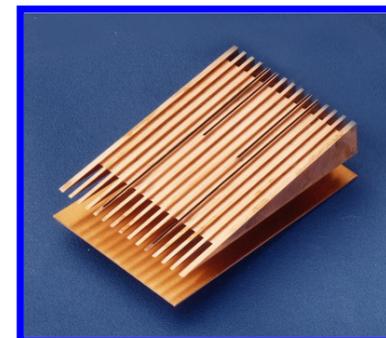
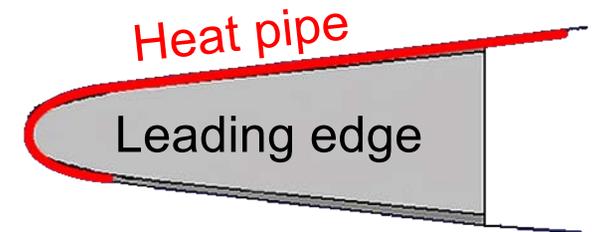
8th European Workshop on Thermal Protection Systems & Hot Structures



Types of Thermal Management

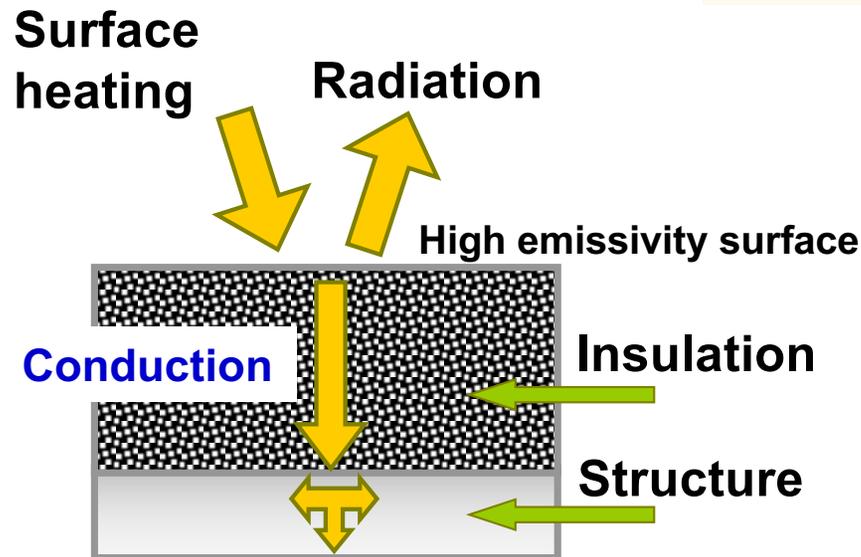
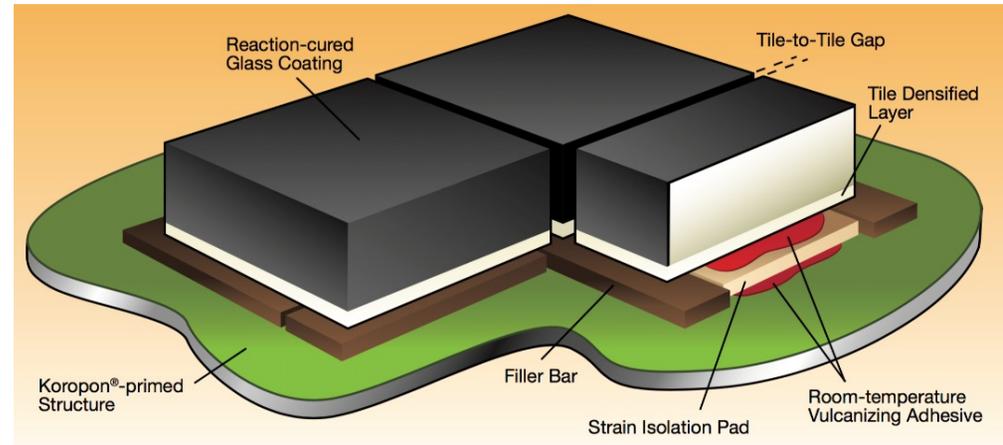
- Passive
- Semi-passive
 - Phase change
- Active
 - Pumped coolant

Tile



Passive: Insulated Structure

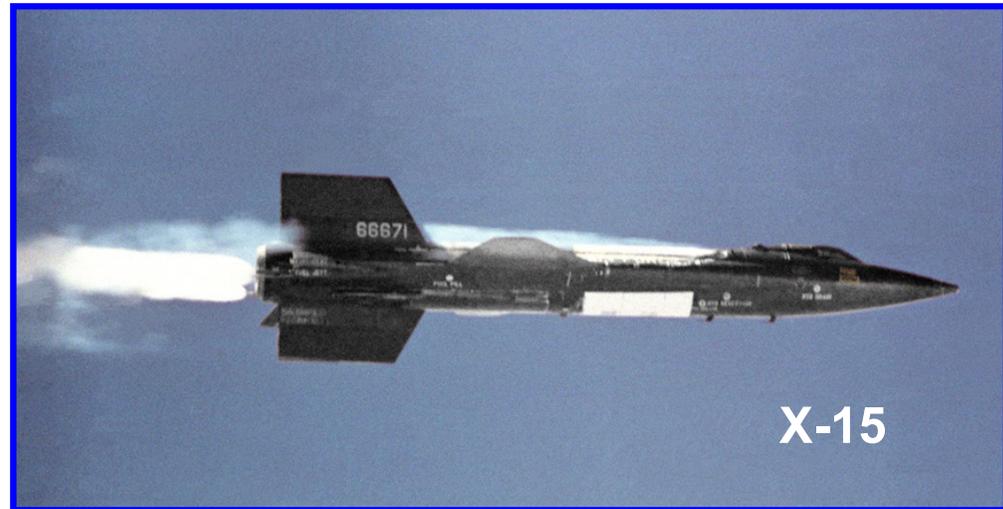
Use: Moderate heat flux, short times



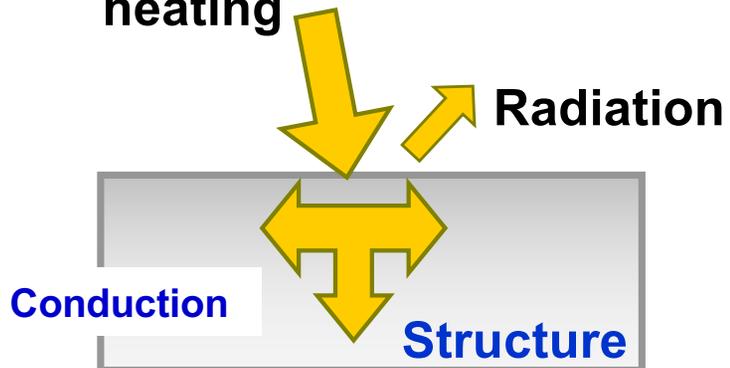
- Heat radiated away
 - Maximize surface emissivity
- Minimal heat conducted inward
- Structure remains cool

Passive: Heat Sink Structure

Use: Moderate heat flux, short times (transient)



Surface heating



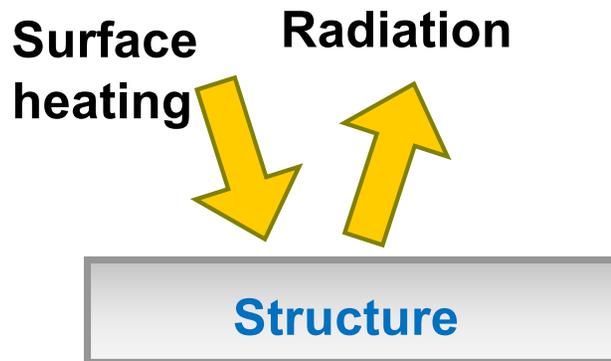
- Heat radiated away
- Heat absorbed by structure

Passive: Hot Structure

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



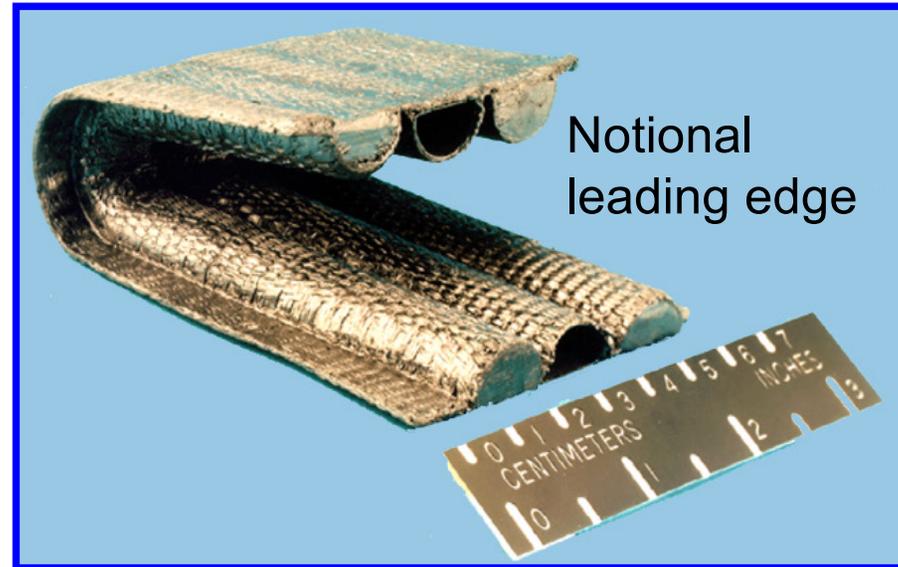
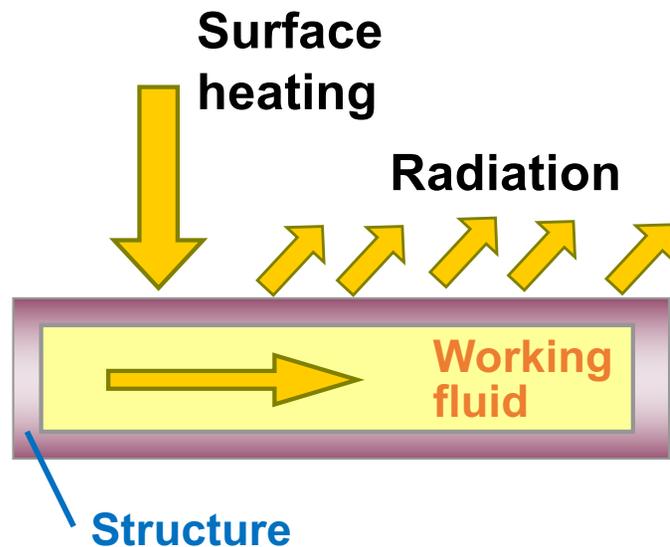
Sub-scale X-37 control surface manufacturing demo



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

Semi-Passive: Heat Pipe

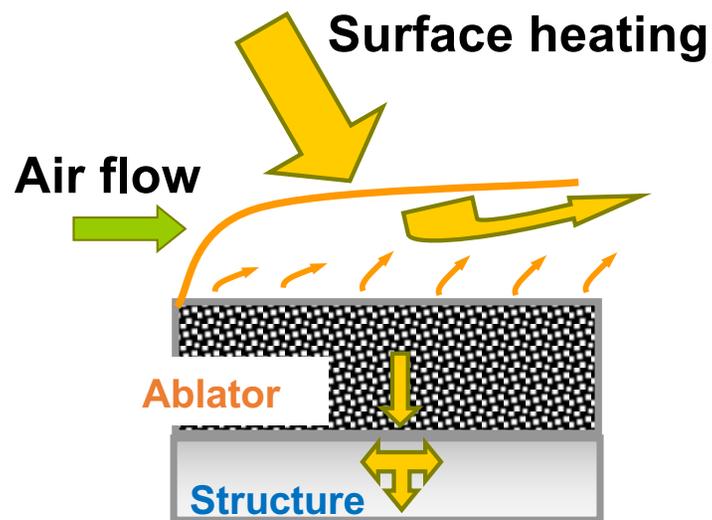
**Use: High heat flux,
long times**



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

Semi-Passive: Ablation

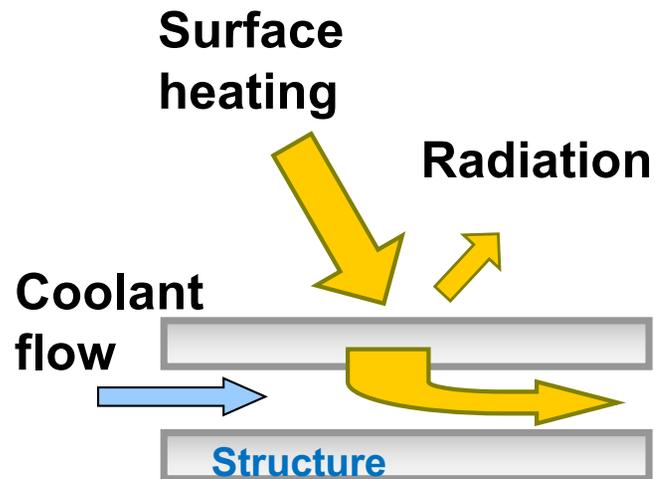
**Use: High heat flux,
short times, single use**



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

Active: Convective Cooling

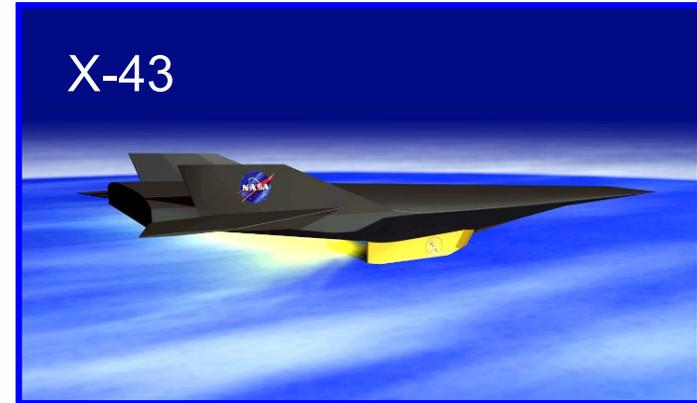
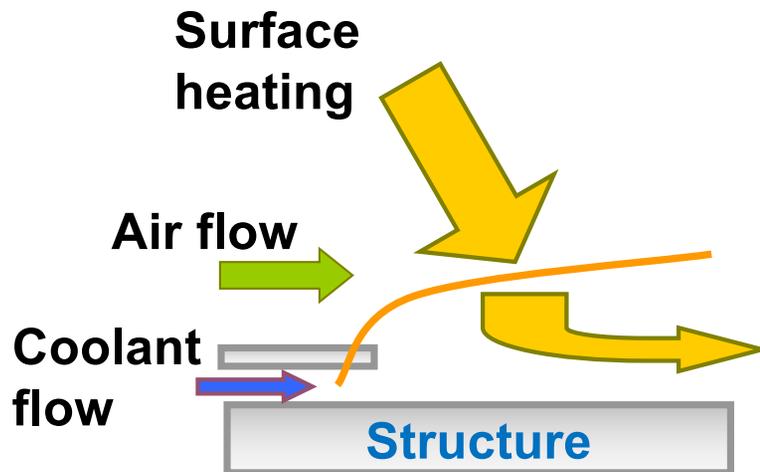
**Use: High heat flux,
long times**



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

Active: Film Cooling

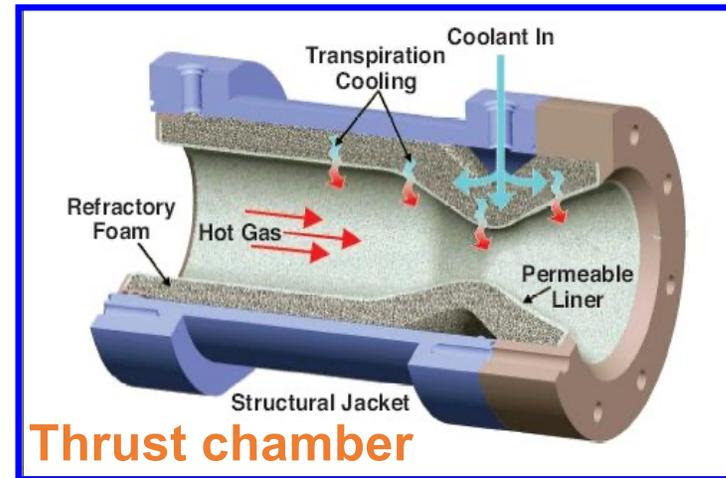
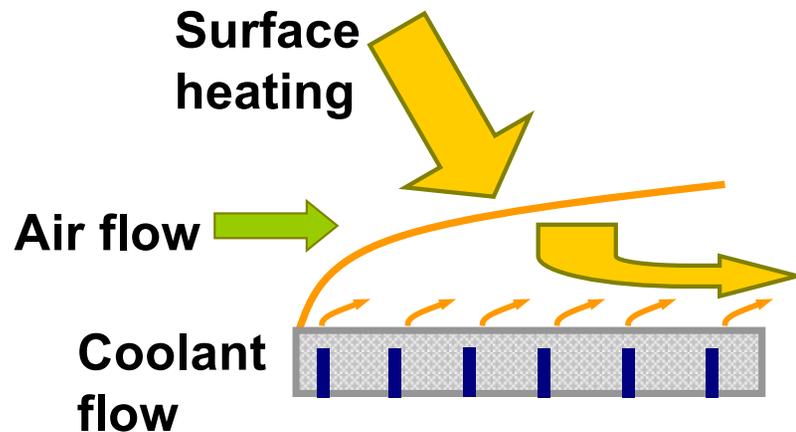
**Use: High heat flux,
long times**



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

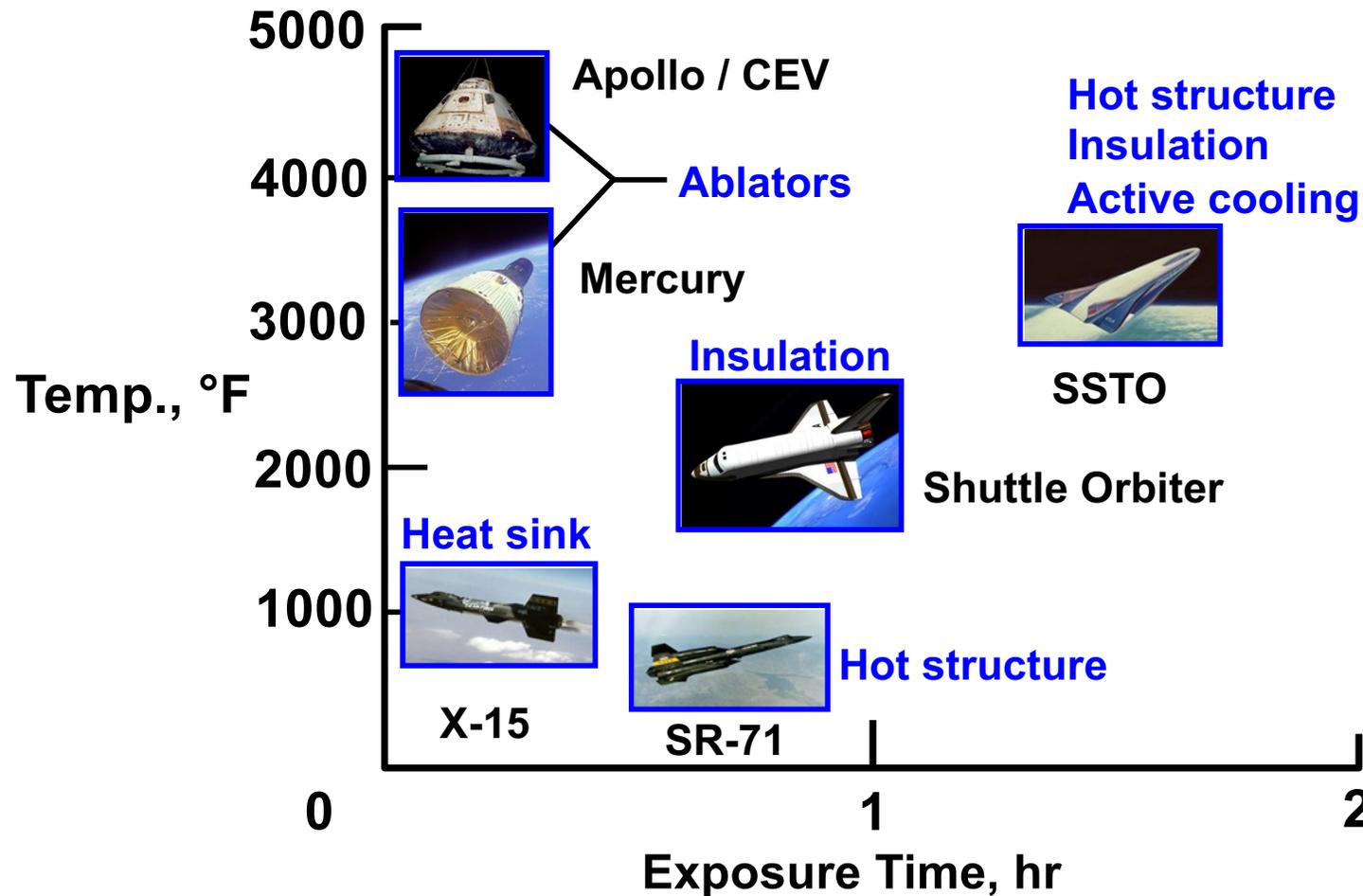
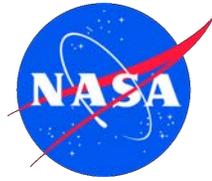
Active: Transpiration Cooling

**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



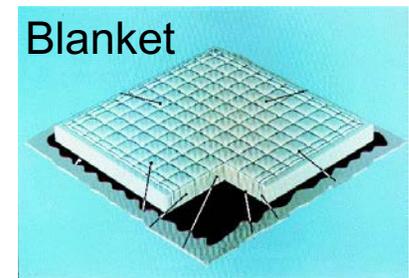
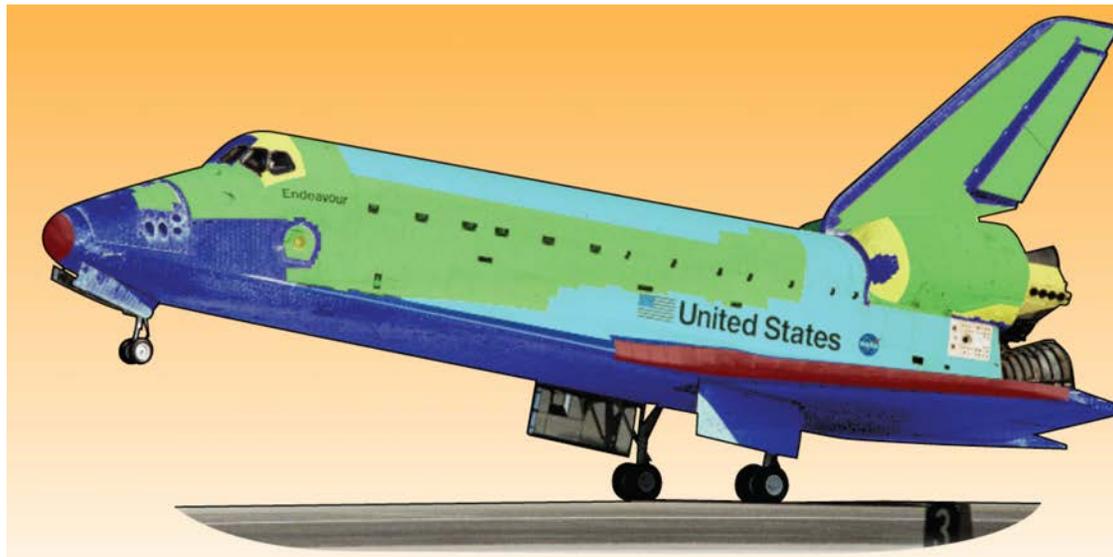
Outline



- 
- A 3D rendering of a spacecraft in orbit above Earth's cloud-covered surface. The spacecraft is white with a dark nose and a large, flat solar panel extending from its side. A smaller, similar spacecraft is visible in the distance.
- Introduction
 - Aerothermodynamic heating
 - Thermal management
 - ▶ – TPS for rocket-launched vehicles
 - TPS and hot structures for hypersonic vehicles
 - TPS and Hot Structures Components
 - Key Technical Challenges
 - Concluding Remarks

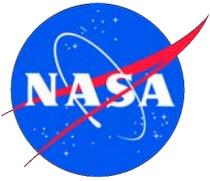
Space Shuttle Orbiter

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



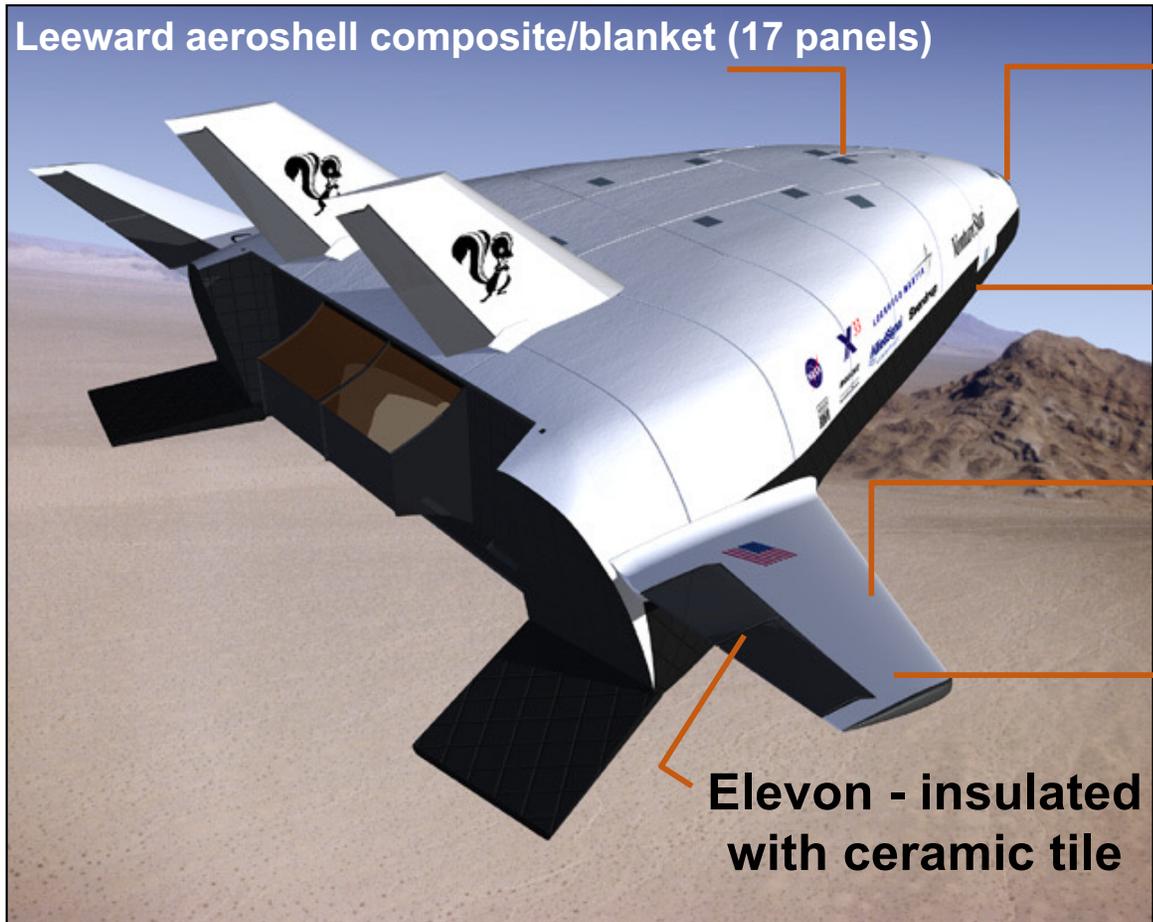
C/C leading edge





X-33 Thermal Protection System

Similar to Orbiter TPS except metallic TPS on windward surface



**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**

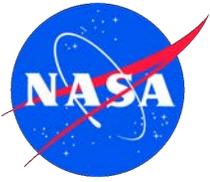
**Canted fin -
metallic (windward)
blanket (leeward)**

**Elevon - insulated
with ceramic tile**

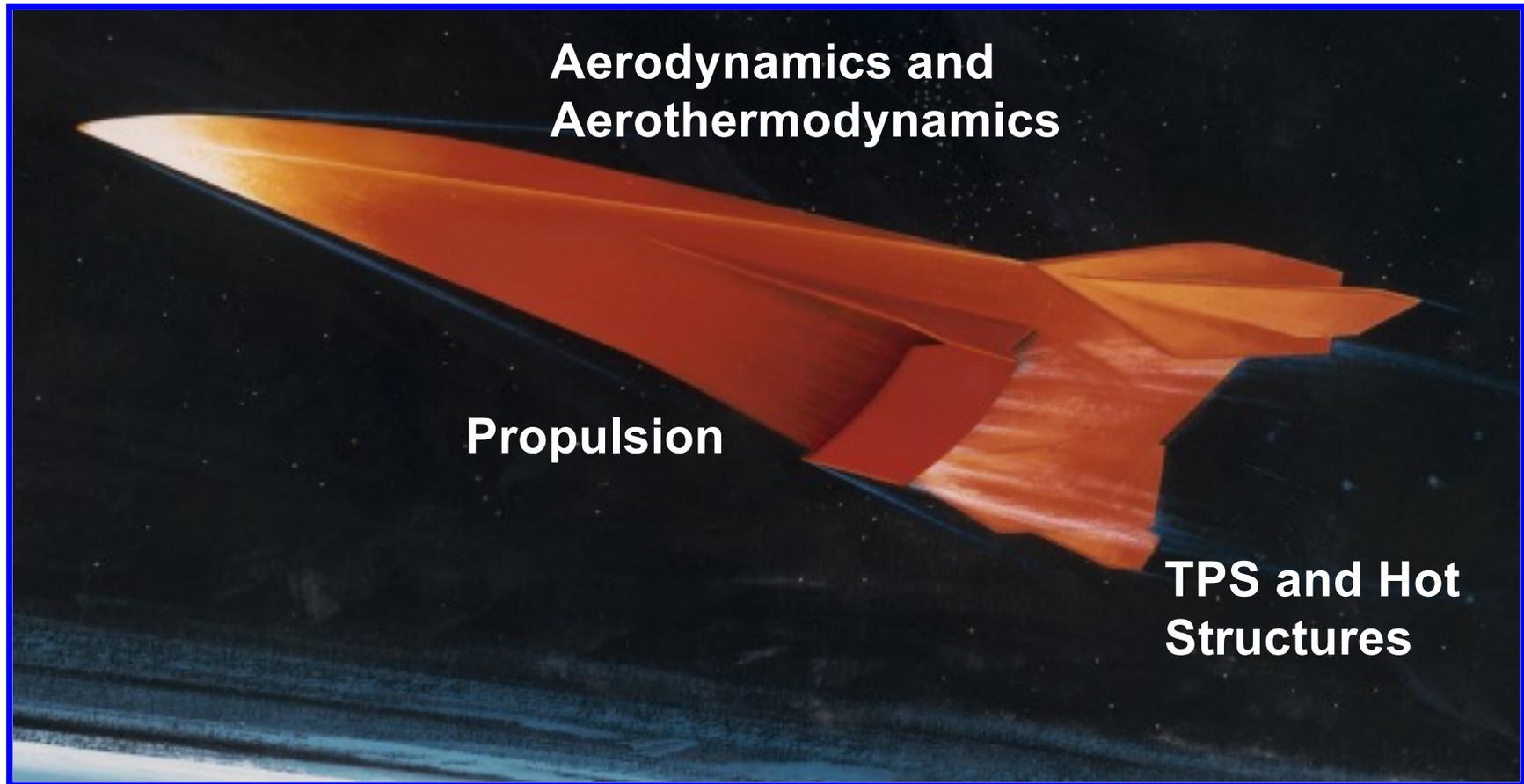
Outline



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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



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

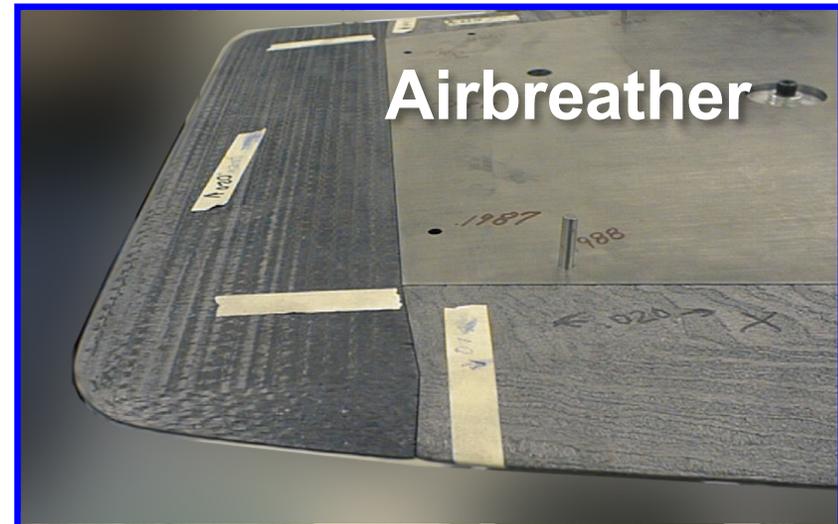


- Driven by ascent, descent, and cruise
- High heat load due to long ascent and cruise time

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

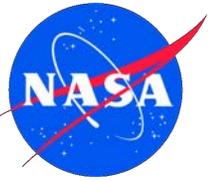


- Propulsion and airframe not highly integrated

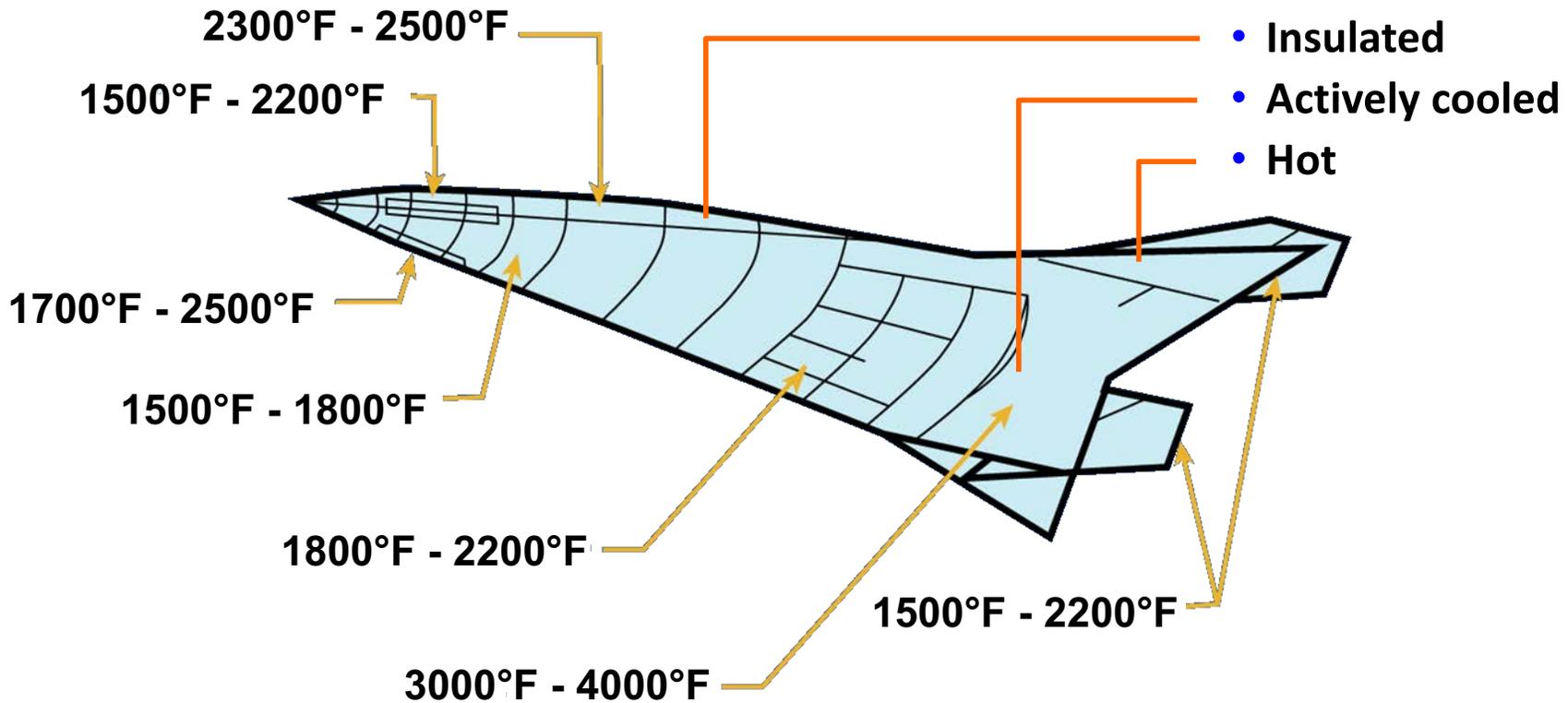


- Propulsion and airframe highly integrated
- Hot wings and control surfaces due to thin cross sections and high heat flux and heat load

Airbreathing Hypersonic Vehicle Temperatures



Structures



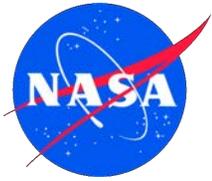
National Aerospace Plane (X-30)



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 outer mold line (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**

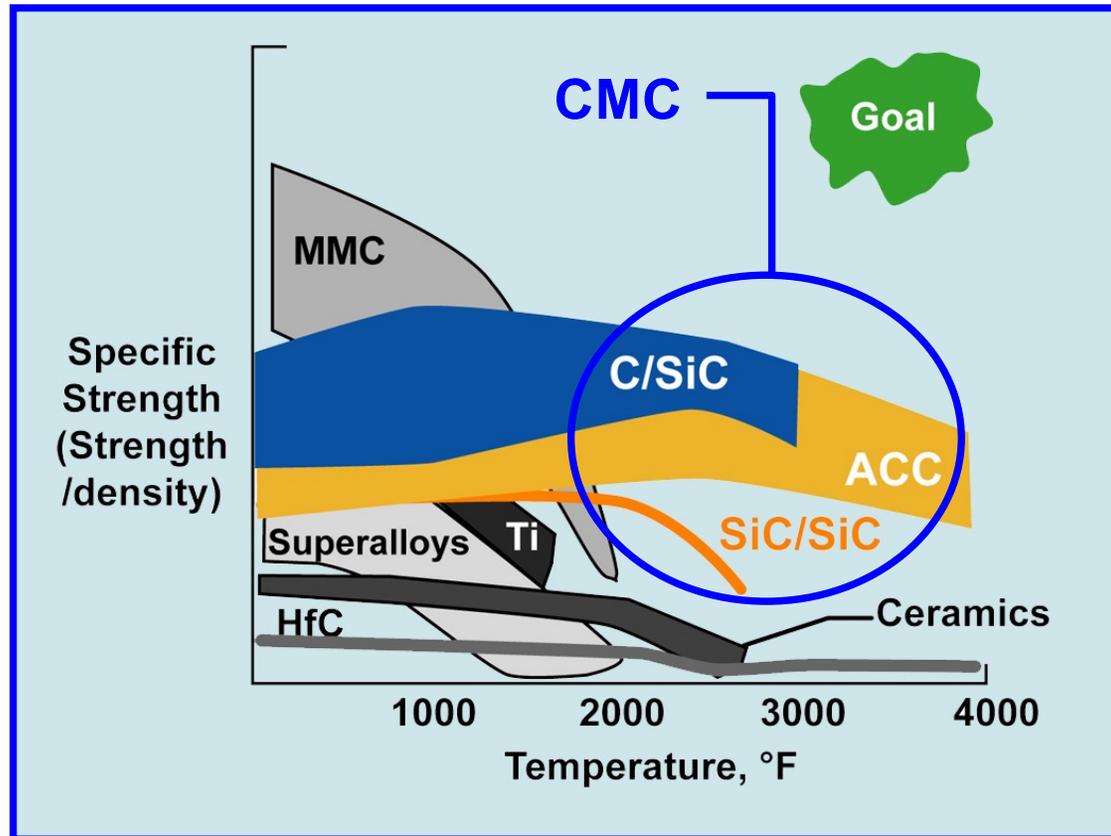
History Shows New Material Systems Help Enable the Vehicle



The image displays four different aircraft or spacecraft against a dark blue background. From left to right: an SR-71 Blackbird, an X-15 hypersonic aircraft, a Space Shuttle Orbiter, and a hypersonic vehicle. Each vehicle is associated with a material system label. The SR-71 is labeled with Titanium. The X-15 is labeled with Inconel. The Orbiter is labeled with Ceramic tiles, blankets, and C/C. The hypersonic vehicle is labeled with Ceramic Matrix Composites (CMCs).

- Titanium
- Inconel
- Ceramic tiles, blankets, and C/C
- Ceramic Matrix Composites (CMCs)

Material Specific Strength

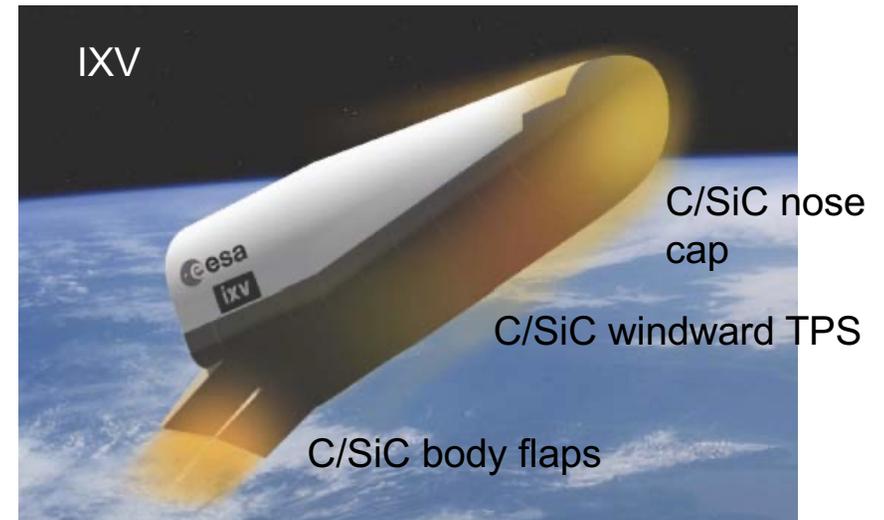


ACC: Advanced carbon/carbon
CMC : Ceramic matrix composite
MMC: Metal matrix composite
HfC: Hafnium carbide
Ti: Titanium

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

Why Hot Structures?

- **We must utilize high-specific-strength structures to expand our exploration goals and achieve hypersonic flight**
 - Strength / density
 - Metals: Al and Ti
 - Composites: PMC, Gr/BMI, Gr/Pi
 - Above Ti temps (M 5ish), we often utilize heavy superalloys, refractory metals, and active cooling
 - Refractory composite hot structures extend high-specific-strength structures to 3000°F and above (required for reentry and high hypersonic velocities)
- **We must open the trade space and provide designers options**
 - Hot structures, when applicable, can offer ~25% weight savings



Outline



- Introduction



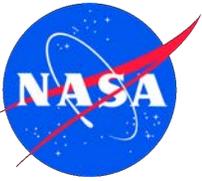
- TPS and Hot Structures Components

- Leading Edges
- Acreage TPS / Aeroshell
- Control Surfaces

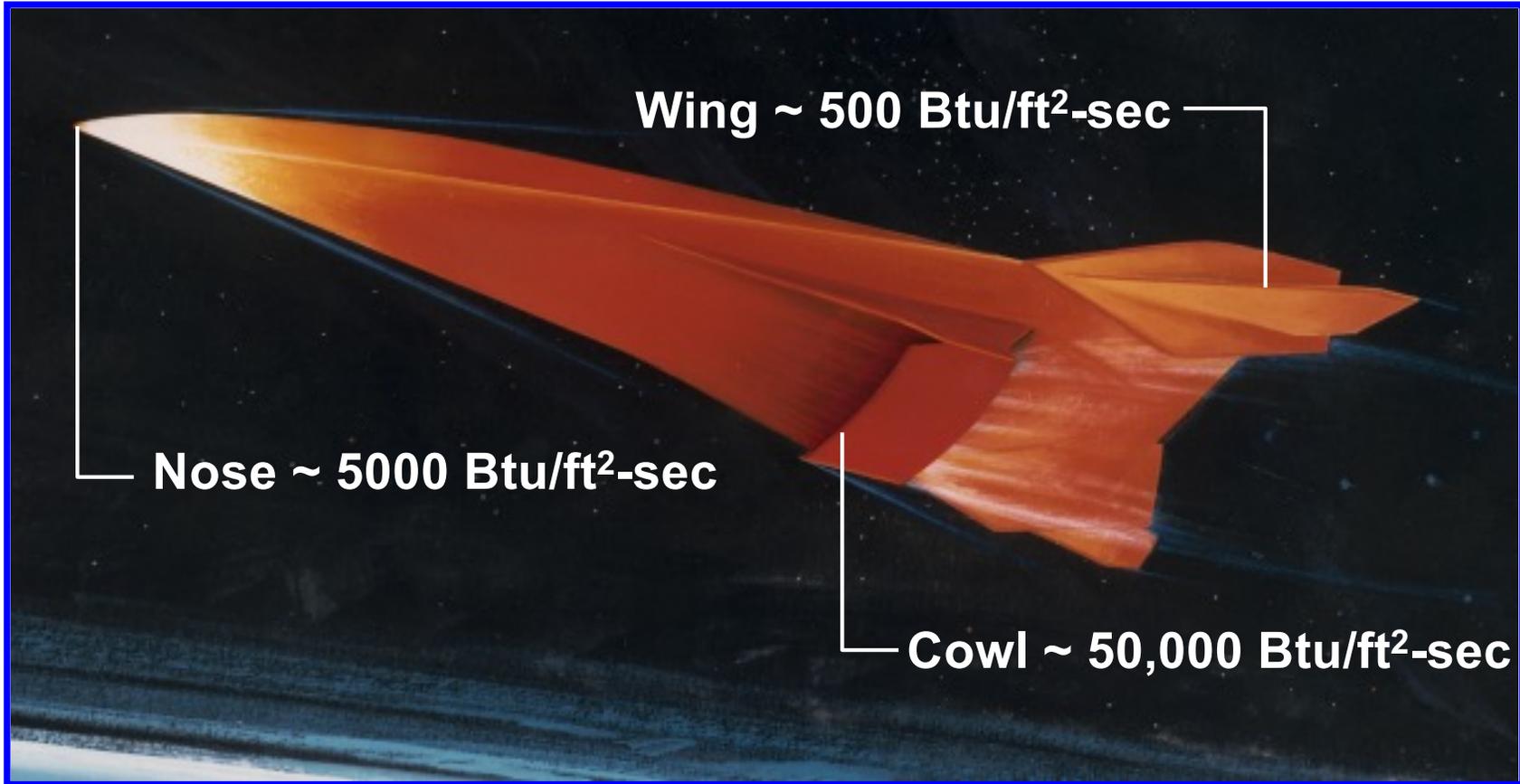
- Key Technical Challenges

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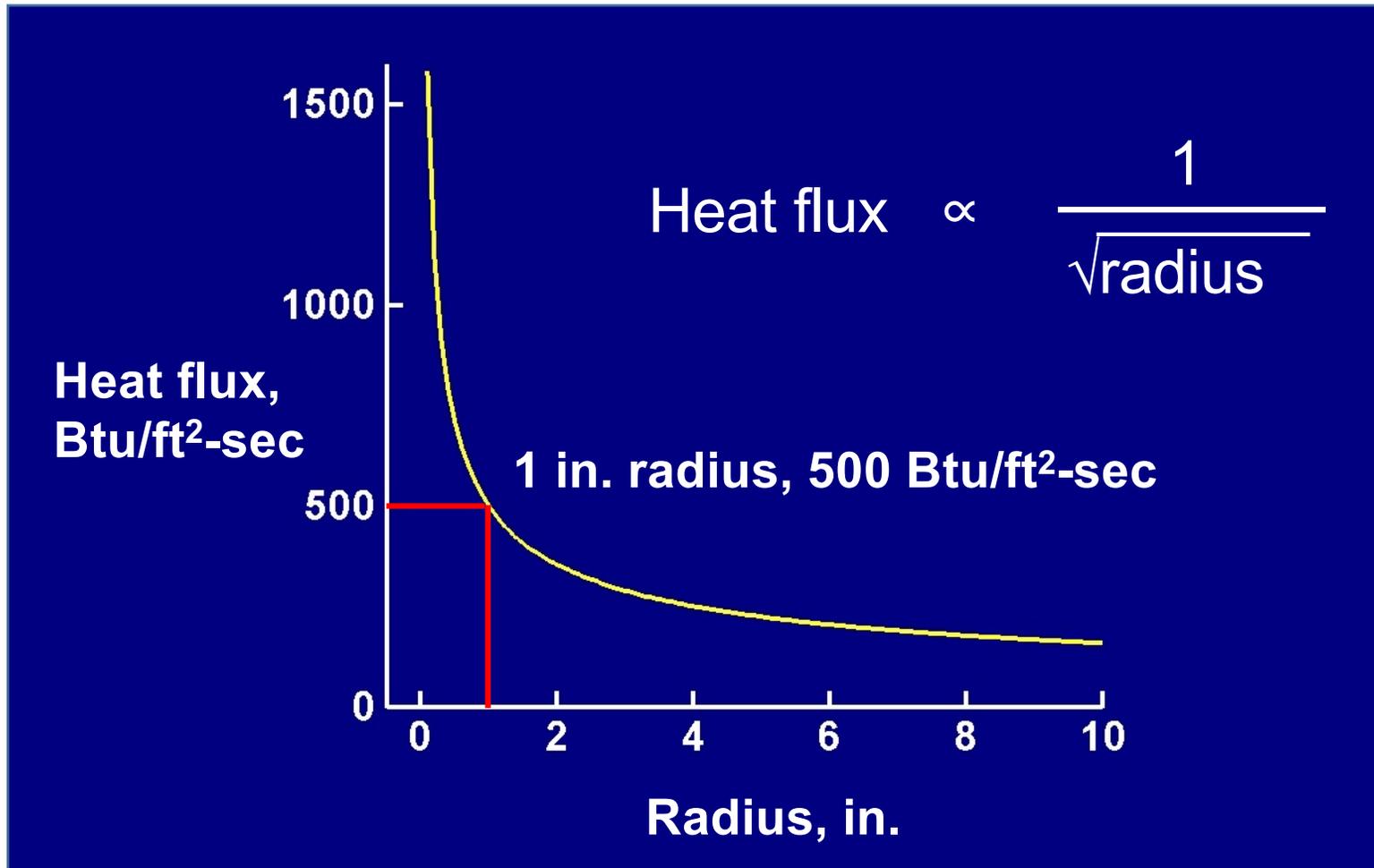
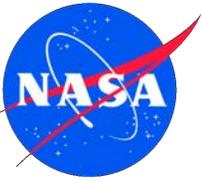


Typical Ascent Leading-Edge Heat Flux for SSTO

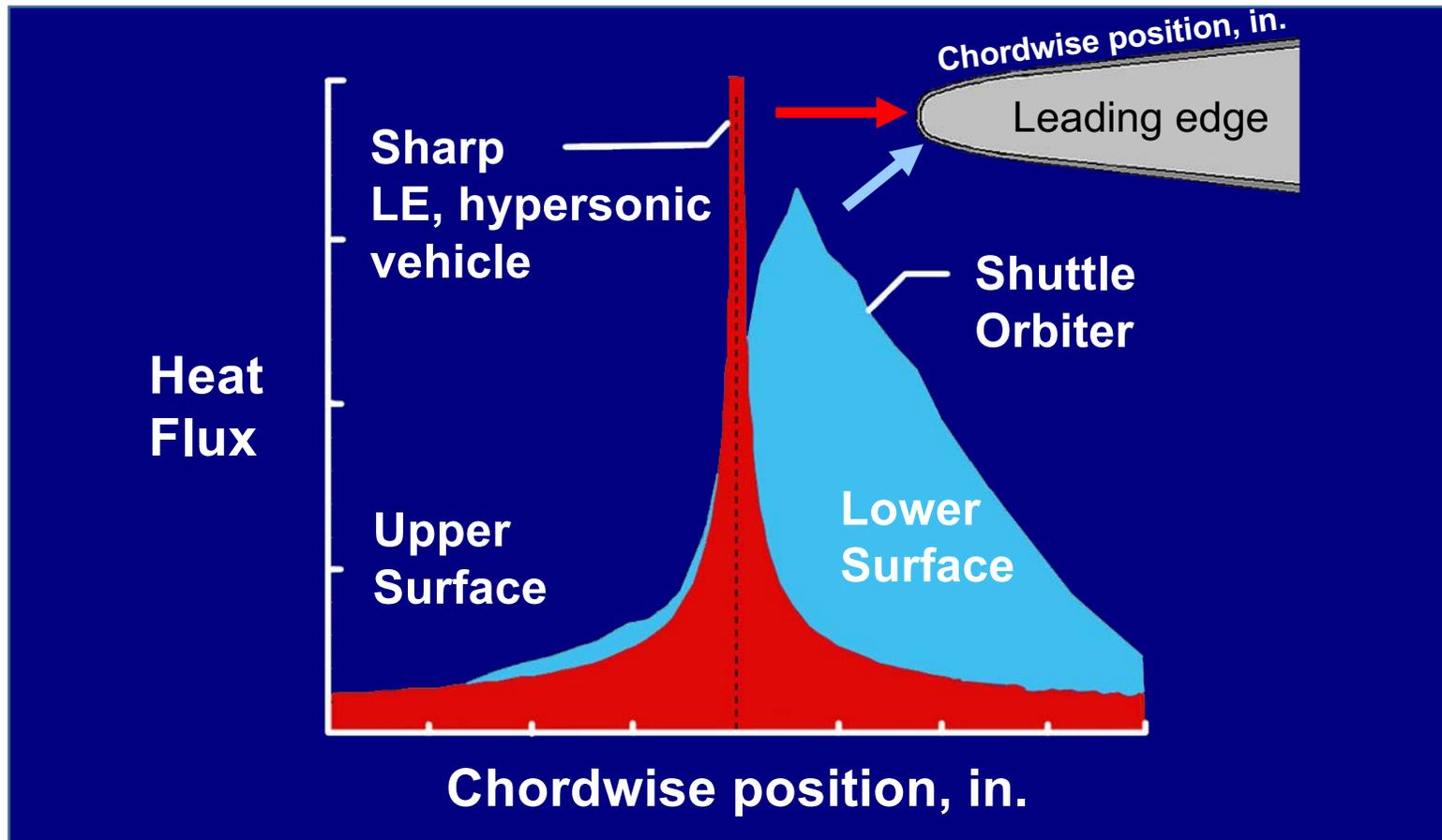


In comparison, Shuttle Orbiter leading edge
~ 70 Btu/ft²-sec, CEV ~ 700 Btu/ft²-sec

Leading-Edge Radius Effect on Heat Flux

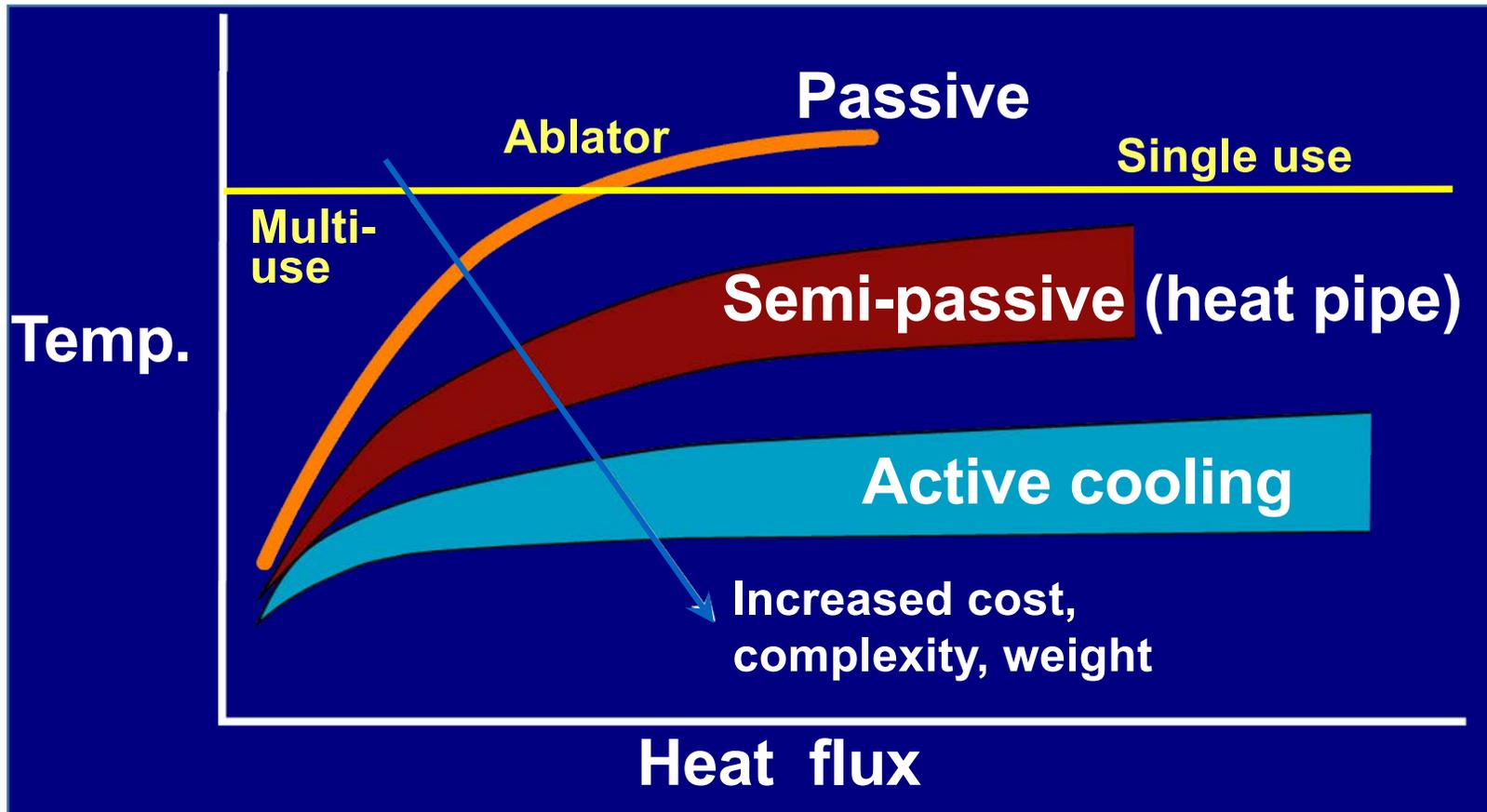
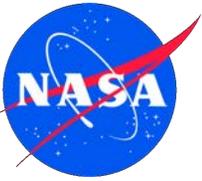


Leading-Edge Heating



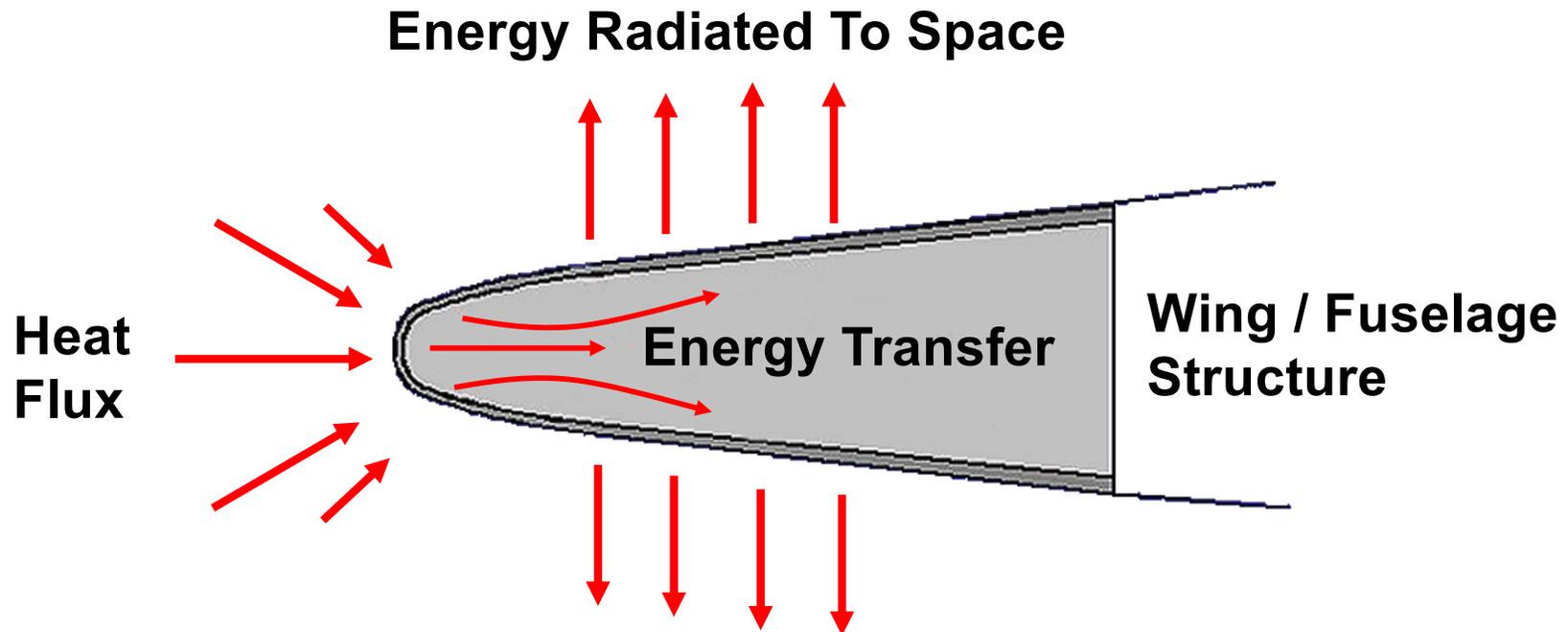
Sharp leading edges produce intense, localized heating

Leading-Edge Thermal Management Options



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

Passive Leading Edges

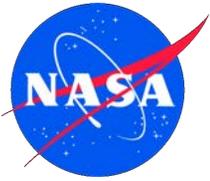


- High-temperature materials to increase capability
- Thermal properties to reduce temperatures

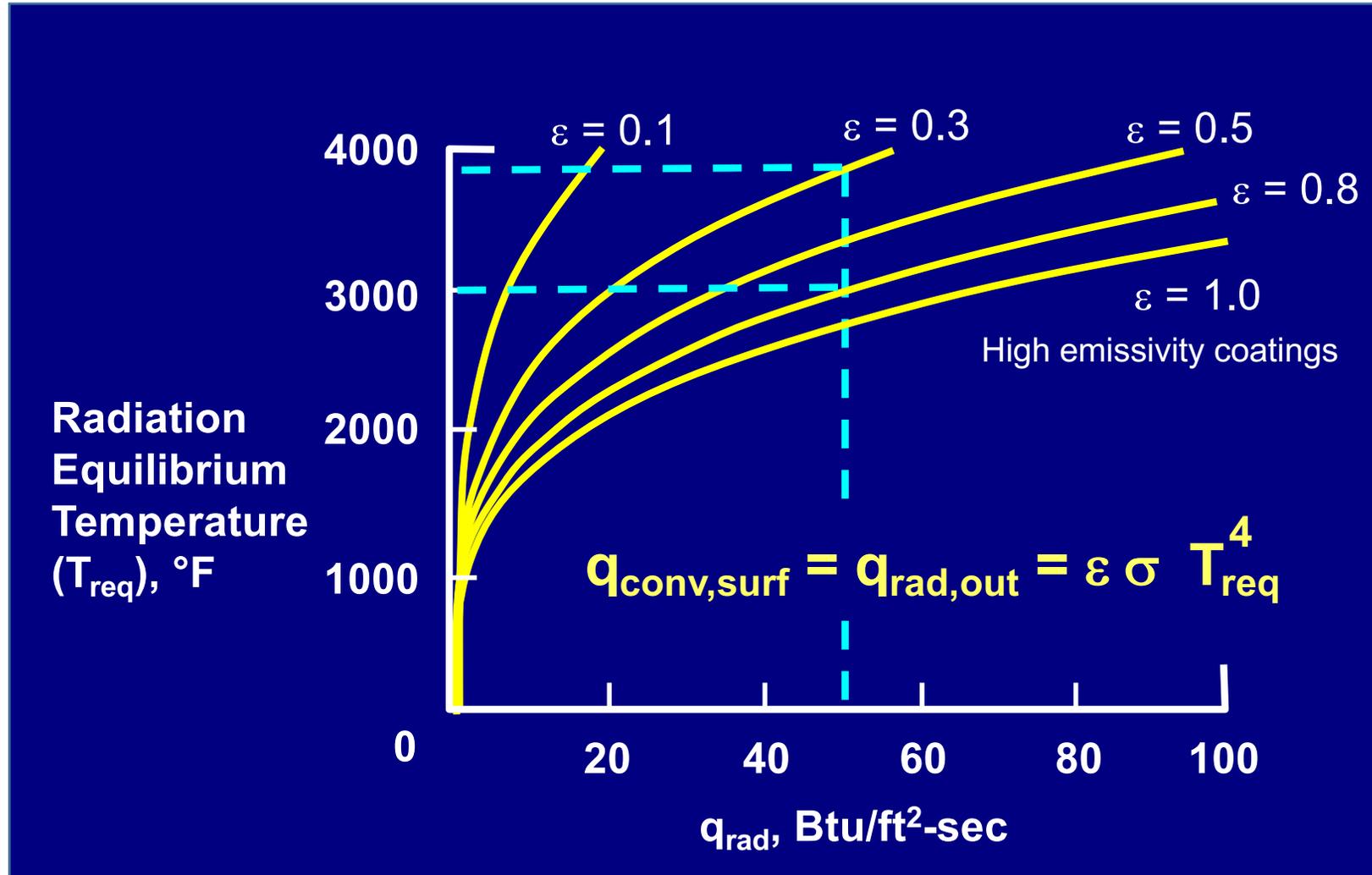
High-Temperature Materials / Coatings



- **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**

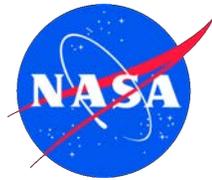


Property: Emissivity (ϵ)



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
 - $\text{Si}_{(g)} + \text{O} \rightleftharpoons \text{SiO}$,
 $\Delta H = -605 \text{ Btu/mol}$

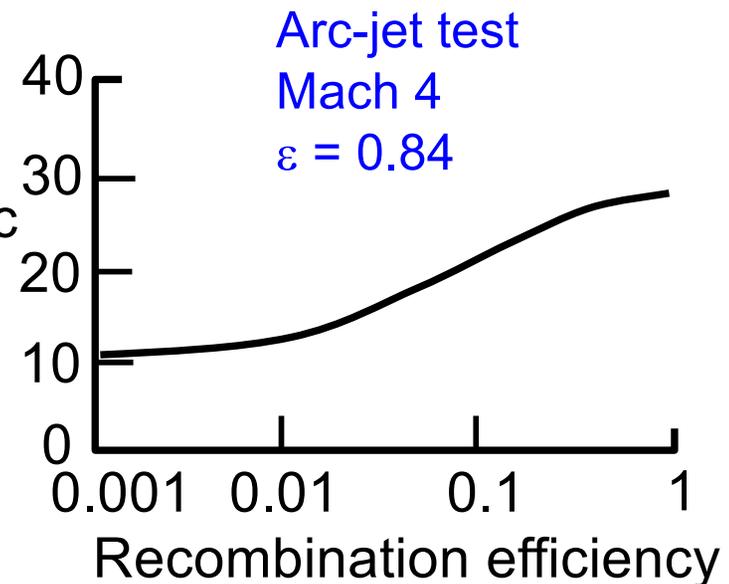
Non-catalytic

$$q = 10.1 \text{ Btu/ft}^2\text{-sec}$$

Catalytic

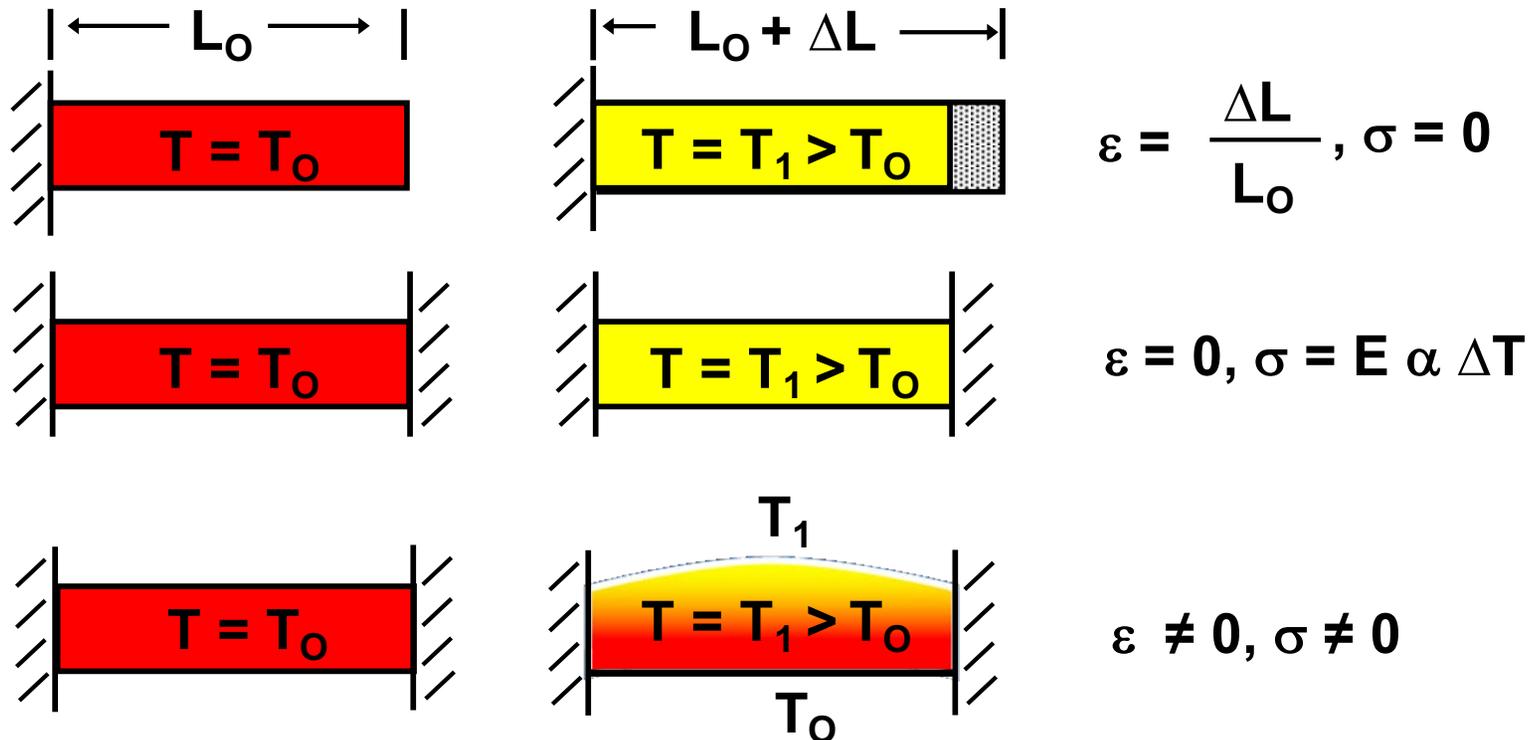
$$q = 28.3 \text{ Btu/ft}^2\text{-sec}$$

Btu/ft²-sec



Low catalycity coatings are very important to keep temperatures down

Property: Thermal Expansion (α)



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

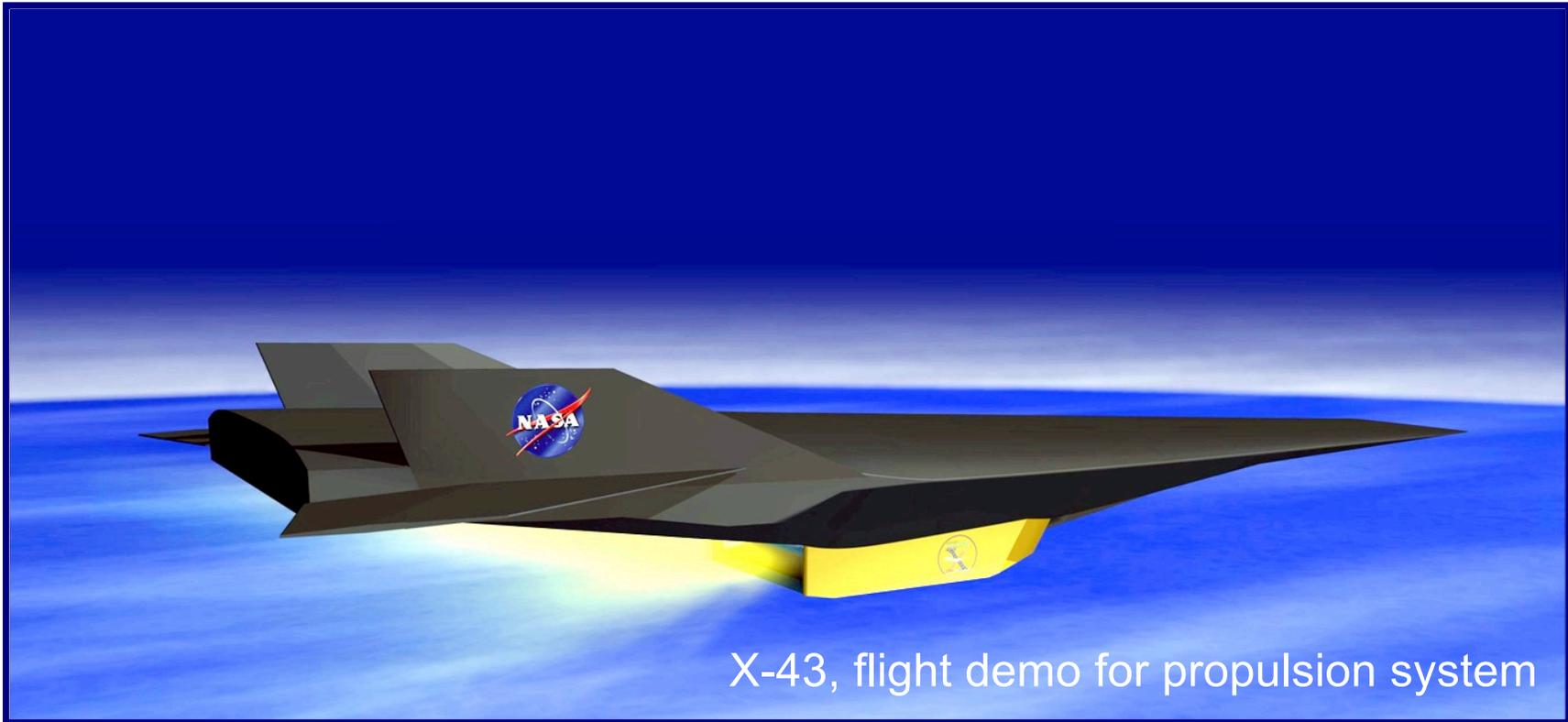
Oxidation of SiC Coatings

- **Passive oxidation (low temperature / high pressure)**
 - $\text{SiC}_{(s)} + 2 \text{O}_{2(g)} \rightarrow \text{SiO}_{2(s)} + \text{CO}_{2(g)}$
- **Active oxidation (high temperature / low pressure)**
 - $\text{SiC}_{(s)} + 1.5 \text{O}_{2(g)} \rightarrow \text{SiO}_{(g)} + \text{CO}_{2(g)}$



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

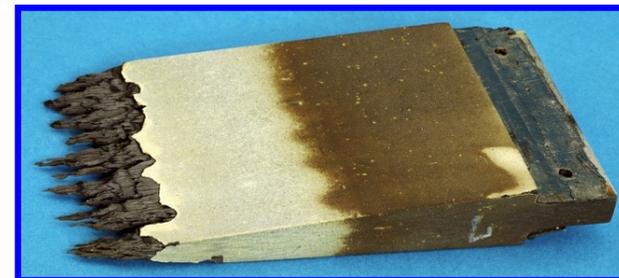
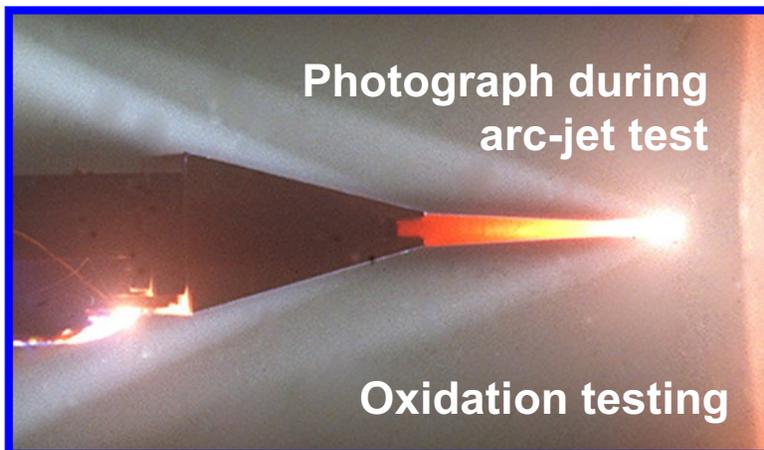
Coating Evaluation of X-43 Leading Edges

Flight conditions simulated during arc-jet test

- Mach 10, 105,000 ft
- Nose radius = 0.03 in.
- $q \sim 1300 \text{ Btu/ft}^2\text{-sec}$
- 130 sec

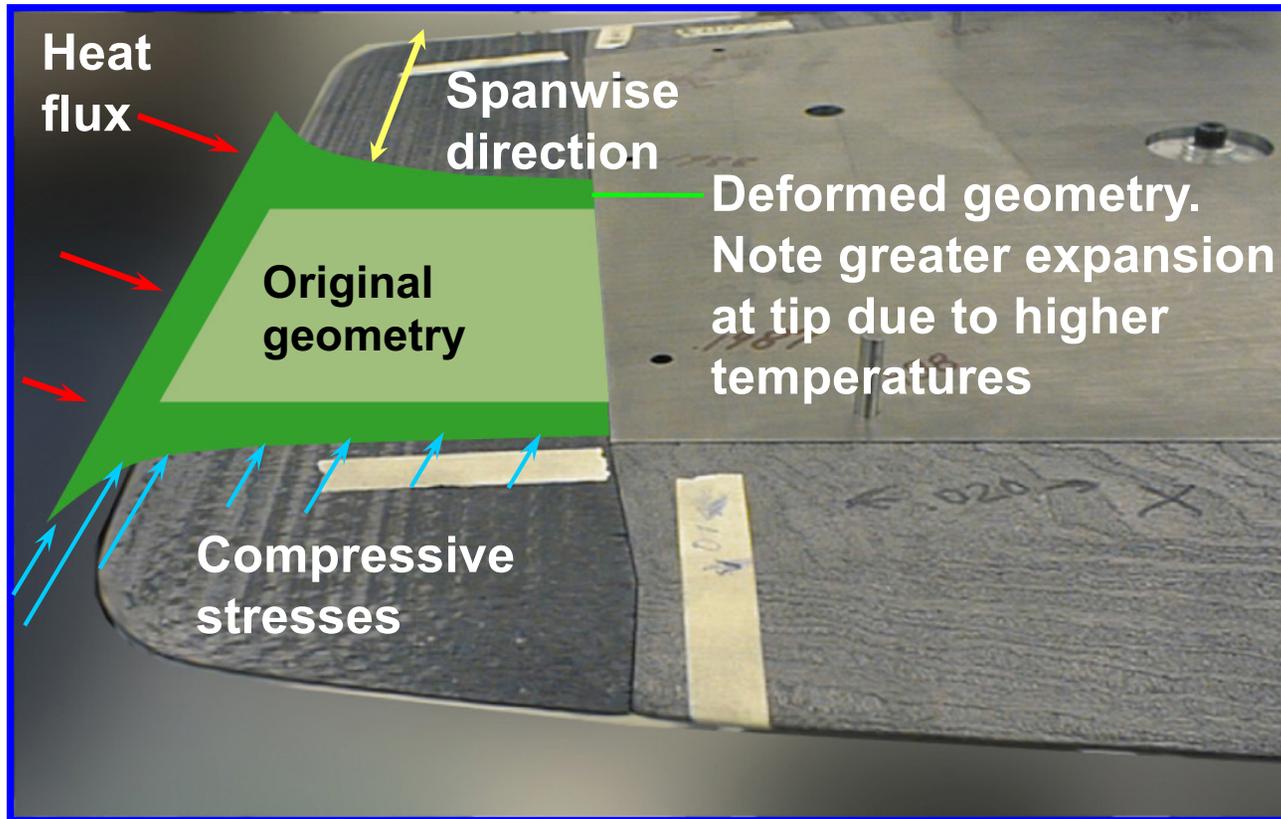
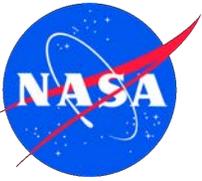


Successful test article



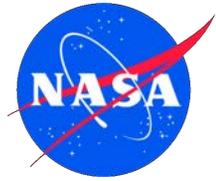
Failed test article

Spanwise Compressive Thermal Stresses

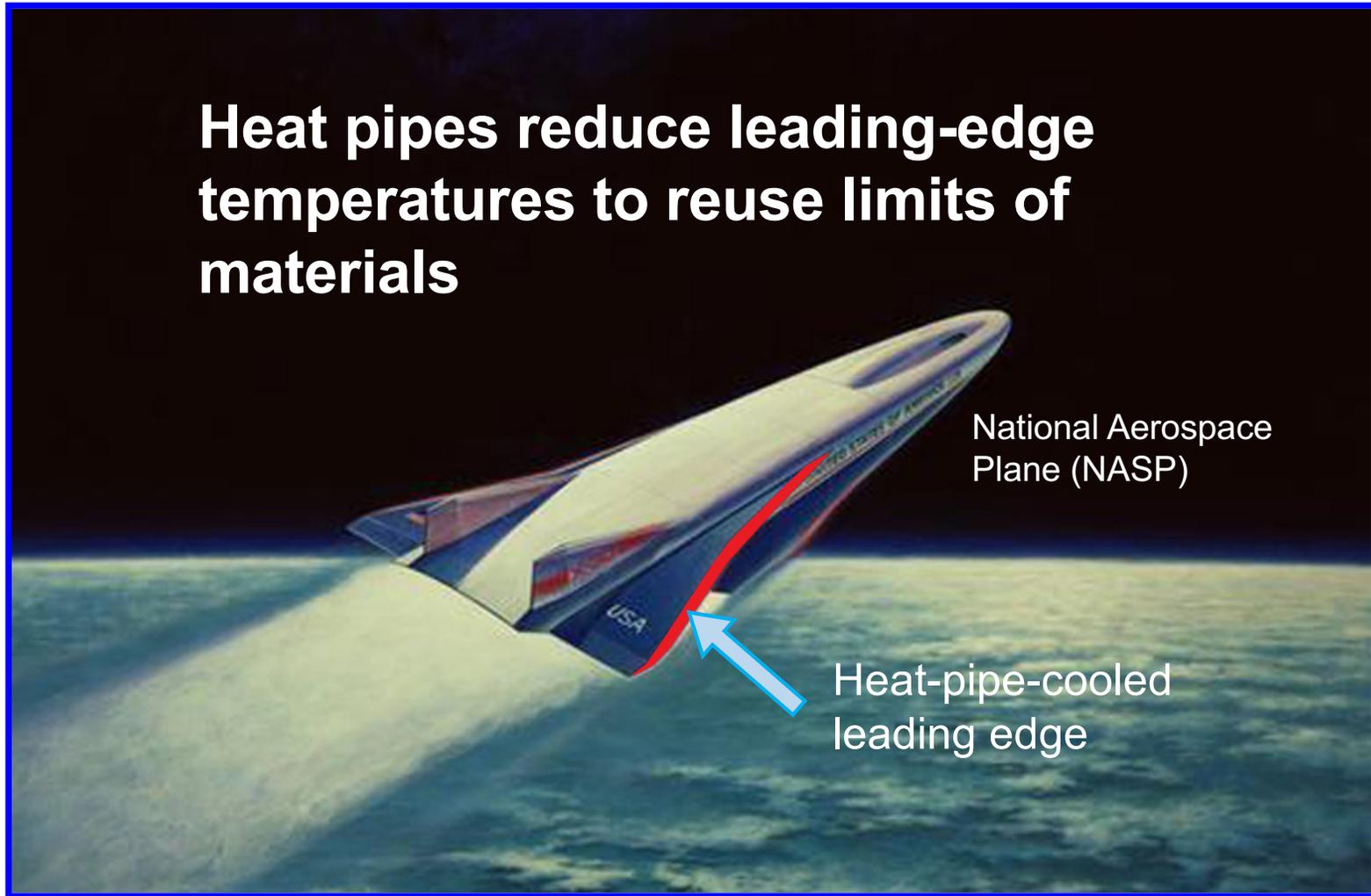


Thermal stresses due to constraint of thermal expansion

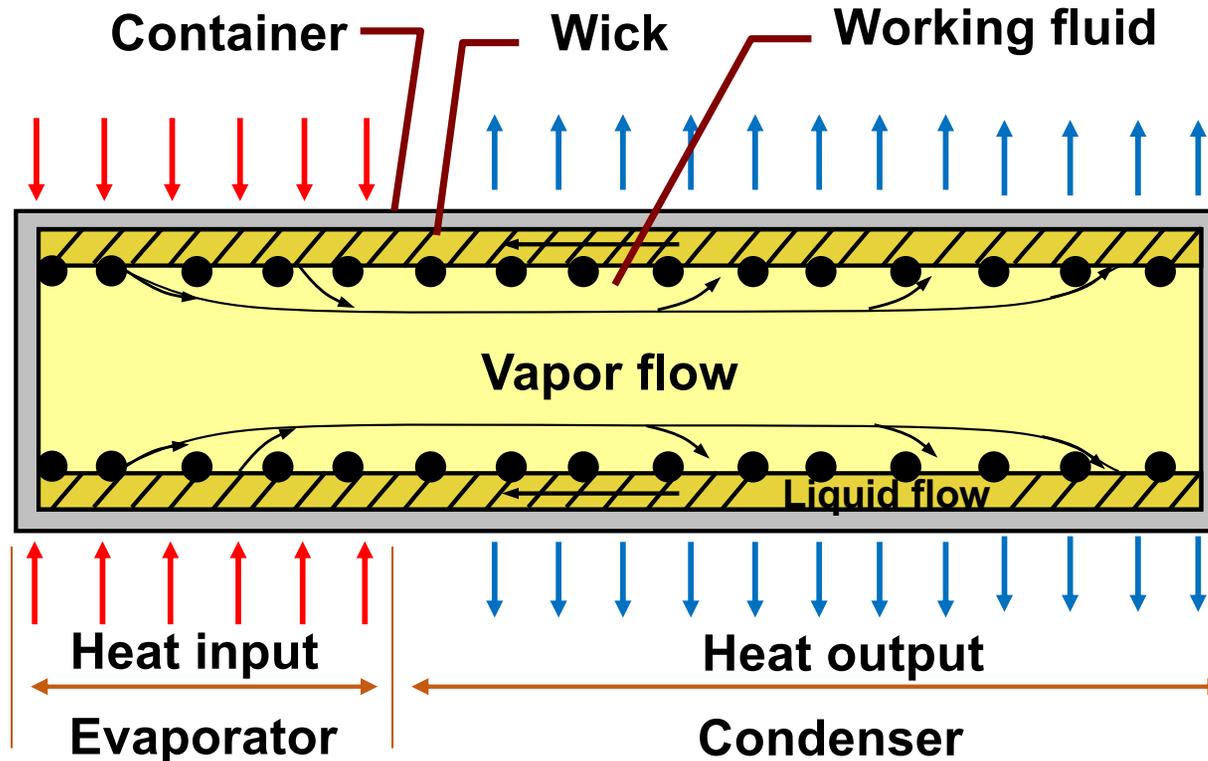
Heat-Pipe-Cooled (Semi-Passive) Leading Edge



Heat pipes reduce leading-edge temperatures to reuse limits of materials

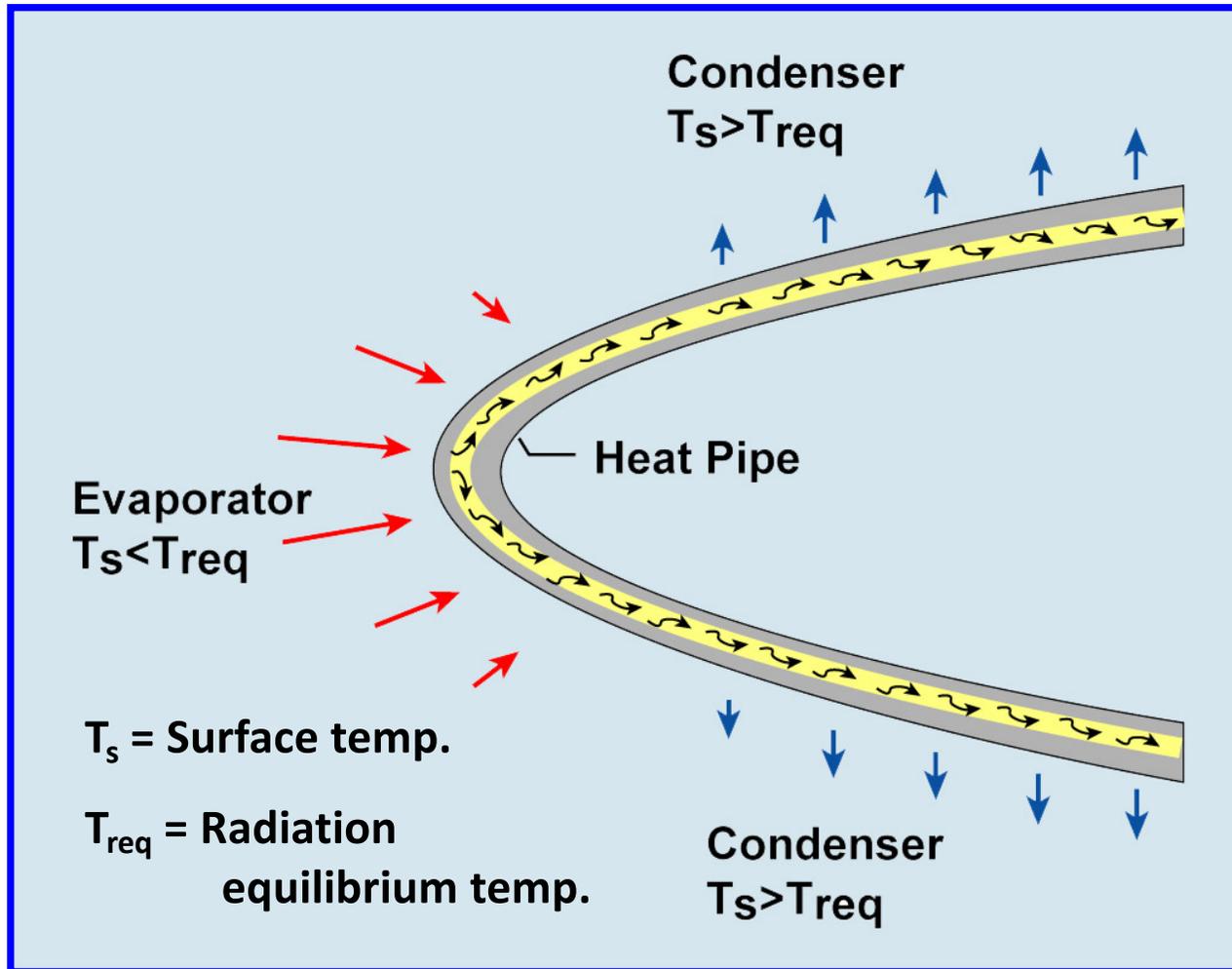


Heat-Pipe Operation



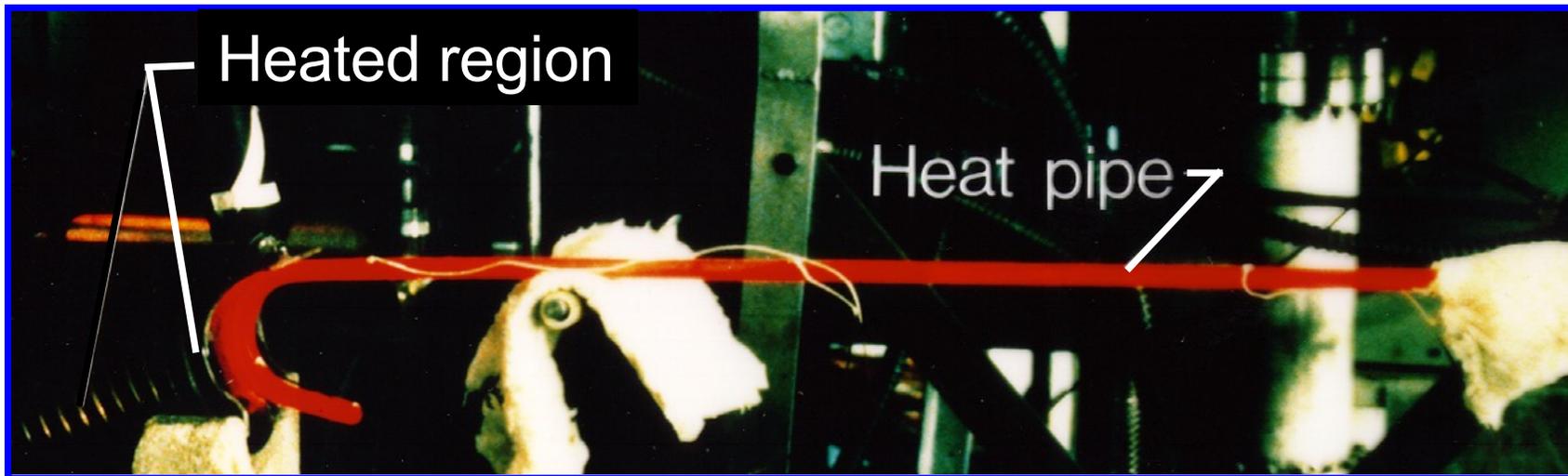
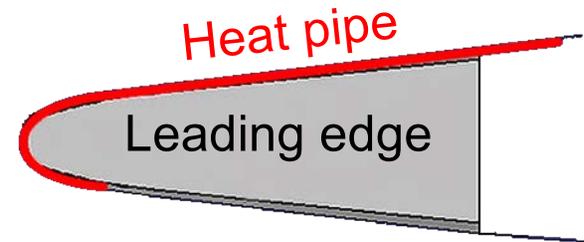
Heat pipes transfer heat isothermally by the evaporation and condensation of a working fluid

Leading-Edge Heat-Pipe Operation



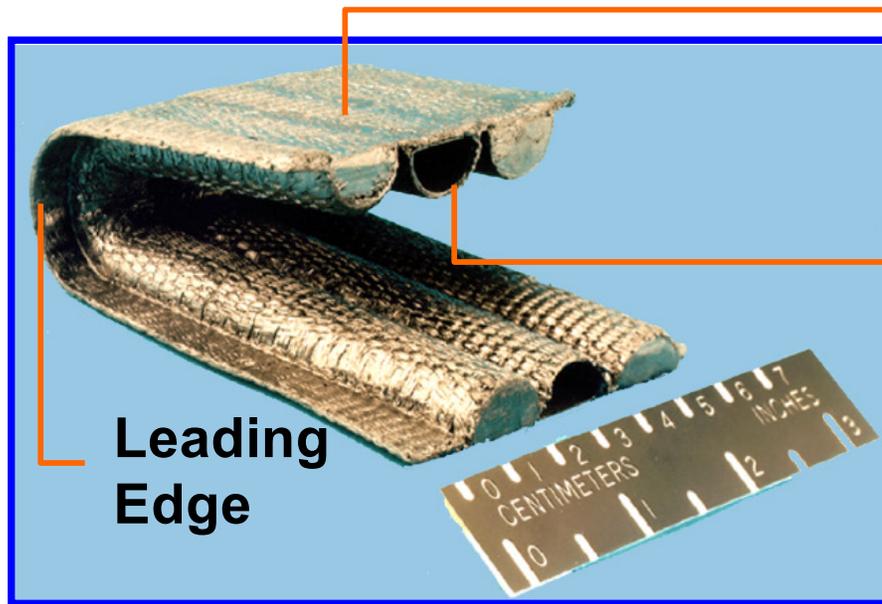
Leading-Edge-Shaped Heat Pipe

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



Heat pipe results in an isothermal leading edge

NASP Heat-Pipe-Cooled Wing Leading Edge

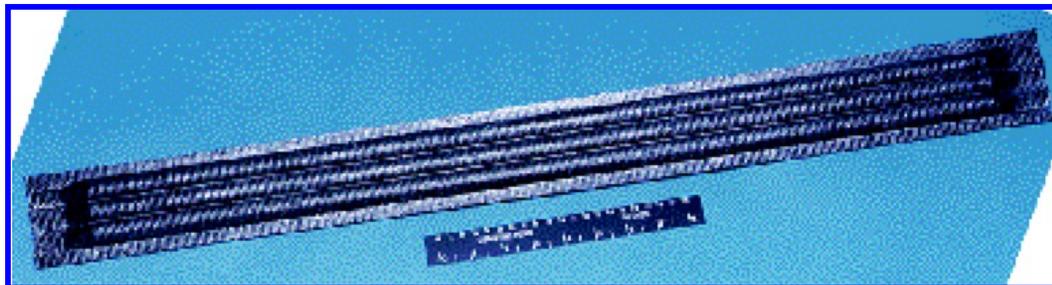


Carbon/carbon (C/C) structure

Mo-Re (molybdenum-rhenium) container

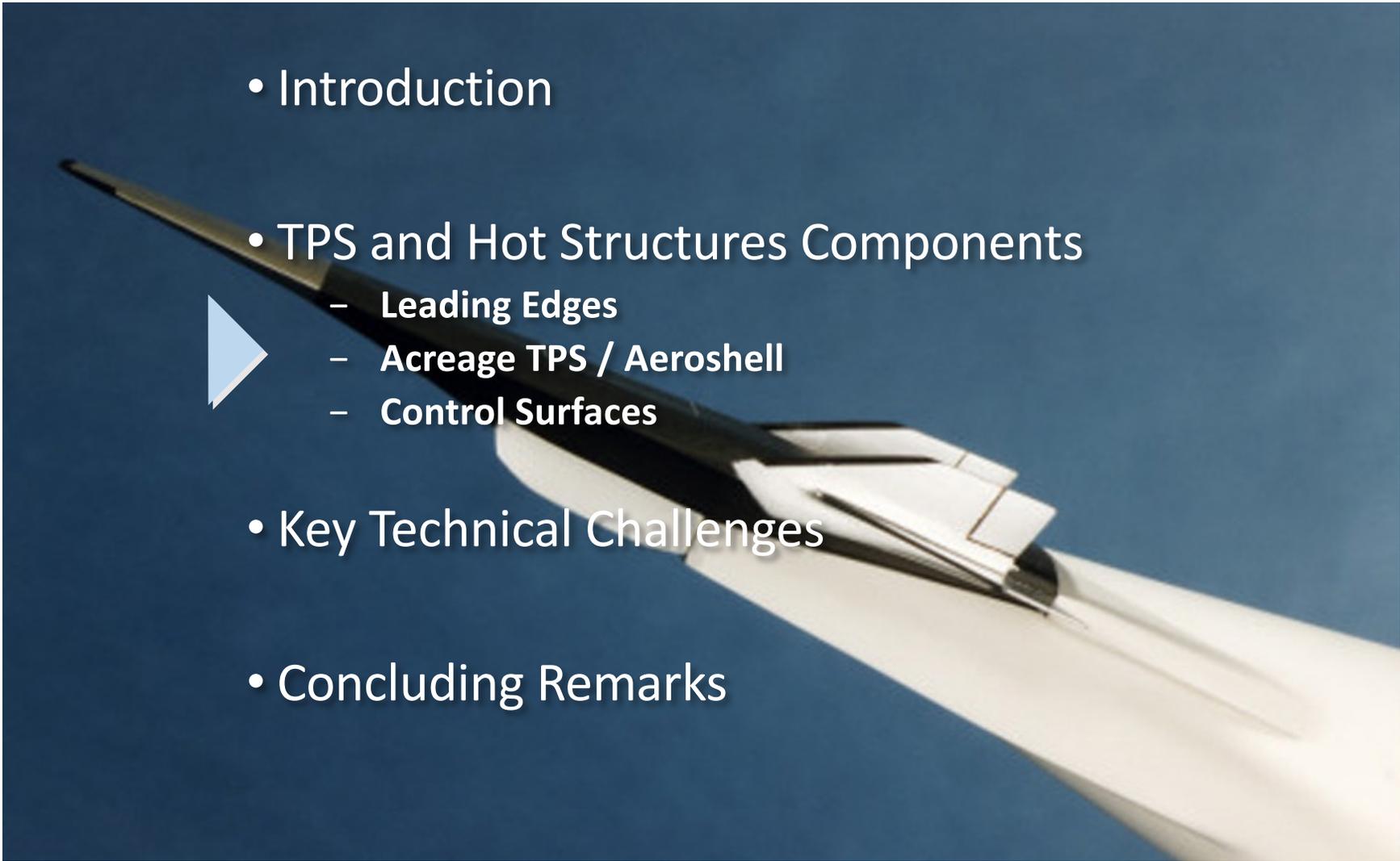
Challenges

- Material compatibility
- Thermal stresses



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

Outline

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

Insulated Structure

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

Damaged tile post-flight



Space Transportation System (STS) - 114

Tile with high emissivity coating

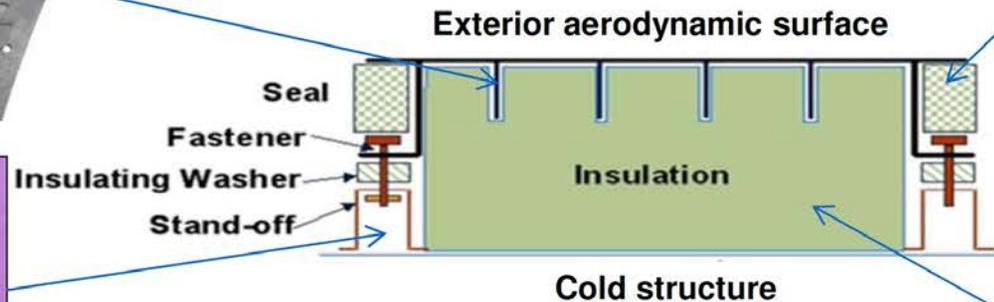


CMC Standoff TPS on Intermediate eXperimental Vehicle (IXV)



ARIANEGROUP THERMAL PROTECTION SYSTEM SHINGLE DESIGN

Thin, heat resistant shells with stiffeners made of C-SiC ceramic matrix composite to withstand mechanical loads.



Seals to fill the gap between panels and prevent sneak flows



Stand-off to fix the panels to the cold structure while limiting the heat transfer and absorbing deformations

Layers of insulation material to absorb the heat load.



Used by permission of ArianeGroup

Load Bearing Aeroshell

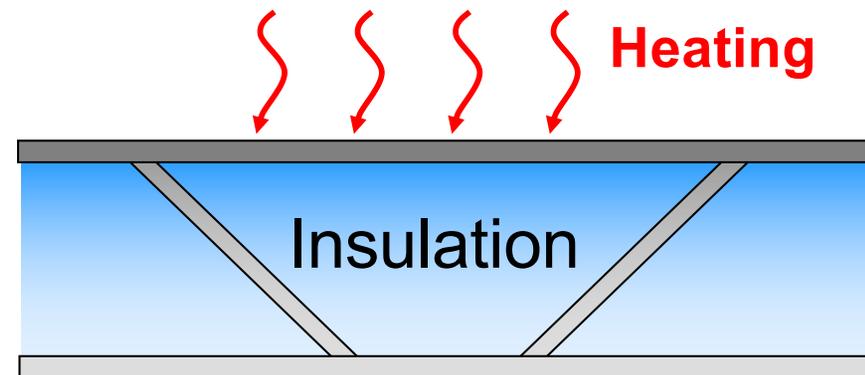


- **Aeroshell carries aero and vehicle axial loads**
- **Insulation incorporated or separate**
- **Potential for reduced weight**

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



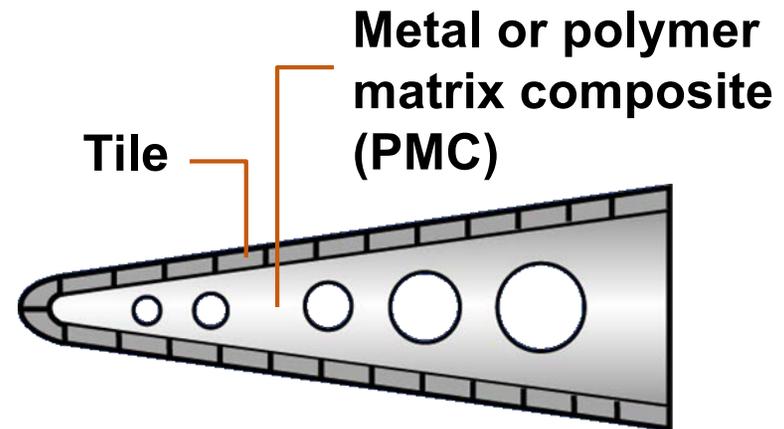
Outline



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Insulated Control Surface

- **Advantages**
 - Suitable for very large structures
 - Minimal thermal expansion issues
- **Disadvantages**
 - Heavy
 - Little thermal margin
 - Thick cross section



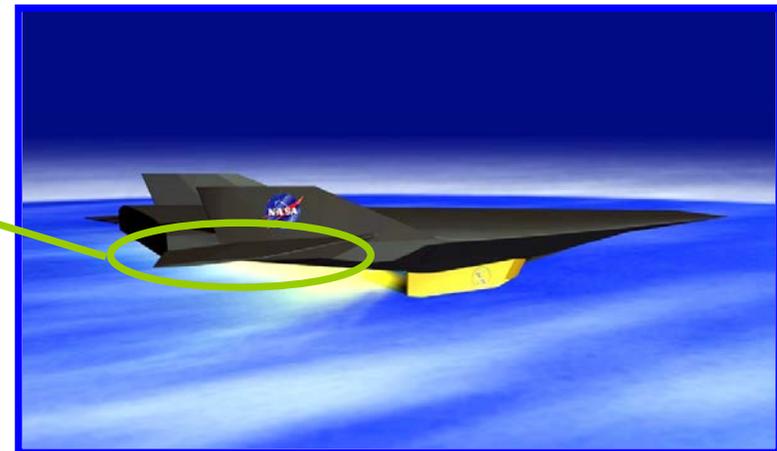
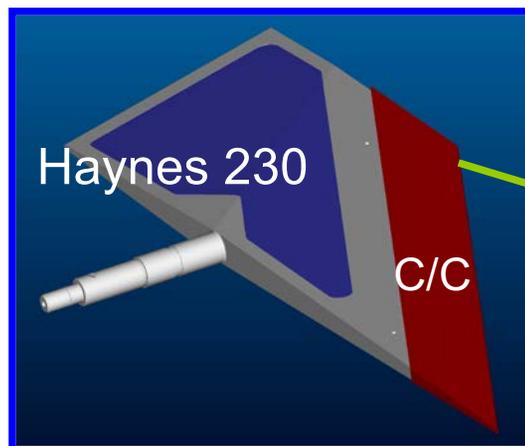
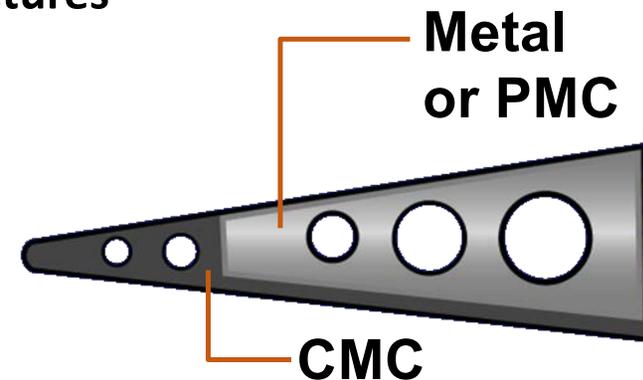
Hybrid Control Surface

- **Advantages**

- More affordable manufacturing for large structures
- May not require TPS on upper surface
- Replace CMC leading and trailing edges if damaged

- **Disadvantages**

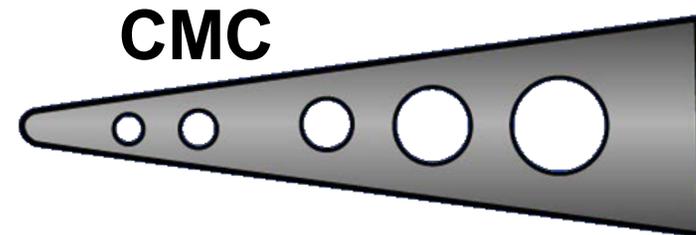
- Thermal growth mismatch between metal/PMC and CMC
- Weight increase 30% - 40% over all CMC
- Insulation of box structure leads to reduced thickness and small moment of inertia or a thicker cross section



CMC Hot Structure Control Surface

- **Advantages**

- Lowest weight and thin cross section
- Minimal thermal expansion mismatch problems
- Thermal margin
- CMC has sufficient strength, stiffness, and damage tolerance for torsional and bending loads
- No external insulation



- **Disadvantages**

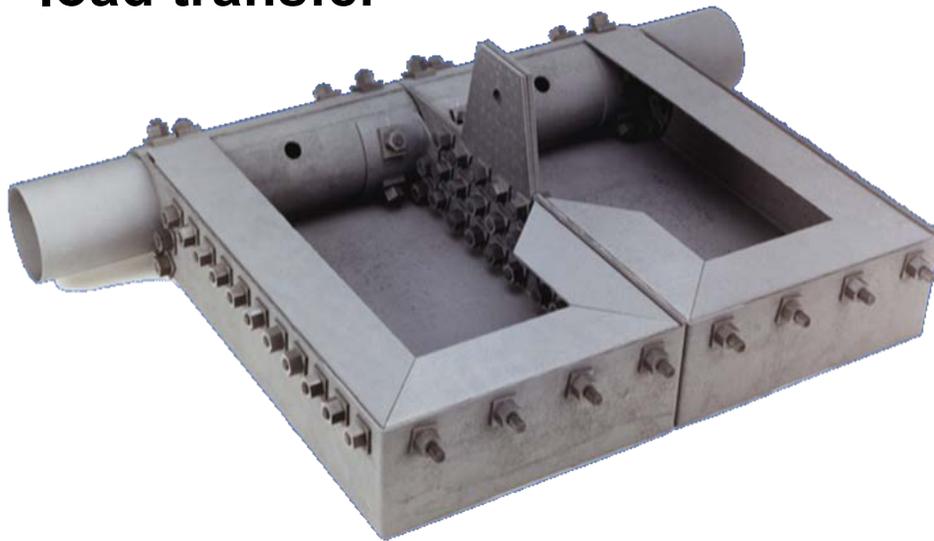
- High manufacturing/tooling costs for box structure
- Challenging for very large structures
- Limited repair capability
- Manufacturing risk in case of production failure or damage
- Access for coating, inspection, and maintenance of internal areas



Mechanically Assembled Control Surface

Key features

- **C/SiC fastened joints**
- **Utilization of thin ply torque tube and box structure**
- **Gusset members for load transfer**



- **Advantages**

- Relatively simple tooling
- Damaged components can be replaced w/o complete scrap of control surface

- **Disadvantages**

- Tolerance buildup can be problematic in assembly of numerous separate parts
- High part count

Integrated Fabrication Approach

- **Advantages**
 - Fewer joints
 - Better mechanical performance
- **Disadvantages**
 - Complex tooling and associated fabrication expense
 - Risk of damage during fabrication





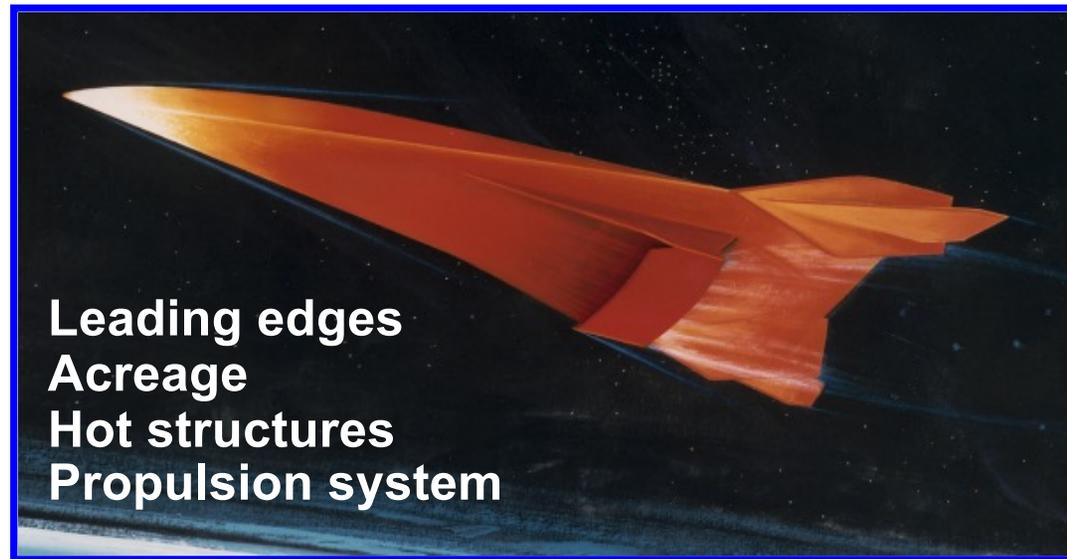
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Hypersonic Vehicles

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



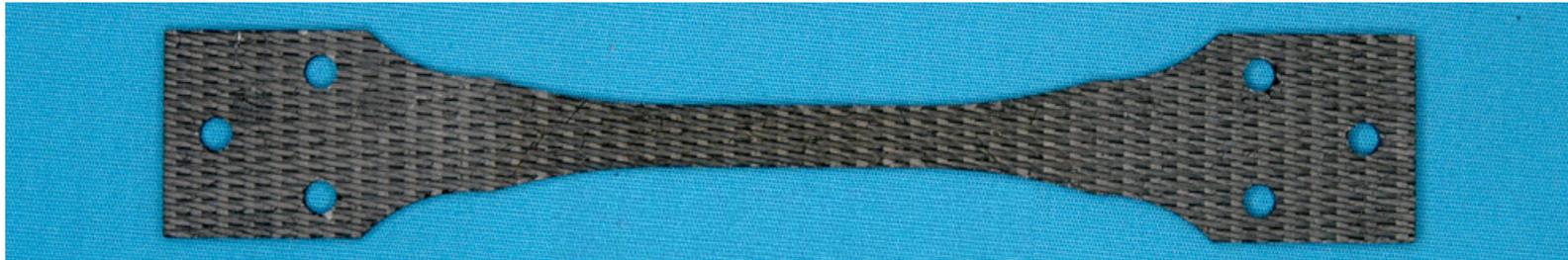
- **For most hypersonic vehicles, there are two key materials and structures technical challenges**

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



Big difference!

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

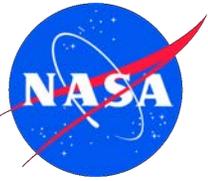
Fabrication Challenges

- 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**

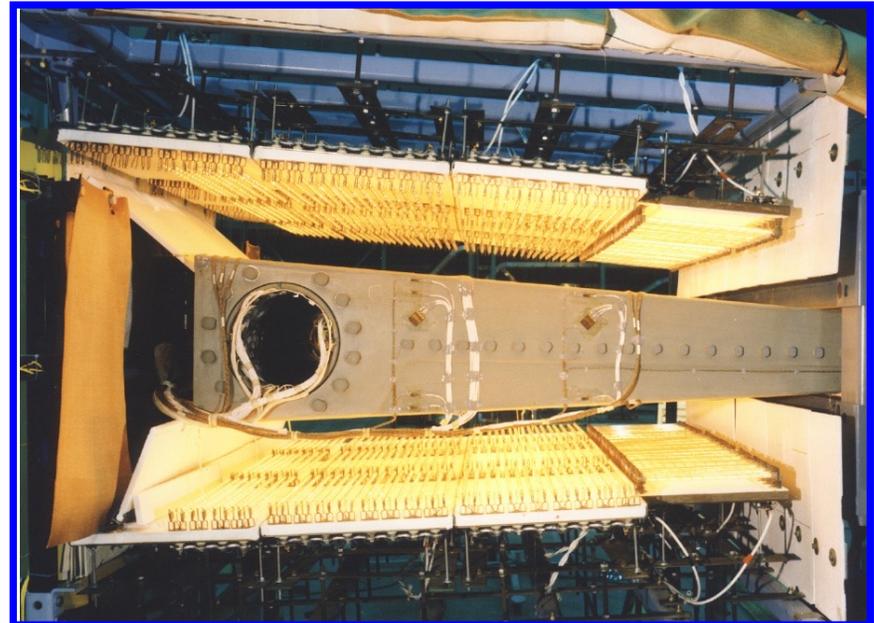


Will Hot Structures Meet Flight Requirements?



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



Testing

- How do we qualify the vehicle for flight?
- We are unable to test many components in relevant, combined loads, environments (even small scale)
 - Thermal, mechanical, plasma, shear, oxygen partial pressure, vibration and acoustic, etc.
 - Apply appropriate boundary conditions over entire structure
 - Thermal gradients (spatial and temporal) from boundary layer transition
- Extensive testing is required
 - Performance testing and benchmarking for analyses
- Building block approach

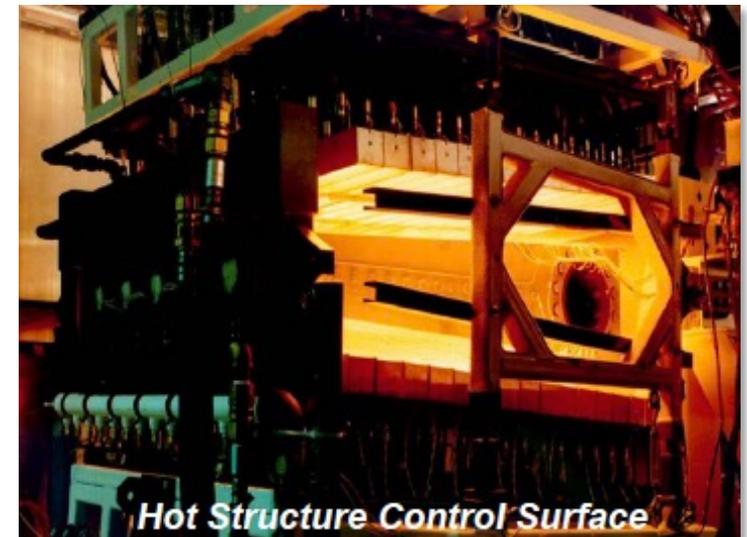
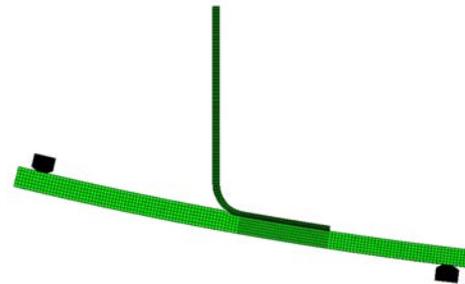


Component test



Material / coupon test

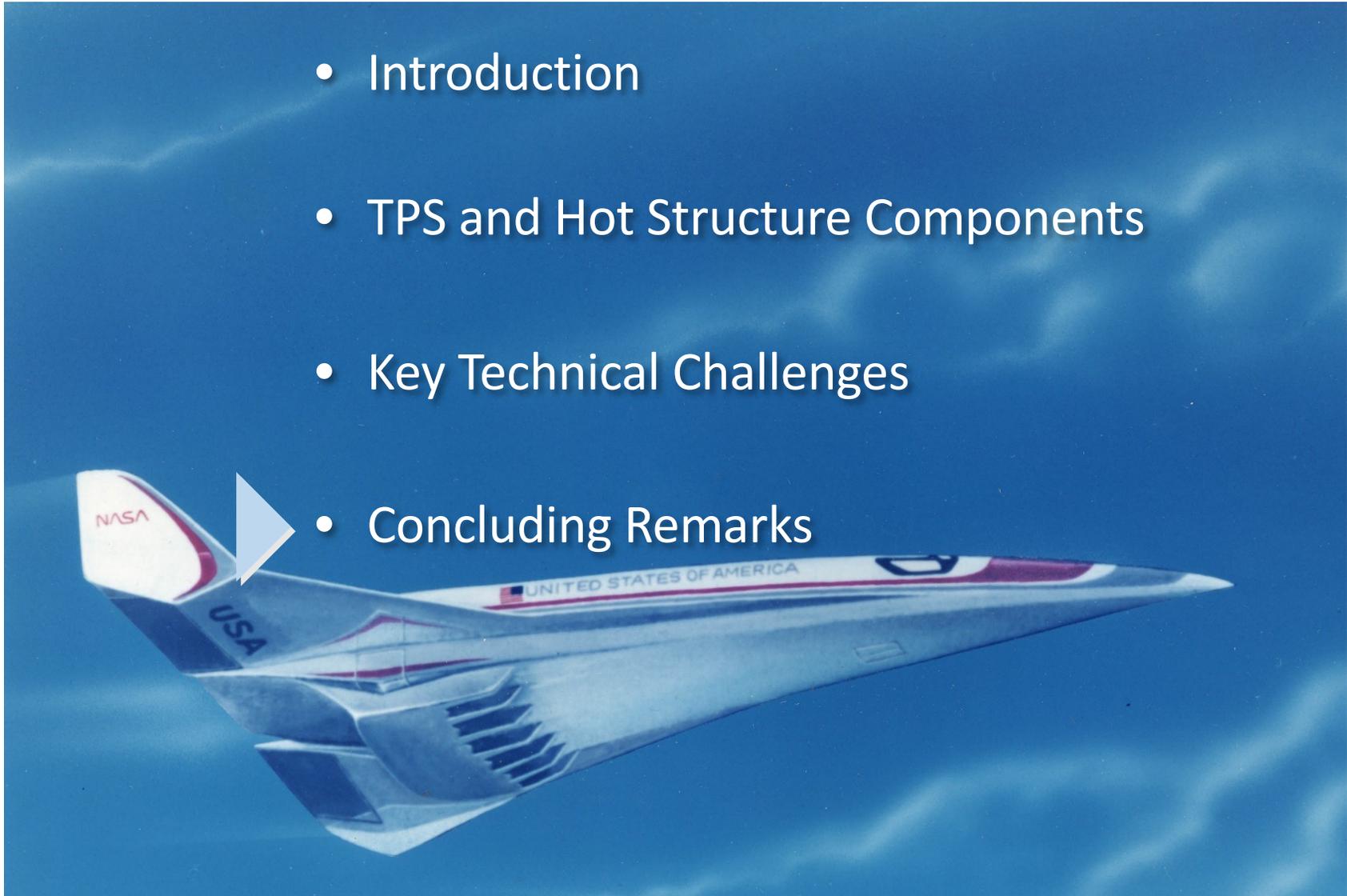
Sub-element test



Test as much as you can, and still include adequate margins for uncertainties

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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](#)