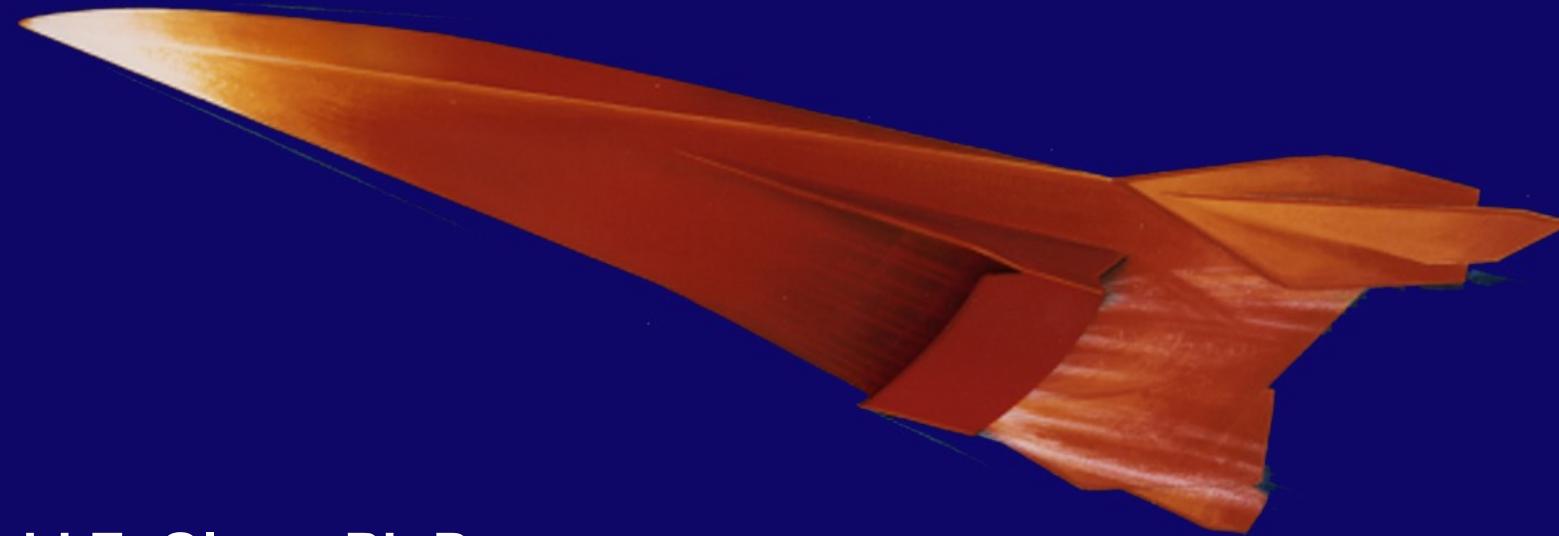


# **Ceramic Matrix Composite (CMC) Thermal Protection Systems (TPS) and Hot Structures for Hypersonic Vehicles**

HRL Laboratories, Malibu, CA

December 14, 2021



**David E. Glass, Ph.D.**

**Senior Technologist, Research Directorate**

**NASA Langley Research Center, Hampton, VA 23681**



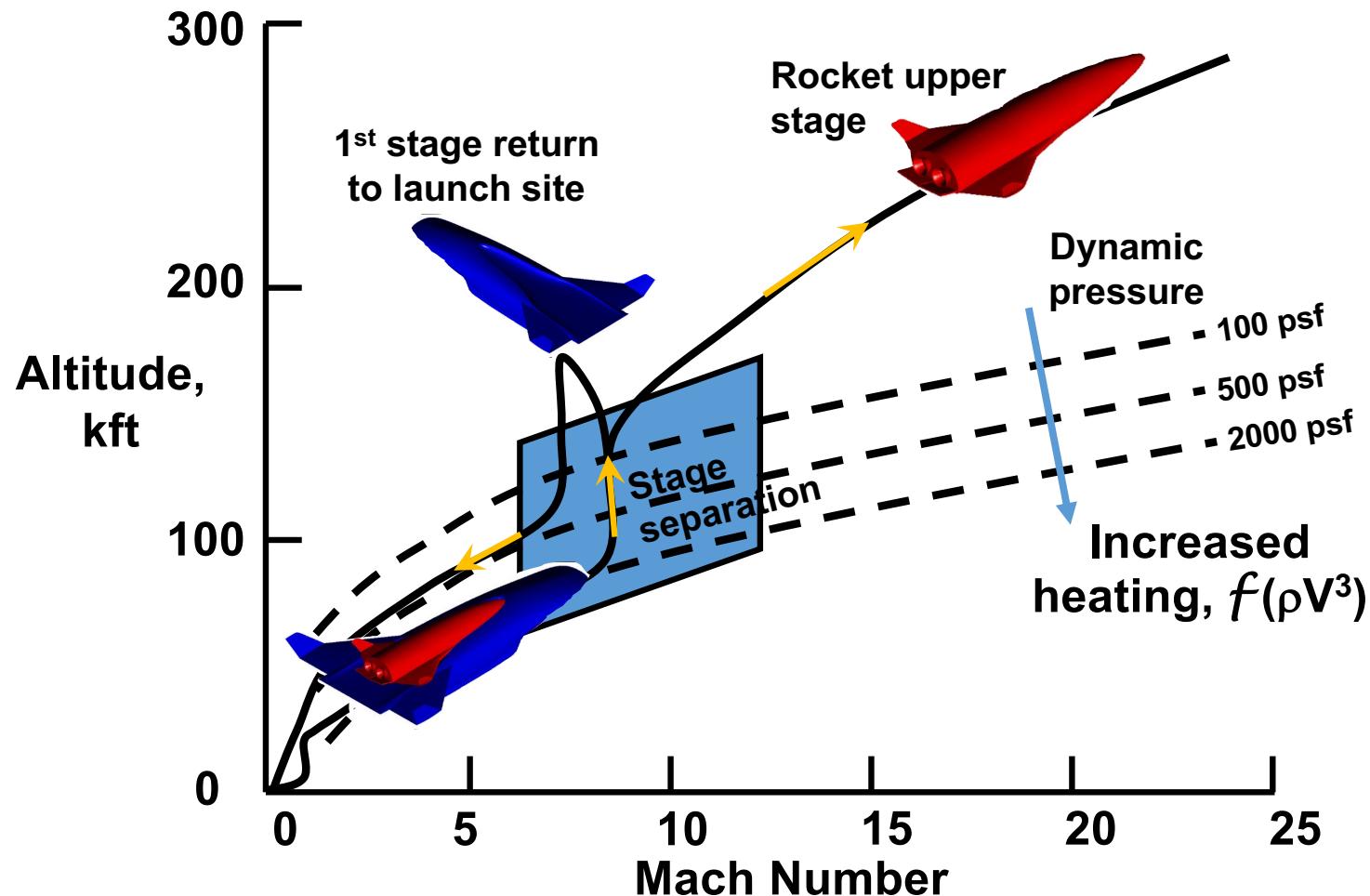
# Outline

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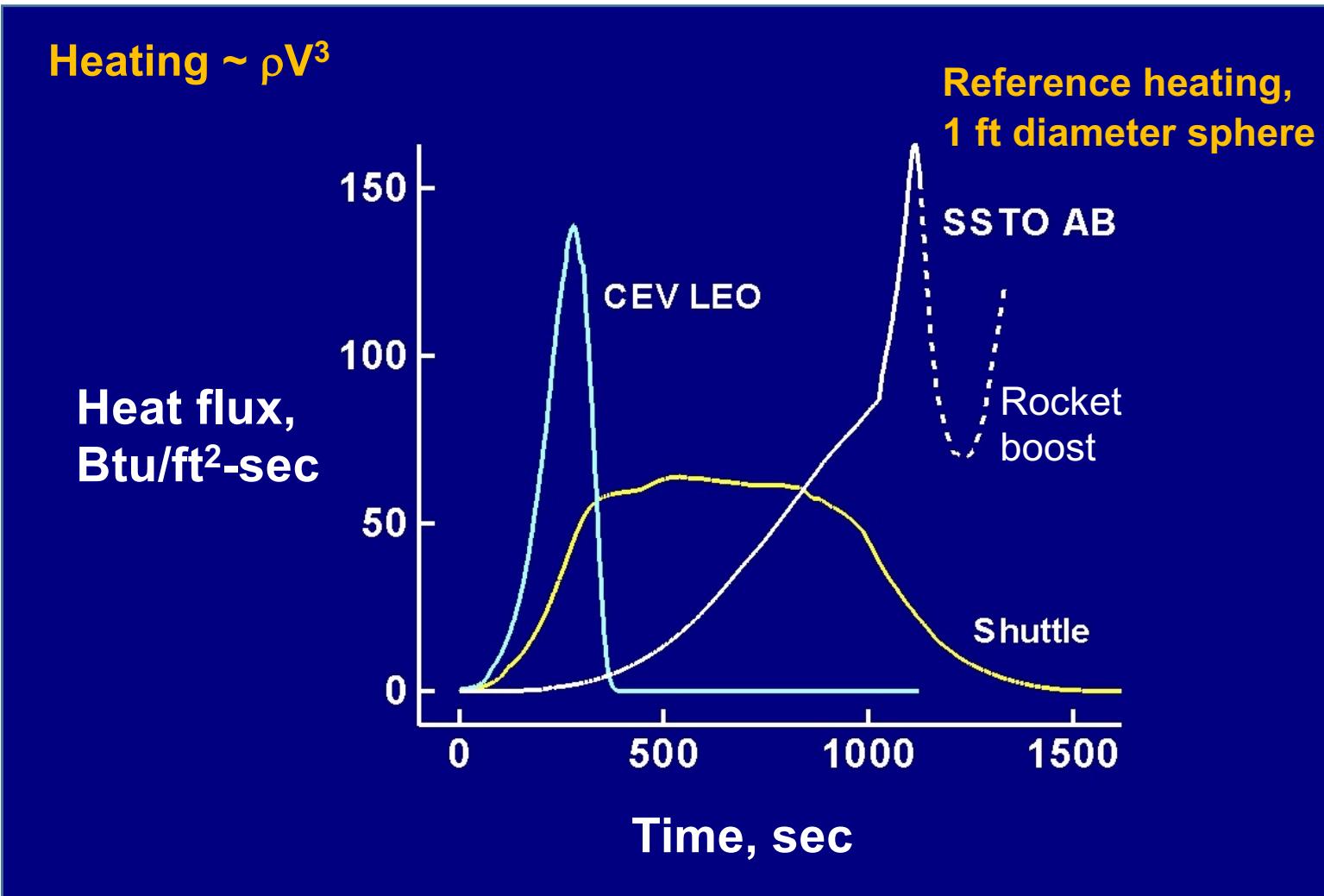


- Introduction
  - Aerothermodynamic heating
  - Thermal management
  - TPS for rocket-launched vehicles
  - TPS and hot structures for hypersonic vehicles
- TPS and Hot Structure Components
- Key Technical Challenges
- Concluding Remarks

# Two Stage to Orbit (TSTO) Reference Vehicle



# Heat Flux

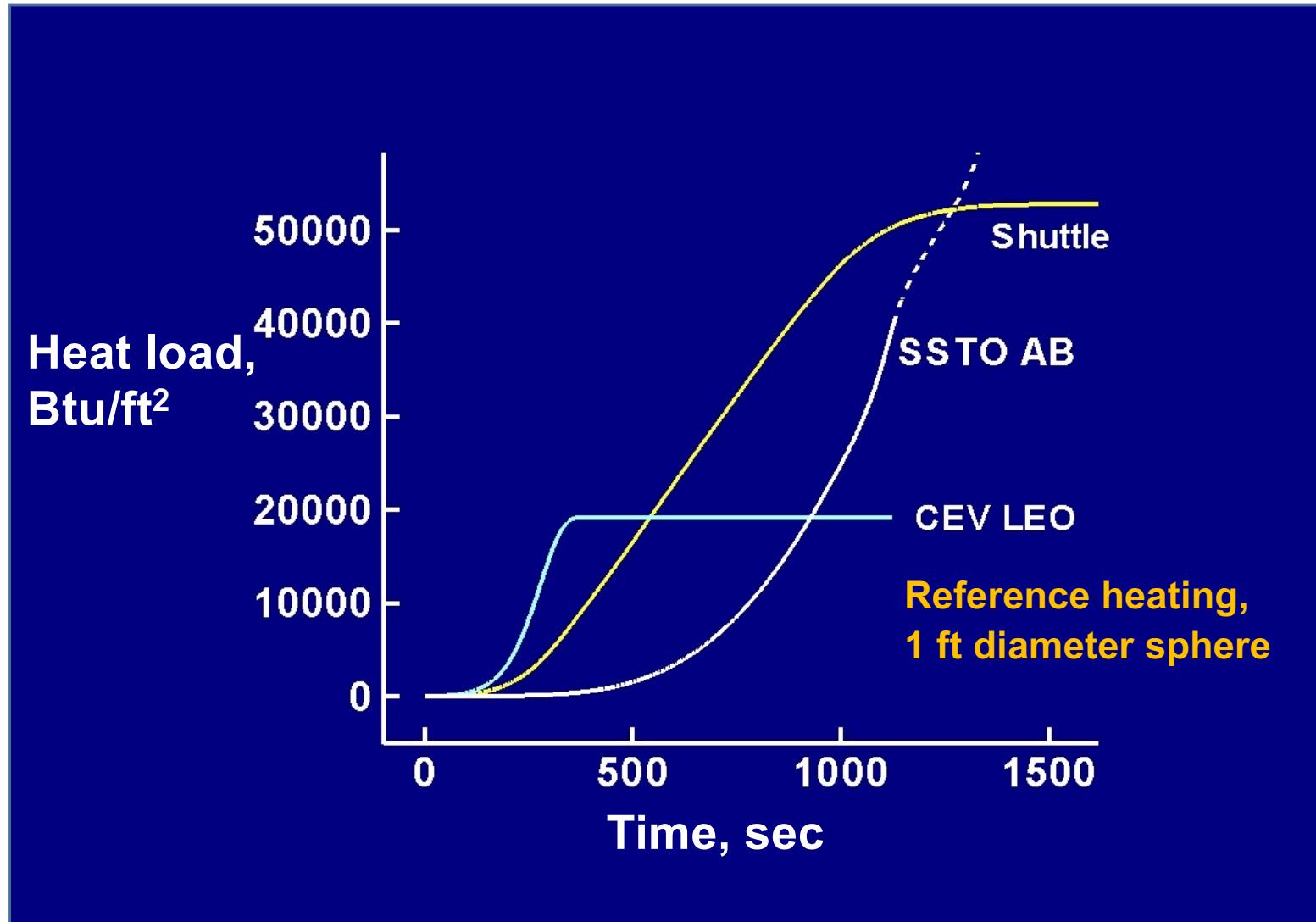


Crew Exploration Vehicle (CEV) Low Earth Orbit (LEO)  
Single Stage to Orbit (SSTO) Airbreather (AB)



# Heat Load

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



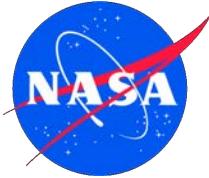


# Outline

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A white NASA X-43 hypersonic aircraft is shown flying through a cloudy sky. The aircraft has a distinctive delta-wing configuration and a pointed nose. The NASA logo is visible on the side of the fuselage. The aircraft is angled upwards, suggesting it is in flight.

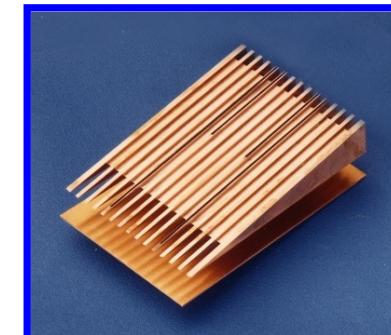
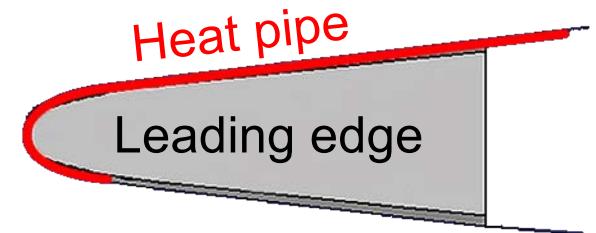
- Introduction
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# Types of Thermal Management

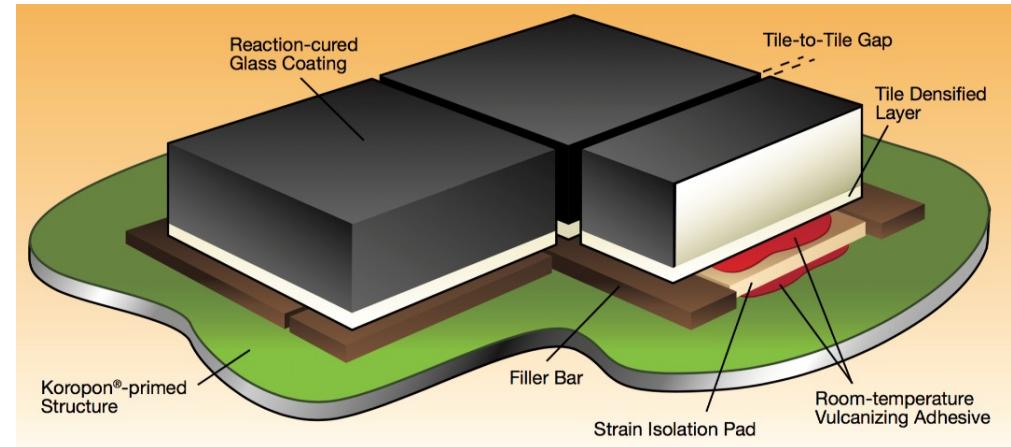
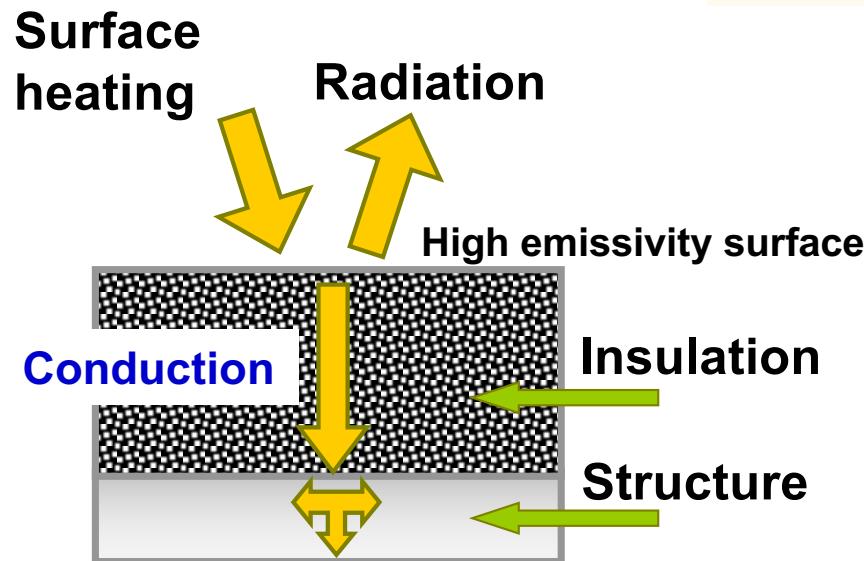
- Passive
- Semi-passive
  - Phase change
- Active
  - Pumped coolant

Tile



# Passive: Insulated Structure

**Use: Moderate heat flux, short times**

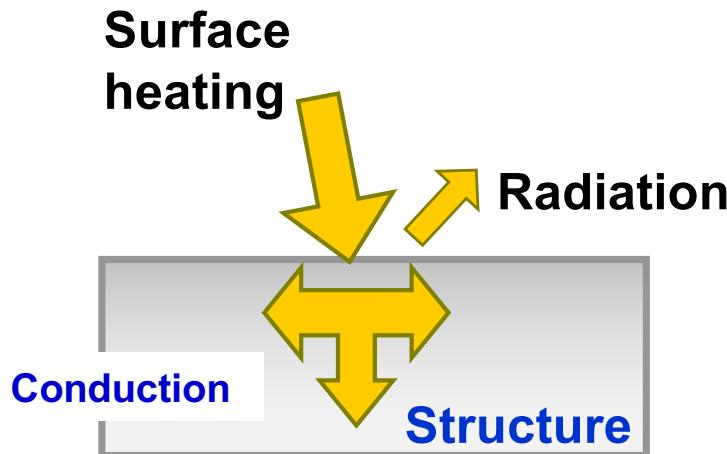


- Heat radiated away
  - Maximize surface emissivity
- Minimal heat conducted inward
- Structure remains cool



# Passive: Heat Sink Structure

**Use:** Moderate heat flux, short times (transient)



- Heat radiated away
- Heat absorbed by structure

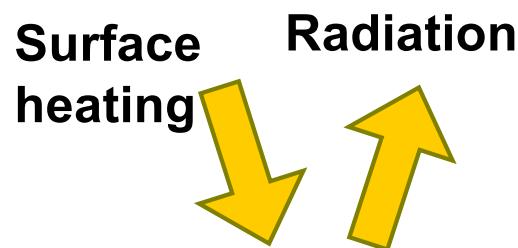


# Passive: Hot Structure

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



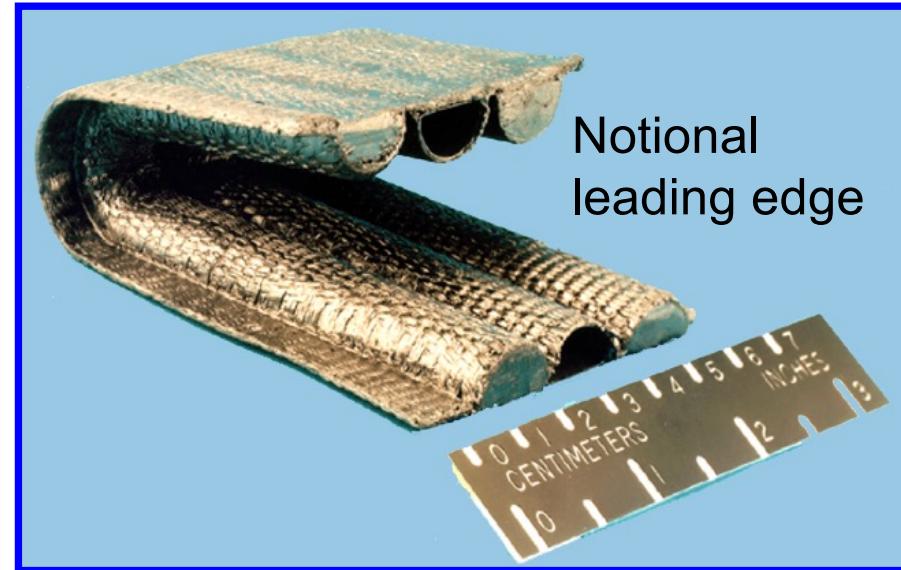
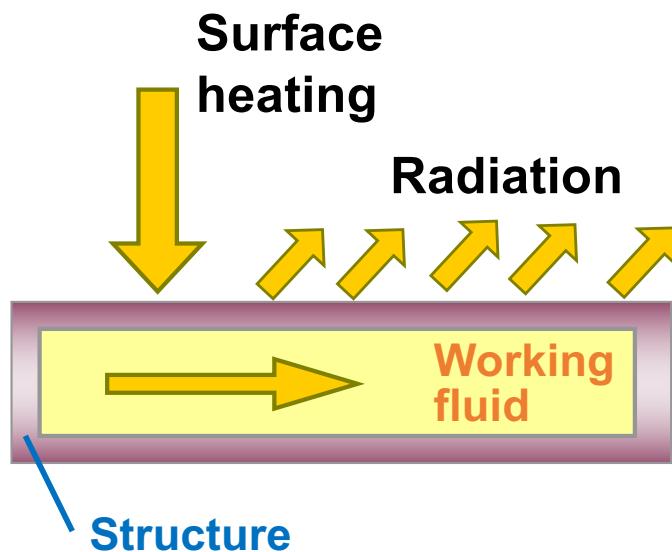
**Sub-scale X-37 control surface manufacturing demo**



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

# Semi-Passive: Heat Pipe

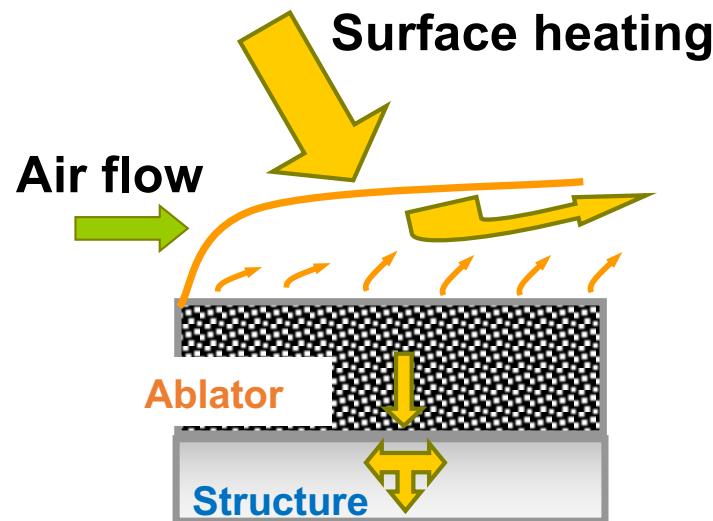
**Use: High heat flux,  
long times**



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

# Semi-Passive: Ablation

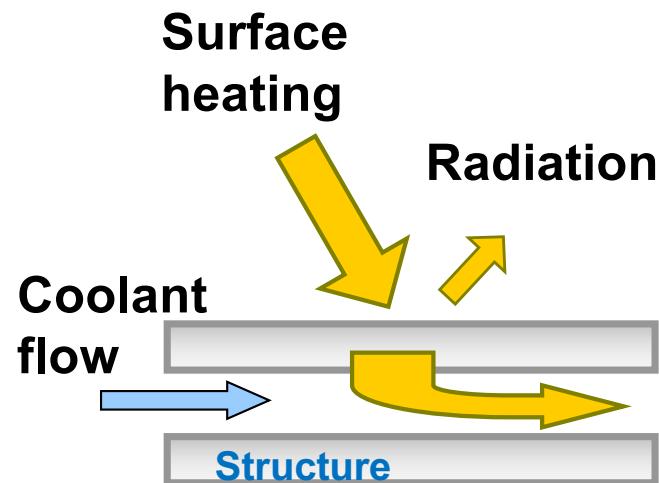
**Use: High heat flux,  
short times, single use**



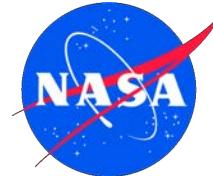
- Heat blocked by products of ablation (ablator consumed)
- Heat absorbed by ablation
- Structure remains cool

# Active: Convective Cooling

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

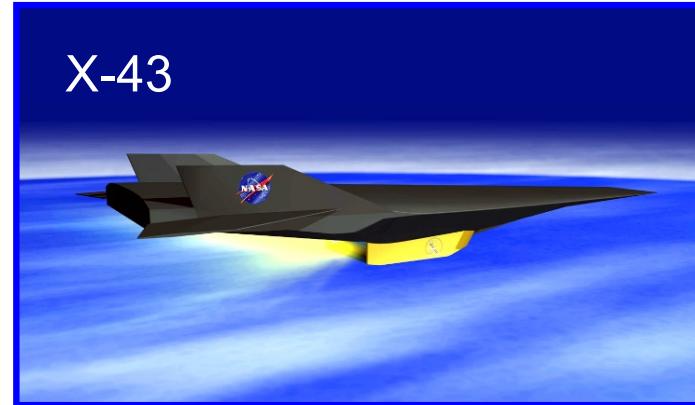
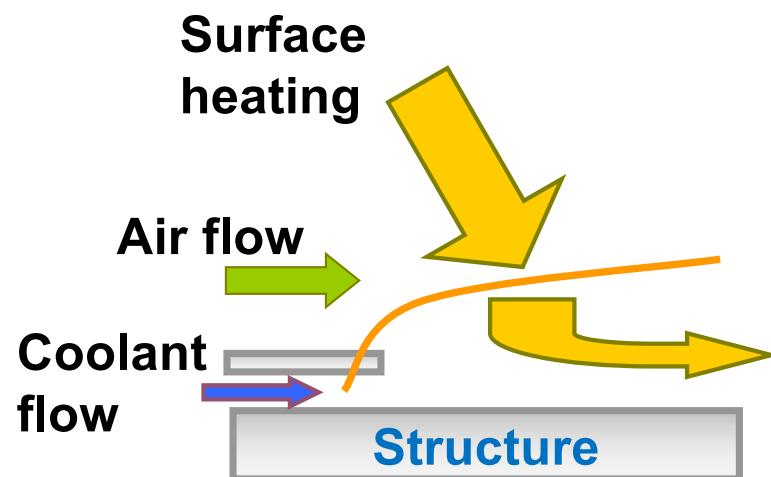


- Heat transferred into coolant
- Coolant heats up and carries heat away
- Structure operates hot



# Active: Film Cooling

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

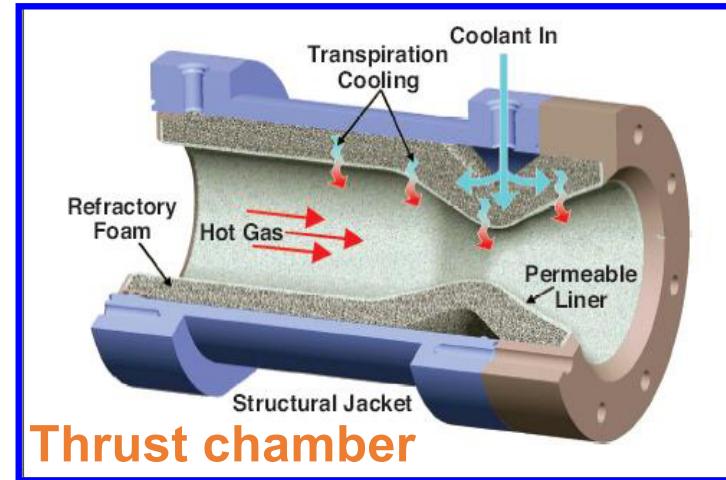
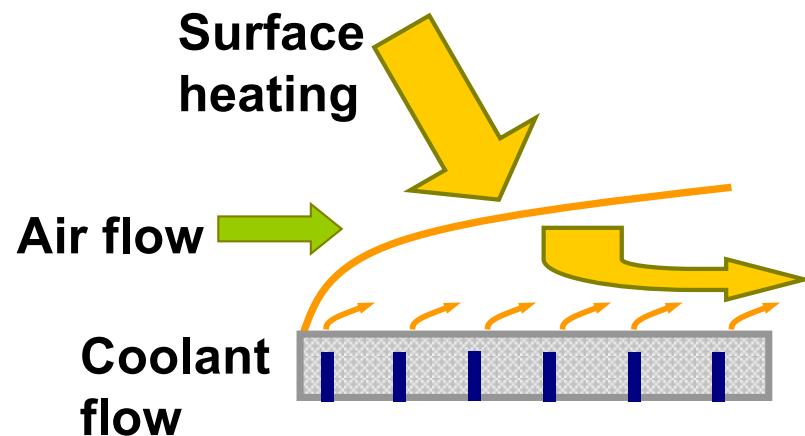


- Coolant injected into flow (upstream)
- Thin, cool, “insulating” blanket
- Structure operates hot



# Active: Transpiration Cooling

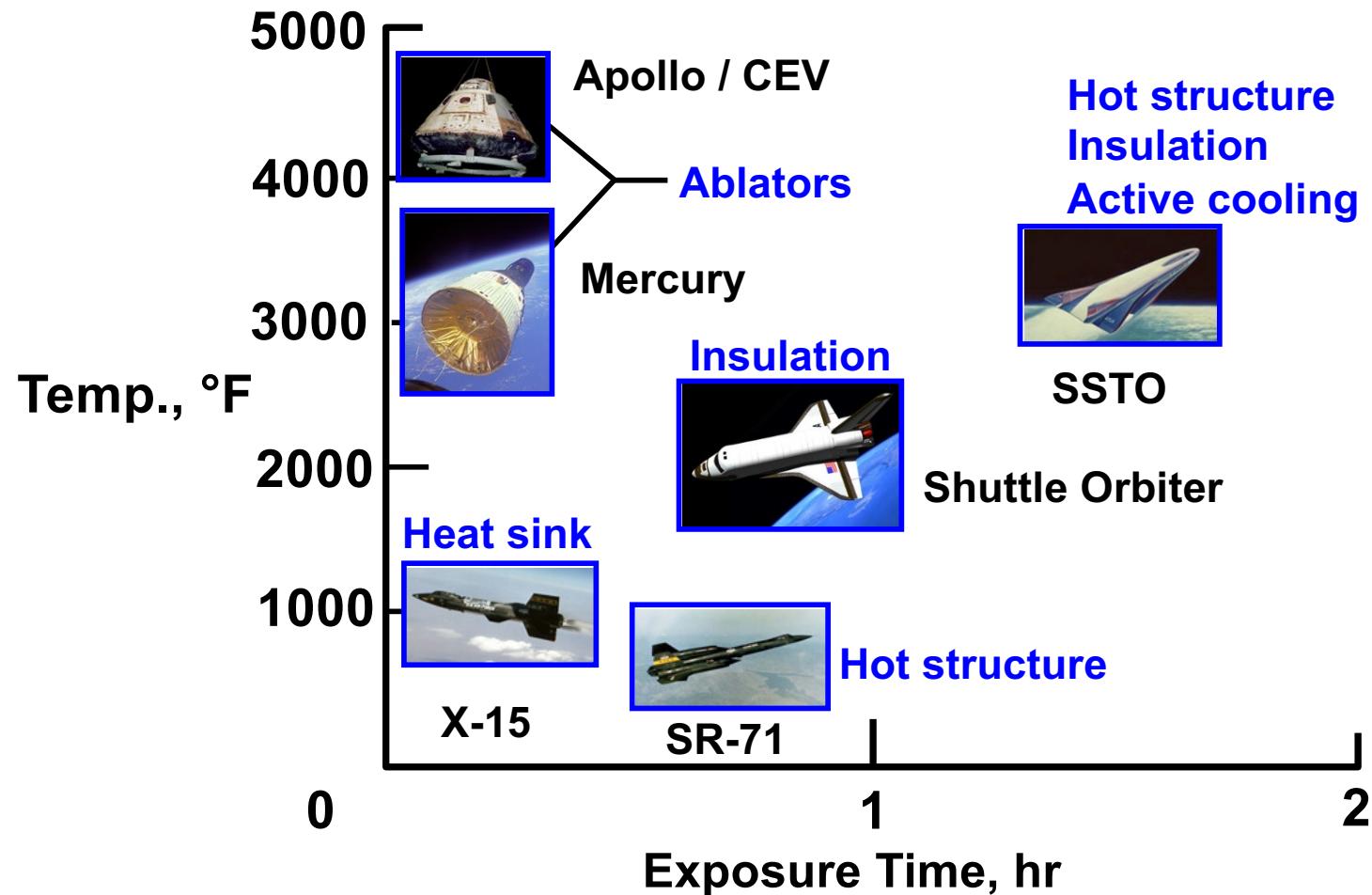
**Use: High heat flux,  
long times**



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



# Flight Vehicle Thermal Management





# Outline

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A large, semi-transparent image of a hypersonic vehicle, possibly a Space Shuttle or similar, flying over a blue and white Earth. A white play button icon is visible on the left side of the image.

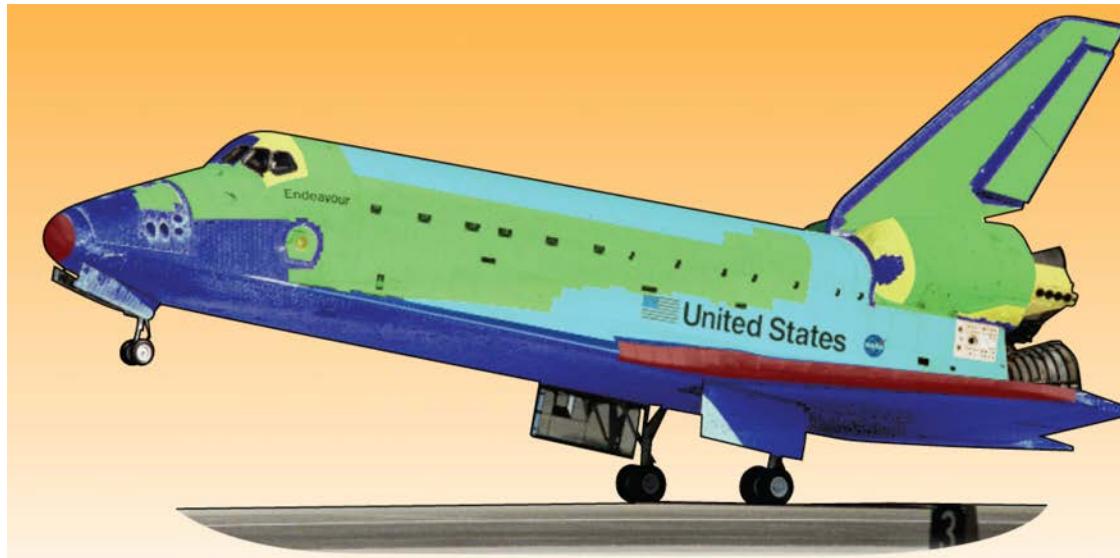
- Introduction
  - Aerothermodynamic heating
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  - TPS for rocket-launched vehicles
  - TPS and hot structures for hypersonic vehicles
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- Concluding Remarks

# Space Shuttle Orbiter



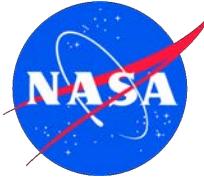
- Conventional skin-stringer aluminum aircraft structure
- Structural temperatures  $< 350^{\circ}\text{F}$
- Reusable surface insulation (RSI) tiles
- Reusable blankets
- Reinforced carbon/carbon (RCC) used for wing leading edges and nose cap,  $T > 2300^{\circ}\text{F}$





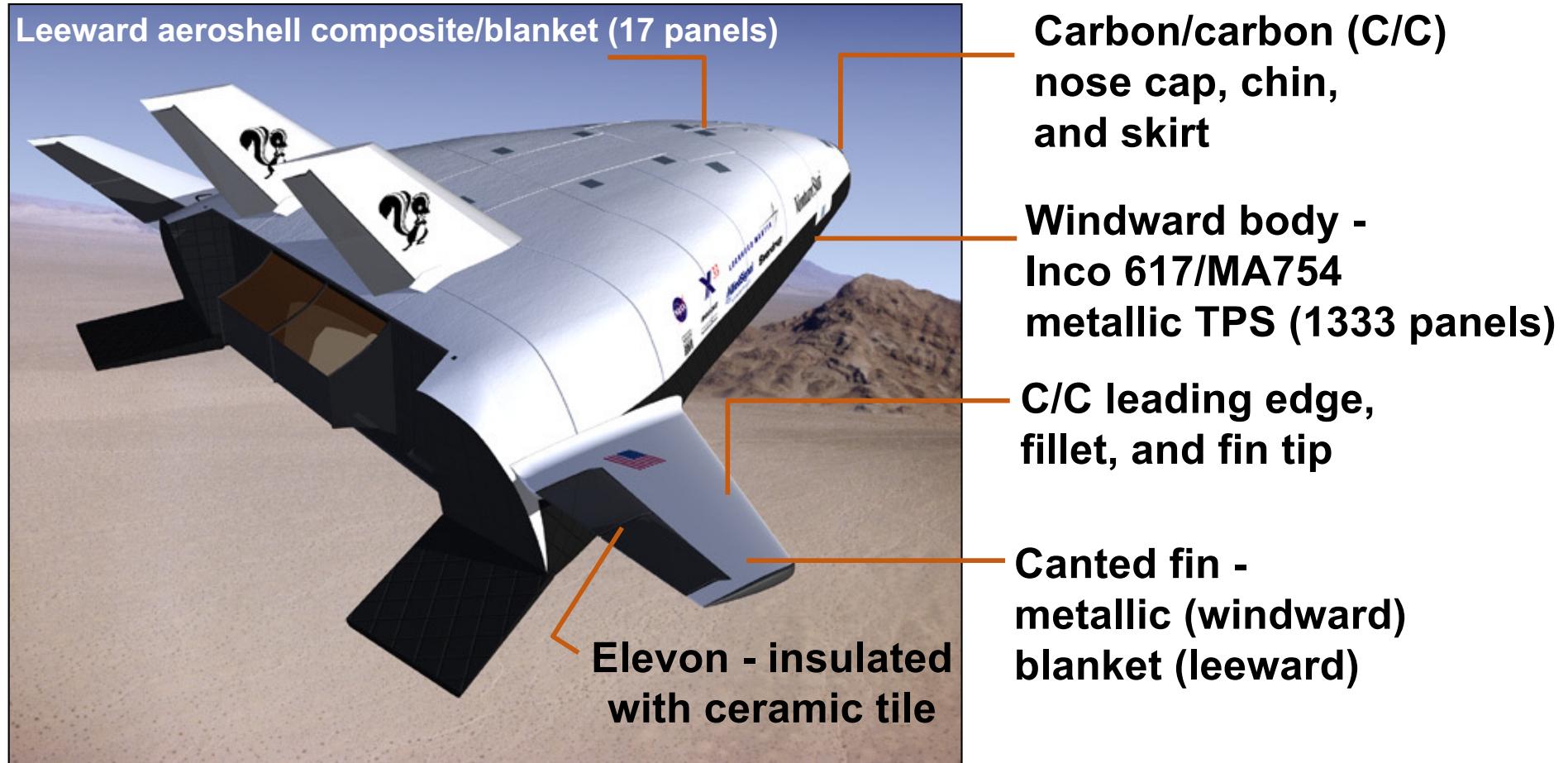
A 3D perspective diagram of a square greenhouse. The top is covered with a translucent, grid-patterned material labeled 'Blanket'. The structure is supported by a white frame and sits on a dark base. Arrows point from the word 'Blanket' to the top covering.





# X-33 Thermal Protection System

Similar to Orbiter TPS except metallic TPS on windward surface





# Outline

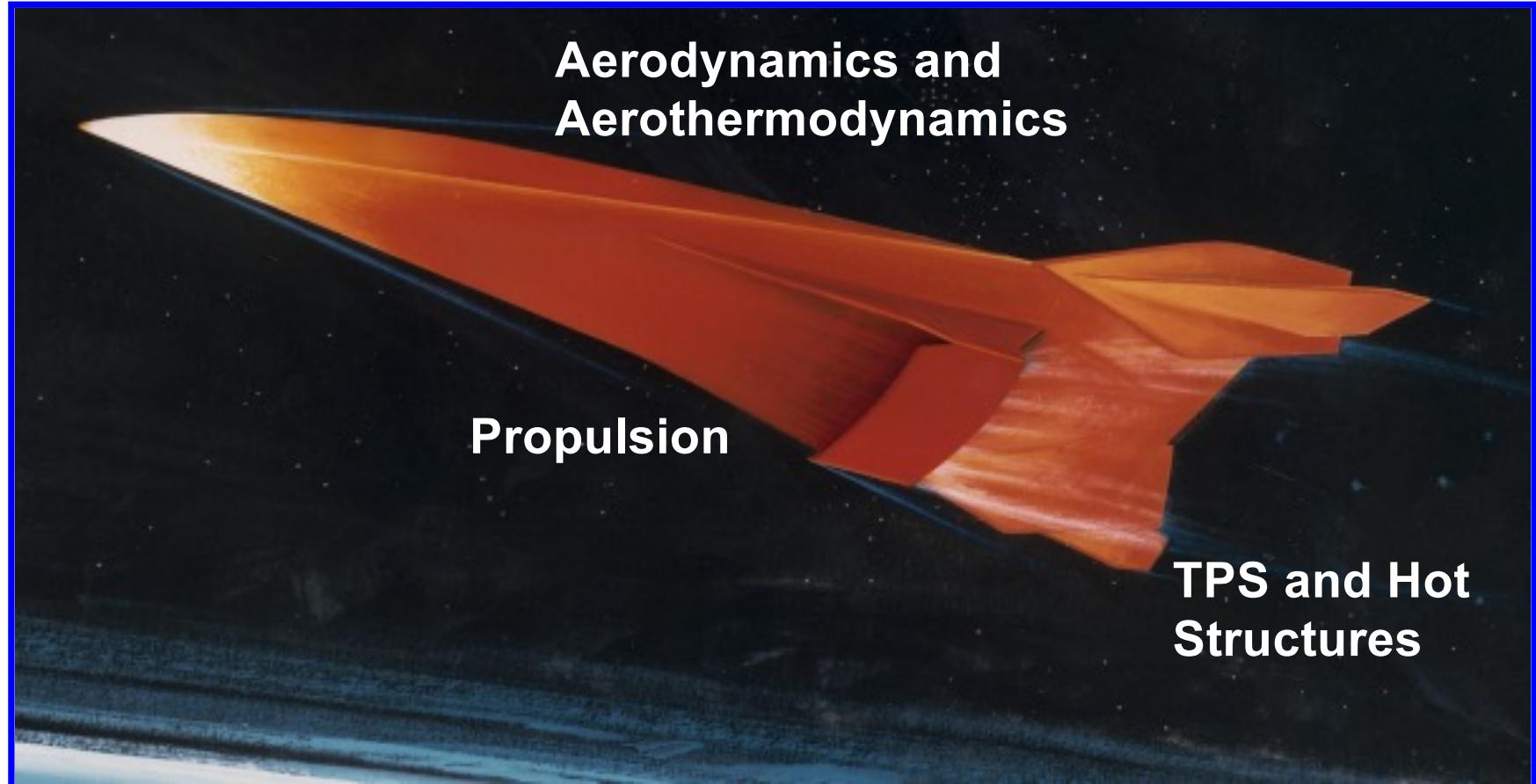
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A large, semi-transparent image of a hypersonic aircraft, possibly a Boeing X-43, is positioned in the background of the slide. The aircraft is shown from a side-on perspective, flying through a blue sky with wispy clouds. It has a distinctive long, slender nose and a delta-wing configuration.

- Introduction
  - Aerothermodynamic heating
  - Thermal management
  - TPS for rocket-launched vehicles
  - TPS and hot structures for hypersonic vehicles
- TPS and Hot Structures Components
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- Concluding Remarks

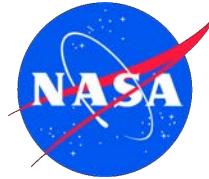


# Airbreathing Hypersonic Vehicles



**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

Rocket



Airbreather



## 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

Rocket

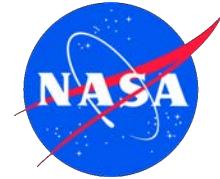


- Driven by descent
- Low ascent heat load due to short ascent time and trajectory

Airbreather



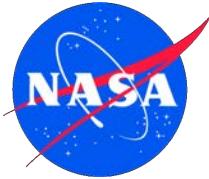
- Driven by ascent, descent, and cruise
- High heat load due to long ascent and cruise time



# 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

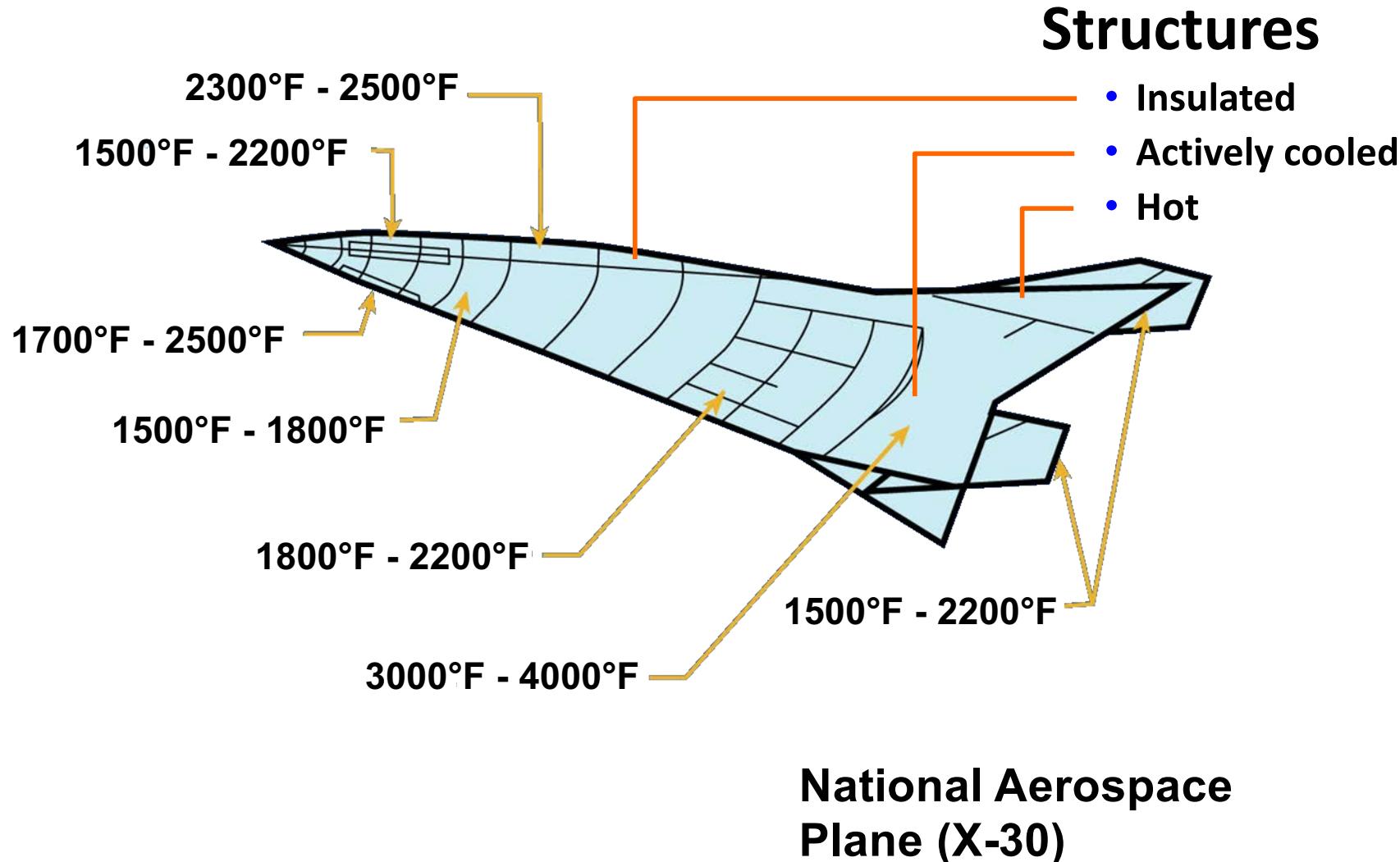
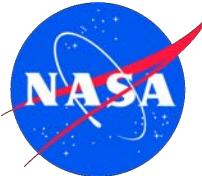


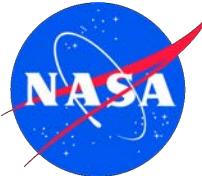
# Rocket vs. Airbreather: Structures



- 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



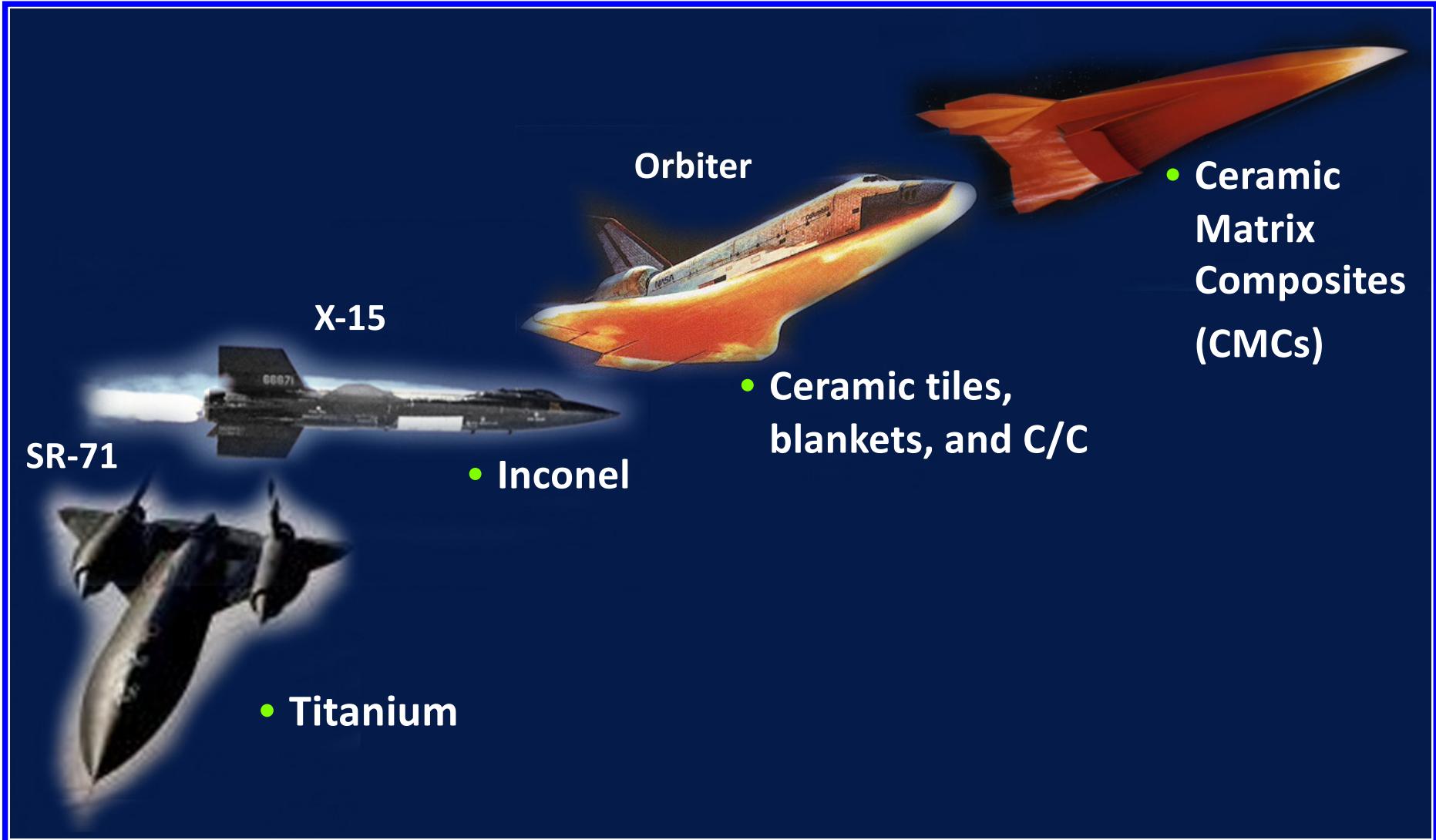
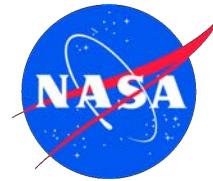


# Thermal-Structural Challenges

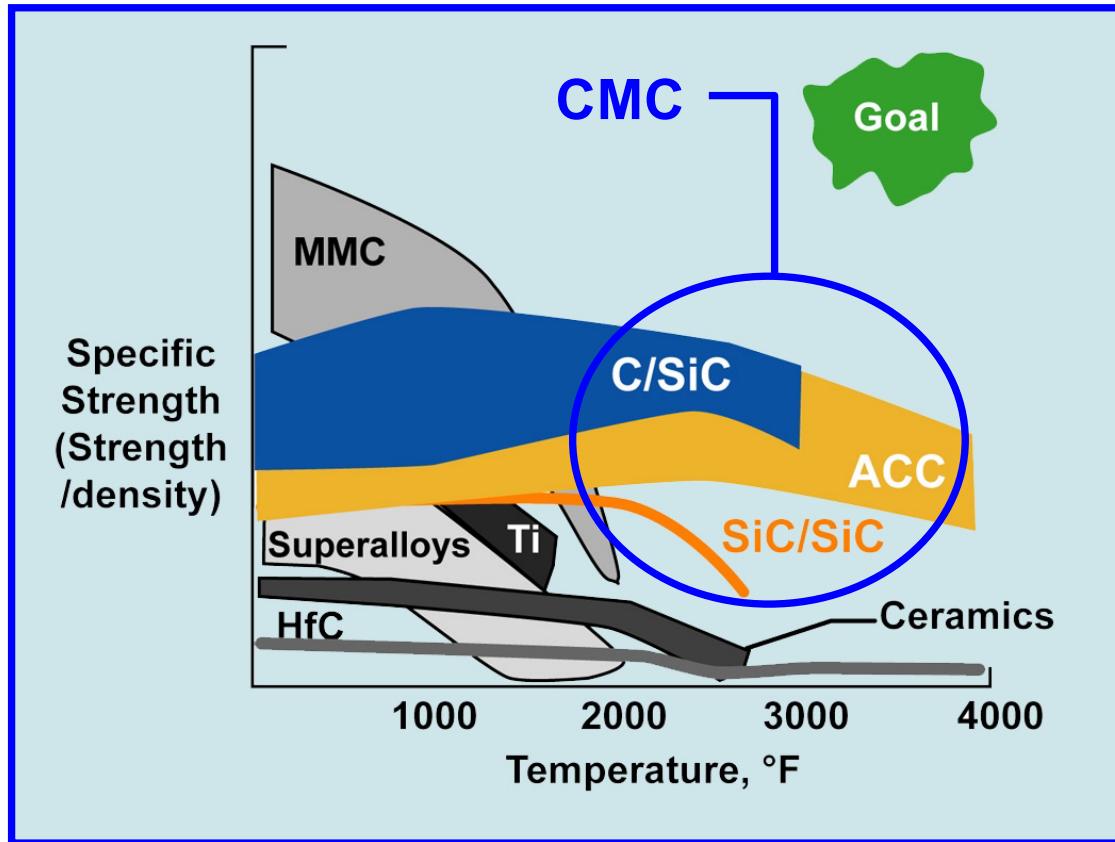
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- **Large thermal gradients**
  - Tank / outer surface
  - Control surfaces / actuators
- **Thin cross sections at high mechanical loads**
- **High mechanical loads at elevated temperatures**
- **Stability of the outer mold line (OML) shape**
  - Performance
  - 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



# Material Specific Strength



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

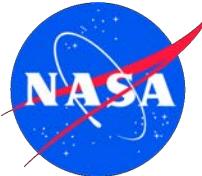
CMCs are the material system that will provide the required strength at elevated temperature



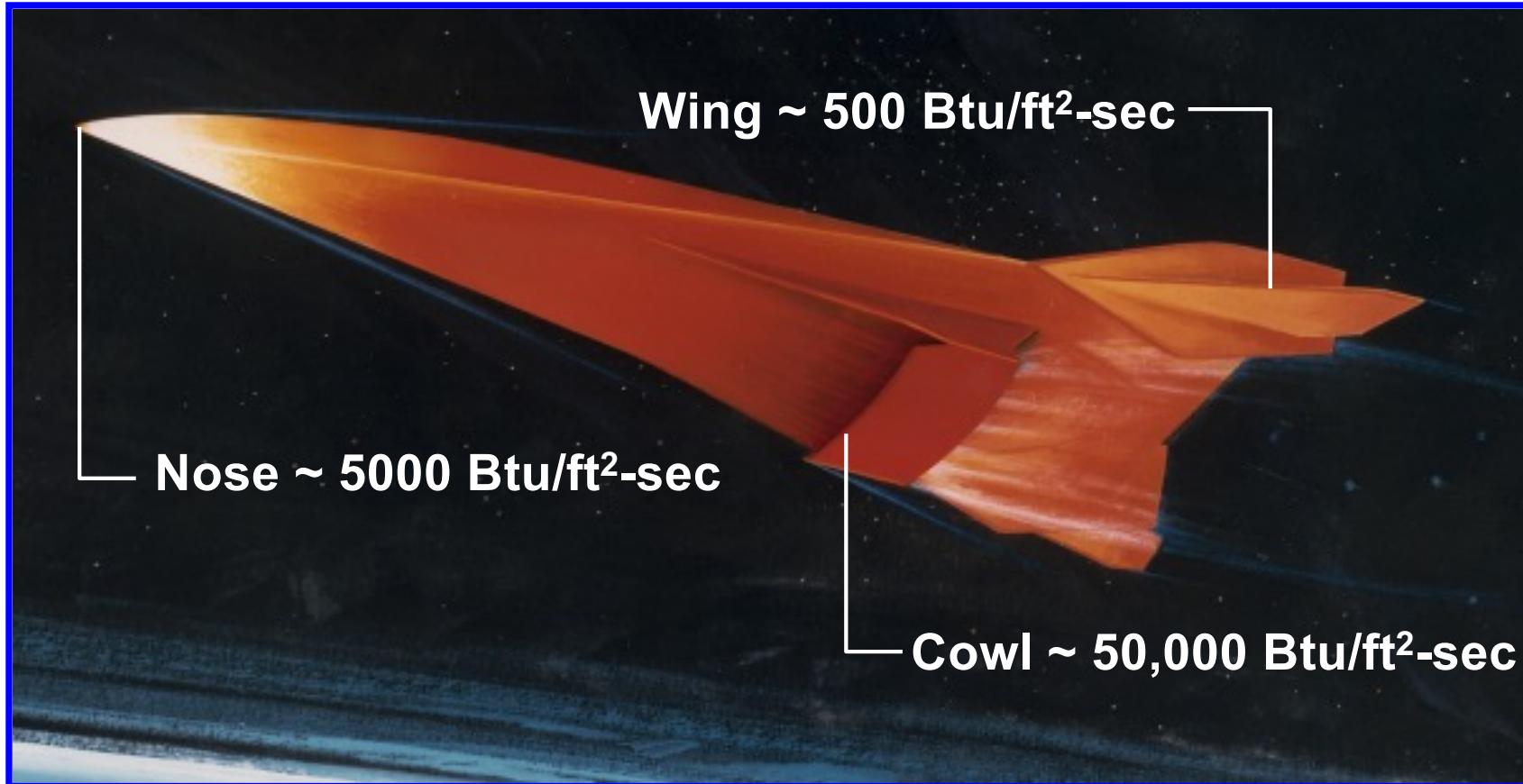
# Outline

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



# Typical Ascent Leading-Edge Heat Flux for SSTO



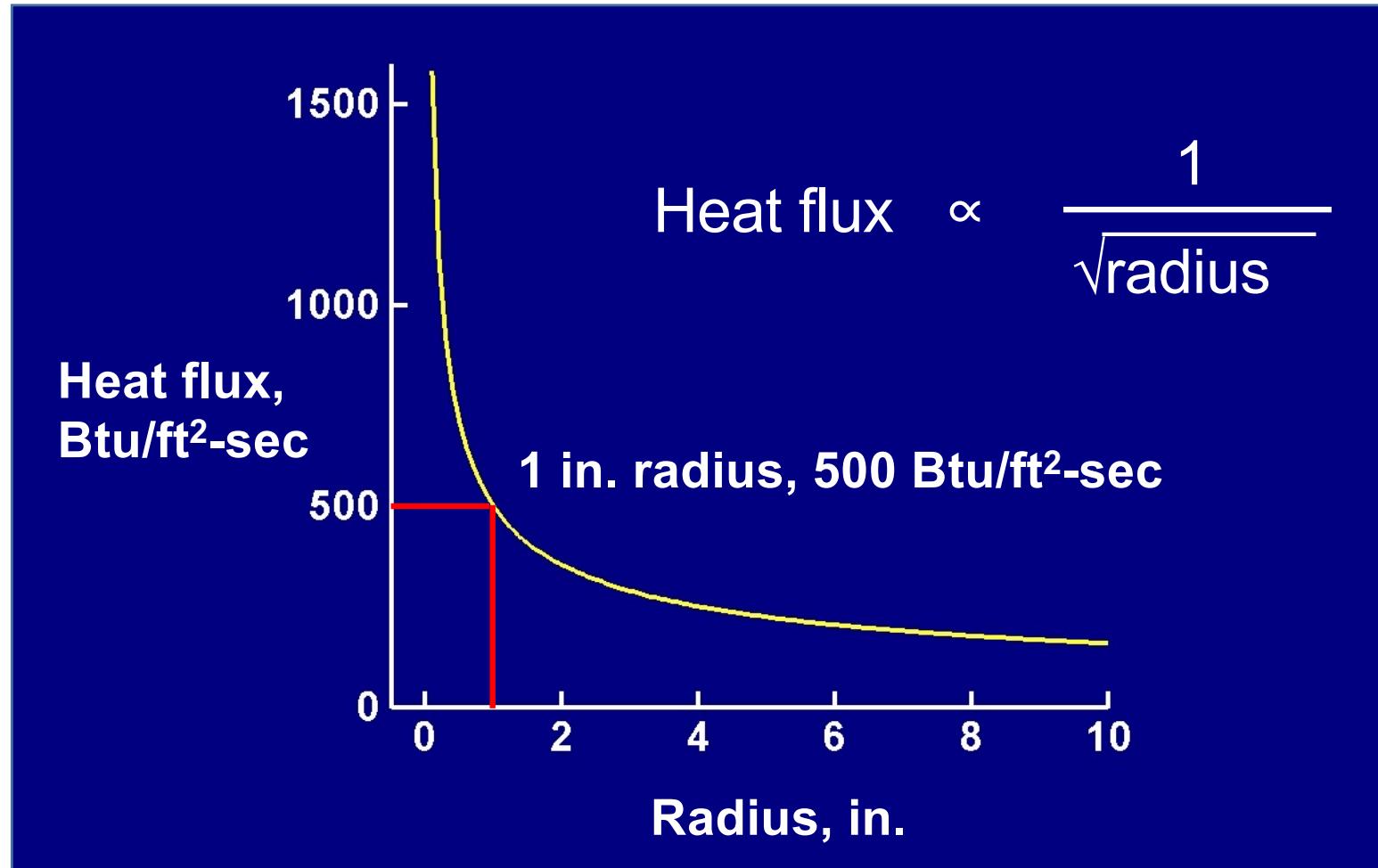
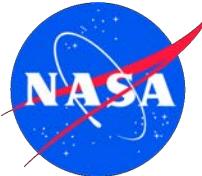
Wing  $\sim 500 \text{ Btu/ft}^2\text{-sec}$

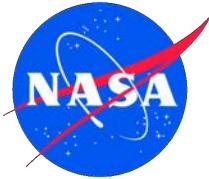
Nose  $\sim 5000 \text{ Btu/ft}^2\text{-sec}$

Cowl  $\sim 50,000 \text{ Btu/ft}^2\text{-sec}$

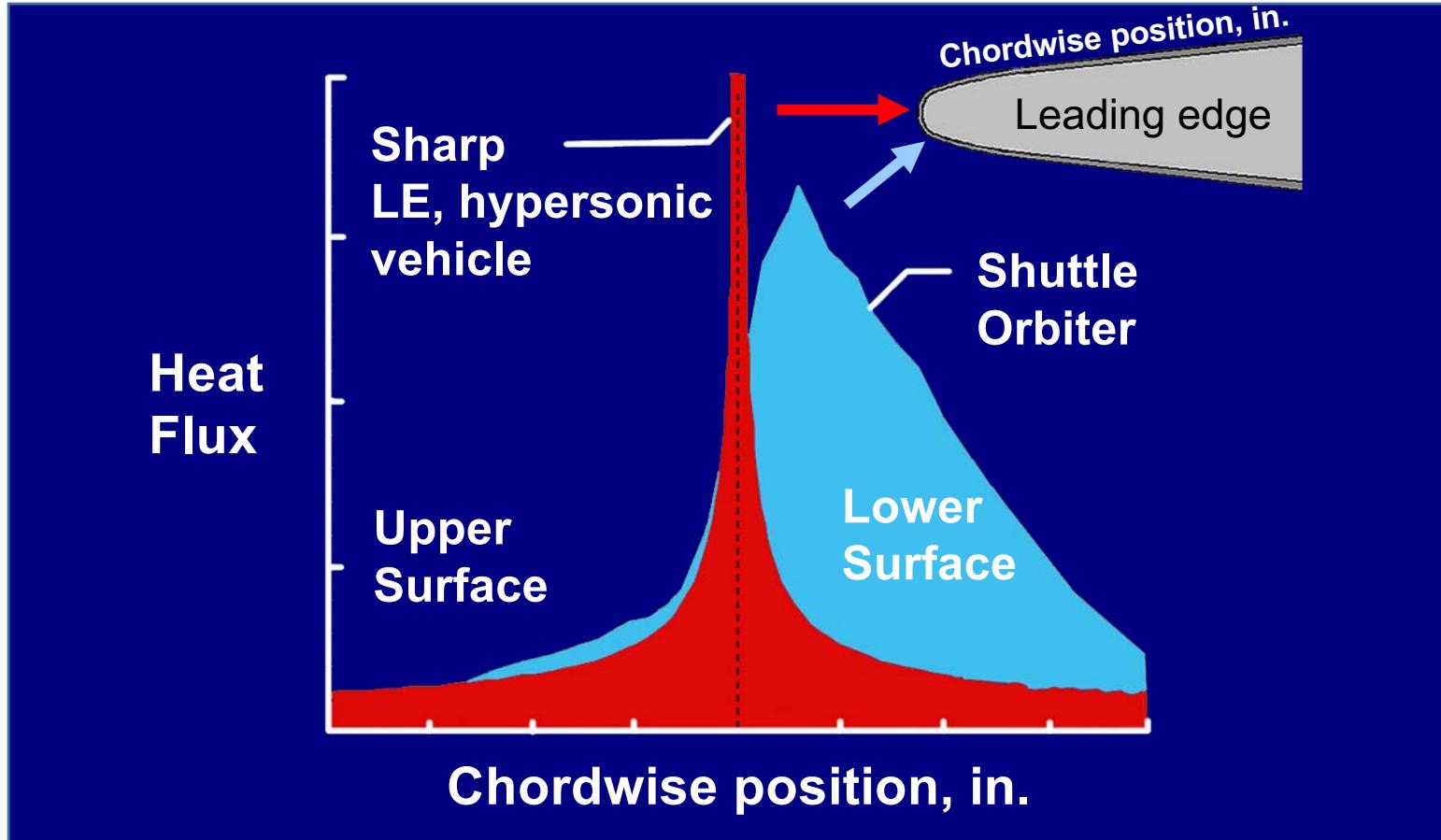
In comparison, Shuttle Orbiter leading edge  
 $\sim 70 \text{ Btu/ft}^2\text{-sec}$ , CEV  $\sim 700 \text{ Btu/ft}^2\text{-sec}$

# Leading-Edge Radius Effect on Heat Flux



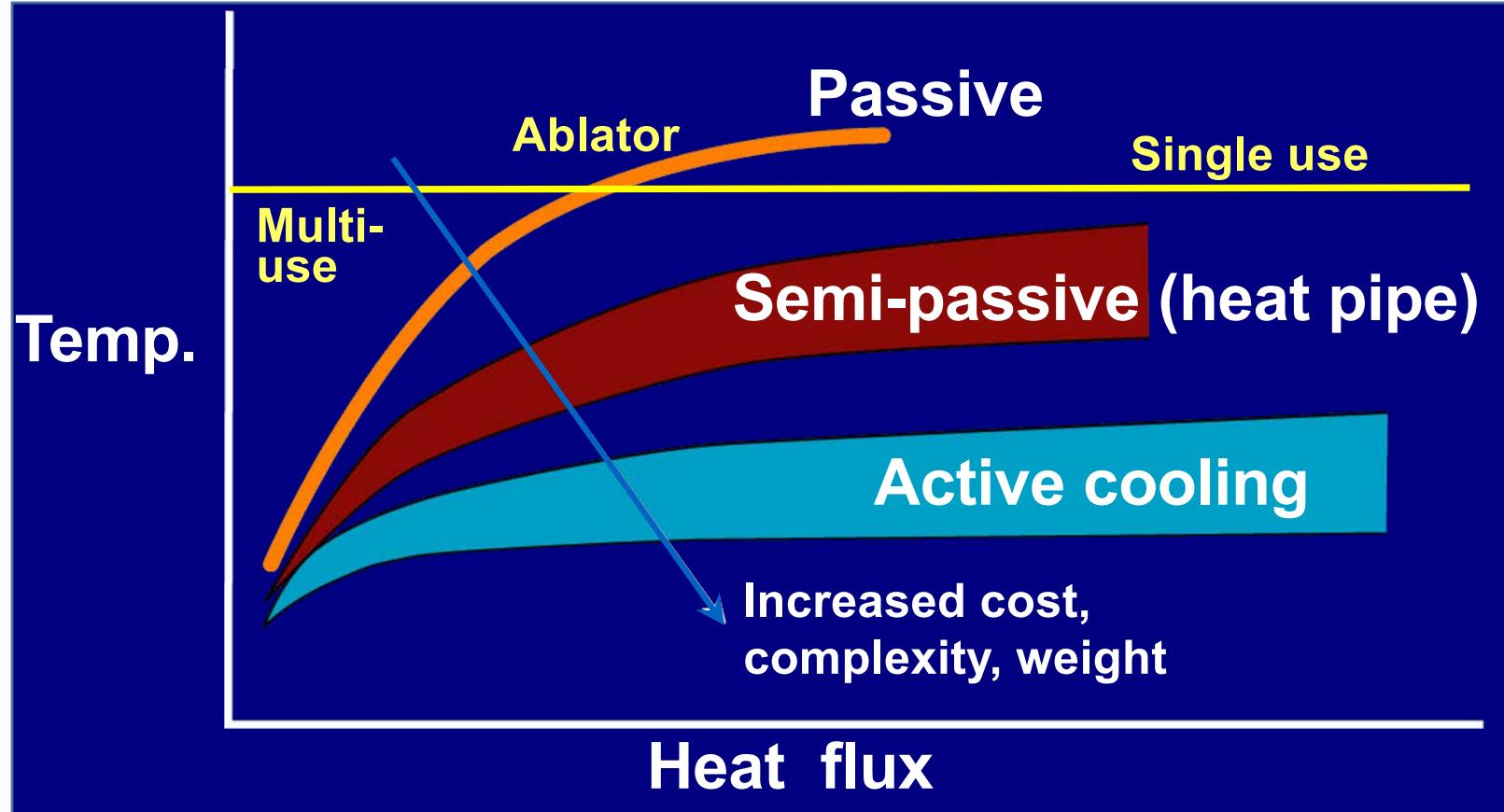
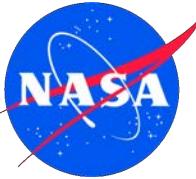


# Leading-Edge Heating



Sharp leading edges produce intense, localized heating

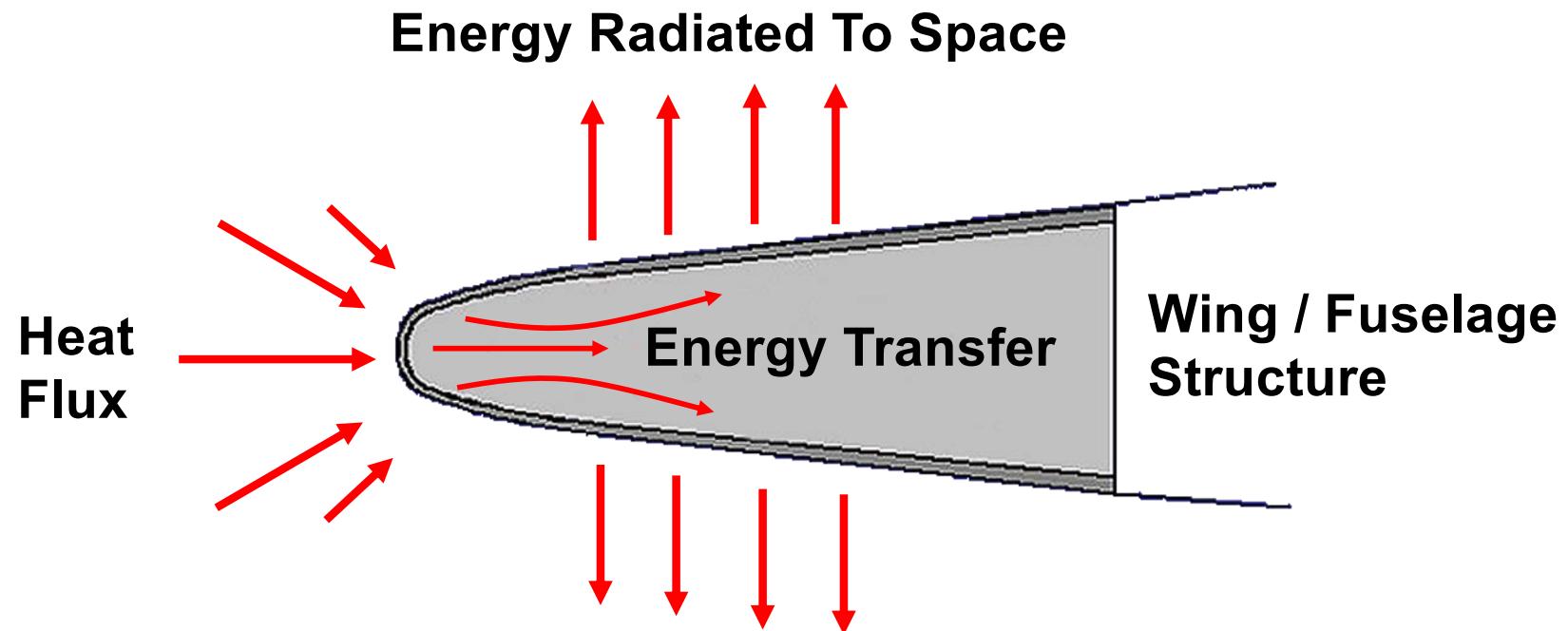
# Leading-Edge Thermal Management Options



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



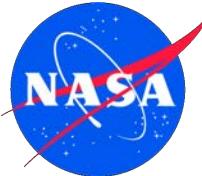
# Passive Leading Edges



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

# High-Temperature Materials / Coatings

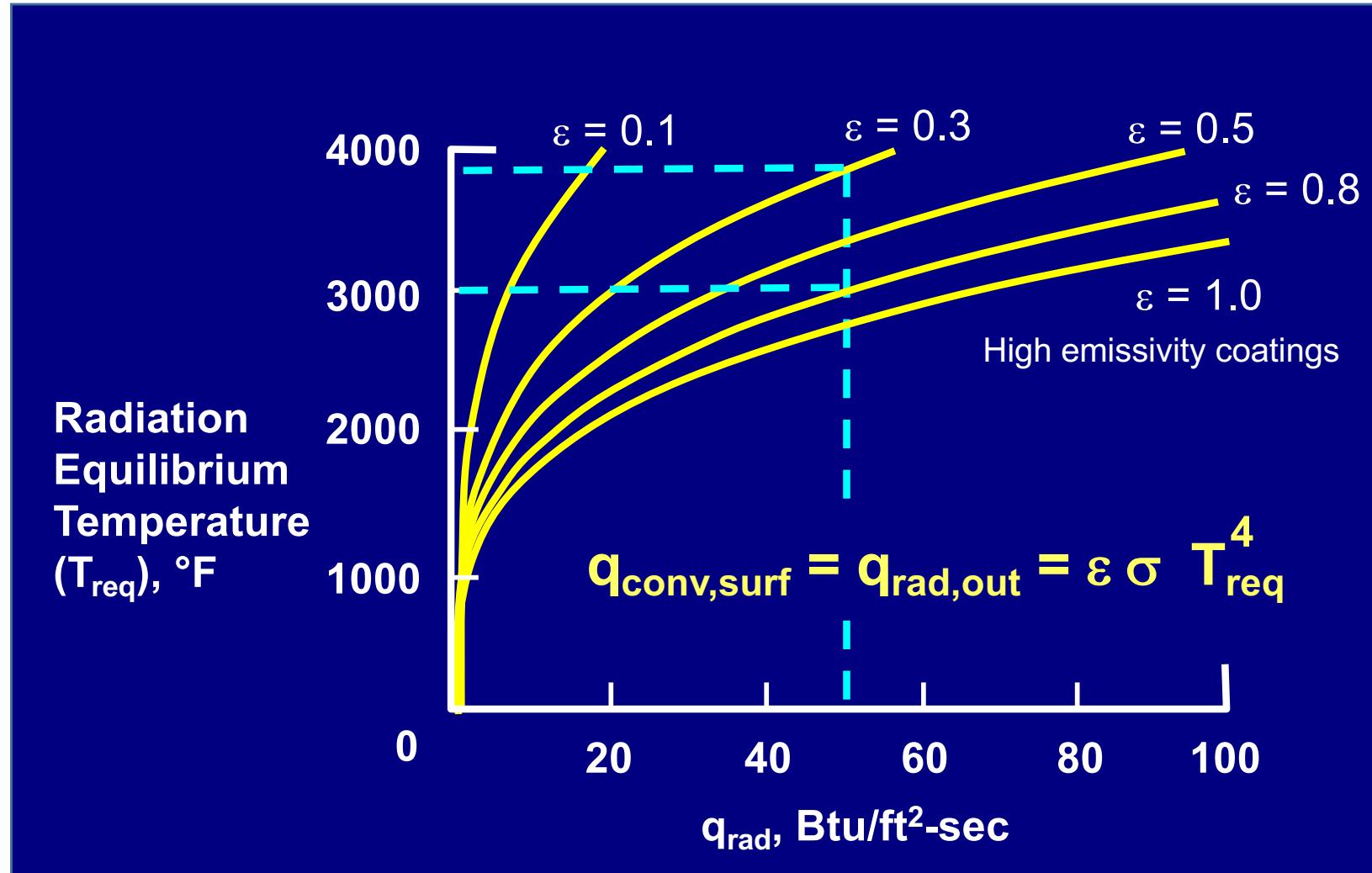
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- **SiC-based coatings as on Shuttle Orbiter leading edges are good to ~ 3000°F**
- **Above ~ 3000°F, different class of materials required**
  - **Carbides, oxides, and diborides of hafnium (Hf) and zirconium (Zr)**
- **Some of these materials can 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**

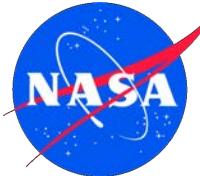


# Property: Emissivity ( $\varepsilon$ )



High emissivity coatings are very important to keep temperatures down

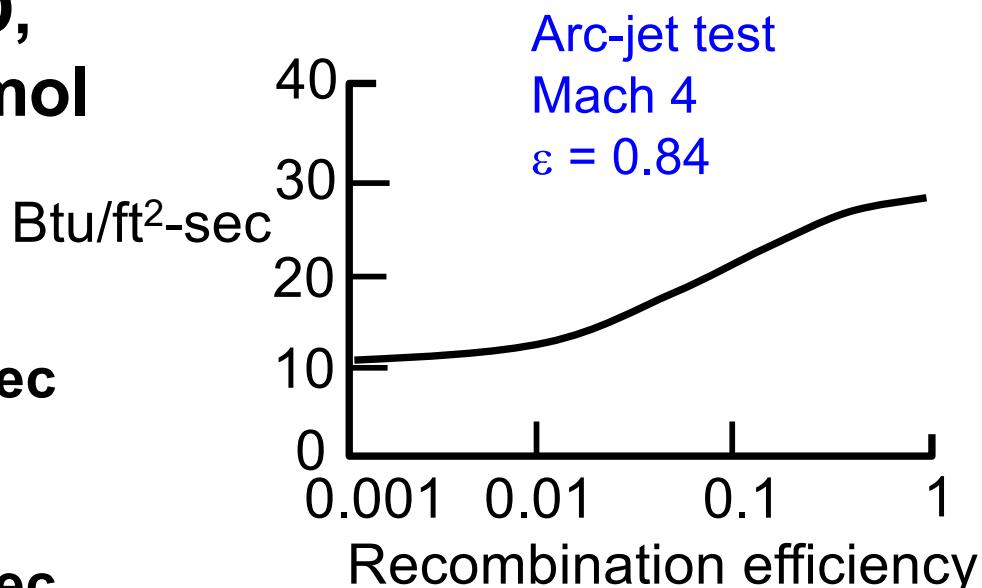
# Property: Recombination (Catalytic) Efficiency



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

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

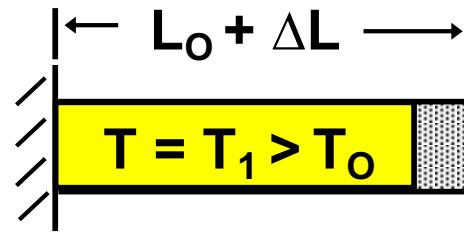
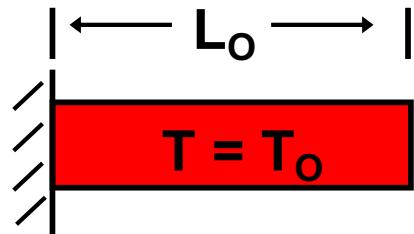
Catalytic  
 $q = 28.3 \text{ Btu/ft}^2\text{-sec}$



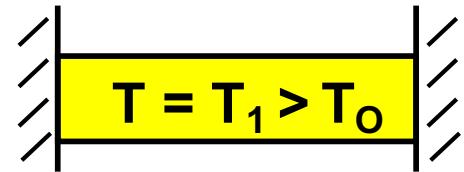
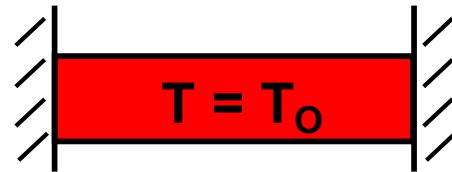
Low catalycity coatings are very important to keep temperatures down



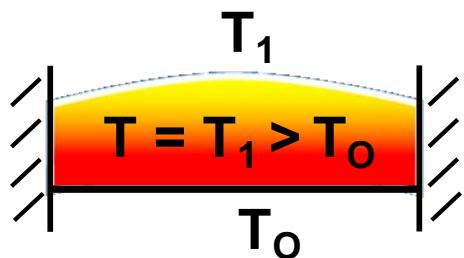
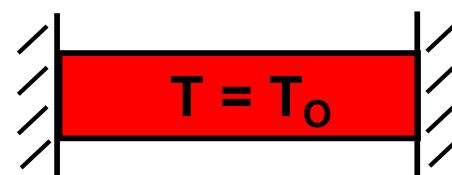
# Property: Thermal Expansion ( $\alpha$ )



$$\varepsilon = \frac{\Delta L}{L_0}, \sigma = 0$$



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



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

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



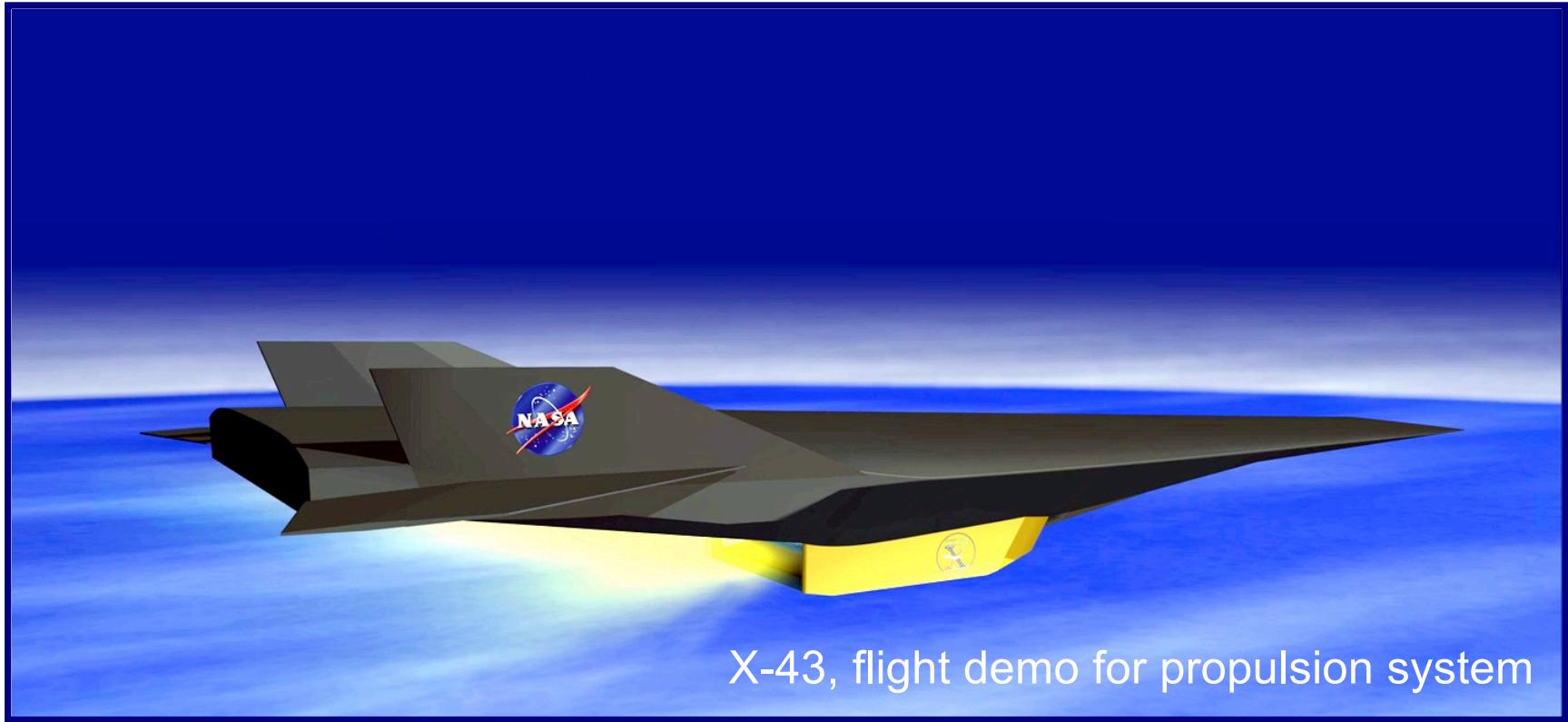
# Oxidation of SiC Coatings

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

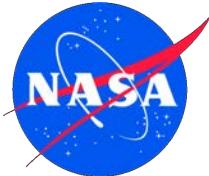


Transition between passive and active oxidation regimes depends on temperature and partial pressure of oxygen

# X-43 (Hyper-X) Passive Leading Edges



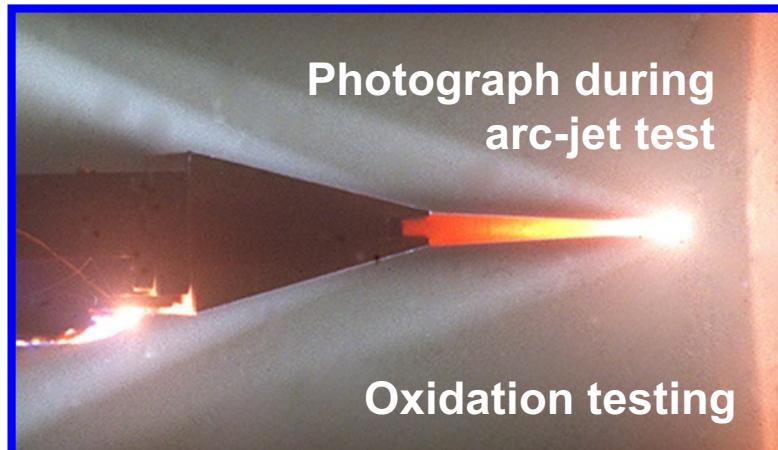
**Hyper-X (Mach 10 vehicle) nose leading edge was designed to reach nearly 4000°F during the 130 s flight**



# 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



Oxidation testing

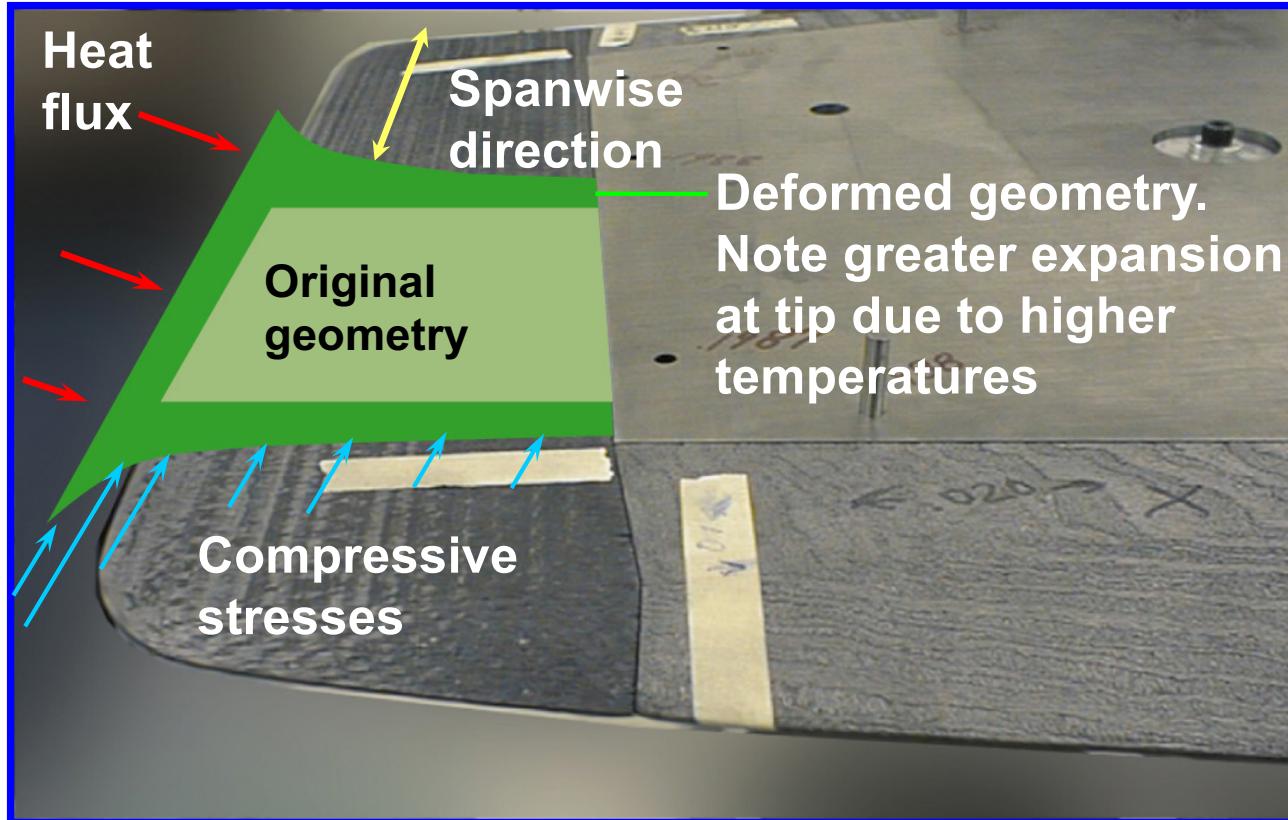
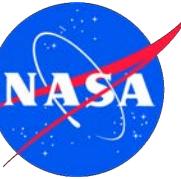


Successful test article



Failed test article

# Spanwise Compressive Thermal Stresses

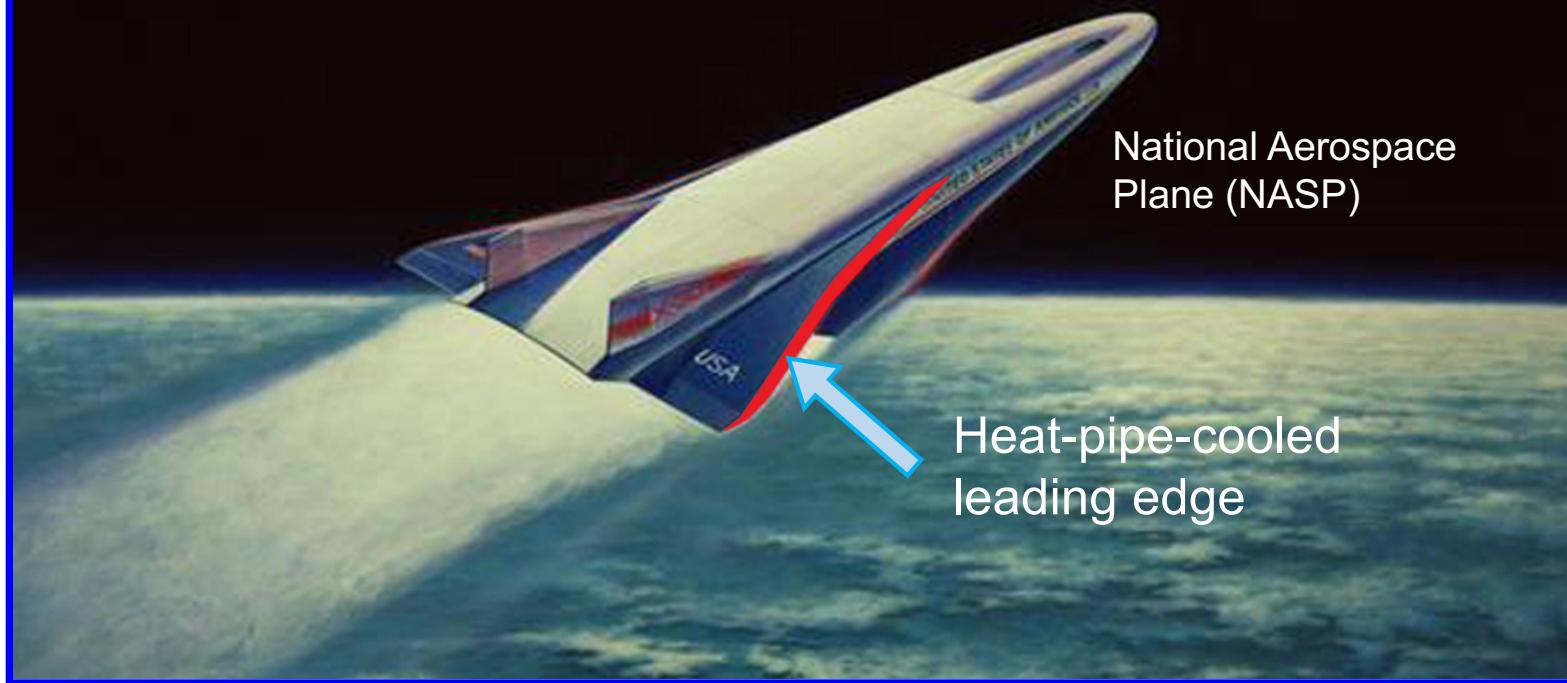


Thermal stresses due to constraint of thermal expansion

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

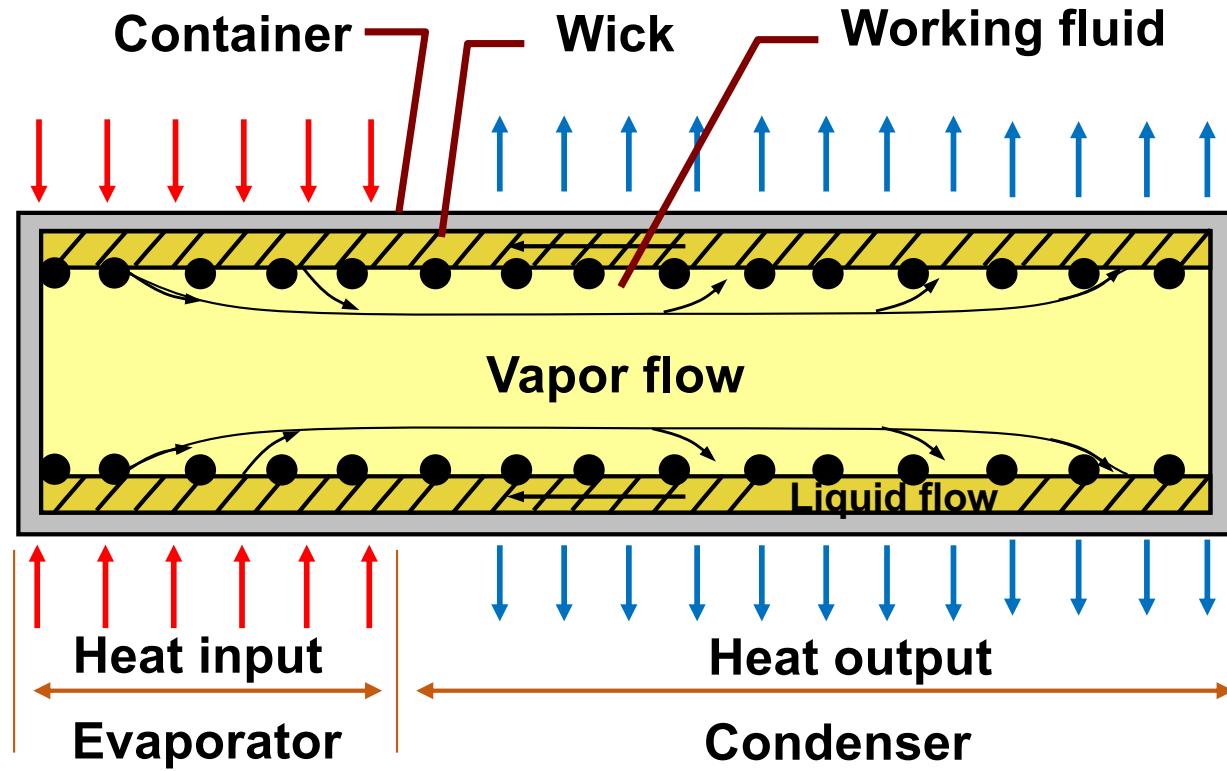


Heat pipes reduce leading-edge temperatures to reuse limits of materials



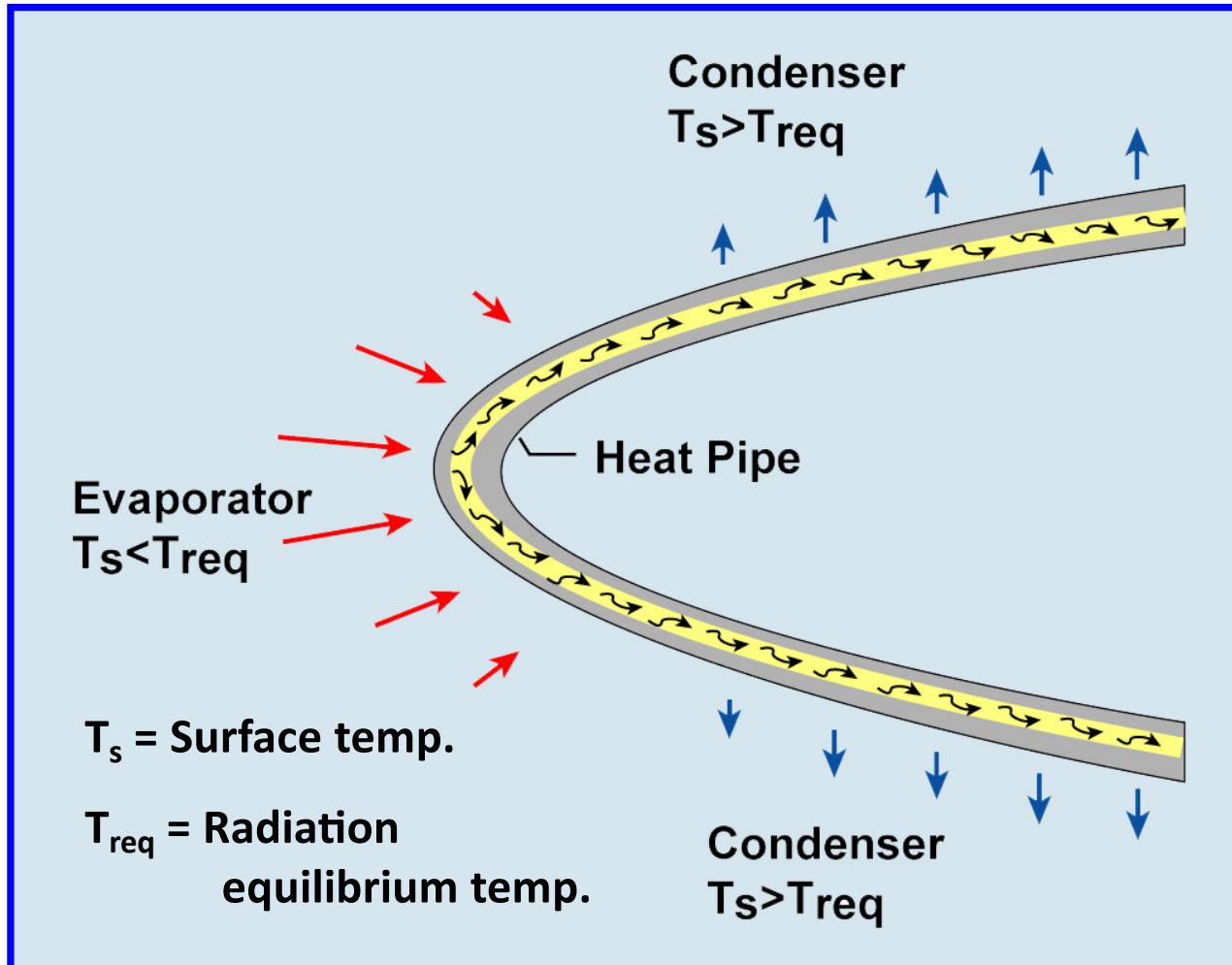


# Heat-Pipe Operation



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

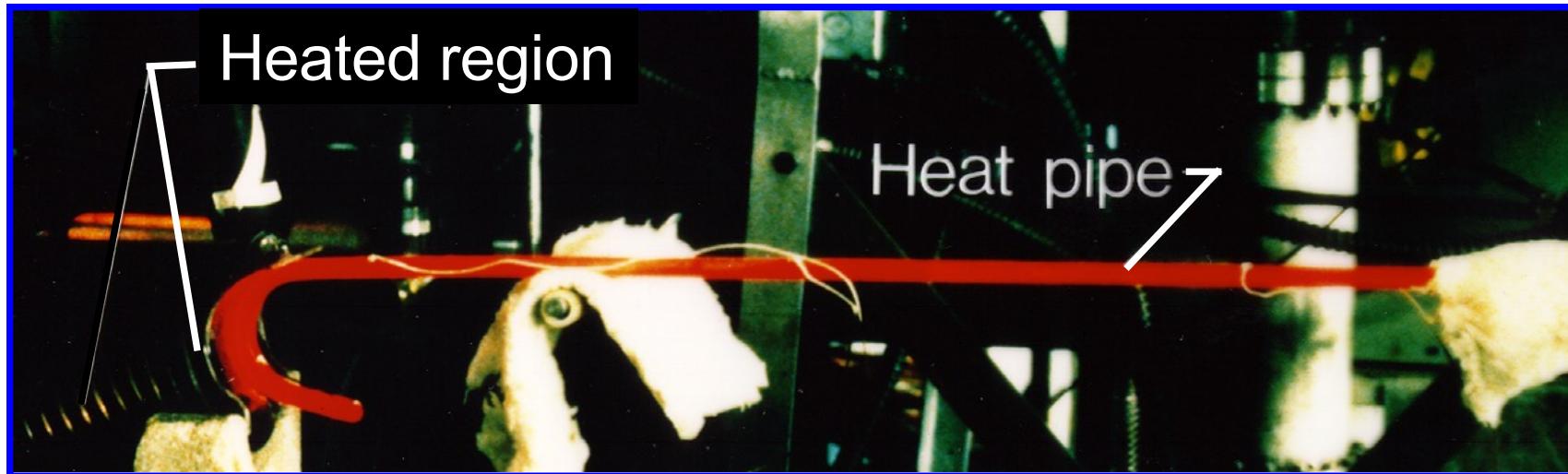
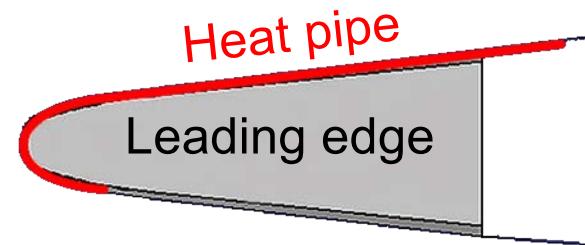
# Leading-Edge Heat-Pipe Operation





# Leading-Edge-Shaped Heat Pipe

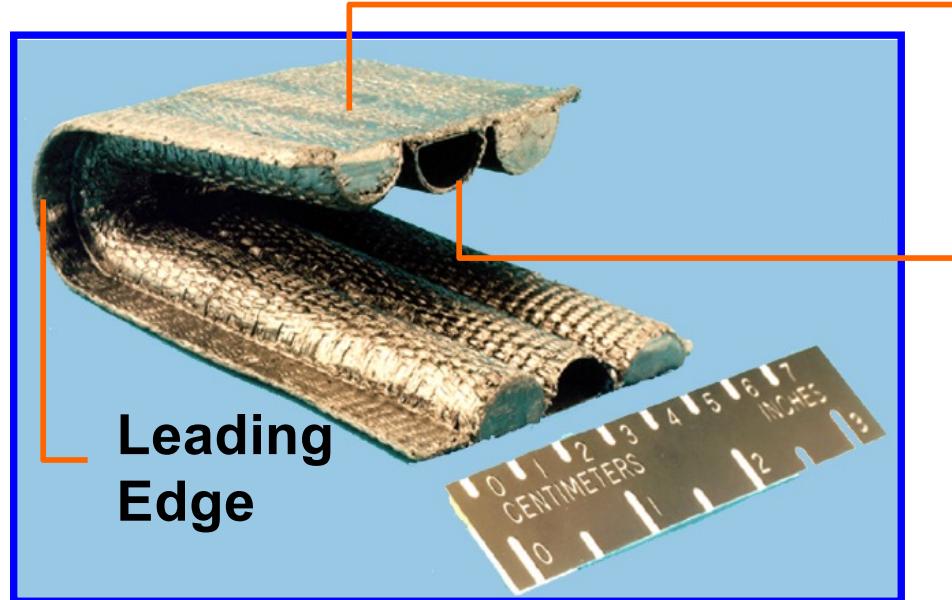
- Hastelloy-X container
- Sodium (Na) working fluid



Heat pipe results in an isothermal leading edge



# NASP Heat-Pipe-Cooled Wing Leading Edge

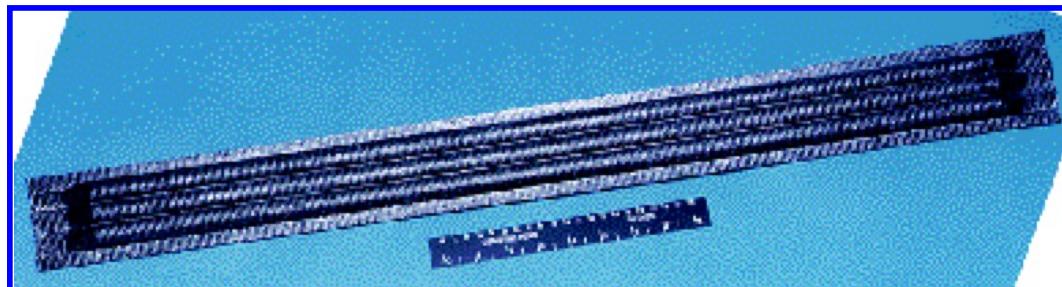


**Carbon/carbon (C/C) structure**

**Mo-Re (molybdenum-rhenium) container**

## Challenges

- Material compatibility
- Thermal stresses



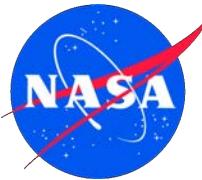
- Mo-Re embedded in C/C
- Lithium working fluid
- D-shaped heat pipes



# Outline

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- 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.)

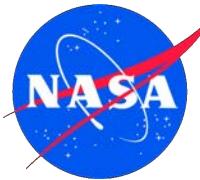
Damaged tile  
post-flight



Space Transportation  
System (STS) - 114

Tile with high  
emissivity coating

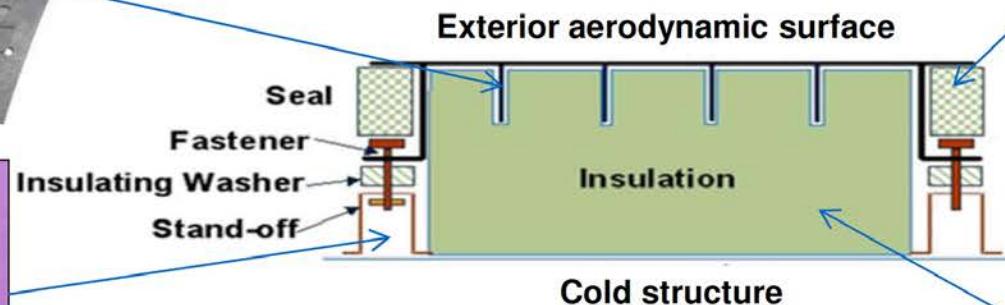




# CMC Standoff TPS on Intermediate eXperimental Vehicle (IXV)

## ARIANEGROUP THERMAL PROTECTION SYSTEM SHINGLE DESIGN

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



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

Seals to fill the gap between panels and prevent sneak flows



Layers of insulation material to absorb the heat load.



Used by permission of ArianeGroup



# Load Bearing Aeroshell

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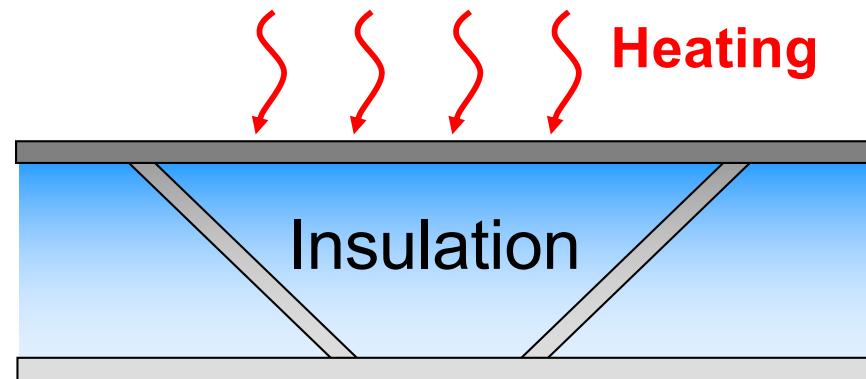
- **Aeroshell carries aero and vehicle axial loads**
- **Insulation incorporated or separate**
- **Potential for reduced weight**

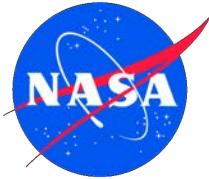


# Structurally Integrated TPS

- 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

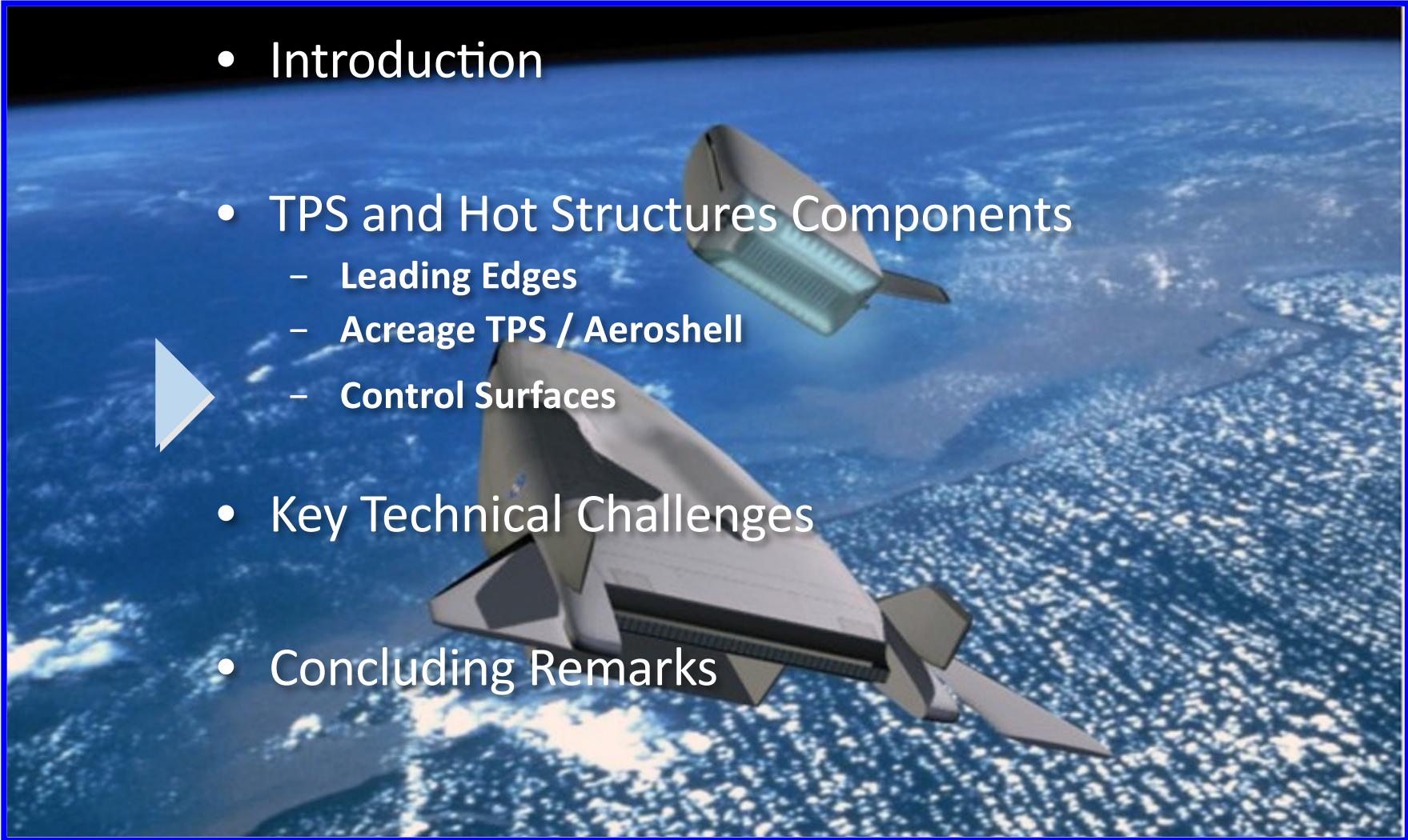




# Outline

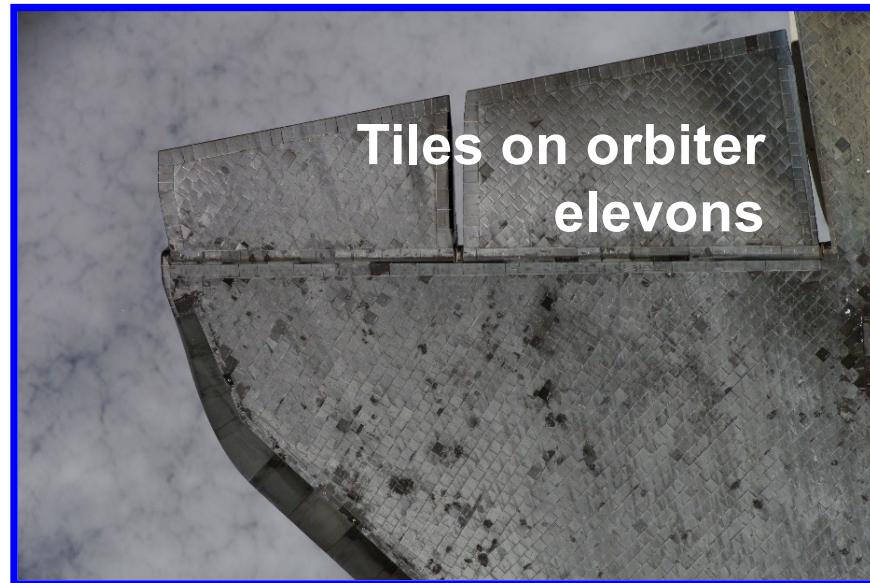
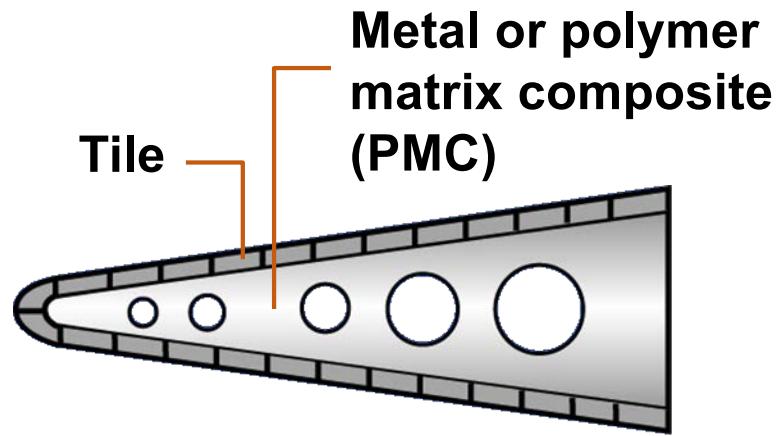
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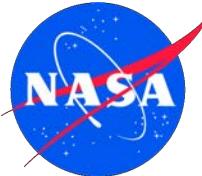
- Introduction
- TPS and Hot Structures Components
  - Leading Edges
  - Acreage TPS / Aeroshell
  - Control Surfaces
- Key Technical Challenges
- Concluding Remarks



# Insulated Control Surface

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





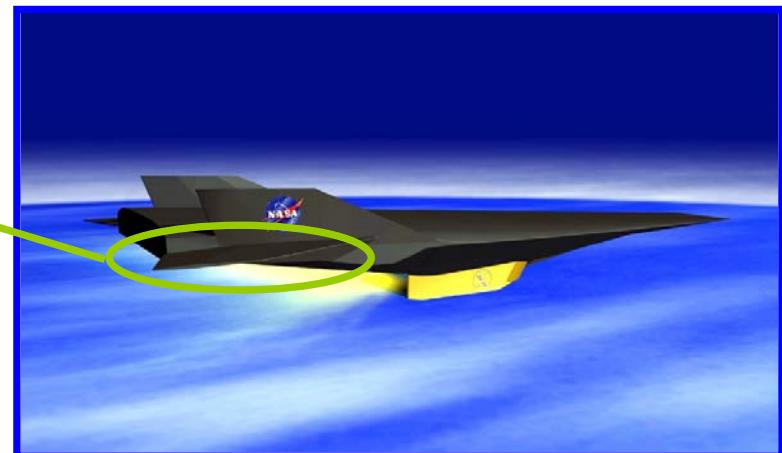
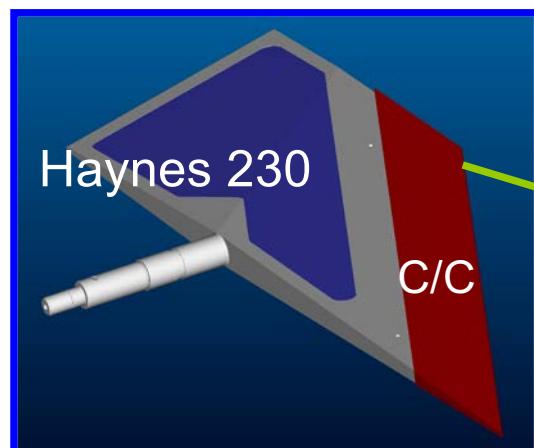
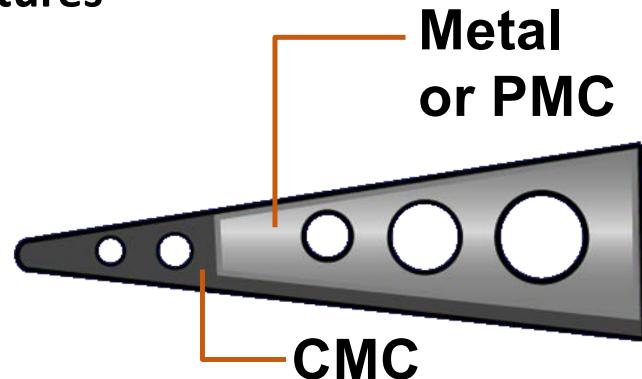
# Hybrid Control Surface

- **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

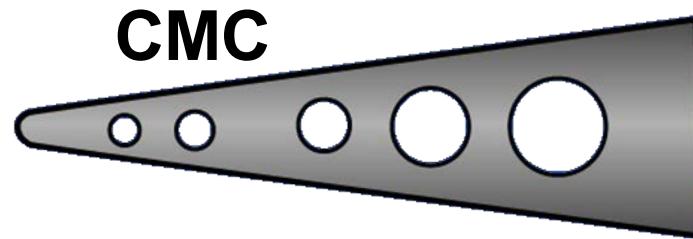




# CMC Hot Structure Control Surface

- **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**

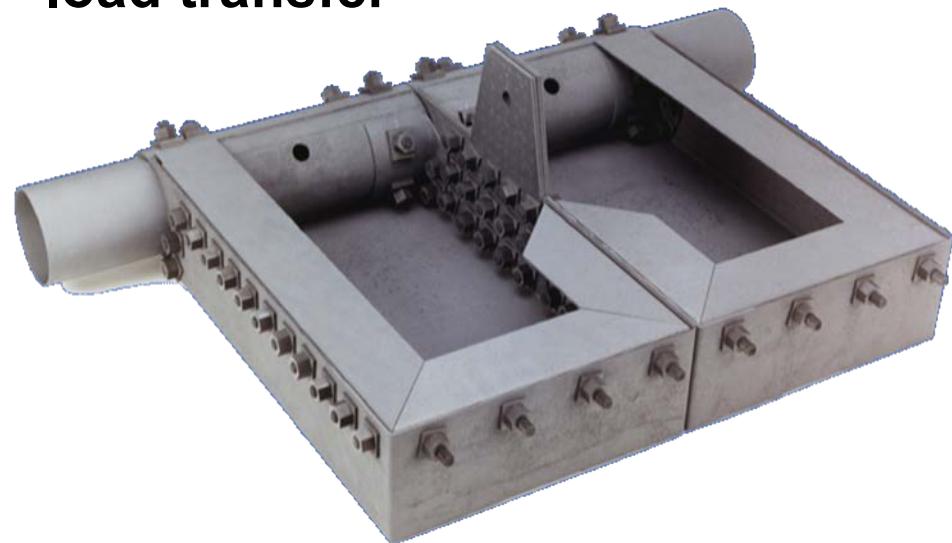
- High manufacturing/tooling costs for box structure
- Challenging for very large structures
- Limited repair capability
- Manufacturing risk in case of production failure or damage
- Access for coating, inspection, and maintenance of internal areas



# 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

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





# Outline

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- Introduction
- TPS and Hot Structure Components
- Key Technical Challenges
- Concluding Remarks

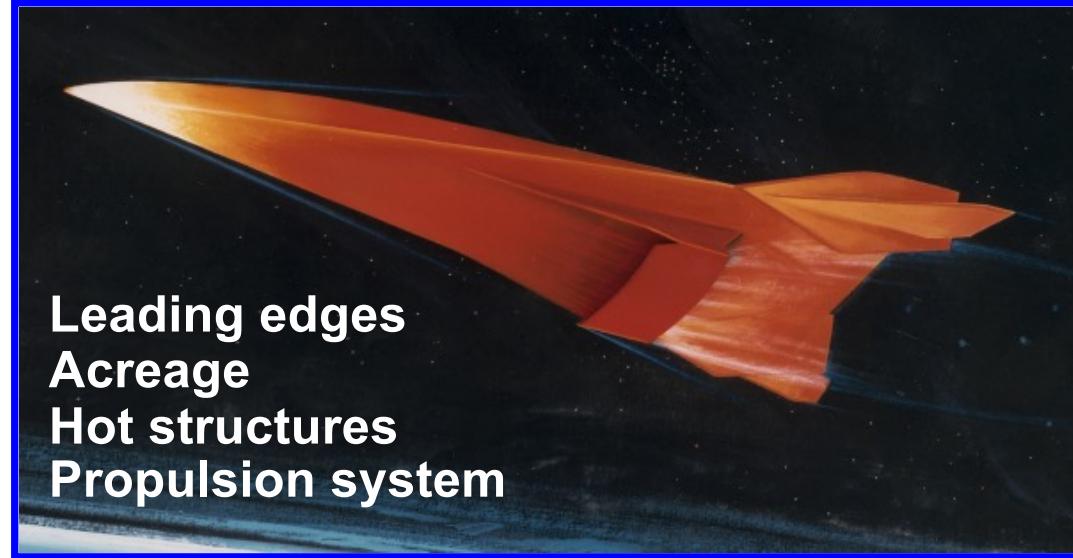




# Hypersonic Vehicles

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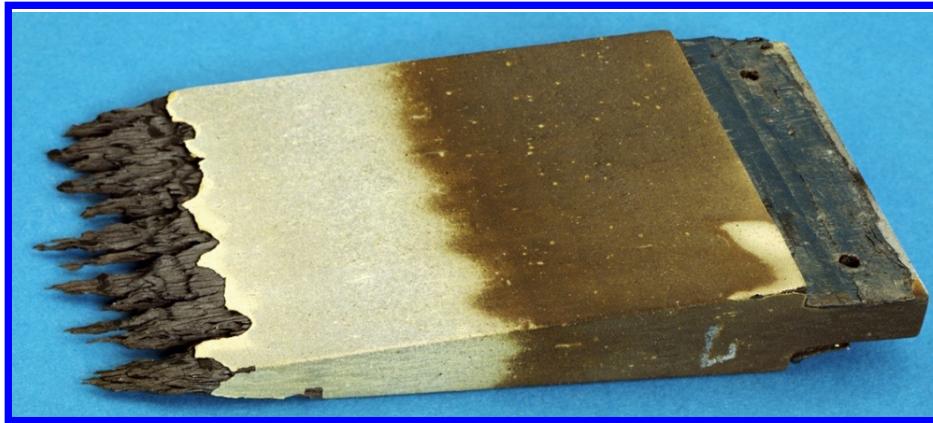
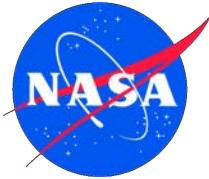
- CMCs are the family of materials that will enable hypersonic vehicles



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

# Key Technical Challenge: Environmental Durability

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- 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**



H. Lange, A Steinacher, K. Handrick, S. Weiland, D. Sygulla, S. Guedron, and T. Salmon, "Status of Flap Development for Future Re-Entry Vehicles (Pre-X)", 5th European Workshop on Thermal Protection Systems and Hot Structures, Noordwijk, The Netherlands, May 17-19, 2006.

**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**



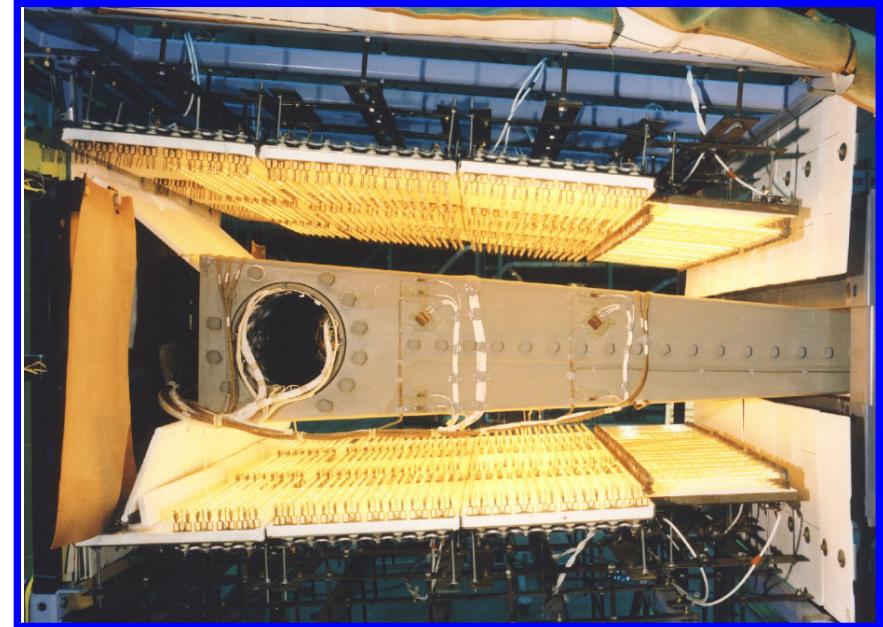
H. Lange, A Steinacher, K. Handrick, S. Weiland, D. Sygulla, S. Guedron, and T. Salmon, "Status of Flap Development for Future Re-Entry Vehicles (Pre-X)", 5th European Workshop on Thermal Protection Systems and Hot Structures, Noordwijk, The Netherlands, May 17-19, 2006.

# 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



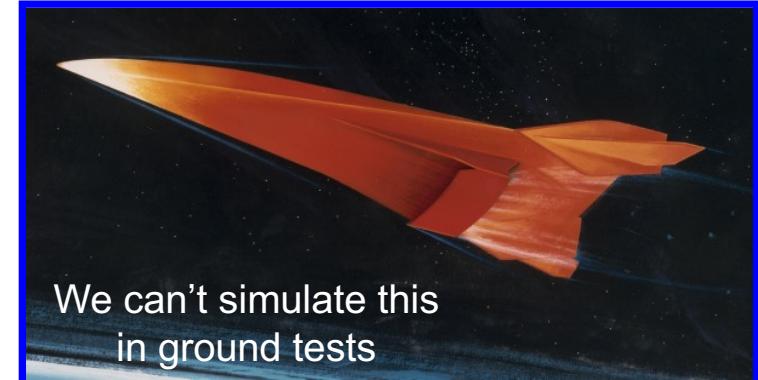
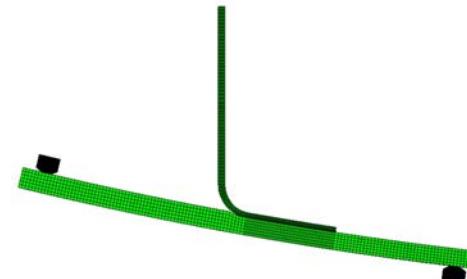
# Testing

- 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



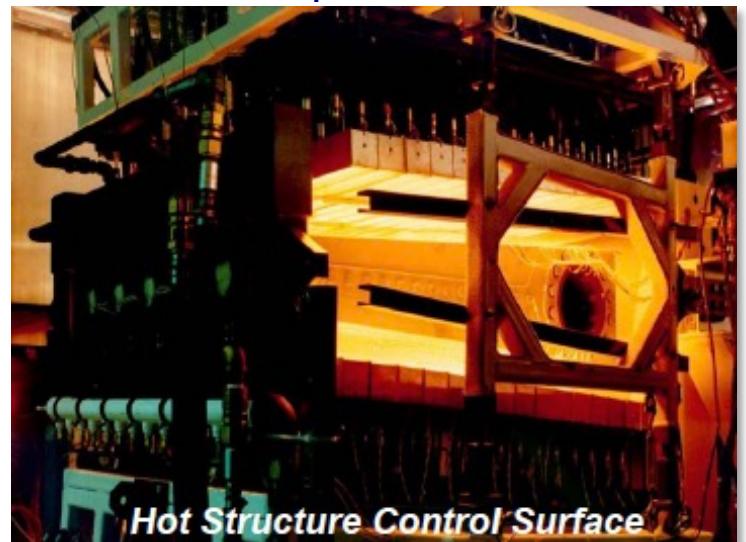
Material / coupon test

Sub-element test



We can't simulate this in ground tests

Component test



Hot Structure Control Surface

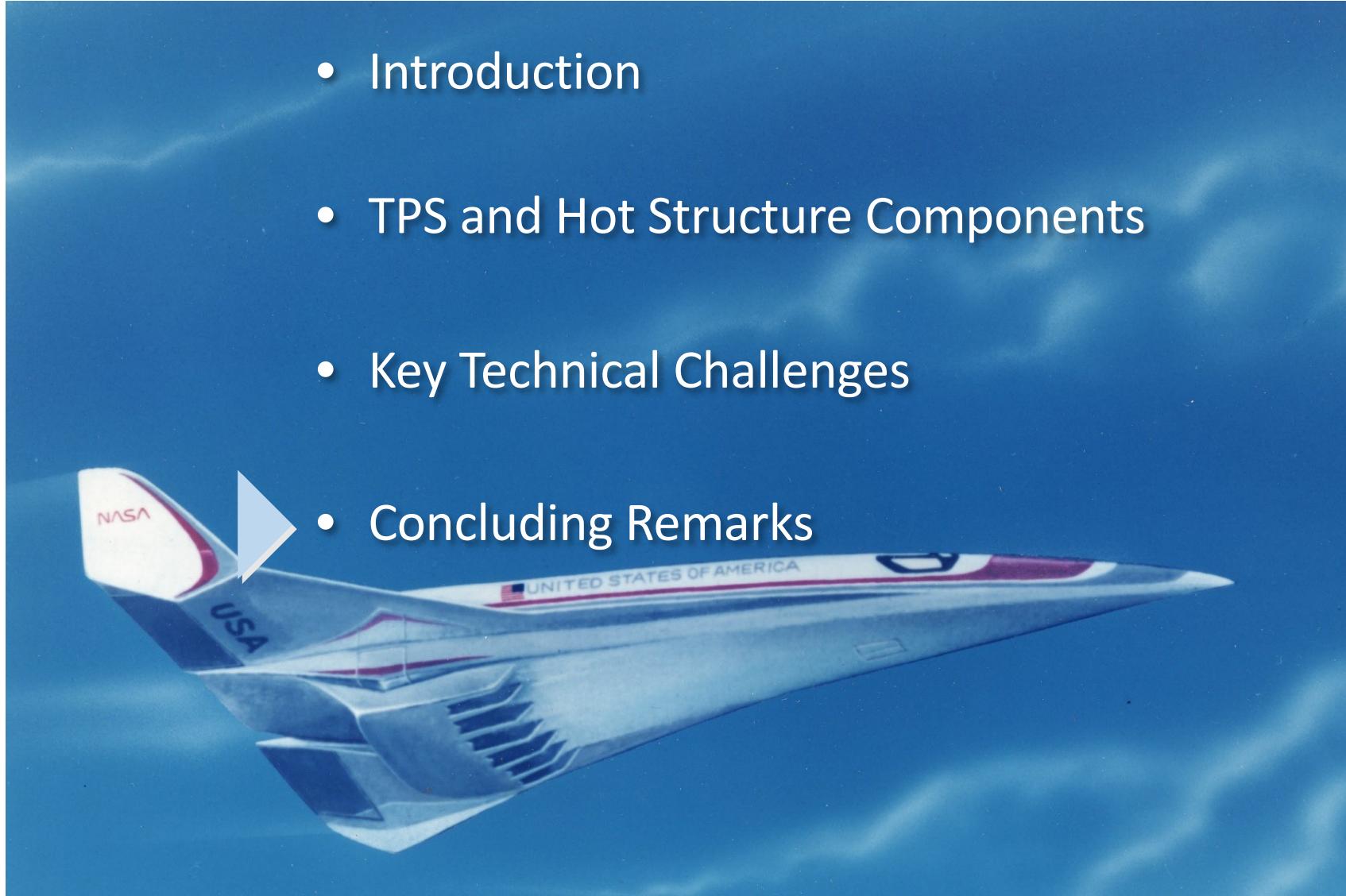
Test as much as you can, and still include adequate margins for uncertainties



# 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