National Aeronautics and Space Administration

Overview of NASA's Hypersonic Air-Breathing Materials & Structures Discipline

Hypersonics Project

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Outline

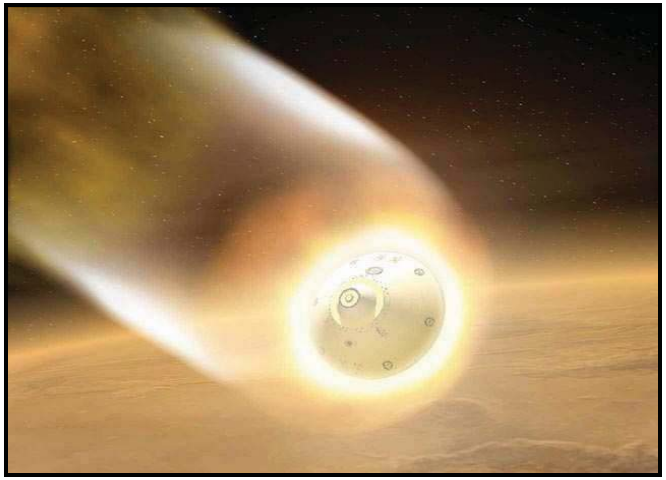
- Hypersonic Materials and Structures Technical Challenges
  - Background
  - Develop integrated light-weight, reusable airframe and propulsion structures
    - Reusable Materials and Models
    - Airframe Subcomponents

- Partnerships
  - National Hypersonic Science Center for Materials and Structures

Technology Challenges
Hypersonic Materials and Structures

The NASA Hypersonic Project is focused on vehicle technologies, tools, and knowledge for two very different mission areas:

- Hypersonic air-breathing vehicles
- Planetary entry vehicles



Each mission area has different challenges and technology solutions:

- Hypersonic air-breathing vehicles
  - Reusable, winged vehicles, complex geometries
- Entry vehicles
  - Single use blunt bodies, high Earth entry velocities, high mass Martian entry

Hypersonic Air-Breathing Technical Challenges

- Develop air-breathing propulsion technology for two-stage-to-orbit vehicles
  - 1x and 10x scramjet propulsion
  - Turbine Based Combined Cycle propulsion

- Develop physics-based integrated multi-disciplinary design tools
  - Integrated multi-disciplinary, multi-fidelity tool suite
  - Vehicle concept studies

- Develop integrated light-weight, reusable airframe and propulsion structures
  - Reusable Materials and Models
    - CMC modeling - integrated analysis methods
    - CMC materials
  - CMC Scramjet Heat Exchangers
    - X-51A flowpath study
  - X-37 Ruddervator Subcomponent Test Article (RSTA)
  - Structurally Integrated Thermal Protection Systems (SITPS)

Hypersonic Air-Breathing Technical Challenges
Integrated Light-Weight, Reusable Airframe & Propulsion Structures

- **Tools:**
  - Probabilistic CMC durability and life prediction methods
  - Coupled thermal-mechanical sizing of SITPS panel concepts
- **Technologies:**
  - SITPS panel concepts (solid and discrete element cores), panel attachments for load transfer, and manufacturing processes
  - CMC heat exchanger panels for propulsion structures
- **Knowledge**:
  - Physics of damage progression in CMCs
  - Understanding the design trade space for SITPS concepts

Hypersonic Air-Breathing Technical Challenges
Integrated Light-Weight, Reusable Airframe & Propulsion Structures

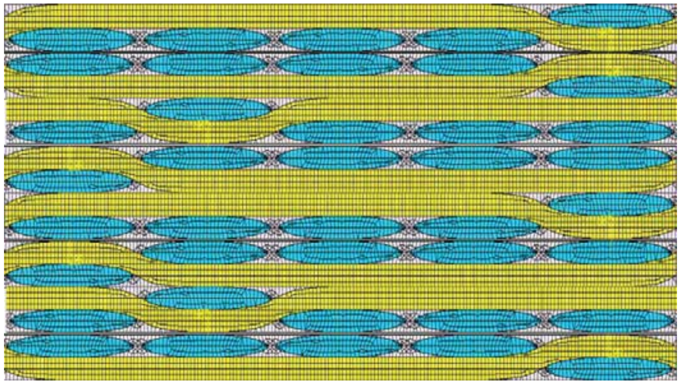
- **What are we trying to do?**
  - Develop durable, reusable TPS technology that has integrated thermal / mechanical load carrying capability and the ability to share mechanical loads with the airframe
  - Develop light-weight and reusable propulsion heat exchangers
- **Why?**
  - To reduce overall vehicle system weight, to improve damage resistance, to reduce operational costs and maintenance time between missions
  - To decrease weight of air-breathing hypersonic propulsion systems
- **How is it done today, and what are the limits of current practice?**
  - Hypersonic vehicles carry mechanical loads via internal truss-structure with metallic skins covered with bonded parasitic TPS that requires long maintenance time and high operational costs
  - Propulsion heat exchangers are metallic (heavy and temperature limited), US experience with CMC-based heat exchangers is limited
- **What is new in our approach?**
  - Use of lightweight and durable CMC / insulation in integrated sandwich panel configurations that share thermal / mechanical loads with the vehicle airframe
  - Development and testing in a scramjet environment of fuel-cooled heat exchangers made from CMCs
- **What are the payoffs if successful?**
  - Reduced airframe structural weight, improved volumetric efficiency, increased durability, reduced operational costs
  - Lighter weight and higher temperature capable scramjet structures

Hypersonic Air-Breathing Technical Challenges
CMC Modeling

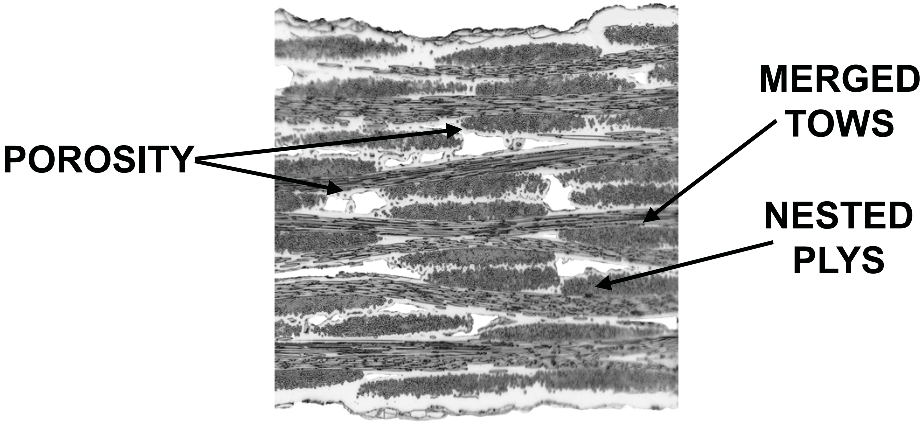
<u>Objective</u>: Improved modeling and physical understanding of CMC behavior for improved durability prediction and extended life.

CMC's are highly ordered textile structures that possess inherent disorder

IDEALIZED STRUCTURE



REAL STRUCTURE



What is the role (good or bad) of inherent disorder in failure initiation and damage evolution?

How do we characterize disorder in a framework meaningful to failure, or life prediction, analysis?

What is the appropriate physical size for a continuum damage analysis?

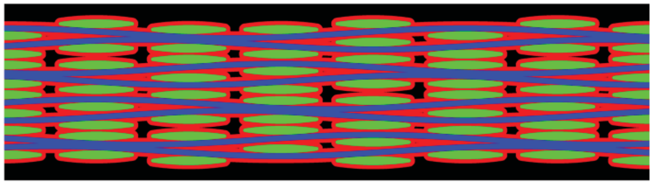
Hypersonic Air-Breathing Technical Challenges

CMC Modeling

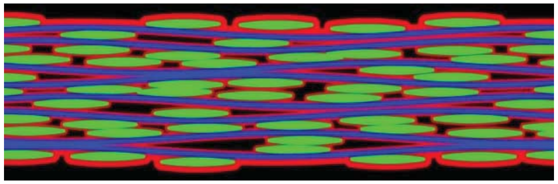
- **FY11-12 Accomplishments:**
  - Developed method to artificially generate 2-D CMC cross-sections with key microstructural features and distribution observed in actual specimens
  - Quantified uneven matrix distribution between edges and center of specimen and developed method to account for phenomena in generated models
  - Developed relationship between microstructure features and initial nonlinearity in overall stress-strain curve (first matrix cracking stress)
    - Damage appears to initiate in transverse tows clustered closely together, and progresses to form bands of matrix damage

FY12-13 Research Focus:

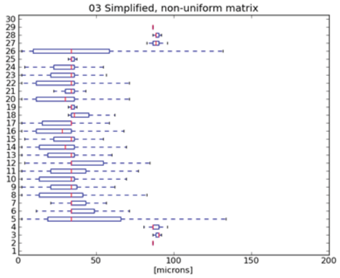
- Research effort transitioned NASA FA Supersonics Project

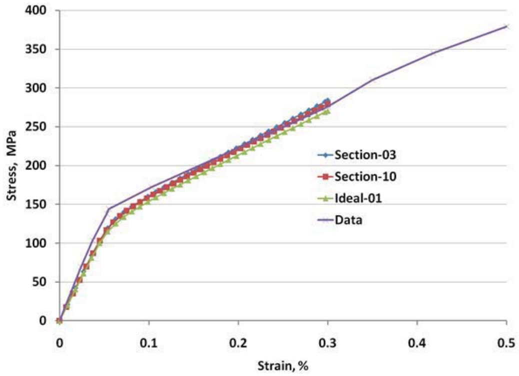


Artificially generated CMC 2-D cross-section

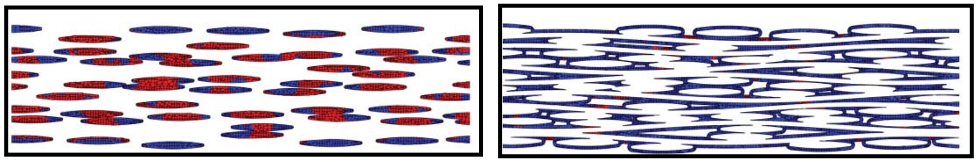


Insertion of uneven matrix distribution





Computed stress-strain curves as compared to experimental data



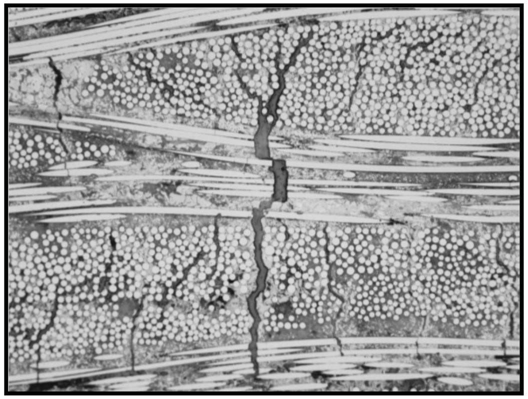
Damage patterns (red elements) in transverse tows (left) and matrix (right) at point of stress strain curve nonlinearity

Hypersonic Air-Breathing Technical Challenges

CMC Materials

Objective: Extend temperature performance capability of CMC's for vehicle airframe applications

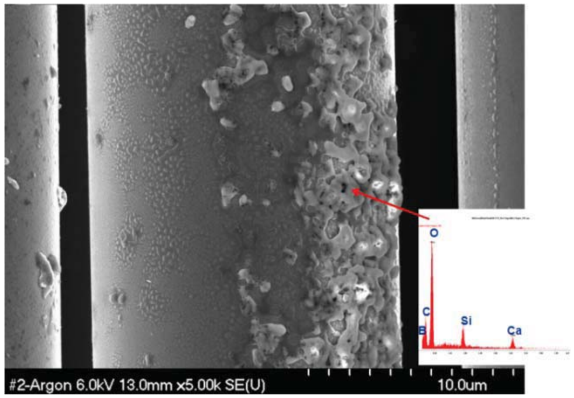
- Establish performance limitations of SOA high-temperature CMC's and identify life limiting damage mechanisms
- Mitigate life limiting damage mechanisms through improved material constituents and processes
- Establish design databases for the best material
- Develop oxidation resistant coatings capable of extending service life to 3000ºF



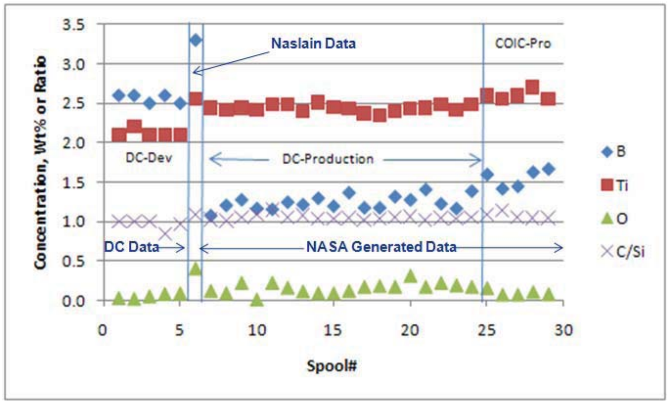
Creep rupture damage analysis

Hypersonic Air-Breathing Technical Challenges
CMC Materials

- **FY11-12 Accomplishments:**
  - Extended tensile and creep rupture testing capability to 3000ºF
  - Established upper temperature / stress / durability of current SOA full CVI and full PIP SiC/SiC composites
  - Demonstrated 100hr creep-run-out life at 5ksi at temperatures to 3000ºF in air for full CVI SiC/SiC composites with 2-D balanced fiber architecture
  - Air Force and NASA are working together with the fiber vendor to determine the source of the reproducibility and reliability issues with the fabrication of Sylramic SiC fibers
    - Fiber-to-fiber bonding has been significantly reduced, but other issues have not been resolved



Low melting glass formed during processing of Sylramic SiC fibers



Chemistry of Sylramic SiC fibers

FY12-13 Research Focus:

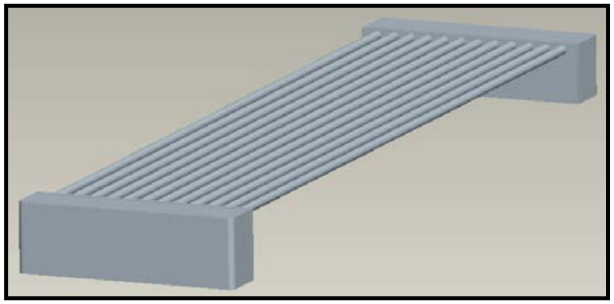
- Continue working with the Air Force and fiber vendor to identify the principle cause for weak Sylramic SiC fibers
- Research effort transitioned NASA FA Supersonics Project

Hypersonic Air-Breathing Technical Challenges

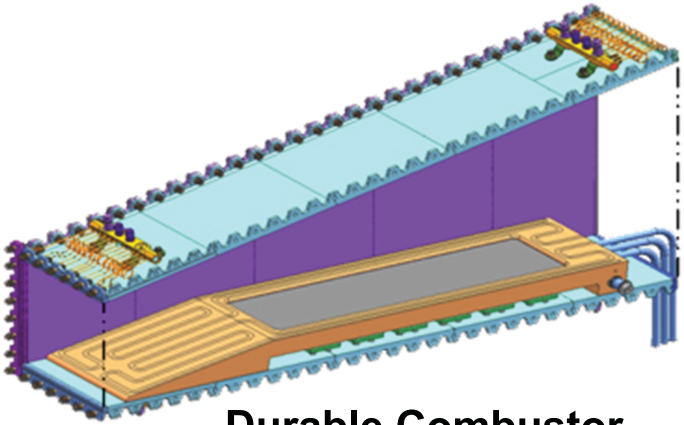
Composite Heat Exchangers (C-Hex)

Objective: Develop light-weight and reusable propulsion heat exchanger technology

- Advanced fabrication methods for flow passage fabrication
    - Goal: metallic coating to avoid the need for integrated tubing
- Design and manufacture C-Hex concepts with progressively advanced features
- C-Hex testing and analysis code validation



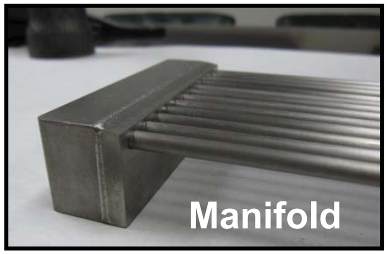
1st Generation: Tube / Manifold Design Approach



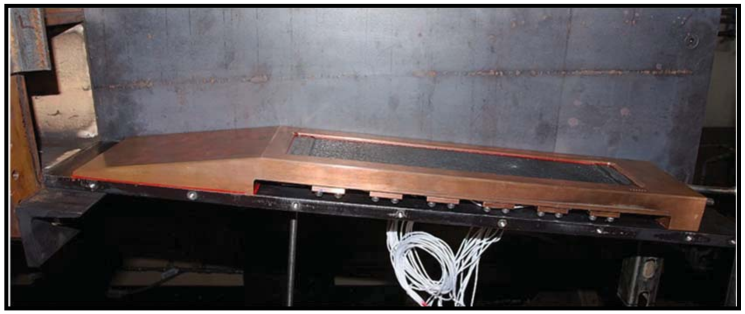
Durable Combustor Rig NASA LaRC

Hypersonic Air-Breathing Technical Challenges

Composite Heat Exchangers (C-Hex)



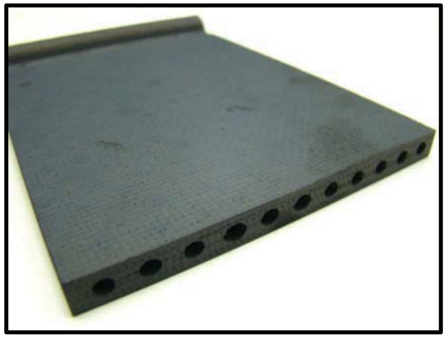
- **FY11-12 Accomplishments:**
  - Design, fabrication, and NDE of C-Hex1 panel completed
    - Metallic tube and manifold design
  - C-Hex1 prepared for testing in the LaRC DCR
  - Fabrication of an alternate panel design (C-Hex2) completed
    - Panel and manifold design with no metallic tubes
- **Partners:**
  - Hyper-Therm HTC



C-HEX1 Panel integrated into LaRC DCR

<u>FY12-13 Research Focus:</u>

- Testing of the C-Hex1 panel expected in March-April 2012
- Document C-Hex1 and C-Hex2 development

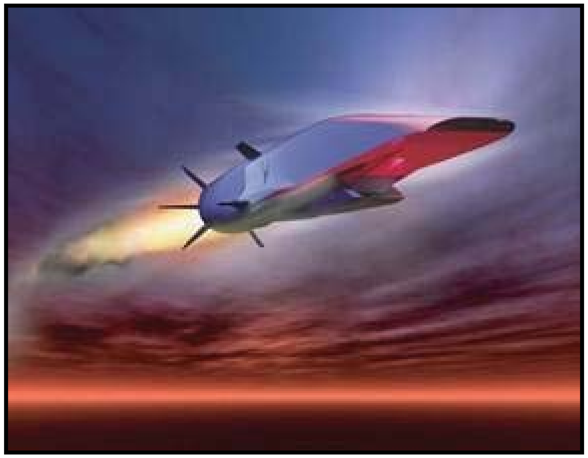


Alternate C-HEX2 Panel (No Metallic Tubes)

Hypersonic Air-Breathing Technical Challenges

X-51 CMC Flowpath Study

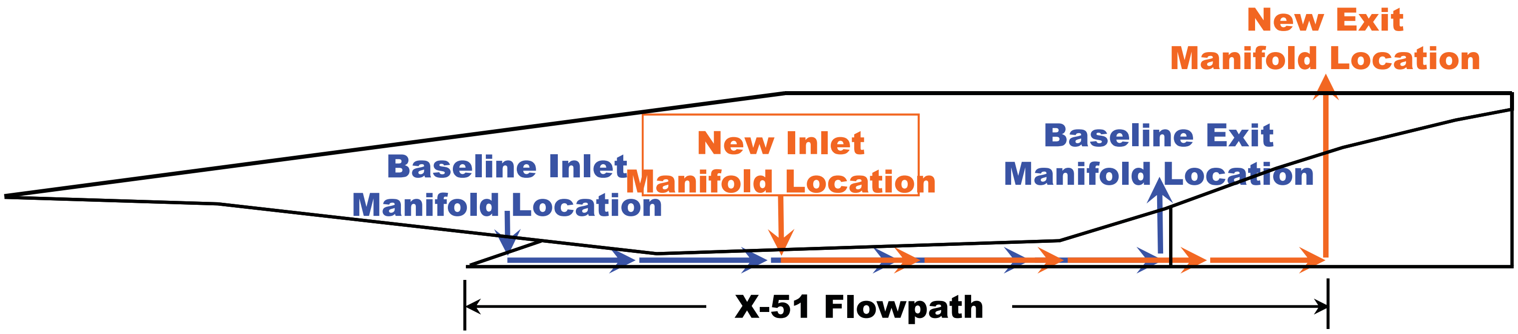
Objective: Determine the impact of a CMC flowpath on the X-51A design including definition of the pluses and minuses in terms of structures, weight, performance, fuel flow and thermal characteristics



- Define integrated solution and performance assessment to determine **X-51A vehicle performance impact and top level benefits**
- Focus on conceptual level design including initial mass properties and performance metrics
- Identified trade study results that were non-proprietary
- **X-51A operational requirements were unchanged** would provide a baseline for comparison (pressures and temperatures from X-51A database)
- Flowpath environment allows use of SiC/SiC exclusively (**data provided by the government**)

Hypersonic Air-Breathing Technical Challenges

X-51 CMC Flowpath Study



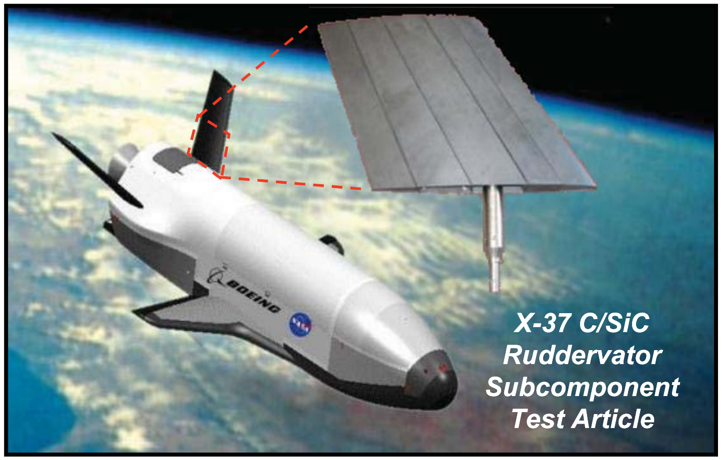
- **FY11-12 Accomplishments:**
  - Baseline HEX assessment indicates feasibility of CMC flowpath components with a passive design before combustor and cooled through to nozzle
  - CMC materials offer improved thermal management through higher operating temperatures and *lower thermal conductivity relative to metallics*
  - CMC materials remove over cooling requirement and reduce the HEX surface area for the uncooled inlet and isolator
  - CMC capability increases flexibility in HEX optimization parameters
  - CMC materials in flowpath can provide significant *engine* weight reductions and further opportunity for secondary improvements
- **Partners:**
  - Boeing, Pratt & Whitney Rocketdyne, and Air Force

Hypersonic Air-Breathing Technical Challenges

X-37 Ruddervator Subcomponent Test Article (RSTA)

Objective: Evaluate the thermal, structural and dynamic performance of a C/SiC Ruddervator Subcomponent Test Article (RSTA)

- Multi-mission testing under re-entry and hypersonic cruise conditions
  - Acoustic and vibration loading
  - Thermal and combined thermal / mechanical testing
  - High-temperature modal survey testing
  - Mechanical testing to 100% design limit loading

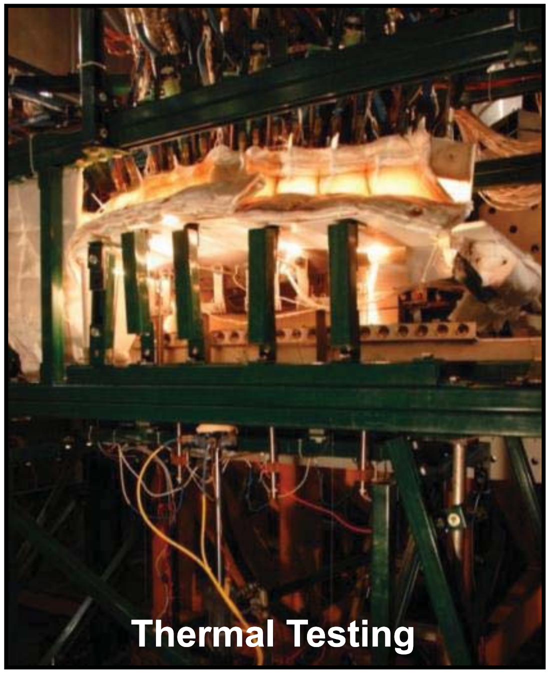


- Tracking of defects and damage via periodic thermography surveys

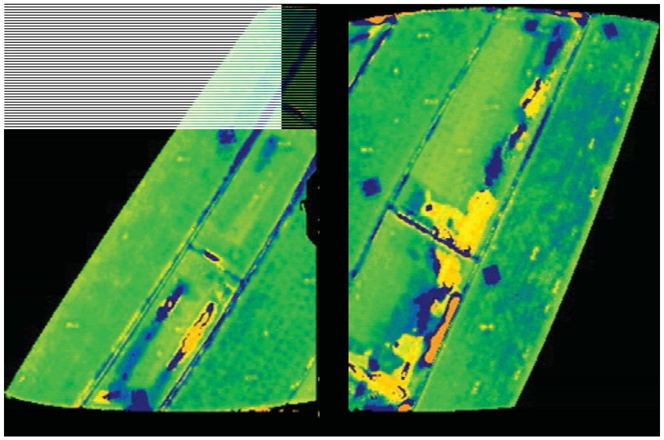
- Generate database for technical community

Hypersonic Air-Breathing Technical Challenges
X-37 Ruddervator Subcomponent Test Article (RSTA)

- **FY11-12 Accomplishments:**
  - Acquired unique test data for a C/SiC hot structured
    - Multi-mission re-entry and hypersonic cruise simulations
    - Measured the effect of high-temperature on modal frequency response
    - Tracked defects and damage accumulation throughout the test program
  - RSTA exhibited no significant structural degradation resulting from thermal and mechanical load testing
  - Test data showed that the RSTA performed more like an integrally designed structure rather than a bolted assembly
  - Generated exhaustive report and database
- **Partners:**
  - GE, Materials Research & Design, and Lockheed Martin


Thermal Testing


Vibration Testing


Thermography Survey

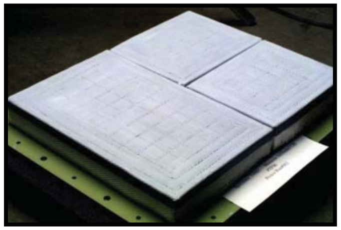

Mechanical Load Testing

Hypersonic Air-Breathing Technical Challenges

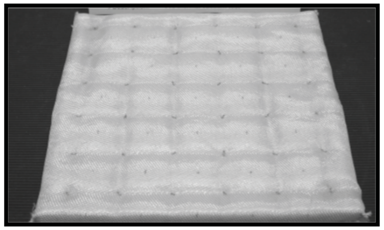
Options for Reusable Vehicle Acreage Thermal Protection

Improved Shuttle tile or blanket insulators

- Insulator bonded or mechanically attached to vehicle mechanical load carrying substructure



Rigid Tiles



Flexible Blankets

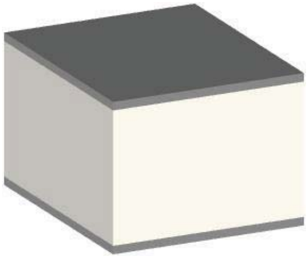
Metallic or CMC standoff TPS

- TPS system isolated from the airframe to prevent thermal loads from reaching the vehicle mechanical load carrying substructure

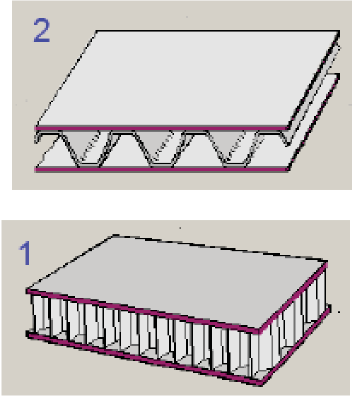
Standoff Tile TPS

Structurally integrated TPS (SITPS)

- TPS with integrated thermal / mechanical load carrying capability <u>and</u> the ability to share mechanical loads with the airframe



Rigid Insulator Core Concept



Discrete Element Core Concepts

SITPS fabricated with CMC materials has the potential of light weight, high volumetric efficiency, and increased durability

Hypersonic Air-Breathing Technical Challenges
Structurally Integrated Thermal Protection Systems (SITPS)

Objective: Establish design tools and fabrication technology for SITPS

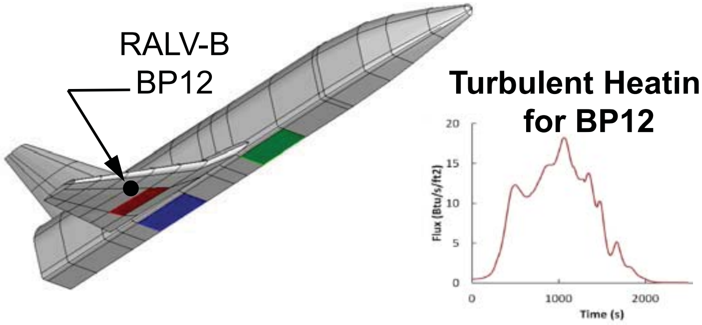
- **Panel detail design and vehicle trade studies**
  - – Panel detail design
    - Identify range of applicability and design drivers for different panel concepts
    - Develop methods for combined thermal-structural sizing of panel concepts
    - Develop suitable models for system level analysis
  - – Vehicle trade studies
    - Study #1: Panel sizing for RALV-B thermal loads only
    - Study #2: Full-vehicle assessment of SITPS versus conventional TPS

- **SITPS manufacturing and testing technology**
  - – Develop design methods and materials & processing (M&P) technology to fabricate SITPS panels
  - – Evaluate panel concepts through testing

Hypersonic Air-Breathing Technical Challenges

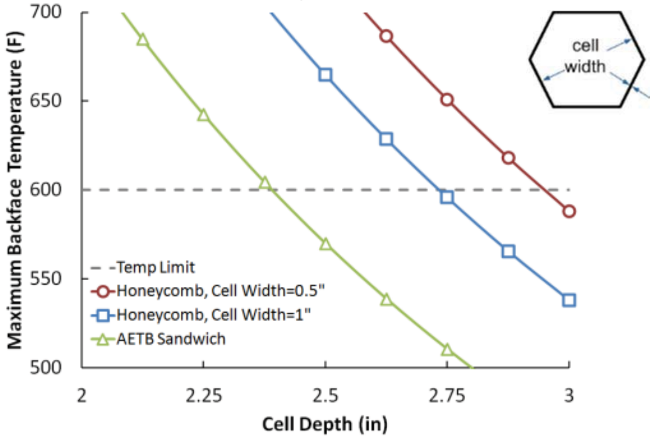
SITPS – Detail Design Study

- **FY11-12 Accomplishments:**
  - Identified vehicle loads, sandwich core concept and materials for initial study
    - RALV-B orbiter panel loads and heating
    - Progress from simple (continuous core) to complex (discrete core) concept architectures
  - Existing thermal-structural analysis methods (low- to high-fidelity) have been used to examine initial sandwich core concepts
    - "Brute-force" approach to combined thermal-structural sizing has been successfully conducted
    - Developing insight into requirements for future combined thermal-structural sizing analysis capabilities



Turbulent Heating for BP12

Thermal Analysis Results



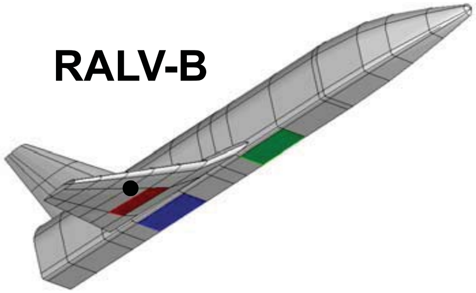
FY12-13 Research Focus:

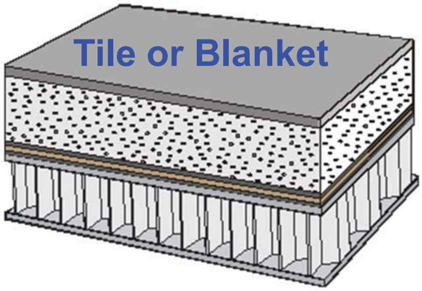
- Complete and document initial design assessment of both a continuous core and a honeycomb design
- Initiate the design study for an alternate discrete core design

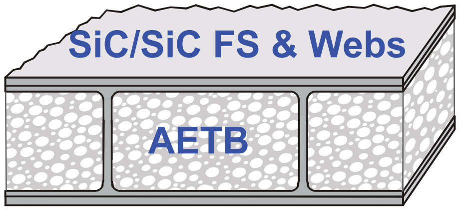
Hypersonic Air-Breathing Technical Challenges

SITPS – Vehicle Trade Study

- **FY11-12 Accomplishments:**
  - Completed an initial full-vehicle assessment of SITPS versus conventional TPS*
    - Analyze RALV-B re-entry cases for vehicle with conventional TPS and SITPS for defined thermal and mechanical load set
    - Commercial thermal-structural sizing tool used
  - Based on the initial investigation, SITPS is weight competitive with conventional TPS
  - General trend for external panels that are not heavily loaded
    - Conventional TPS is lighter that SITPS for areas with low heating (leeward surfaces)
    - SITPS is lighter than conventional TPS for areas with high heating (windward surfaces)
  - Various SITPS layouts yield vehicle weight savings >9.3%
- **Partner:**
  - NRA: Collier Research Corporation







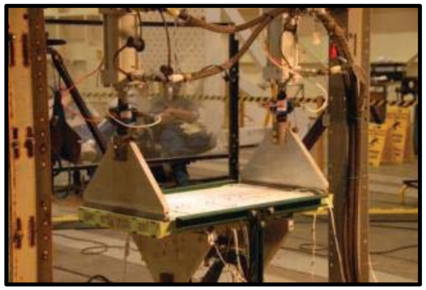
FY12-13 Research Focus:

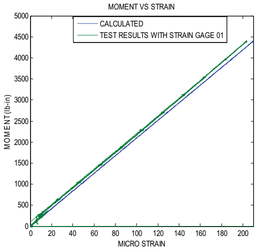
- Complete and document the full-vehicle assessment of SITPS versus conventional TPS

*Bey, Kim, "Is There a Benefit in Using Structurally Integrated Thermal Protection Systems? Progress in Getting an Answer," 36th Annual Conference on Composites, Materials, and Structures, Cocoa Beach, FL, 25 Jan 2012.

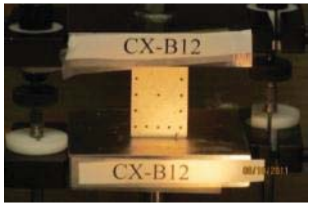
Hypersonic Air-Breathing Technical Challenges
SITPS – Manufacturing & Testing Technology

- **FY11-12 Accomplishments:**
  - SITPS-1 panel (20-in x 36-in) fabrication completed March 2012
    - To undergo NDE examination
  - Phase 1 ground-test capabilities to measure SITPS-1 stiffness coefficients have been developed and validated
    - 4-point bend, torsional, and pressure tests
    - Surrogate panel used to validate test setups
  - Material database for the constituent materials for SITPS-1 being documented
- **Partners:**
  - Contract: ATK-COIC, SITPS panel M&P
  - NRA: MR&D Inc., SITPS design analysis support
  - Contract: TPRL and SRI, material testing





4-point Bend Test of Aluminum Surrogate Panel



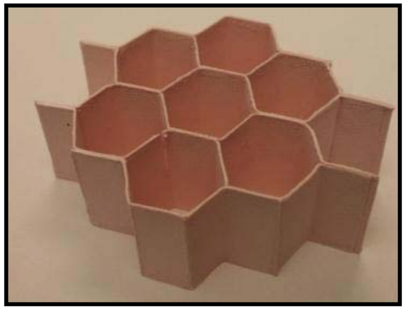
AETB-12 Compression Specimen

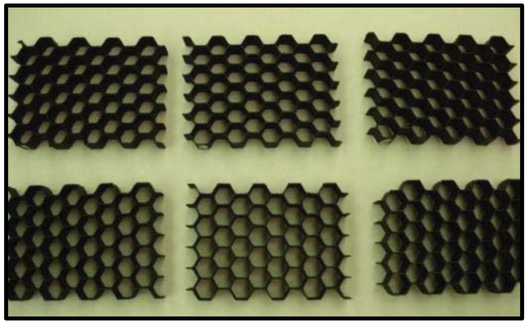
FY12-13 Research Focus:

- Complete the Phase 1 ground tests of SITPS-1
- Document the design, manufacturing, and testing of SITPS-1 concept
- Begin work to identify SITPS-2 concept for development
- Begin investigating vehicle integration technologies

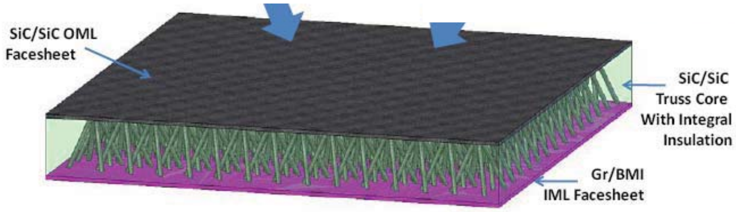
Hypersonic Air-Breathing Technical Challenges
SITPS – Alternate Core Technology

- **FY11-12 Accomplishments:**
  - **SMARF:** Improved manufacturing / processing techniques for alumina paper foils
    - Room-temperature flat-wise compression strength of 1480 psi
  - **Ultracor, Inc.:** Initiate the development of SiC/SiC honeycomb core and further develop the C/SiC honeycomb material database
  - **Boeing:** To develop a hybrid SiC/SiC truss core SITPS with integral insulation
    - Recently awarded with NRA start expected by end of Q3FY12
- **Partners:**
  - NRA: SMARF, Oxide/Oxide honeycomb panel
  - Phase 2 SBIR: Ultracor Inc., CMC honeycomb
  - NRA: The Boeing Company, Pin-Core panel


Alumina Paper Honeycomb


Infiltrated C/SiC Honeycomb

FY12-13 Research Focus:
- Continue monitoring the progress of alternate core technology and examine technology for SITPS-2 development effort



SiC/SiC Truss Core

National Hypersonic Science Center for Materials and Structures

AFOSR: ***A. Sayir***
NASA: ***A. Calomino***

Teledyne Scientific
D. Marshall (materials & structures)
B. Cox (mechanics of materials)

Missouri University
W. Fahrenholtz
G. Hilmas
(UHTCs)

UC Santa Barbara
F. Zok (structural materials)
R. McMeeking (mechanics)

new materials & processing routes
new experimental methods
multi-scale models
Combine experiments and multi-scale models
into a virtual test system

UC Berkeley/ALS
R. Ritchie
(mechanics, imaging)

U. of Colorado
R. Raj (high temp. materials & properties)

U. of Miami
Q. Yang
(mechanics)

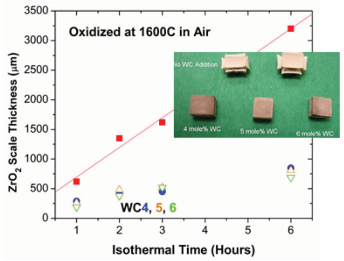
U. of Texas
P. Kroll
(atomistics)

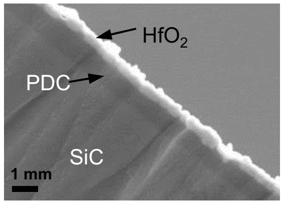
Collaborations, test and advisory support
AFRL/WPAFB (M. Cinibulk)
NASA, Boeing, ATK, Lockheed -Martin

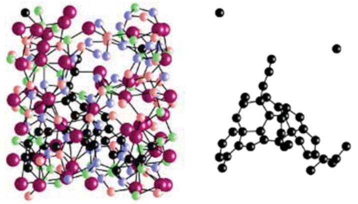
International affiliate
University of Canterbury
(S. Krumdieck)

New Materials & Processing

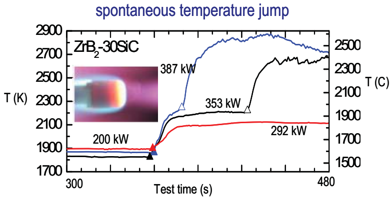
- Doped diborides for oxidation resistance at ultra high temperatures (~2000ºC); behavior in plasma envir.
- Hf-PDC based CMCs for 1600ºC
- Atomistic modeling structure & oxygen diffusion
- Processing modeling (PP-MOCVD, liquid precursors





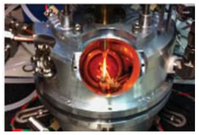


carbon flakes in $Hf_{40}Si_{40}C_{40}N_{40}O_{80}$

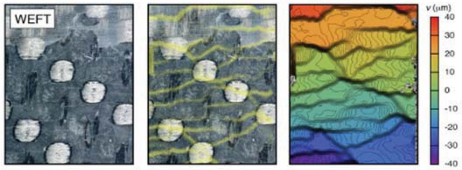


New Experimental Methods

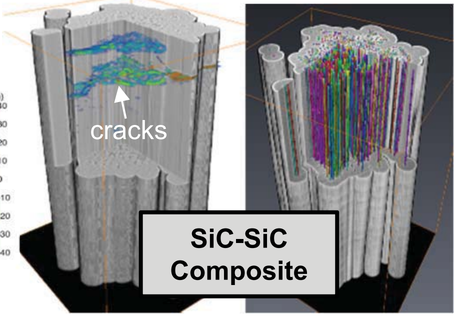
- Synchrotron micro tomography of CMCs
  - 3-D imaging of microstructure
  - In situ imaging of damage during testing at 1500ºC
- Laser-based testing
  - High thermal gradients
  - In-situ strain mapping at 1500ºC



C-SiC Composite



Optical
Superposition
Strain Map



SiC-SiC Composite

Multi-Scale Models / Virtual Test

- Numerical methods for discrete damage in CMCs
  - Augmented FEM
- Build hierarchical geometry generator based on 3-D microstructure images; port to computational mesh for each scale; add constitutive laws; run Monte Carlo predictions for damage, strength, and diffusion

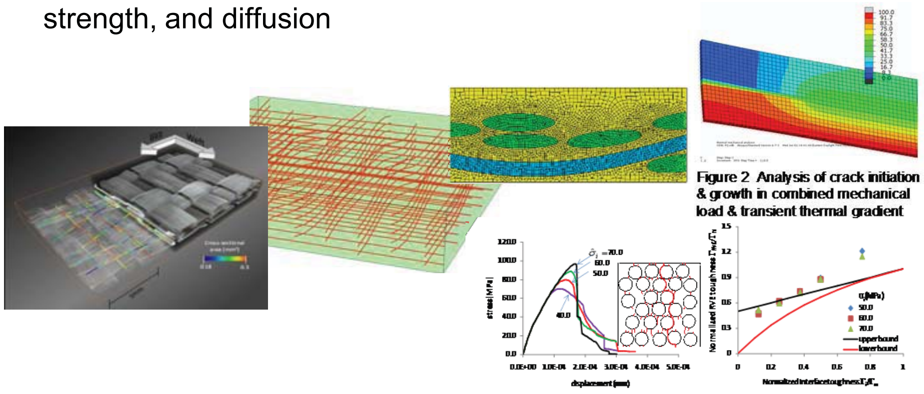
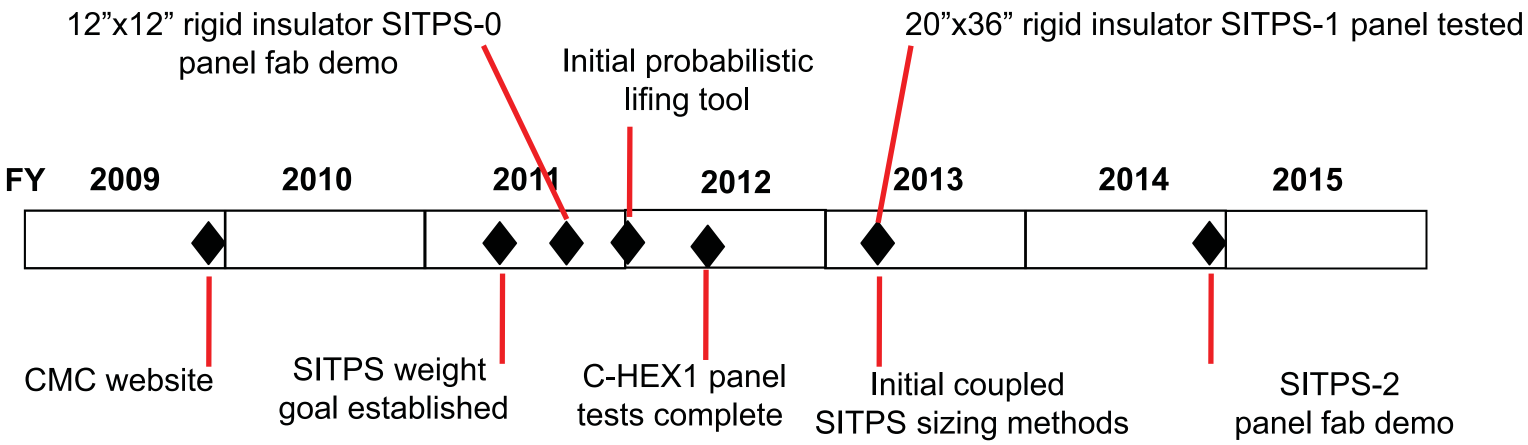


Figure 2 Analysis of crack initiation & growth in combined mechanical load & transient thermal gradient

Air-Breathing Technical Challenge

Develop integrated light-weight, reusable airframe and propulsion structures



12”x12” rigid insulator SITPS-0 panel fab demo

Initial probabilistic lifing tool

20”x36” rigid insulator SITPS-1 panel tested

FY 2009 2010 2011 2012 2013 2014 2015

CMC website

SITPS weight goal established

C-HEX1 panel tests complete

Initial coupled SITPS sizing methods

SITPS-2 panel fab demo

Intermediate Goals (2011)

Tools: Initial coupled thermal / mechanical sizing methodologies developed. Initial probabilistic approach to CMC lifing methods.

Technologies: Small-scale design, fabrication, and testing of SITPS concepts. Small-scale C-HEX panel design, fabrication, and testing.

Knowledge: Degradation of CMC materials under thermal / mechanical cycling incorporated into lifing models.

Summary

- NASA FA Hypersonic Materials and Structures – Air-Breathing Technologies is focused on developing integrated light-weight, reusable airframe and propulsion structures

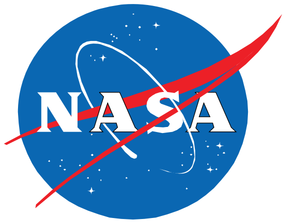
- FY11-FY12 Technical challenges focused on:
  - CMC modeling and materials
  - CMC heat exchanger development and testing (C-Hex1)
  - SITPS
    - NASA developing the technology required to advance this next generation TPS
    - Initial vehicle trades show SITPS reducing vehicle weight (>9%)
    - Developing analytical tools for system level analysis

- FA Hypersonics continues jointly funding National Hypersonic Science Centers for Materials & Structures with AFOSR

- Activities beyond FY13 uncertain

Acronyms

AFOSR: Air Force Office of Scientific Research
CFD: Computational Fluid Dynamics
CMC: Ceramic Matrix Composite
CVI: Chemical Vapor Infiltration
C-Hex: Ceramic Composite Heat Exchanger
C-Hex1: C-Hex panel with metallic tube and manifold design
C-Hex2: C-Hex panel and manifold with no metallic tubes
C/SiC: Carbon (matrix) - Silicon Carbide (fiber) CMC
DCR: Durable Combustor Rig (NASA Langley)
FA: Fundamental Aeronautics
FS: Facesheet
H/C: Honeycomb
M&P: Manufacturing & Processing
NASA: National Aeronautics and Space Administration
NDE: Non-Destructive Evaluation
PIP: Polymer Impregnation and Pyrolysis
RALV: Re-usable Air-breathing Launch Vehicle
RSTA: Ruddervator Subcomponent Test Article
SiC/SiC: Silicon Carbide (matrix) – Silicon Carbide (fiber)
SITPS: Structurally Integrated Thermal Protection Systems
SOA: State-of-the-art
TPS: Thermal Protection System


NASA