NASA Hypersonic Technology Project (HTP) SiC/SiC Research for Hypersonic Airframe Hot Structures

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Hypersonic Weapons Summit

Pentagon City, VA

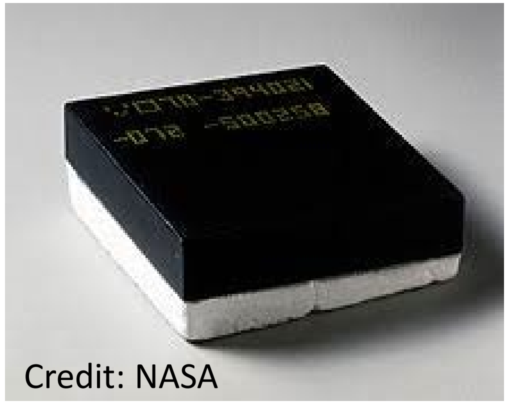
September 19-20, 2023

Outline

- **Introduction**
  - Thermal protection systems (TPS) and hot structures
  - Hot structures weight savings
- **Ceramic matrix composite (CMC) hot structures**
  - Carbon/carbon (C/C)
  - Carbon/silicon-carbide (C/SiC)
  - Silicon-carbide/silicon-carbide (SiC/SiC)
- **Technical challenges**
- **Concluding remarks**

TPS and Hot Structures

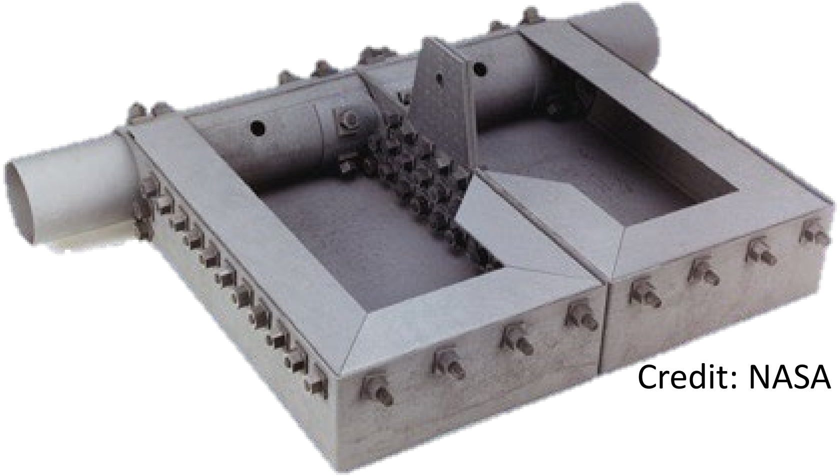
- **In the US, the term “TPS” is usually used to include:**
  - Acreage TPS such as tiles, blankets, and ablators
    - Insulation
  - Hot structures such as leading edges, nose caps, control surfaces, and aeroshells
    - Multi-functional structure that carries load at operating temperatures



Tile TPS

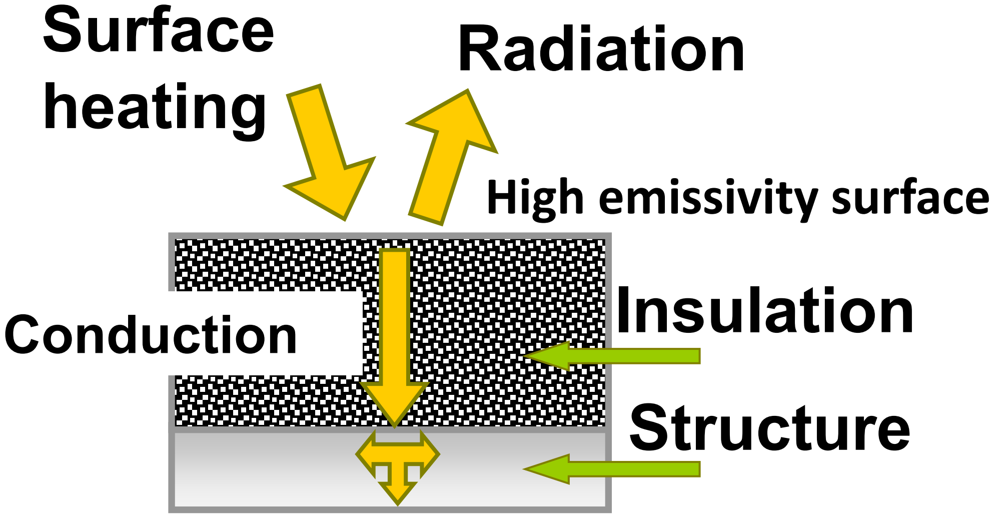
- **Europe (and the rest of the world) uses the terms TPS and hot structures**

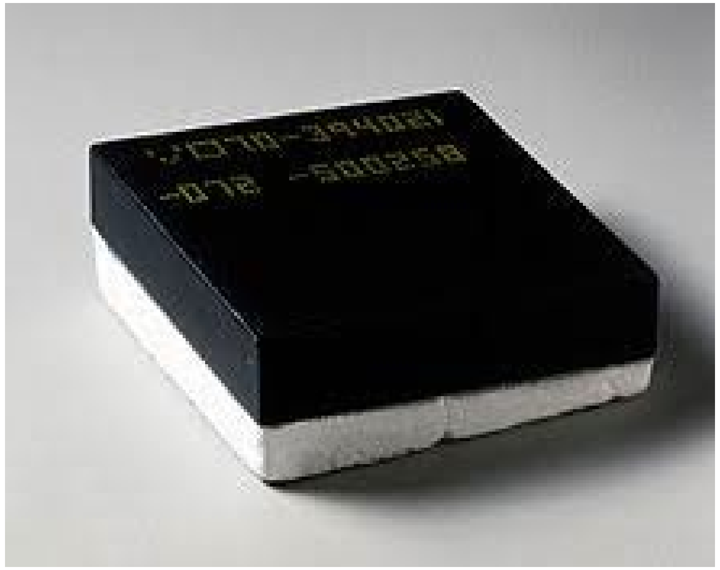
The US will only realize the benefits of hot structures by first understanding the differences from TPS



Hot structure control surface

Use: Moderate heat flux, short times



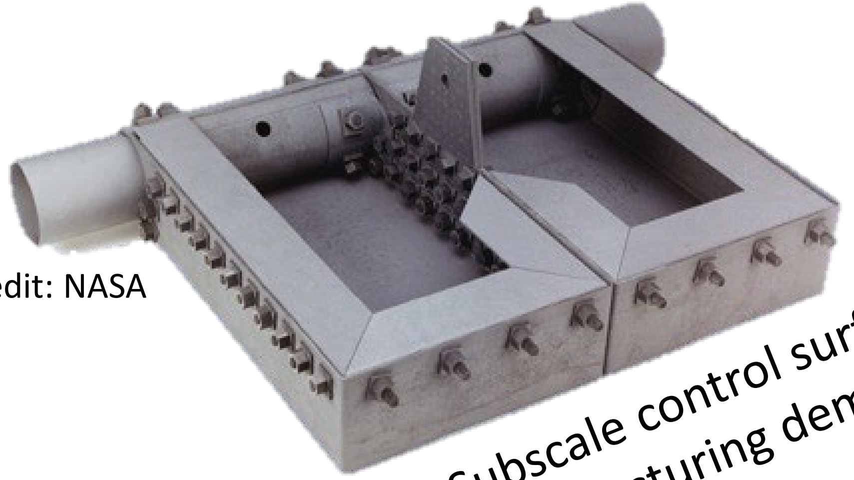


Tile TPS

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

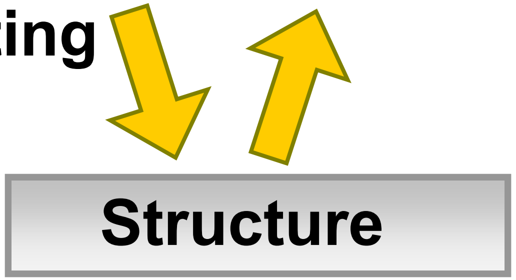
Hot Structure

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



Credit: NASA

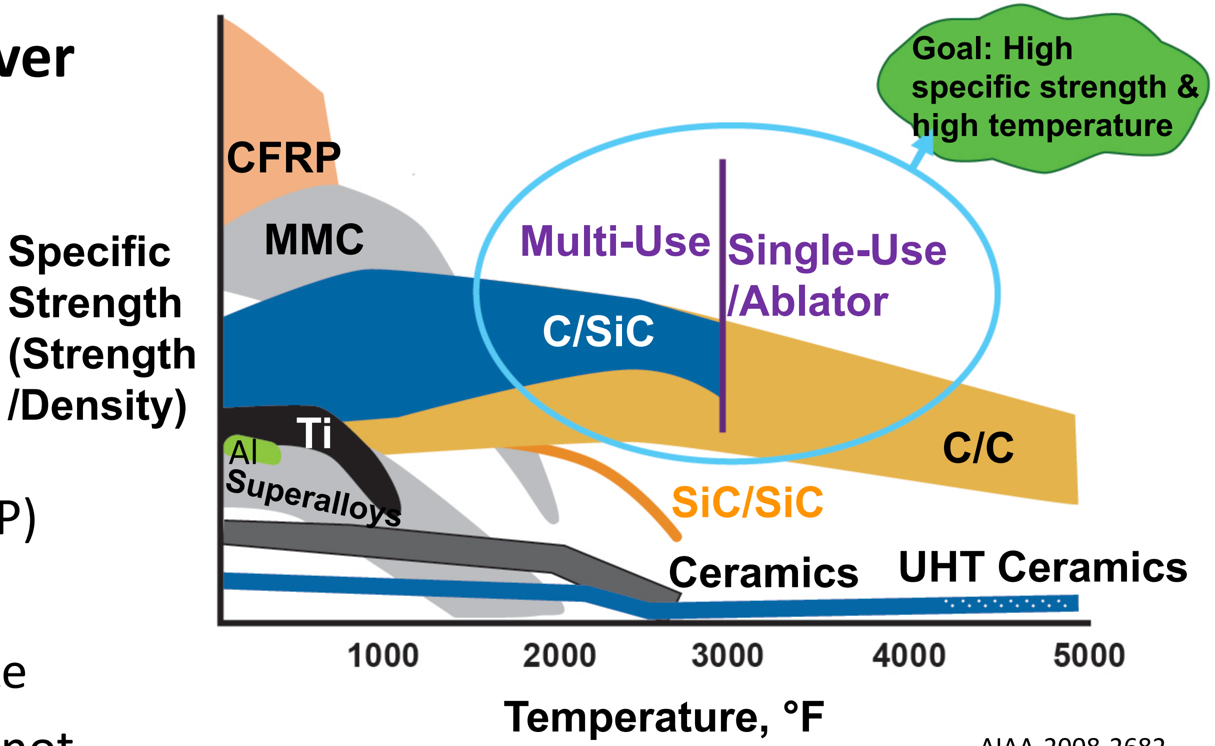
Subscale control surface manufacturing demo



- **Heat radiated away**
- **Heat conducted inward**
- **Structure carries load while operating hot**

Why CMC Hot Structures?

- **Hot structures provide ~ 25% weight savings over insulated cold structure**
- **High-performance vehicles utilize high specific strength/stiffness materials**
  - Aluminum (Al)
  - Composites: carbon fiber reinforced polymers (CFRP)
  - Titanium (Ti)
  - Beyond Ti use temperatures (~ Mach 5), often utilize superalloys, refractory metals, and active cooling – not high specific strength
  - Refractory composite hot structures extend high specific strength structures to 3000°F and above



AIAA-2008-2682

ACC: Advanced carbon/carbon
MMC: Metal matrix composite
HfC: Hafnium carbide
C/SiC: Carbon/silicon carbide
UHT: Ultra high temperature

Hot-Structure Weight Savings Over Insulated Cold Structure

- **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)
- **Space shuttle orbiter body flap (AIAA-1983-913)**
  - Baseline 1460 lb, insulated cold structure
  - ACC body flap 1207 lb (253 lb, 17% weight savings)
- **X-37 hot structures**
  - 50% weight savings potential over metallic structure with TPS
- **JSF (Joint Strike Fighter) 3rd stage, low pressure, CMC turbine vanes**
  - ~200 lb weight savings per mid-size turbine engine
- **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

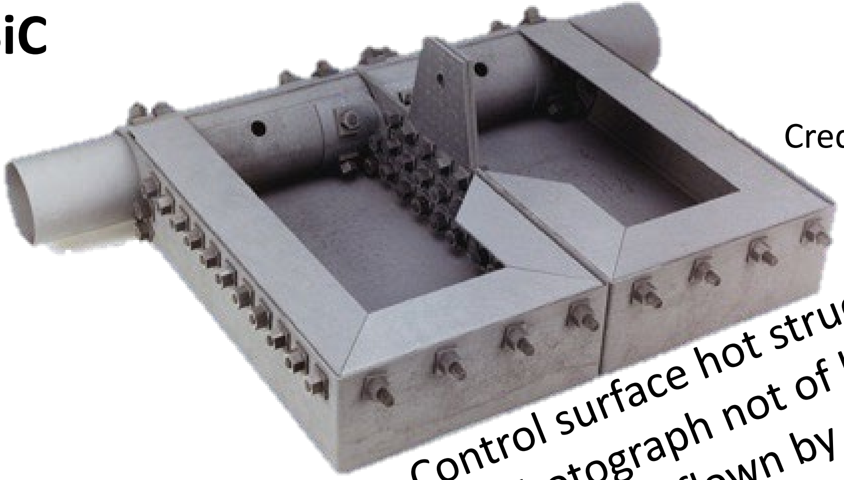
Selected Refractory Composites

- **Advanced carbon/carbon-6 (ACC-6)**
  - Oxidizes in air if uncoated > ~ 800°F
  - When coated, oxidation resistance to ~ 3000°F
  - Limited reusability
  - Low interlaminar properties
  - Used on Parker Solar Probe, rocket nozzle extensions, and aeroshells

Parker Solar Probe heat shield (ACC-6)

Credit: NASA

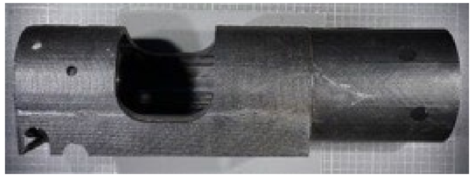
- **Chemical vapor infiltration (CVI) C/SiC**
  - Good oxidation resistance to ~ 3000°F
  - Reasonable reusability
  - Good interlaminar properties
  - Flown by European Space Agency (ESA)



Credit: NASA

Control surface hot structure (photograph not of hot structure flown by ESA)

- **SiC/SiC**
  - Expect excellent oxidation resistance in air
  - Expect excellent reusability
  - High interlaminar properties
  - Challenges scaling up with tolerances required for airframe hot structures
  - Primary design challenge is high coefficient of thermal expansion (CTE) coupled with high modulus

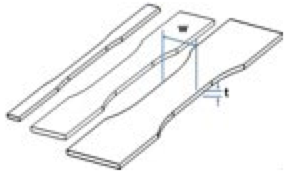


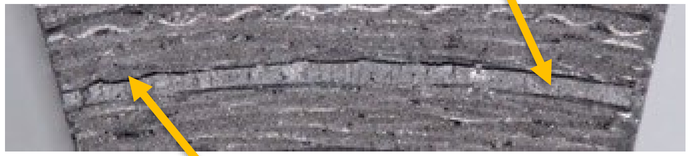
SiC/SiC torque tube

LaRC C/C Applied Research and Development

Objectives
- Provide design data for ACC-6
- Increase understanding of ACC-6
- Workforce development

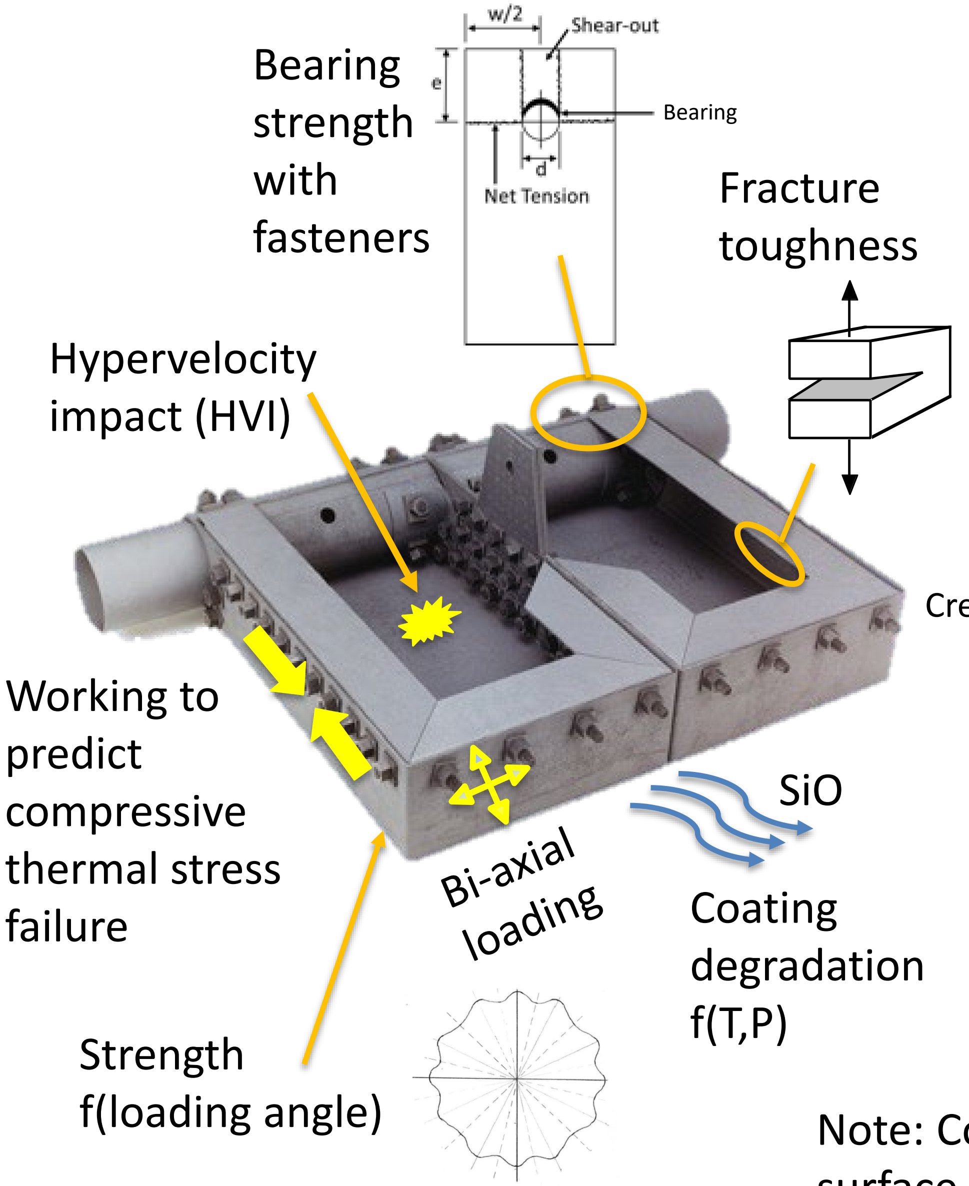
Special topics
- Flat panels vs. flight structures
- Strength f(specimen width)
- DoE for testing
- Manufacturing features
  - Butt splices
  - Assembly bonds





Credit: NASA

Challenges
- Difficult to measure our “weakest” property (ILT) at elevated temp
- Uncertainty in thermal conductivity data

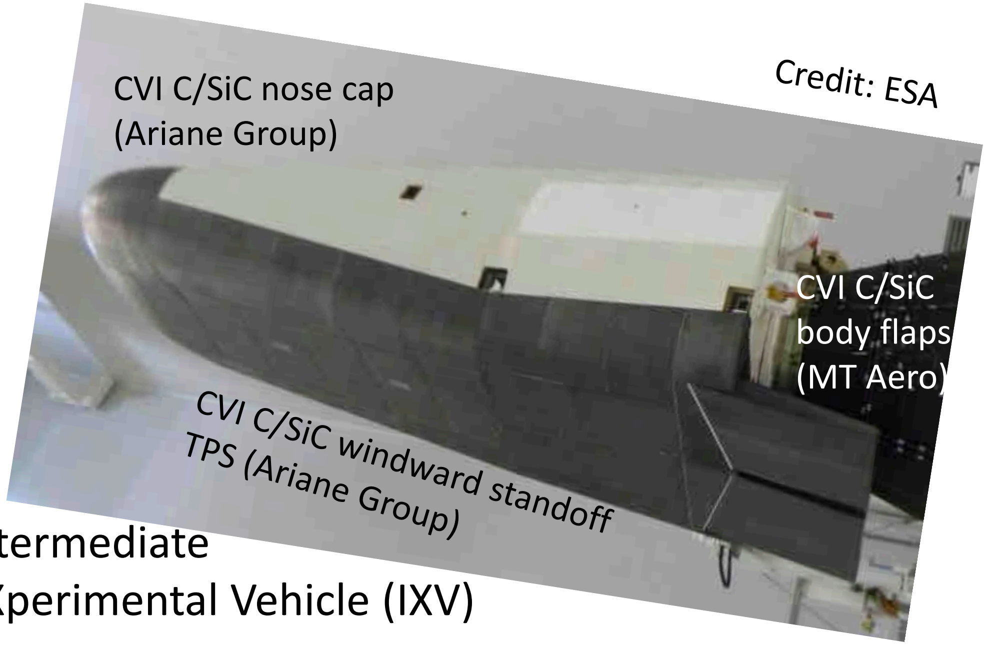


Credit: NASA

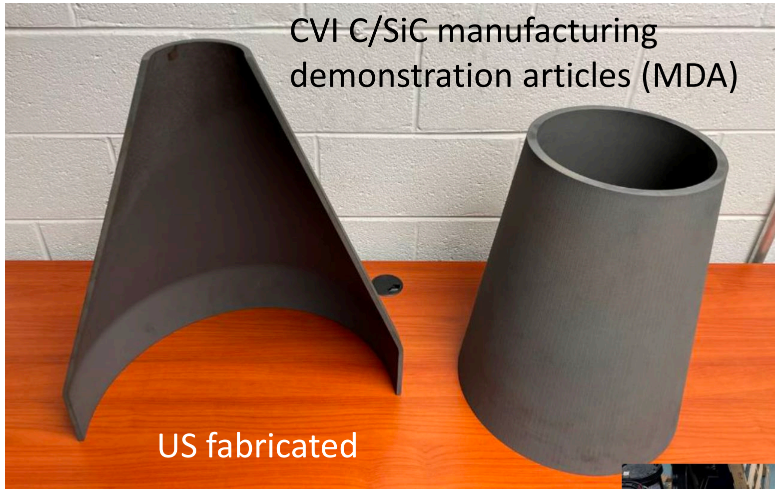
Note: Control surface is CVI C/SiC

C/SiC Hot Structure

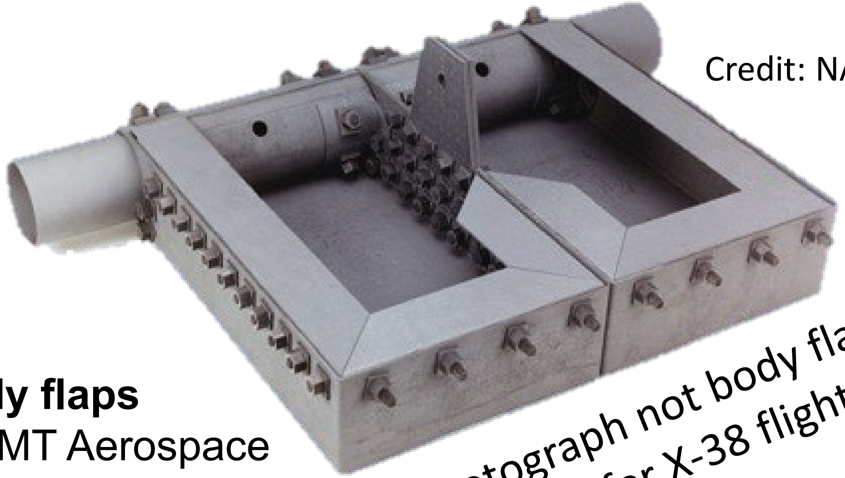
High technology readiness level (TRL) material for single use and reusable hypersonic vehicles



Intermediate eXperimental Vehicle (IXV)



Credit: NASA



Photograph not body flap qualified for X-38 flight

- ♦ **X-38 C/SiC body flaps**
  - Provided by MT Aerospace
  - Qualified for flight

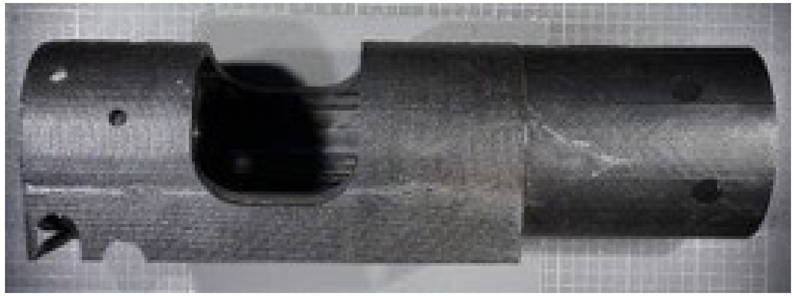
Space Shuttle nose cap shown

- ♦ **X-38 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

SiC/SiC for Reusable Airframe Hot Structures

- **SiC/SiC benefits**
  - Demonstrated by GE Aerospace as a highly reusable, high-temperature material system
  - High interlaminar properties compared to 2-dimensional ACC-6 and C/SiC
  - Strong GE industrial base with market pull
    - Fiber (joint venture) and unidirectional tape pre-preg plants in Huntsville, AL
    - Fabrication facility in Asheville, NC
    - Prototyping facility in Evendale, OH

- **SiC/SiC challenges**
  - Manufacturing scale-up to the complexity of high tolerance and highly-loaded structures
  - High CTE coupled with high modulus (design issue not a material limitation)

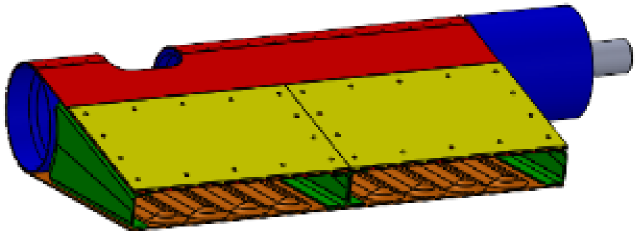


SiC/SiC torque tube

Multiple advantages provided by SiC/SiC hot structures for reusable hypersonic vehicles

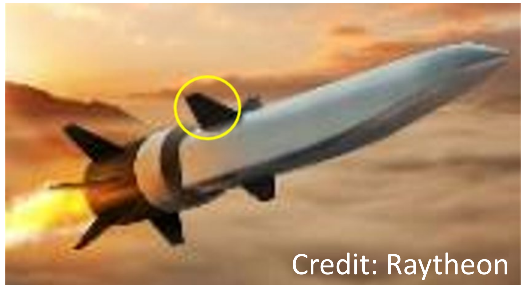
LaRC SiC/SiC Hot-Structures Efforts

- **Design of X-37-based flaperon component**
  - Detailed design and analyses of X-37-based structural test article (STA)
  - Support building block testing and modeling efforts
    - Gain understanding of SiC/SiC for hot-structure applications
  - MDA completed



STA

- **Ceramic Matrix Composite Control Surface (CMCS)**
  - Different thermal management than STA
  - Thick monolithic versus stiffened-skin structure



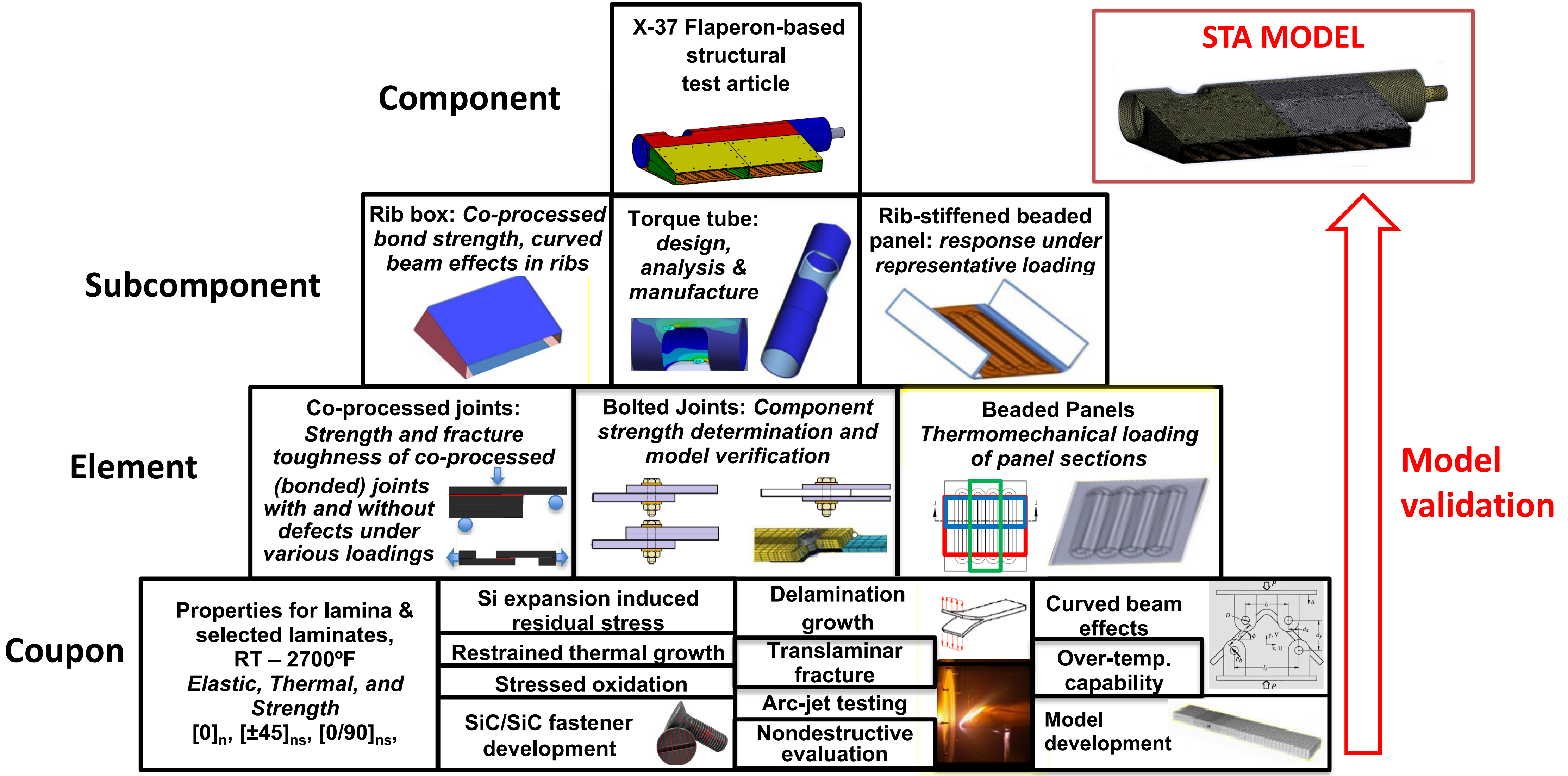
Credit: Raytheon

- **Hypersonic vehicle wing supporting studies**
  - Static, fatigue, and creep properties for variety of layups
  - Rib, spar, and stiffened-skin trade studies
- **Automated fiber placement (AFP)**
  - High speed, low cost, repeatable structures

NASA ISAAC

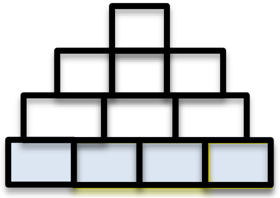
NASA LaRC has extensive on-going efforts toward enabling reusable hypersonic vehicles with SiC/SiC hot structures

SiC/SiC STA Building-Block Overview



Coupon Level: SiC/SiC Allowables Testing

- **For any material system to be utilized on a flight vehicle, properties must be available for detailed finite element analysis**
- **Panels are being procured from GE for testing at NIAR (mechanical) and Kratos (thermal)**
- **Mechanical Properties (RT – 2700°F)**
  - Static mechanical properties
    - Proportional limit, moduli, and Poisson's ratio
  - Bearing strength
  - Fatigue up to 100k cycles (or failure) and 2 stress levels (above and below the proportional limit)
  - Creep



Number Plies	Layup	Number Panels	Comments
16	$[(45/0/-45/90)_{2D}]_s$	7	L & T properties the same, testing only required in 1 dir
12	$[(0/\pm60)_{2D}]_s$	14	Testing in L&T dirs, fatigue and creep
12	$[(0/90)_{3D}]_s$	7	L & T properties the same, testing only required in 1 dir
12	$[(45/-45)_{3D}]_s$	6	L & T properties same, testing in 1 dir, no fatigue or creep
12	$[(0/90/0)_{2D}]_s$	12	Testing in L&T dirs, no fatigue or creep
12	$[(0/\pm30)_{2D}]_s$	14	Testing in L&T dirs, fatigue and creep
12	$[(0/\pm45)_{2D}]_s$	12	Testing in L&T dirs, no fatigue or creep
8	$[0_{4D}]_s$	6	Testing in L&T dirs, no bearing, fatigue or creep
	TOTAL	**78**	

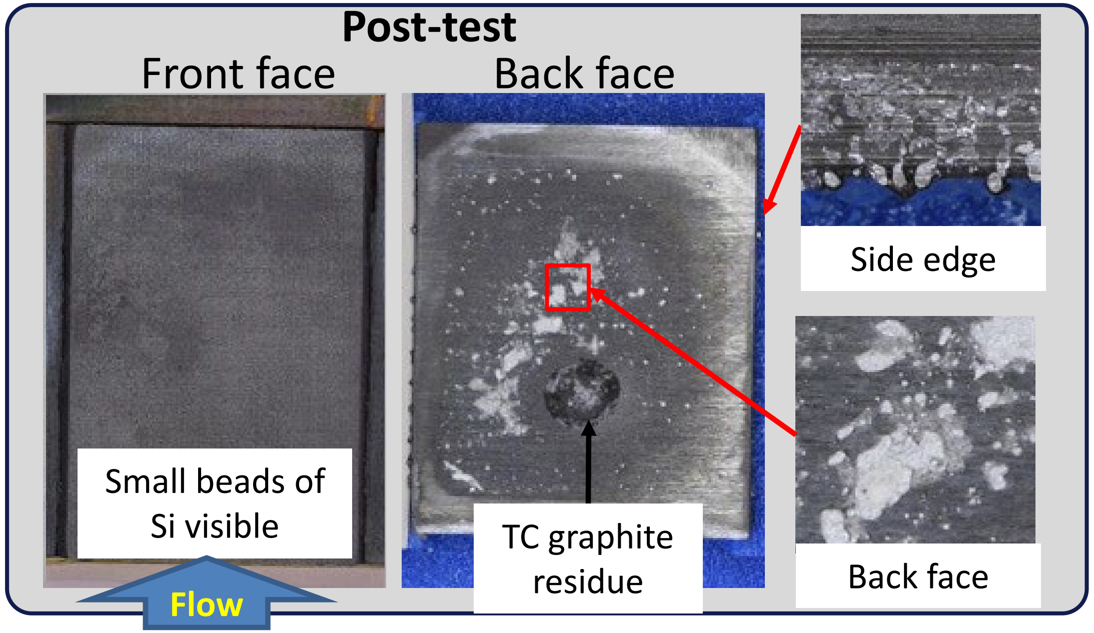
(Fatigue and creep testing at 2200°F)

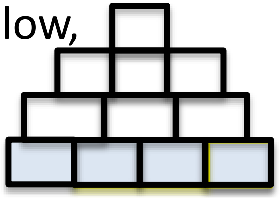
Coupon Level: Arc-Jet Tests

- **Testing performed at Large Core Arc Tunnel (LCAT)**
- **Use of novel reusable Type-C thermocouples**
- **Diagnostics**
  - Three pyrometers with spot size ~ 0.4-in. diameter
  - Pre/post-test photography and blue-light scanning
  - Post-test X-ray computed tomography (CT)
- **Results**
  - All specimens survived full durations

Spec. No.	Run No.	Cold-Wall Heat Flux, Center Slug (BTU/ft^2-s)	Pressure (atm)	Run Time (s)	Max Surface Temp (°F)
ARC-07	1	127	0.199	180	2673
ARC-08	1	140	0.208	64	2640
ARC-09	1	145	0.207	180	2750
ARC-10	1	178	0.271	180	2975
ARC-11	1	177	0.211	300	2725
ARC-11	2	169	0.195	600	2743

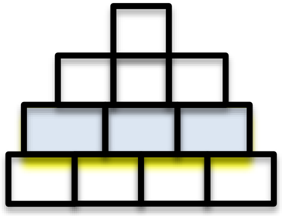
  - Material contains ~ 20 vol % free Si
    Above 2550°F, liquid Si preferentially flowed to cooler back face and side edges where pressure was low, then resolidified
- **Detailed post-test analyses in progress**

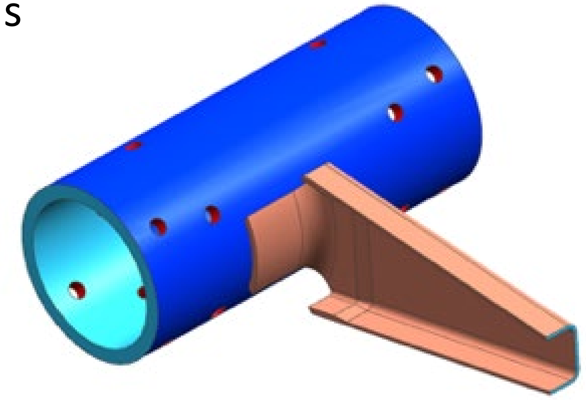




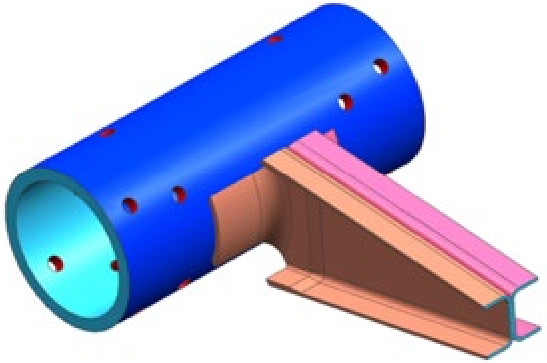
Torque Tube / Rib Study

- **Objective**
  - Evaluate the manufactured bond line between the torque tube and a single rib, as well as back-to-back ribs bonded to a torque tube
- **Approach**
  - Fabricate two of each type of torque tube with ribs
  - Apply mechanical load to the ribs to evaluate integrated manufacturing
  - Perform parallel experimental studies to determine bond strength and toughness under various modes of loading



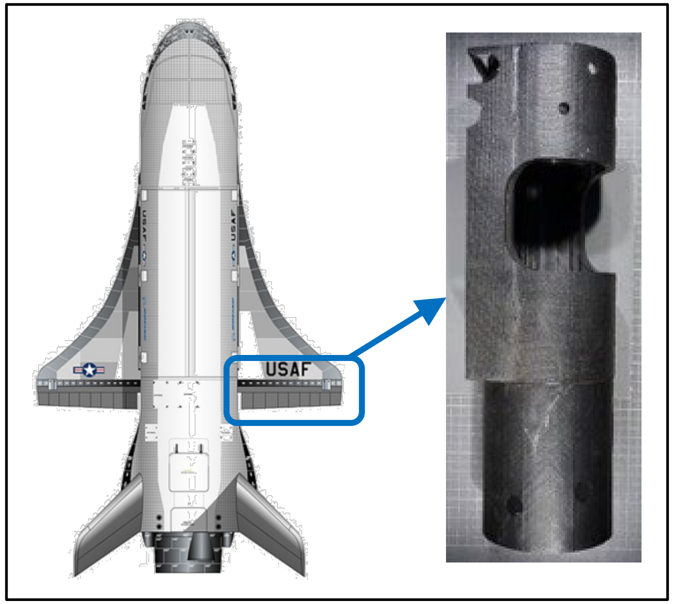


- **Accomplishments / status**
  - Modifying Task Order to address torque tube / rib manufacturing
- **Plans**
  - Evaluate bond line via nondestructive evaluation (NDE)
  - Perform finite element analysis (FEA) to predict load at which the bond will fail and the load and failure mode for structural failure.
  - Perform room temperature tests applying load to the ribs to evaluate failure mode and load
  - Perform post-test NDE
  - Perform post-test FEA to correlate test and analysis



SiC/SiC MDA Flaperon Torque Tube Test

- **Objective**
  - Verify impact of ply-breaks and other manufacturing defects on the load-carrying capability of a SiC/SiC torque tube for an X-37-based flaperon
  - Develop and validate SiC/SiC modeling approaches for complex airframe hot structures
  - Identify damage mechanisms leading to torque tube failure
- **Approach**
  - Test MDA torque tube in torsion and offset tension-bending load cases, which are the driving load cases as predicted by STA model
  - FEA-informed fixture design and predicted failure loads
  - Pre- and post-test NDE (CT scanning) for defect quantification and VCCT modeling
  - In-situ monitoring with strain gauges and digital image correlation (DIC)
- **Accomplishments / Status**
  - FEA predictions complete, test plan drafted, parts fabricated, NDE of tube in progress
- **Plans**
  - Instrumentation, testing, data analysis



X-37 flaperon and extracted MDA torque tube (test article)

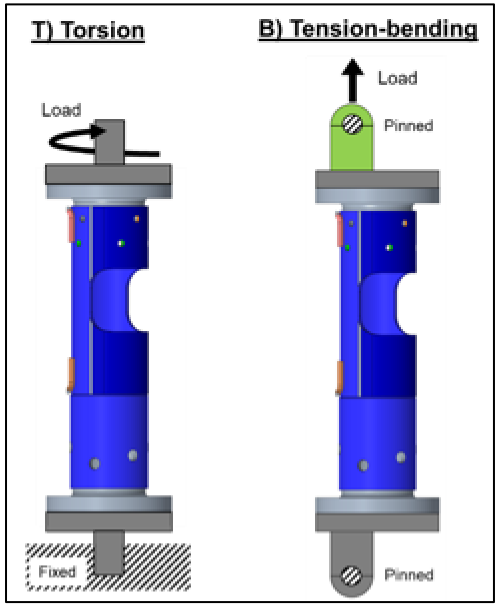
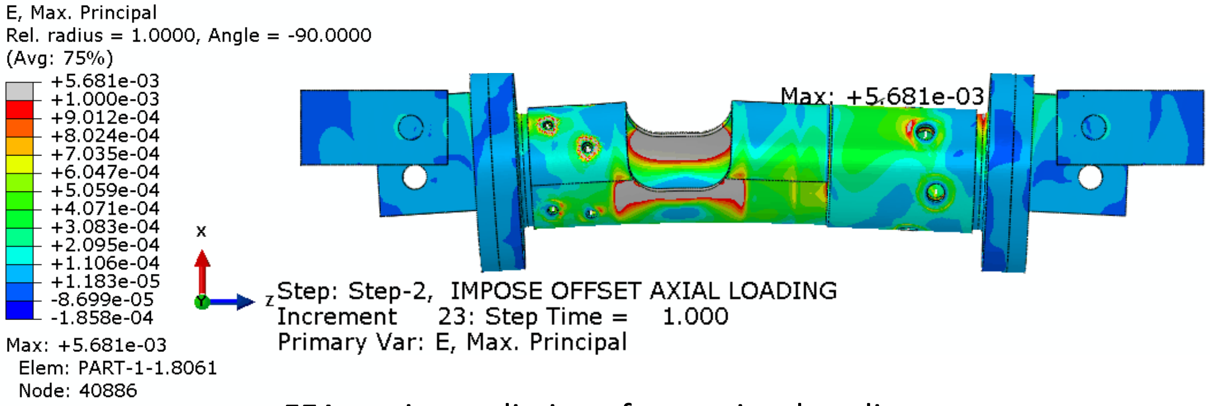


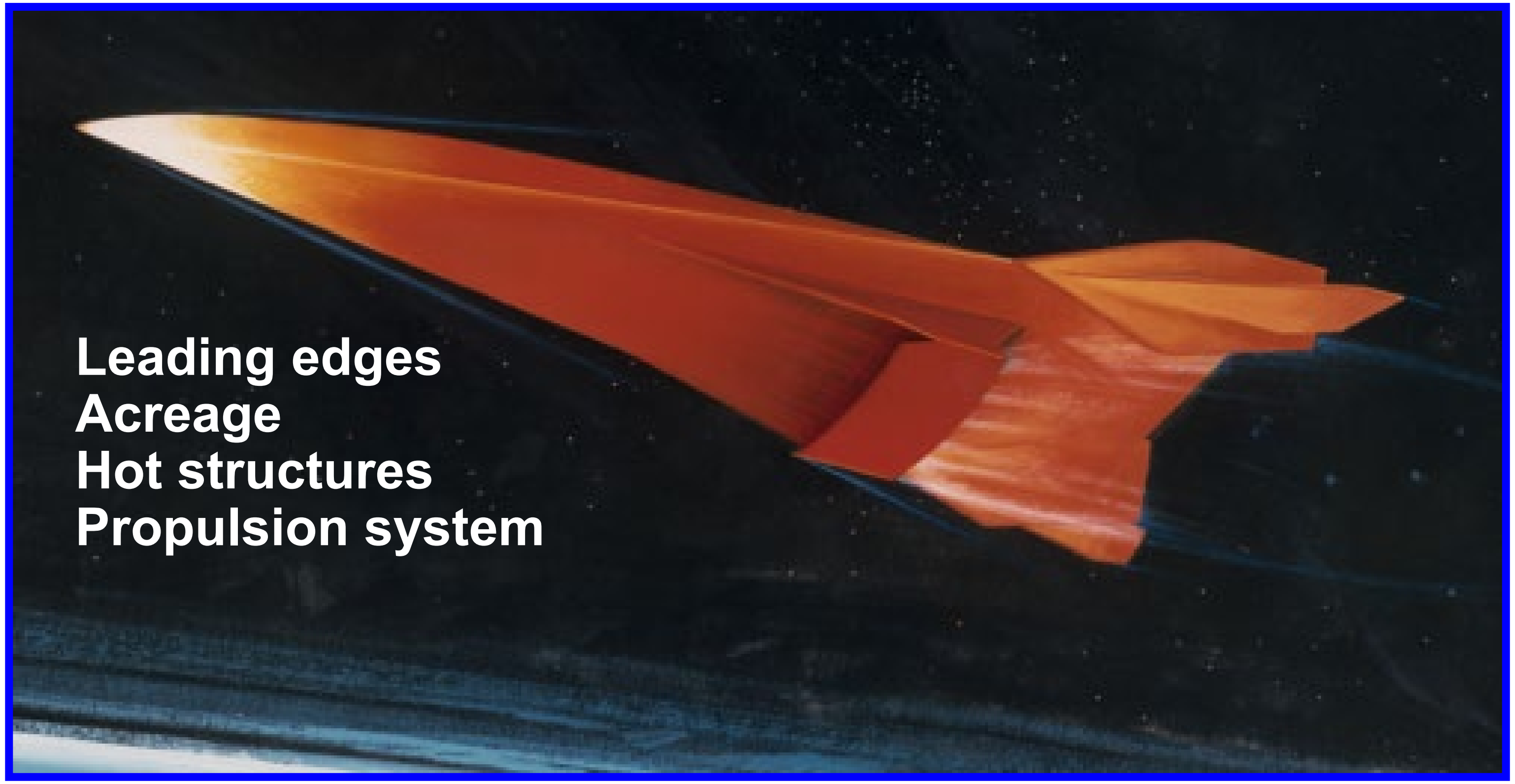
Diagram of loading configurations and fixturing



FEA strain predictions for tension-bending test

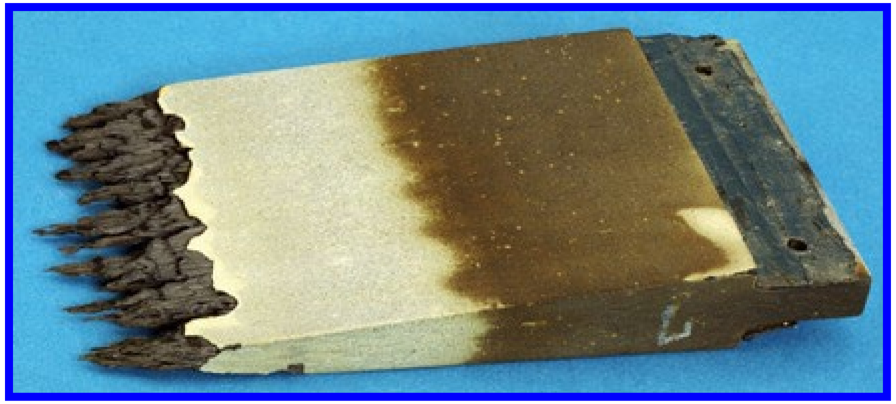
Hypersonic Vehicles

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



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

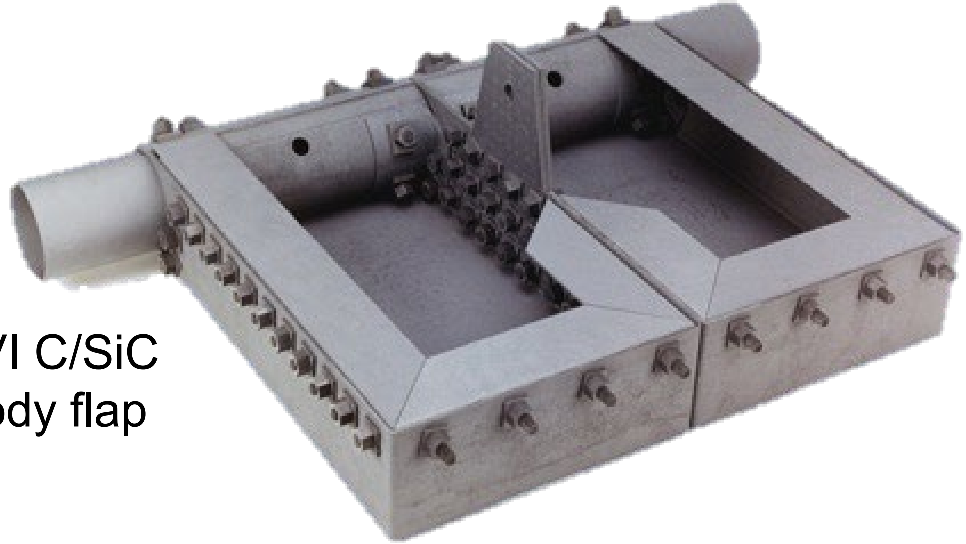
Key Technical Challenge: Environmental Durability



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

Key Technical Challenge: Hot-Structures Manufacturing

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



CVI C/SiC body flap

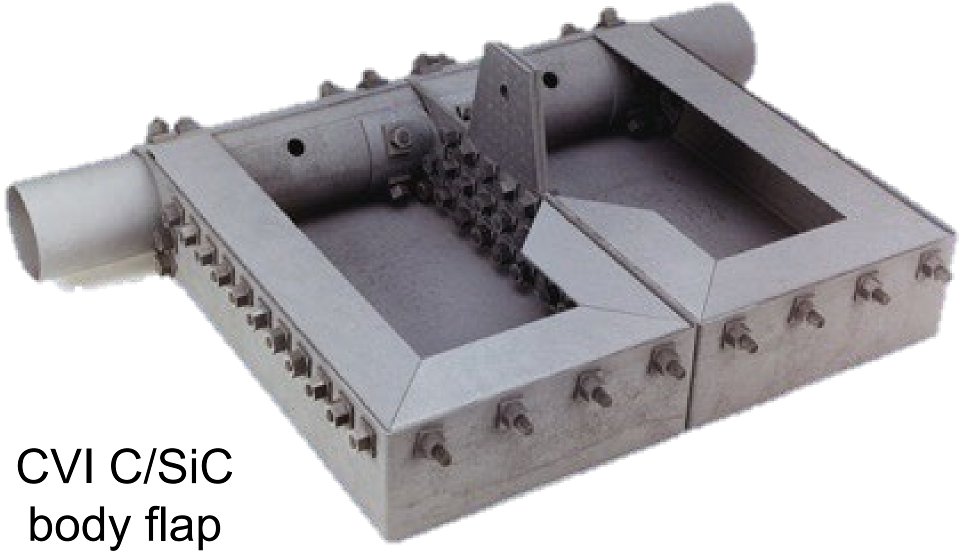
Big difference!

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 (cannot throw the design “over the wall”)
- Affordable (cost and schedule) fabrication techniques

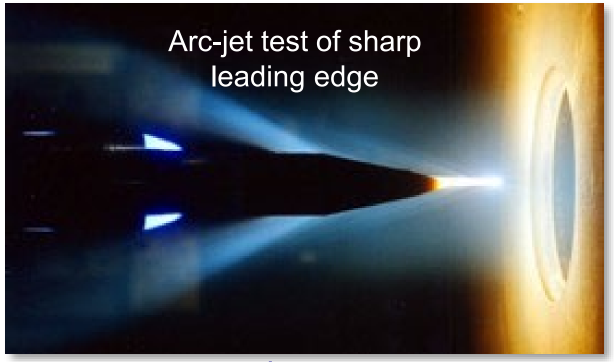
Fabrication challenges are process dependent



CVI C/SiC body flap

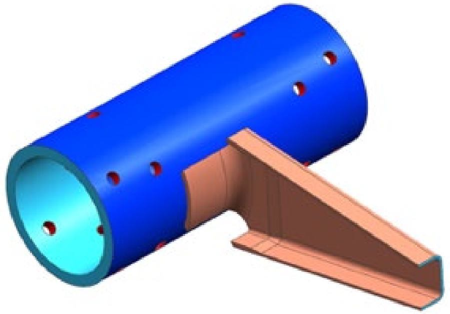
Testing

- **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**

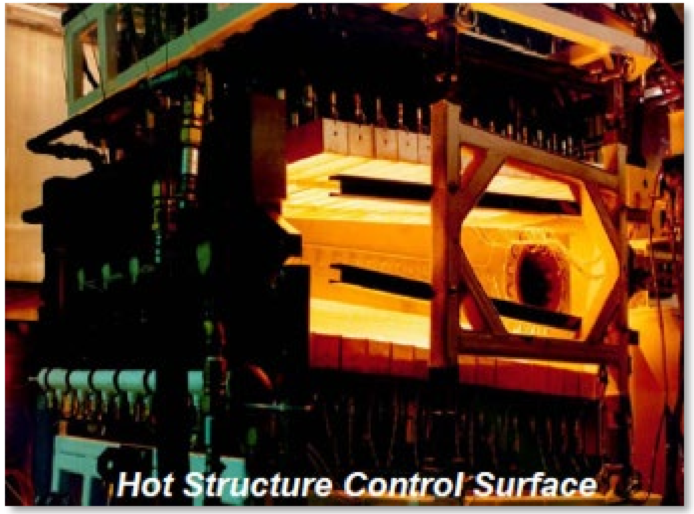


Material / coupon test

Sub-element test



Component test



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

Workforce Development

Langley Hot Structures Team

- **Interns (undergraduate, masters, and PhD)**
  - 58 students (107 sessions) since 2013
  - 23 with aerospace-related jobs (> 10 still in school)
    - Psionic Technologies, JPL, Lockheed Martin
    - Peraton, Boeing, Blue Origin, C-CAT, Actalent
    - Northrop Grumman, Lockheed Martin, HRL
    - Motiv Space Robotics, NASA Langley (3 former interns)
    - NASA Marshall, Relativity Space, SpaceX
  - Cocoa Beach / CMS, AIAA, AFOSR, and JANNAF attendance and papers

Interns on education / team-building trip (all 4 planning to present at CMS in January)

- **Early-career mentorship**
  - Conference attendance: CMS, NSMMS, JANNAF, HTSC
  - International conference: FAR, HiSST, HT-CMC
  - Partner visits:
    - NASA Glenn, GE, APL
    - CA: HRL, Allcomp, Ultramet, NASA Armstrong
    - AL/MS: AvMC, PPI, MSFC, Kratos, GE, ReLogic, Mississippi State Univ.
    - Northeast: GE GRC, TEAM (Spirit), Draper Labs, Textron, Bond Enterprise, FMI (Spirit), Exothermics, PSI

Early-career employees on NE partner visit

Concluding Remarks

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

- Results to-date support that SiC/SiC may be a key enabler of reusable hot structures for hypersonic vehicles

- 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