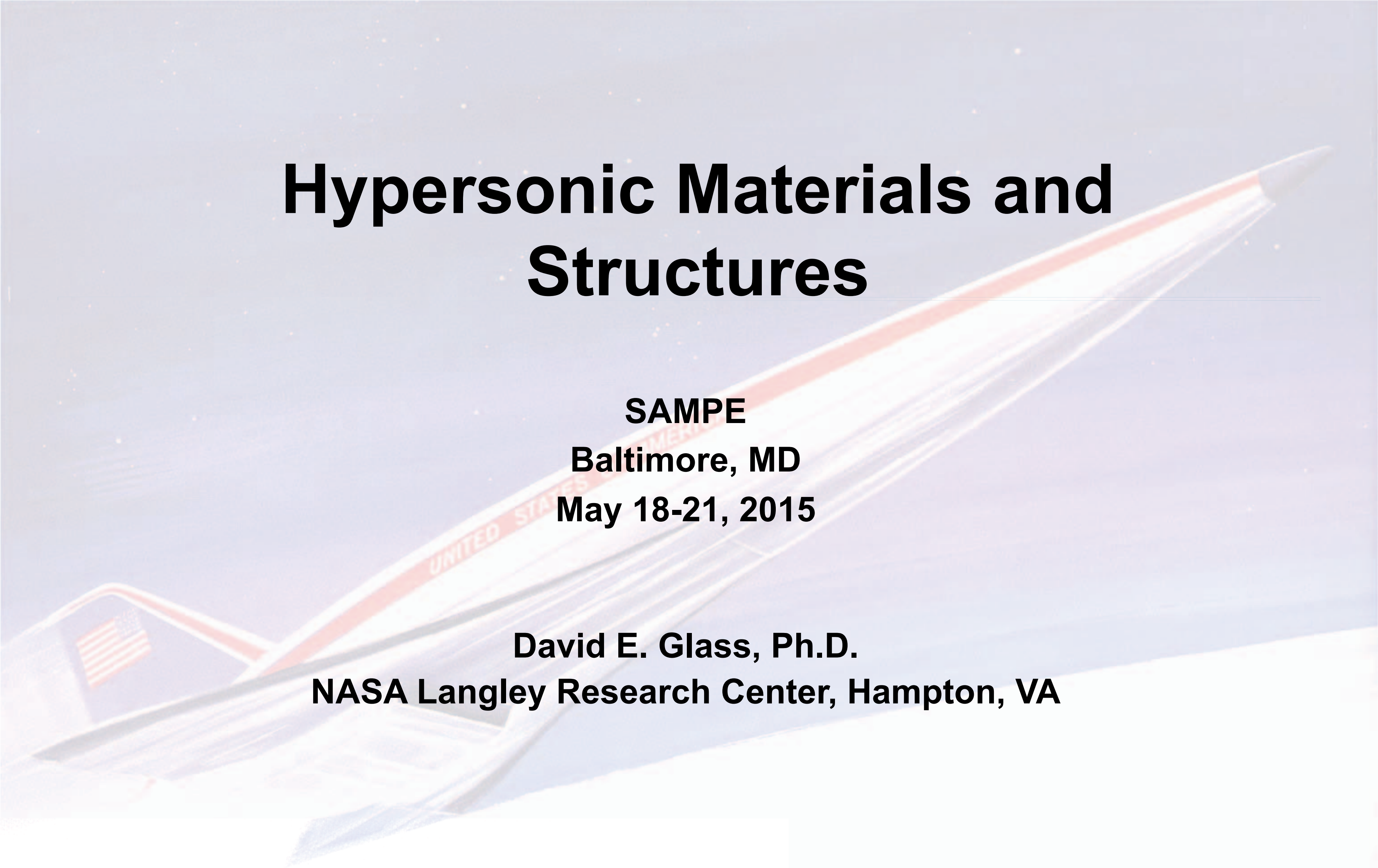

Hypersonic Materials and Structures

SAMPE
Baltimore, MD
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NASA Langley Research Center, Hampton, VA

Outline

- Introduction
- Vehicle components
- Technical challenges
- Concluding remarks

Rockets vs. Airbreathers

Rockets

- **Don't like the atmosphere**
  - Accelerate only
  - Get out quick
  - Tend toward vertical launch
  - Low ISP

- **Drag**
  - High drag not a problem on ascent, desirable on descent for deceleration
  - Blunt leading edges
- **Weight critical**
  - Mass fraction ~ 10% of GTOW
  - Requirement to be weight sensitive
- **Engine in back**
  - Weight drives components to be clustered near engine
  - Tail heavy
  - Hard to get forward c_g
  - Highly compressive loaded structure

Airbreathers

- **Like the atmosphere**
  - Accelerate and cruise in atmosphere
  - Tend toward horizontal launch
  - High ISP

- **Drag**
  - Optimize for low drag
  - Thin, slender body, low thickness/chord
- **Volume critical**
  - Mass fraction ~ 30% of GTOW
  - Requirement to be volume sensitive, volume drives drag
- **Engine in mid-body**
  - Stability easier
  - Easier to control c_g

Structural Differences Between Rockets and Airbreathers

- **Tanks**
  - Cylindrical, since vehicle is weight sensitive and volume insensitive
- **TPS**
  - Driven by descent
  - Low heat load due to short ascent
- **Leading edges**
  - Blunt, due to desire for descent drag
  - Highheat flux
- **Structure**
  - Lightly loaded wings
  - Propulsion and airframe not highly integrated

- **Tanks**
  - Conformal, since vehicle is drag, and thus volume, critical
- **TPS**
  - Driven by ascent
  - High heat load due to long ascent time
- **Leading edges**
  - Sharp, due to low drag, low thickness/chord
  - Severe heat flux
- **Structure**
  - Highly loaded wings (some air breathers)
  - Hot wings and control surfaces due to thin cross sections and high heat flux/load
  - Propulsion and airframe highly integrated

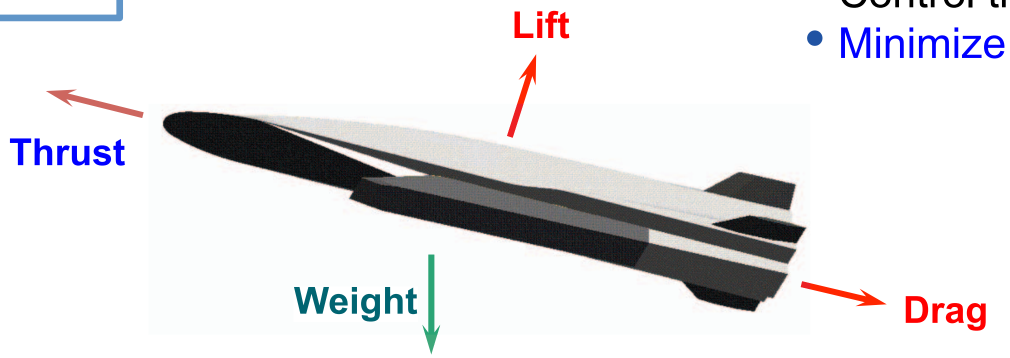
Drag is the big driver for hypersonics

Hypersonic Vehicles

- **Goal**
  - Speed
  - Range

- **Propulsion**
  - Provide thrust

- **Aerodynamics**
  - Provide lift
  - Control the vehicle
  - Minimize drag

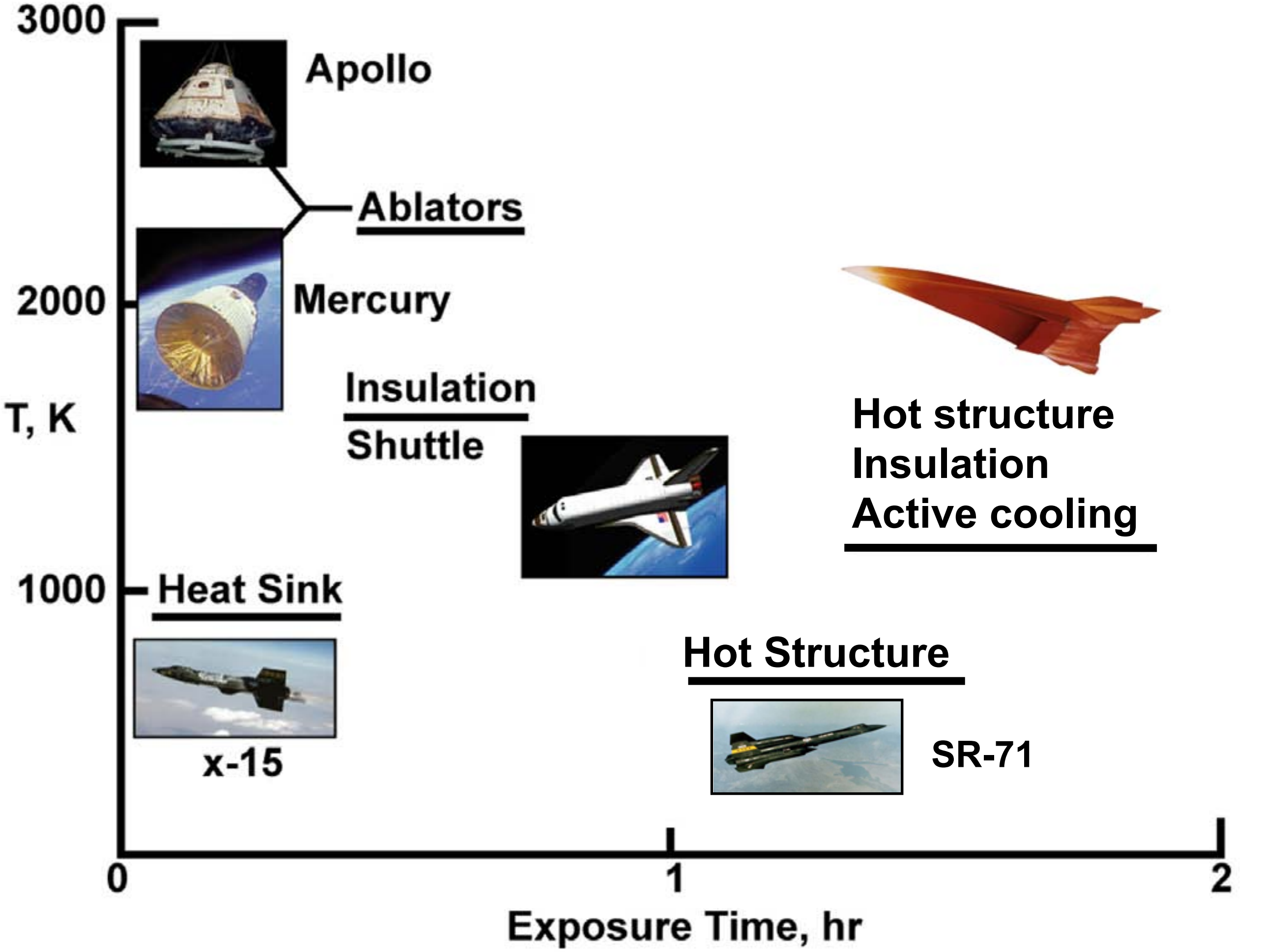


- **Structures and materials**
  - Minimize weight
  - Survive required mission
    - Thermal / structural
    - Acceleration
    - Acoustic / vibration
    - Environmental

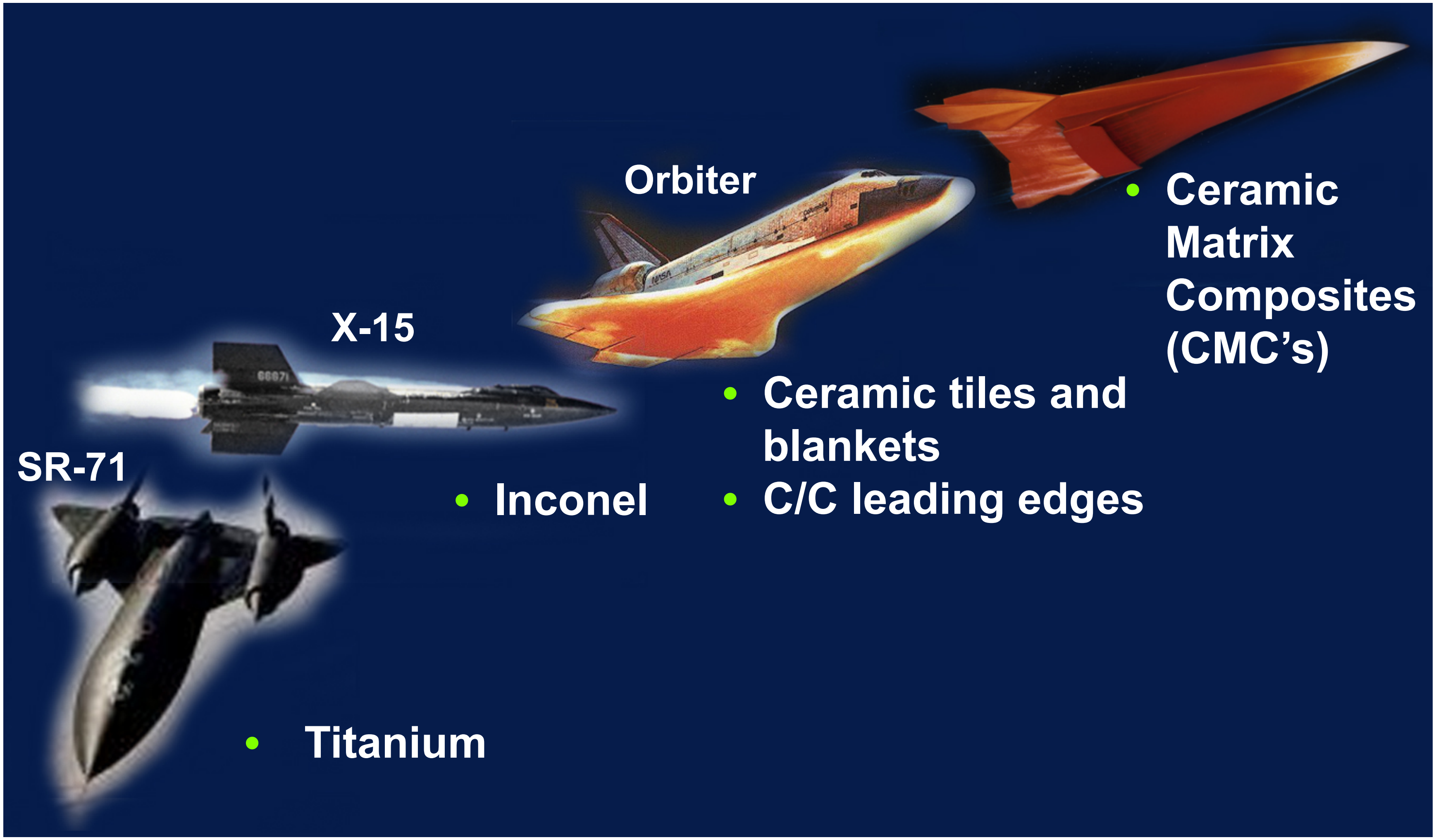
- **Weight reduction**
  - High specific strength materials (high strength, low density)
- **Drag reduction**
  - Thin vehicle cross-sections
    - ☐ Insulating a cold structure adds cross-sectional area
  - Sharp leading edges
  - Smooth surfaces

Hot structures

Flight Vehicle Thermal Management

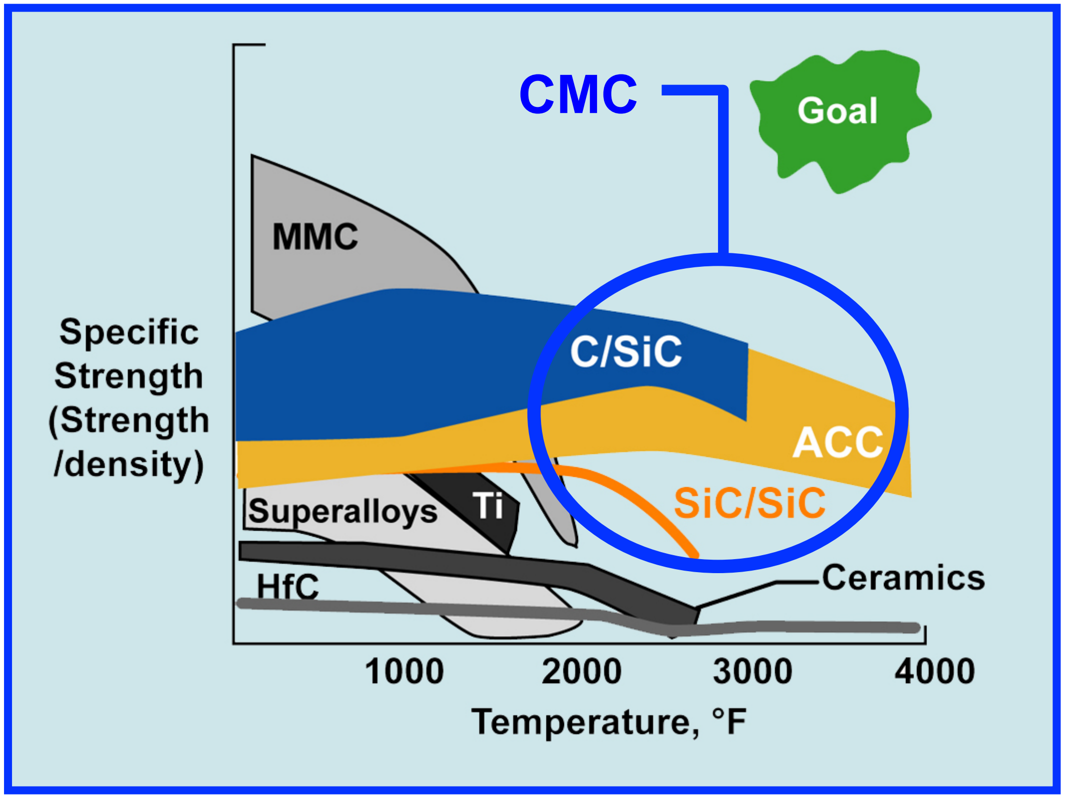


History Shows That New Material Systems Help Enable the Vehicle



- Titanium
- Inconel
- Ceramic tiles and blankets
- C/C leading edges
- Ceramic Matrix Composites (CMC’s)

Material Specific Strength



CMC's are the material system that will provide the required strength at elevated temperature.

CMC Hot Structure Weight Savings

- **Space Shuttle Orbiter Body Flap (AIAA-1983-913)**
  - Baseline 1460 lb, insulated cold structure
  - ACC body flap 1207 lb (253 lb, 17% weight savings)
- **HSR (NASA High Speed Research program) SiC/SiC Combustor Liner**
  - Projected 30% weight savings
  - Reduced NOx and CO emissions due to higher temp
- **X-38 C/SiC Hot Structures**
  - Bearings 50% lighter weight than traditional bearings
  - Body flap 50% less than insulated cold structure (5.25 ft x 4.6 ft, 150 lb)
  - Rudder (different design temperature)
    - PM-1000 with Ti inner structure and insulation: 133 lb with growth factor of ~ 5%
    - CMC: 97 lb with higher growth factor (27% weight savings)
- **Aircraft brakes**
  - 500-1000 lbs per plane weight savings
- **Actively cooled CMC combustor (French study, AIAA-2011-2208)**
  - 30% weight savings over metallic

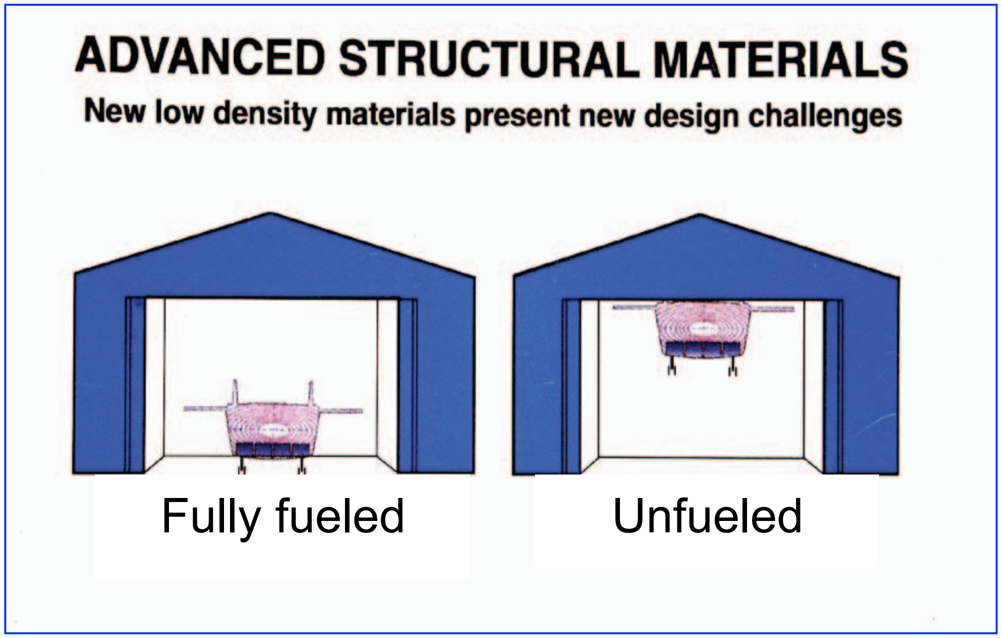
Rule of thumb, ~ 25% weight savings with CMCs

Key Point – Drag Reduction

- **Reentry vehicles (most of our prior experience), want drag to reduce velocity as they reenter.**
- **Cruise vehicles must minimize drag as they cruise through the atmosphere.**
  - Surface and cross-section
- **Hot structure is the preferred approach (rather than TPS over cold structure)**
  - Large, smooth, hot airframe has not been addressed

A Few General Thoughts

- ♦ **Weight is always critical**



- ♦ **High risk ≠ high payoff**
  - Might be, but not an automatic
- ♦ **Requirements have a significant impact on TRL**
  - Number of cycles
  - Mechanical loads
  - Pressure (oxidation)
  - Heat flux
  - Etc.

TRL = f(requirements)
Can't change requirements and expect to keep TRL the same

- ♦ **Thinking of how much it will cost to develop a technology is often a better gage of how far away we are than asking how long it will take**

Leading Edges

♦ State of the art

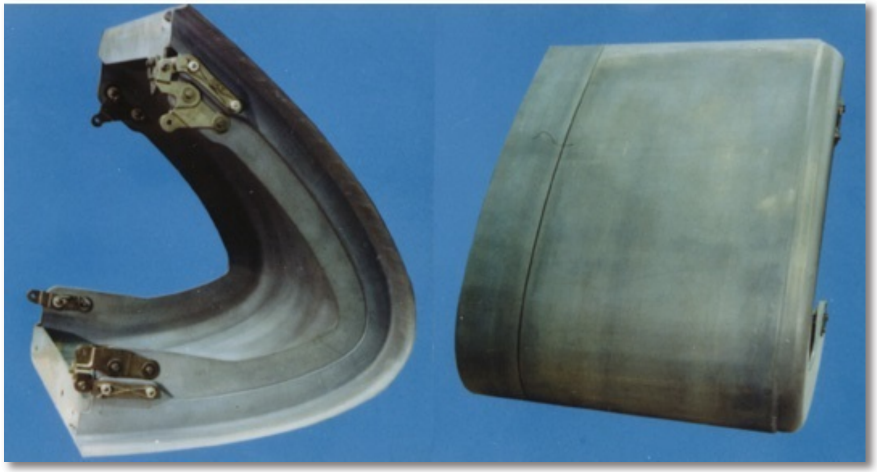
- Space shuttle orbiter RCC
- Hyper-X coated C/C
- HTV-2 oxidizing C/C

♦ Requirement

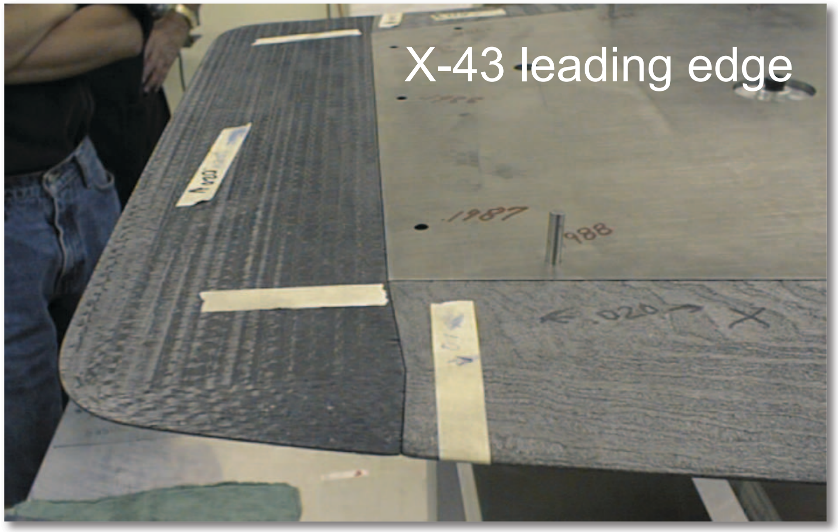
- Multi-use
- Light weight
- Durable
- Sharp

♦ Technical challenges

- Manufacturing
- Life
- Thermal stress
- High heat flux / temperature
- Environmental durability

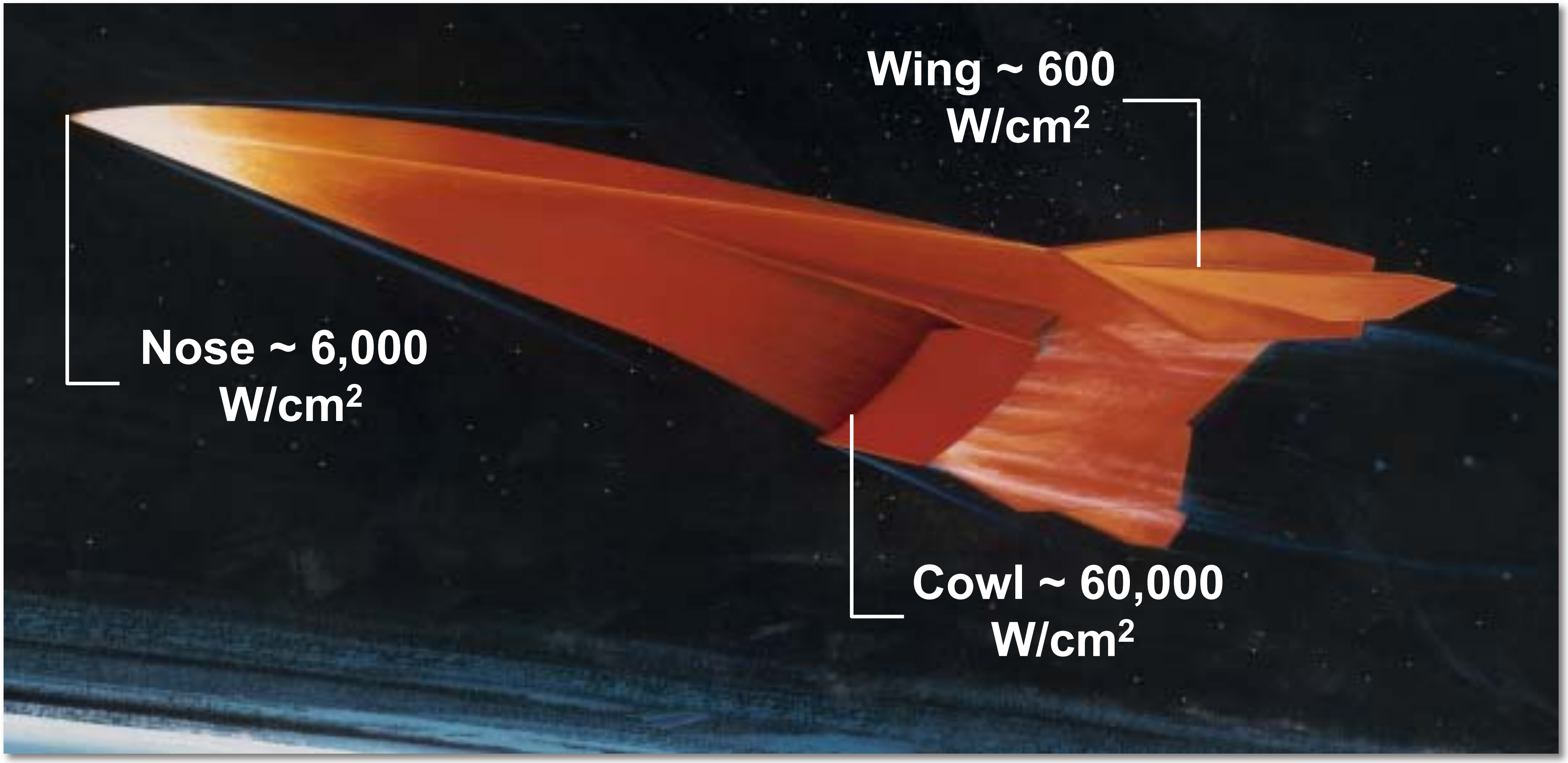


Space shuttle orbiter leading edge



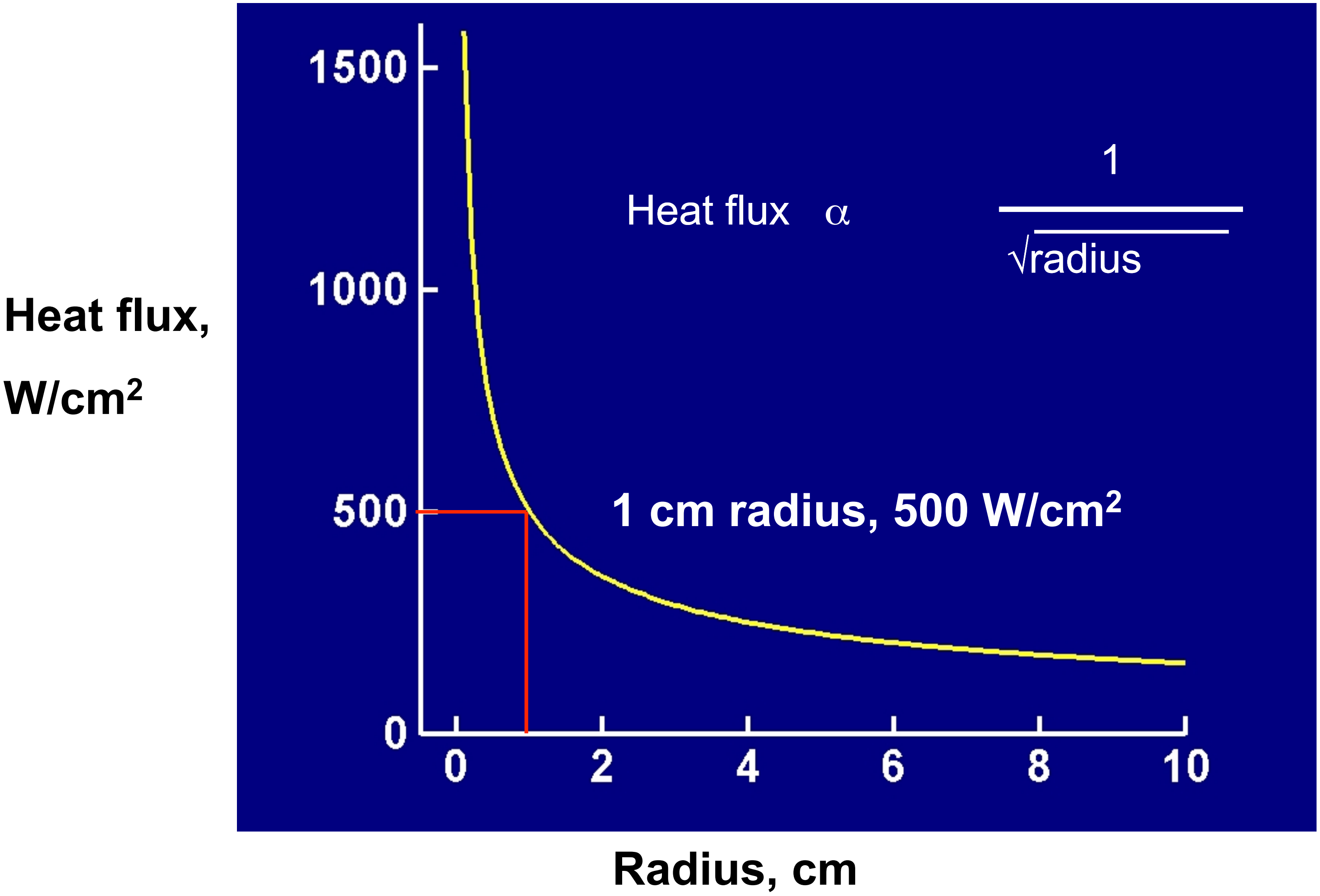
X-43 leading edge

Typical Ascent Leading-Edge Heat Flux for SSTO

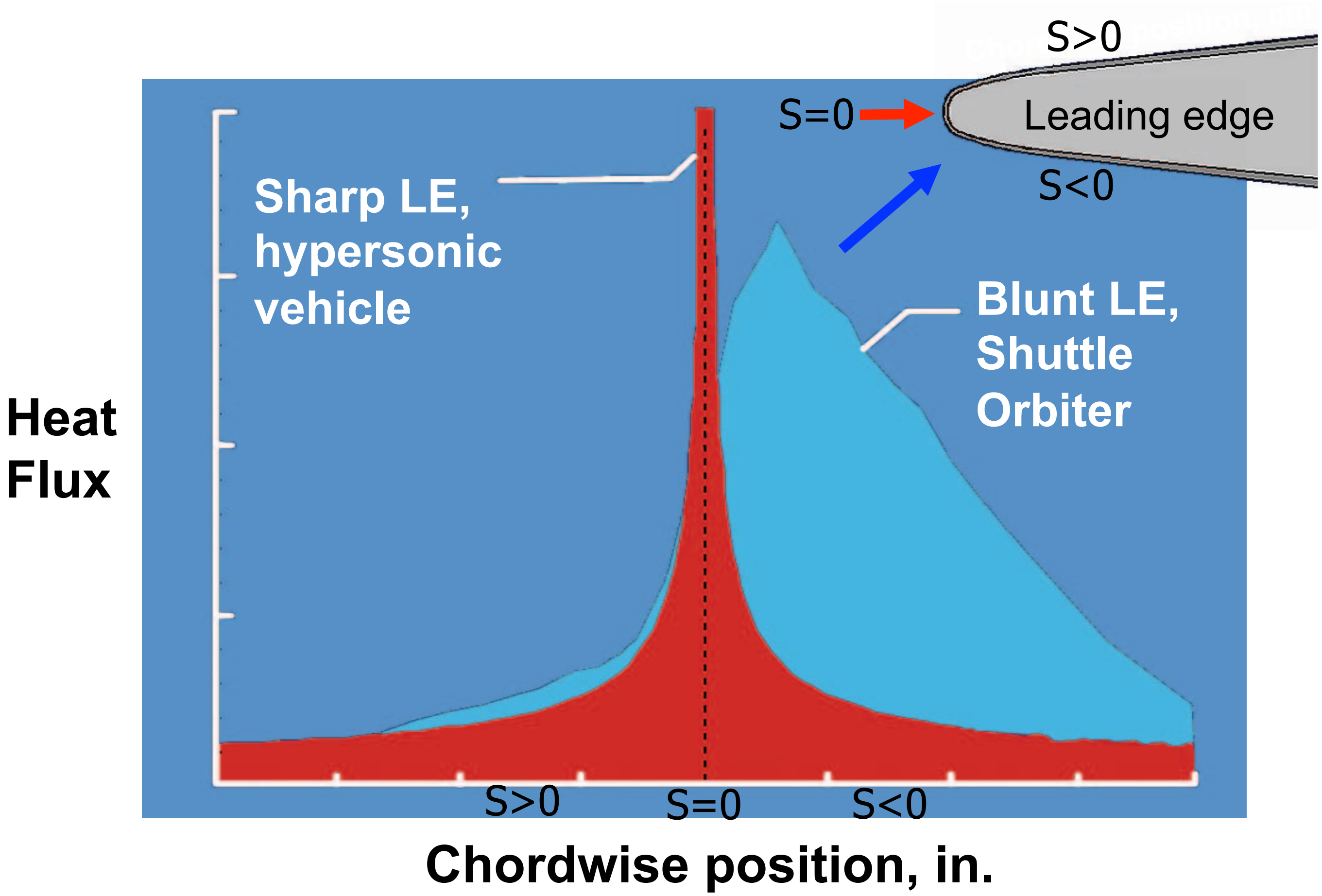


In comparison, Shuttle Orbiter leading edge ~ 80 W/cm^2,
CEV heatshield ~ 800 W/cm^2

Leading-Edge Radius Effect on Stagnation Heat Flux



Leading-Edge Heating

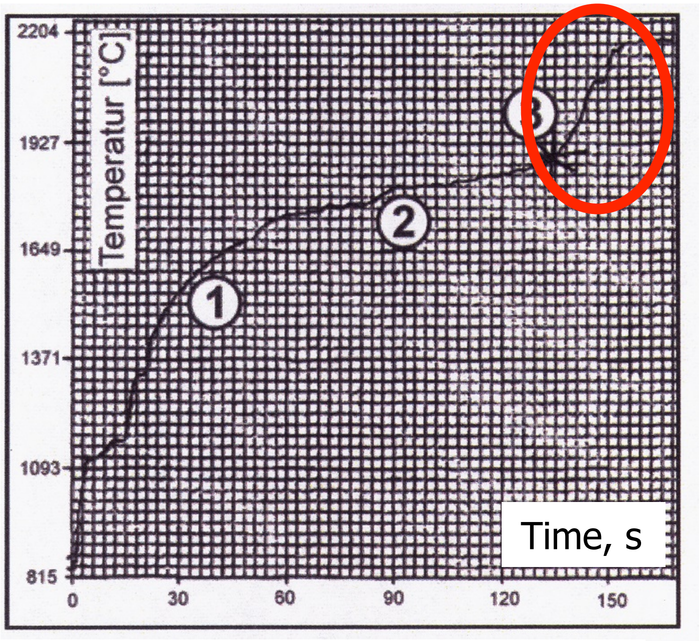


Sharp leading edges produce intense, localized heating.

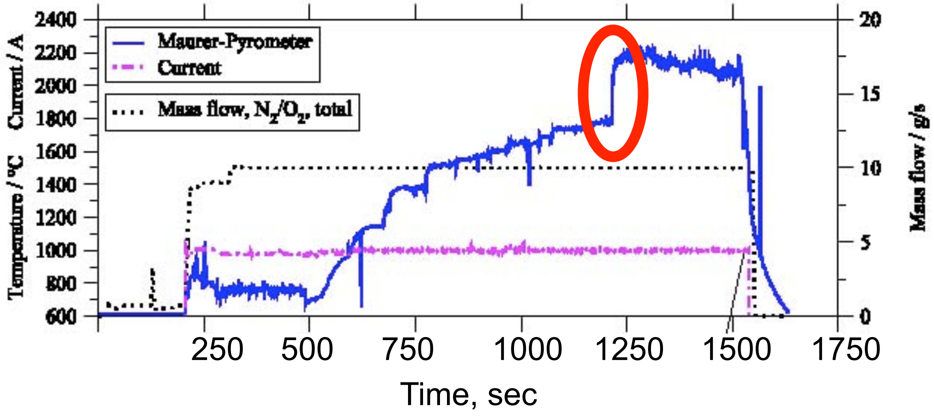
Active Oxidation of Si-Based Materials

- ♦ **Transition from passive to active oxidation function of**
  - Temperature
  - Oxygen partial pressure
  - Plasma speed
  - Degree of dissociation
- ♦ **Destroys protection of Si containing system**
  - C/SiC
  - SiC/SiC
  - Coated C/C
  - UHTC
  - … etc.

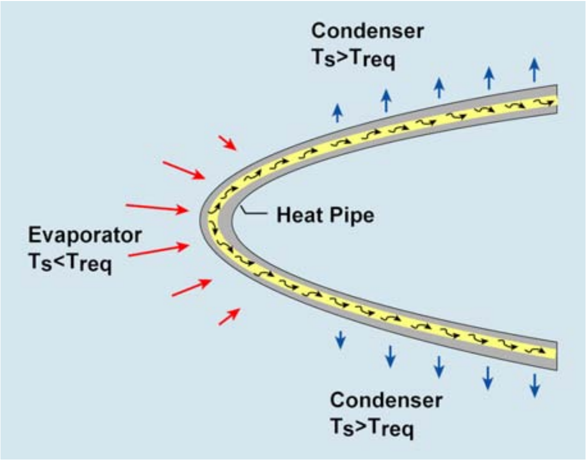
Arc-jet test of DLR C/C-SiC for X-38 at NASA JSC

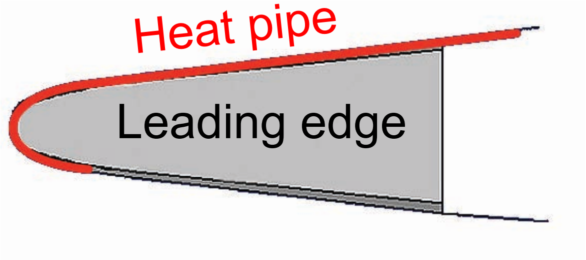


Arc-jet test of MT Aerospace C/SiC in the German PWK2 facility



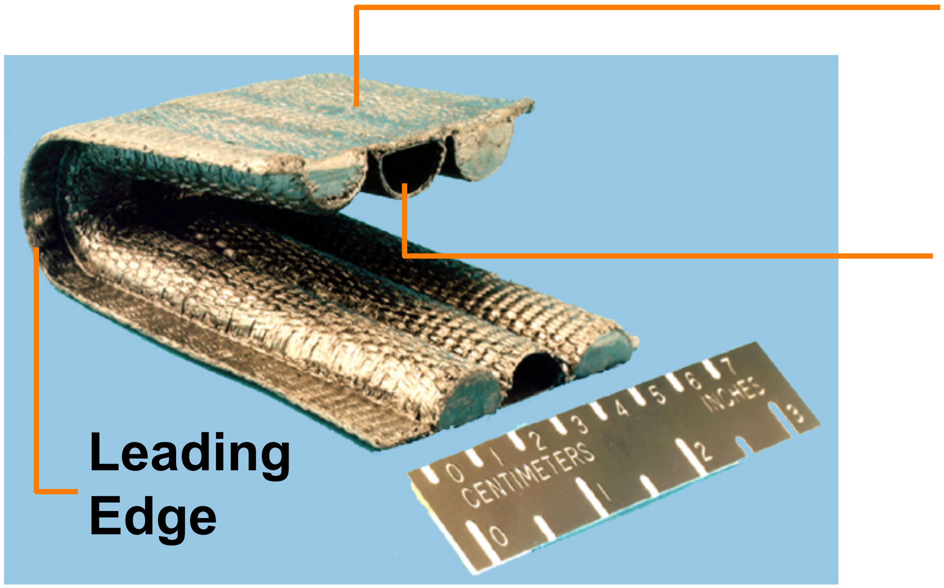
Heat-Pipe-Cooled Leading Edges





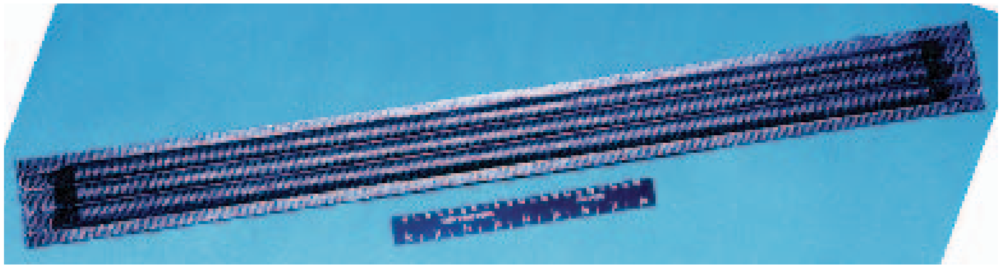
Heat pipe results in an isothermal leading edge.

NASP Heat-Pipe-Cooled Wing Leading Edge



Challenges

- ♦ Material compatibility, f(t,T)
- ♦ Thermal stresses



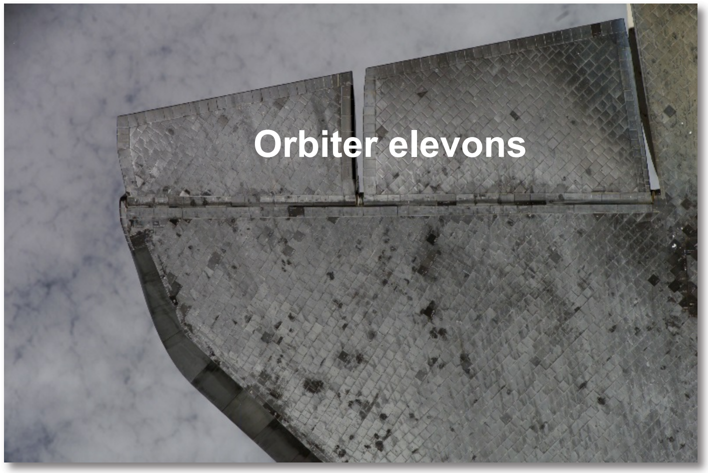
- ♦ **Mo-Re embedded in C/C**
- ♦ **Li working fluid**
- ♦ **D-shaped heat pipes**

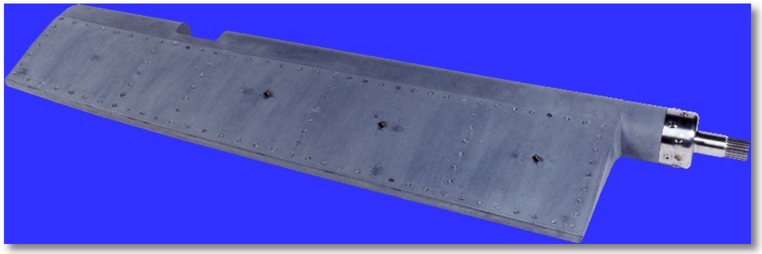
Control Surfaces

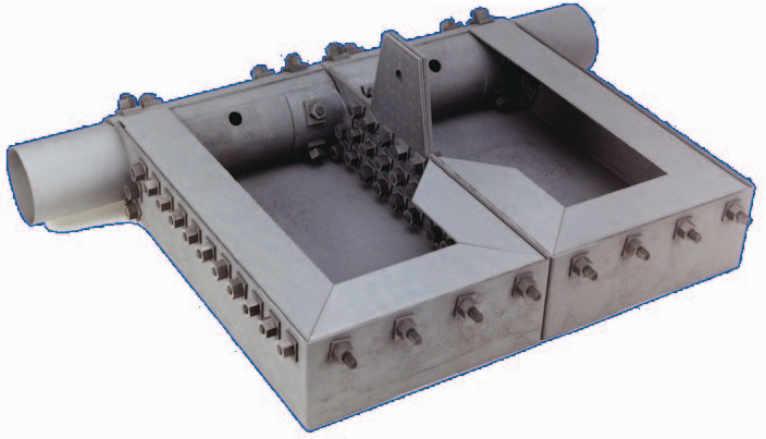
- **State of the art**
  - Space shuttle orbiter (insulated)
  - X-38 (CMC hot structure)
  - HTV-2 C/C
  - NASA X-37 evaluated C/C and C/SiC

- **Requirement**
  - High strength at elevated temperature
  - Light weight

- **Technical challenges**
  - Volume constrained
  - Manufacturing
  - Recession / stressed oxidation
  - Thermal stress
  - High heat flux / temperature
  - High heat load
  - Heat conduction into vehicle / insulation

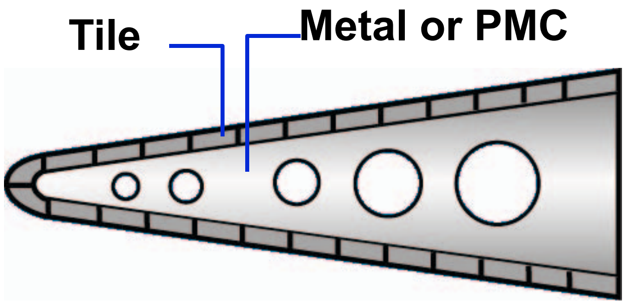




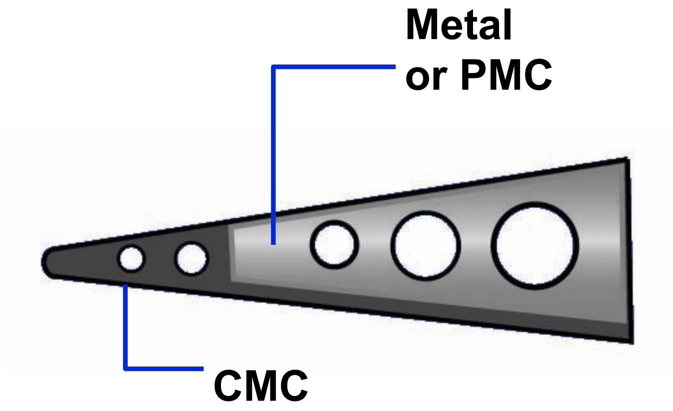


Types of Control Surfaces

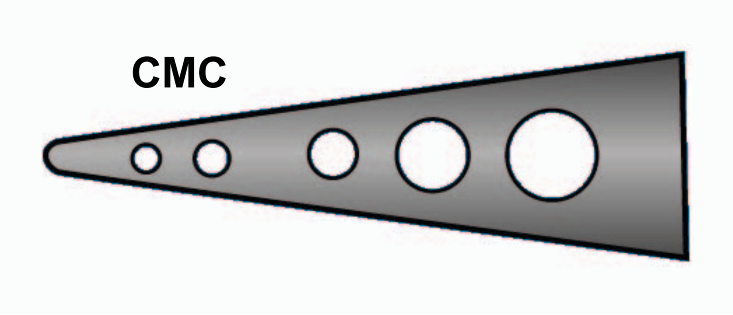
- **Insulated**
  - Suitable for very large structures
  - Minimal thermal expansion issues
  - Heavy
  - Little thermal margin
  - Thick cross section



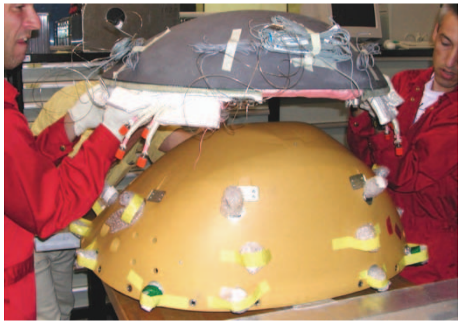
- **Hybrid**
  - Affordable manufacturing for large structures
  - May not require TPS on upper surface
  - Thermal growth mismatch between metal/PMC and CMC
  - Weight increase 30-40% over all CMC

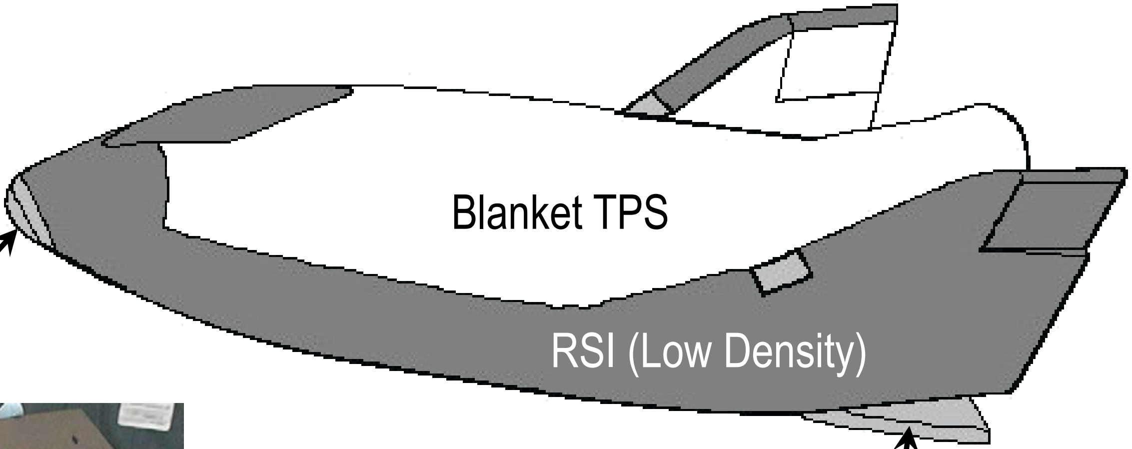


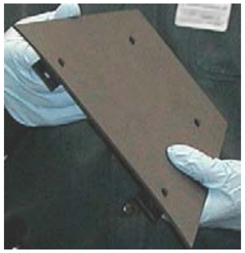
- **Hot Structure**
  - Lowest weight and thin cross section
  - Minimal thermal expansion mismatch problems
  - Thermal margin
  - High manufacturing/tooling costs for box structure
  - Challenging for very large structures



X-38 Hot Structures







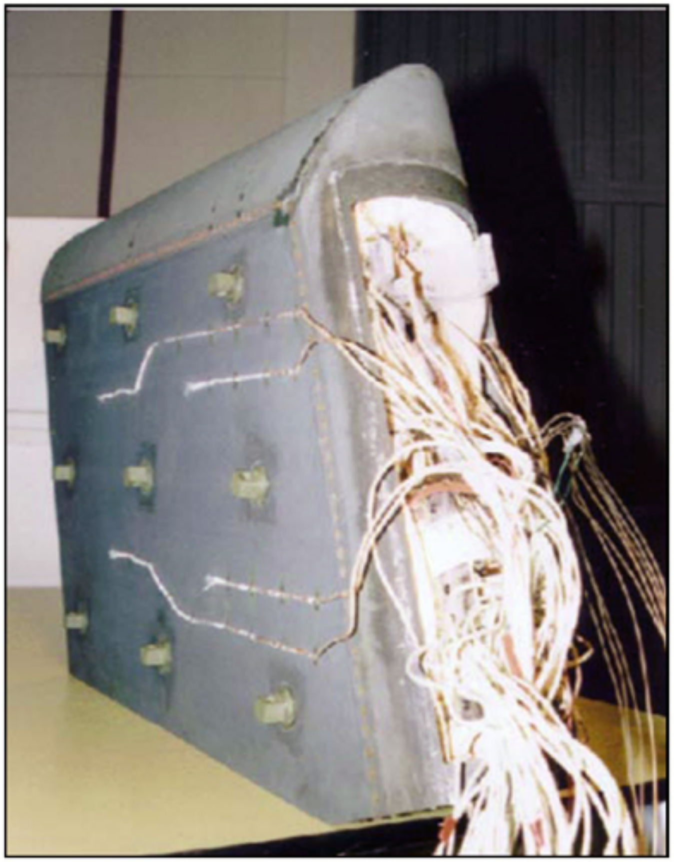
- **C/SiC nosecap, skirts & chin panel**
  - Nosecap provided by DLR (Germany)
  - Nose skirts (2) provided by Astrium (Germany)
  - Chin panel provided by MT Aerospace
  - Nose assembly has undergone full qualification (qual units)
    - Vibration
    - Thermal (radiant)
    - Mechanical

- **C/SiC body flaps**
  - Provided by MT Aerospace
  - Qualified for flight

Dutch Space Metallic Hot Rudder

♦ X-38 hot rudder

- Fabricated and tested a PM-1000 rudder to 2192°F (1200°C) in 1 yr
- Requirements changed
- Qualified Ti/ceramic tile rudder (1 yr)
- Planned Ti/CMC rudder for crew return vehicle (CRV)



MT Aerospace Integrated Fabrication Approach

- **Advantages**
  - Fewer joints
  - Better mechanical performance
- **Disadvantages**
  - Complex tooling and associated fabrication expense
  - Risk of damage during fabrication
- **Fabrication**
  - 2-D prepreg of carbon fabric
  - Cured and pyrolyzed
  - Further densified with CVI SiC
  - No fasteners (less mass)

MT Aerospace Pre-X body flap

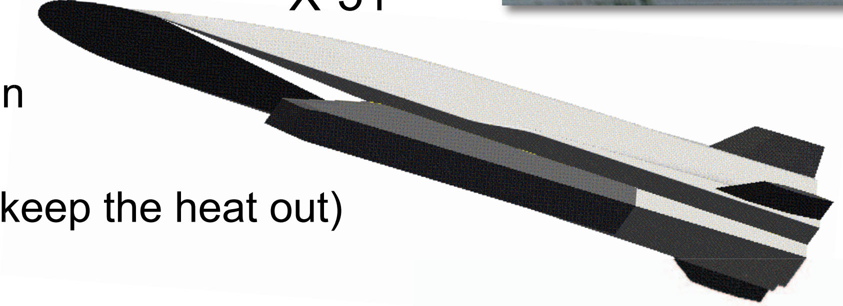
Acreage TPS / Hot Structure Aeroshell

- **State of the art**
  - Ceramic tiles and blankets
  - Ablators
  - Oxidizing C/C hot structure

- **Requirement**
  - Durable
  - Thin cross section
  - Smooth OML
  - Insulate interior (keep the heat out)

- **Technical challenges**
  - Manufacturing
  - Durability
  - High temperatures
  - Large heat load due to extended duration flight
  - High temperature insulation
  - Combined loads


Shuttle Orbiter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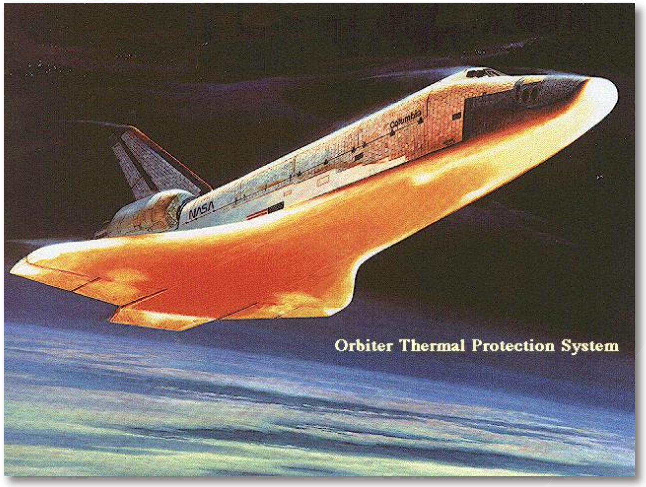
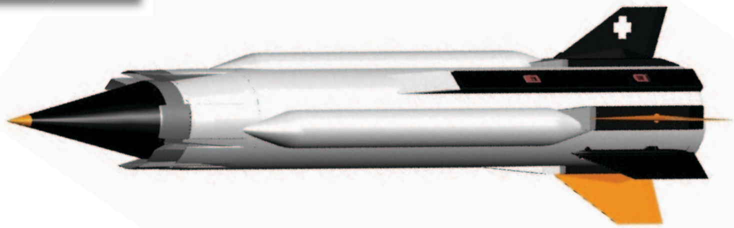
HTV-2

Hot Structure Versus TPS Over Cold Structure

Shuttle orbiter (Al load-bearing airframe with tiles and blanket TPS)



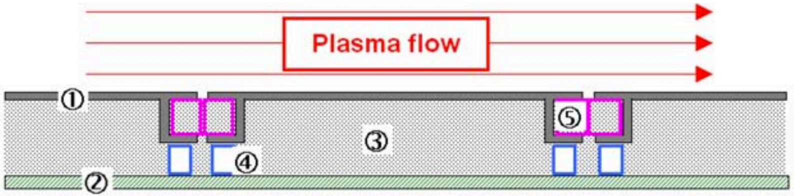
Falcon HTV-2 (C/C aeroshell primary load bearing structure)



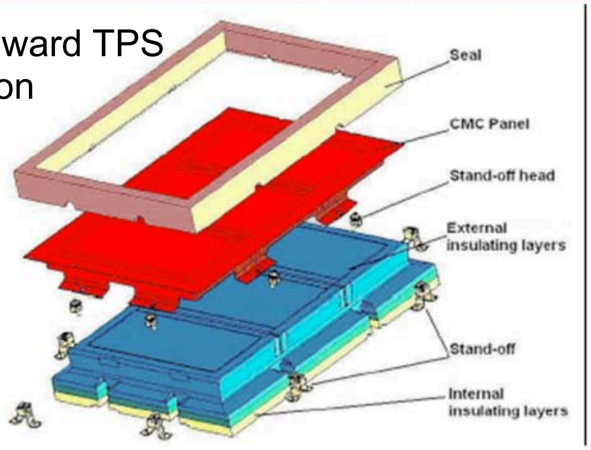
HyFly (load shared between C/C combustor / nozzle assembly and Ti tank, which carried most of the load, ablative TPS)

Trade studies required on how to best meet requirements and optimize performance – need to keep trade space wide open

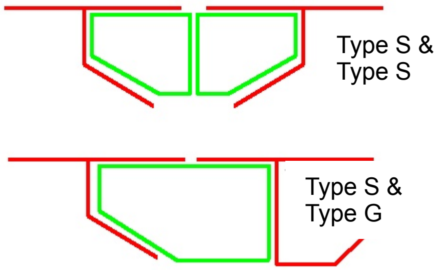
Windward CMC Standoff (Shingle) TPS (Snecma, IXV)



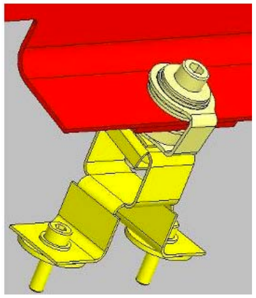
30 windward TPS panels on IXV



- **Total mass of CMC shingle system**
  - ~3 lb/ft^2 (15 kg/m^2) (very much f(req.))
  - Not optimized
- **Attachment system design**
  - Mechanically attach panel to structure
  - Transfer loads from panel to structure
  - Enable expansion differences
  - Prevent large OML deformation through sufficient stiffness
  - Participate in thermal protection of structure
  - Easily replaced

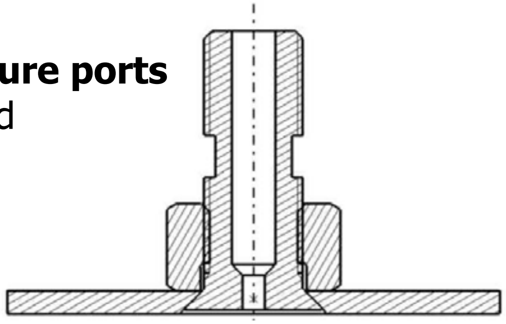


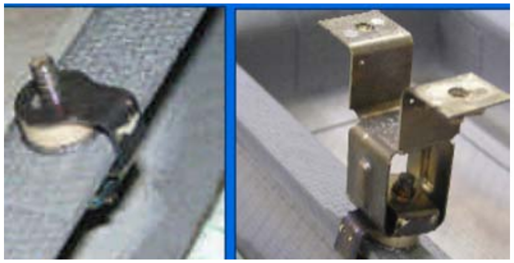
Sealing approaches

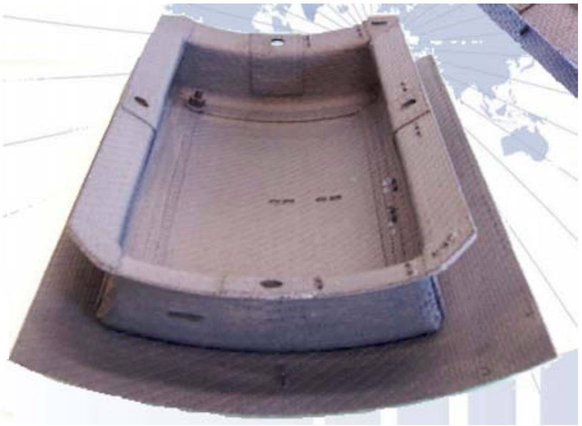


Attachment approach

- **C/SiC pressure ports**
  - 10 windward



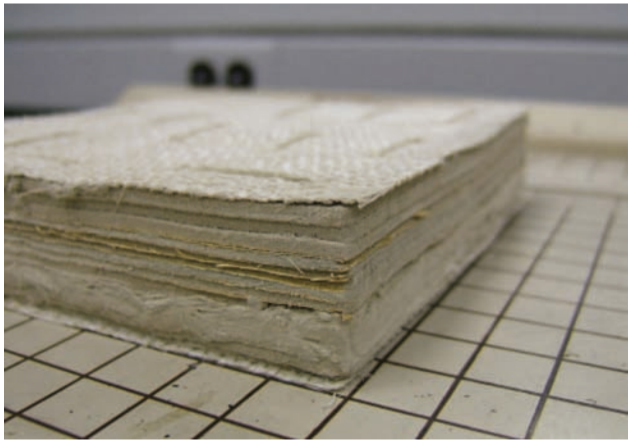


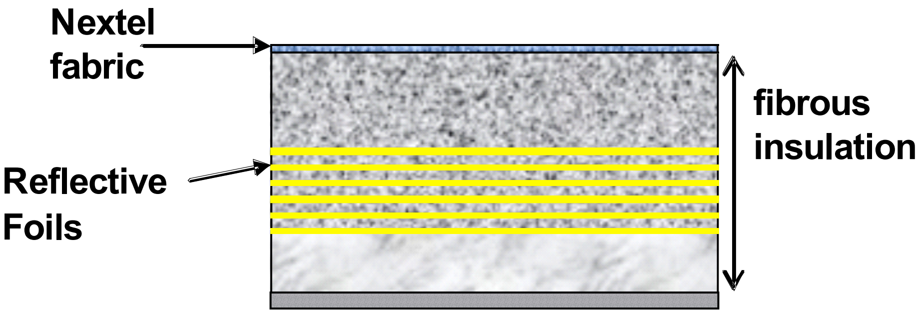


Curved C/SiC panel (IXV side panel)

Internal Insulation

- Light-weight
- Flexible
- Non load-bearing
- Non-oxidizing
- Reflective foils or no foils
- High volumetric heat capacity
- Low effective thermal conductivity
- Capable of long duration flight at elevated temperatures





Propulsion Structures

State of the art

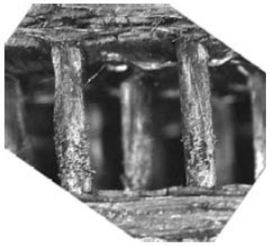
- Passive heat sink
- Actively cooled superalloy

Requirement

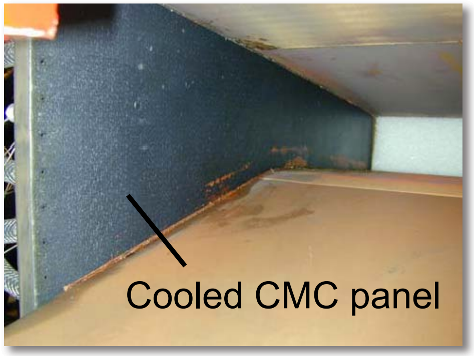
- Light weight
- High heat flux/temperature
- Reduced fuel

Technical challenges

- Hermetically sealed CMC with no tubes
- Manifold



Stitched yarns



MBDA (France)

- Fuel cooled CMC combustor
- No metallic tubes

NASA & AF (Teledyne Scientific)

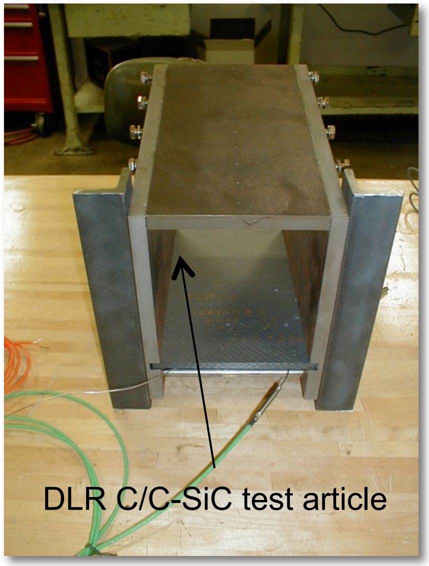
- Last funding several years ago
- No tubes

NASA (HyperTherm)

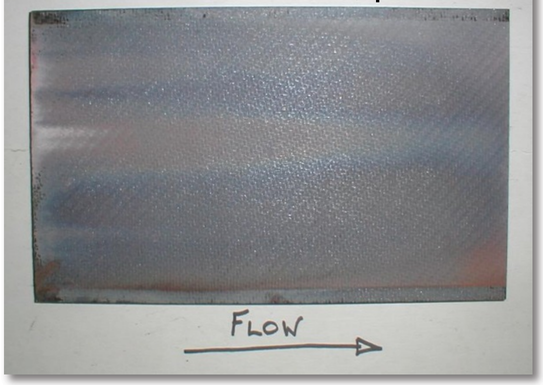
- SiC/SiC with refractory metal tubes

Passive CMC Combustor Material Evaluation

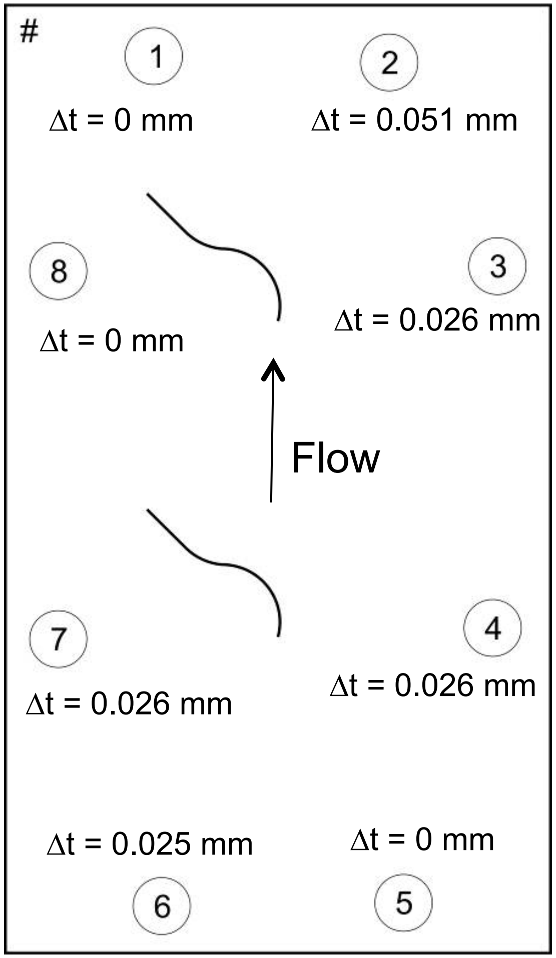
- **Simulated Mach 6 conditions**
  - Actual flow velocity ~ Mach 2
  - q = 1000 psf (479 hPa)
  - H = 793 Btu/lb (1.846 MJ/kg)
- **Hydrogen fuel**
- **4 tests**
  - M ~ 6 enthalpy
  - 20 sec tare (no fuel)
  - 3 x 44 sec fueled tests



C/C-SiC hot surface, post test



- **C/C-SiC Panel #1 Post Test**
  - 4 tests
  - M ~ 6 enthalpy
  - 20 sec tare (no fuel)
  - 3 x 44 sec fueled tests



Design and Manufacturing

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

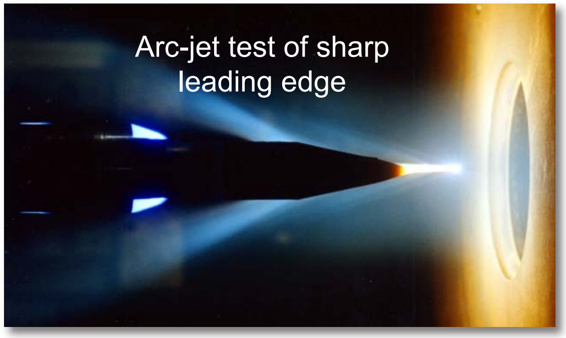
Big difference!

- **Design for manufacturing**
  - Involve manufacturers in the process
  - Don't "throw it over the wall"
- **Properties in a complex structure are often different than material test coupons**
- **Attachments and joints**
  - Different material systems
    - Severe thermal gradients in multiple directions
  - Mechanical loads
- **Metrology often "required" for accurate fabrication and assembly**
  - Optical / laser devices
  - Accuracy to < 0.001 in., f(size)
- **TRL = f(requirements / loads)**
  - Can't change the requirements / loads and keep the TRL
- **Affordable, robust, & simple**

Testing

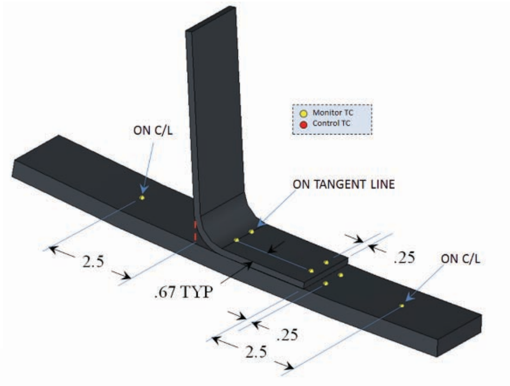
- **How do we qualify the vehicle for flight?**
- **We are unable to test many components in relevant, combined loads, environments (even small scale)**
  - Thermal, mechanical, plasma, shear, oxygen partial pressure, vibration and acoustic, etc.
  - Apply appropriate boundary conditions over entire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


We can’t simulate this in ground tests

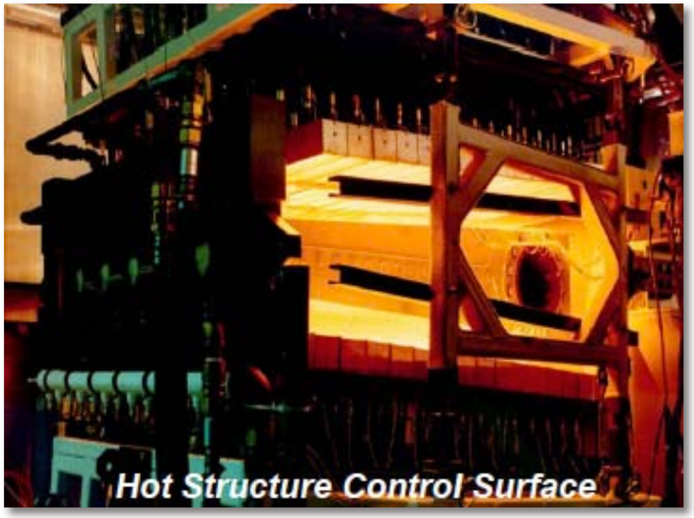

Arc-jet test of sharp leading edge

Material / coupon test

Sub-element test



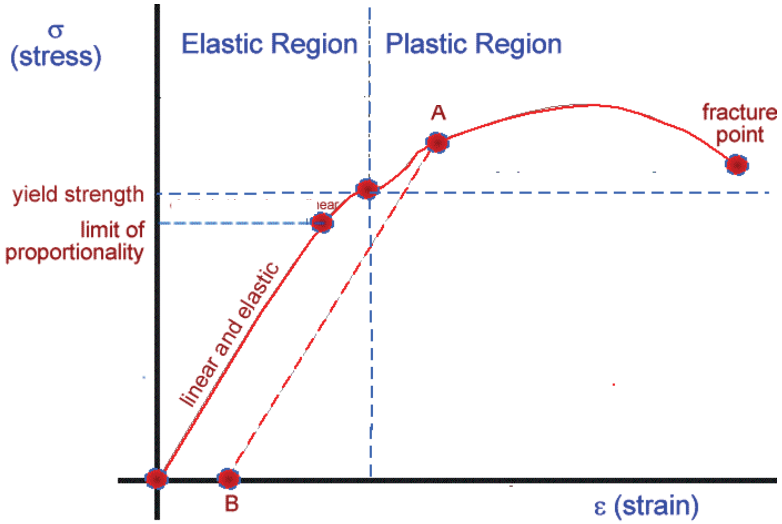
Component test

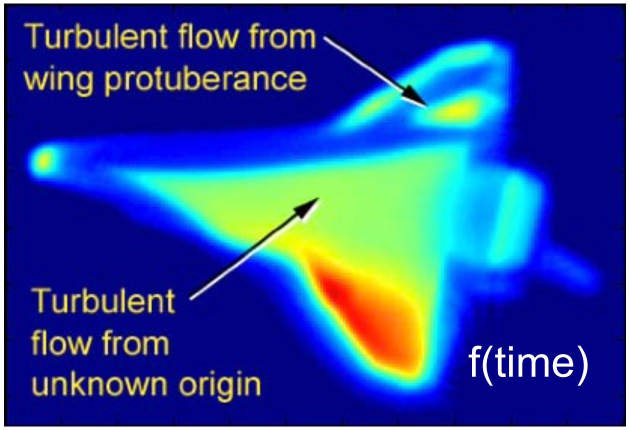


Test as much as you can, and still include adequate margins for uncertainties

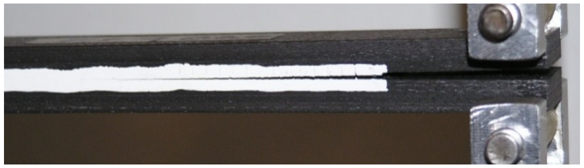
Thermal-Structural Analysis

- **Adequate material properties**
  - f(T), f(processing), etc.
  - Adequate quantities (shape of curve and statistics)
  - Capture non-linear behavior
- **Boundary conditions**
  - Thermal, mechanical
  - Boundary layer transition
- **Mesh convergence**
- **Local / global models**
  - Apply global loads to local models
- **Mechanical / thermal stresses**
- **Factors of Safety (FOS)**
- **Failure modes**
  - Biaxial stress interaction
  - Thermal ≠ mechanical failure





Boundary layer transition



Failure modes

Thermal Stress

- **Generated by restrained thermal growth**
  - Temperature gradients and / or different materials (CTE)
- **Very different from mechanical stresses**
  - Driven by thermal gradients, not just high temperatures
  - Thicker structure can make it worse
  - Structurally connected, dissimilar materials, also drive thermal stress
- **Complicated by different materials, 3-D thermal gradients, moving hot spots, asymmetric heating, etc.**

SR-71 grows ~ 3 in. during flight

Thermal stress failure due to differential thermal expansion at uniform temperature

Thermal stress must be understood and accurately tested and modeled

Concluding Remarks

- **Reduction of weight and drag are key for all hypersonic vehicles**
- **A state-of-the-art material is not the same thing as a state-of-the-art structure**
- **TRL = f(requirements / loads)**
  - Can't change the requirements / loads and keep the TRL
- **Long duration flight results in high integrated heat loads that impact design**
- **Hot structure should be traded versus insulated (TPS) cold structure**
  - Open up the trade space
- **Thermal stress must be understood and accurately tested and modeled**