11-6-2017

Overview of ceramic matrix composite research at NASA Glenn Research Center

James D. Kiser et al
NASA Glenn Research Center, USA, james.d.kiser@nasa.gov

Joseph E. Grady
NASA Glenn Research Center, Cleveland, OH

Craig E. Smith
NASA Glenn Research Center, Cleveland, OH

Roy M. Sullivan
NASA Glenn Research Center, Cleveland, OH

Valerie L. Wiesner
NASA Glenn Research Center, Cleveland, OH

See next page for additional authors

Authors
James D. Kiser et al, Joseph E. Grady, Craig E. Smith, Roy M. Sullivan, Valerie L. Wiesner, Janet B. Hurst, Steven M. Arnold, Dongming Zhu, Amjad S. Almansour, Ramakrishna T. Bhatt, Sreeramesh Kalluri, and Sai Raj

OVERVIEW OF CERAMIC MATRIX COMPOSITE RESEARCH AT NASA GLENN RESEARCH CENTER

J. Douglas Kiser[1], Joe Grady[1], Ram Bhatt (OAI*), Amjad Almansour[1], Craig Smith[1], Roy Sullivan[1], Sreeramesh Kalluri (OAI*), Sai Raj[1], Valerie Wiesner[1], Janet Hurst[1], Steven Arnold[1], and Dongming Zhu[1]

[1] NASA (National Aeronautics and Space Administration) Glenn Research Center Cleveland, OH USA

*** Ohio Aerospace Institute at NASA Glenn, Cleveland, OH USA**

Advanced Ceramic Matrix Composites: Science and Technology of Materials, Design, Applications, Performance and Integration (Engineering Conferences International), Santa Fe, NM Nov. 2017

CMC Research at NASA Glenn—OVERVIEW

- **NASA Glenn**
- **SiC/SiC Ceramic Matrix Composites (CMCs) and Environmental Barrier Coatings (EBCs) for Aircraft Gas Turbine Engine Applications**
- **Development & Characterization of SiC/SiC CMCs and EBCs**
- **Generation of SiC/SiC Minicomposite and SiC Fiber Creep Data to *Support* Modeling of CMC Behavior**
- **Collaborations With Other Organizations**
- **Higher TRL (Technology Readiness Level) Testing**
- **Modeling of GRC 2700°F Hybrid SiC/SiC CMC Performance**
- **Future Directions *and* Summary**

Our research has been focused on the next generation of CMC/EBC systems capable of operating at 2700°F with reduced or no cooling

Additional GRC CMC and EBC Presentations

These other presentations will be given Tuesday - Thursday

Tuesday, November 7, 2017

09:50 - 10:15 **Creep durability of 3D woven SiC/SiC composites with (CVI+PIP) hybrid matrix**
R.T. Bhatt, OAI/NASA Glenn Research Center, USA

10:15 - 10:40 **SiC fibers and SiC/SiC ceramic matrix minicomposites damage behavior**
Amjad Almansour, NASA Glenn Research Center, USA

Wednesday, November 8, 2017

17:15 - 17:40 **Calcium-magnesium alumino-silicates (CMAS) reaction mechanisms and resistance of advanced turbine environmental barrier coatings - SiC/SiC CMCs**
Dongming Zhu, Gustavo Costa, Bryan Harder, Valerie L. Wiesner, Janet B. Hurst
NASA Glenn Research Center, USA

Thursday, November 9, 2017

09:00 - 09:25 **Current EBC development and testing at NASA**
Kang Lee, Deborah Waters, Gustavo Costa, Bernadette Puleo, NASA GRC, USA

10:15 - 10:40 **Development of NASA's advanced environmental barrier coatings for SiC/SiC composites: Prime-reliant design and durability perspectives**
Dongming Zhu, NASA GRC, USA

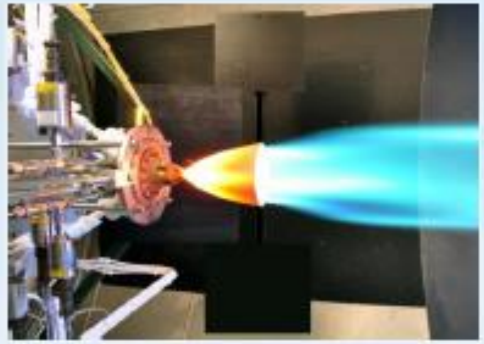
National Aeronautics and Space Administration

John H. Glenn Research Center (GRC)

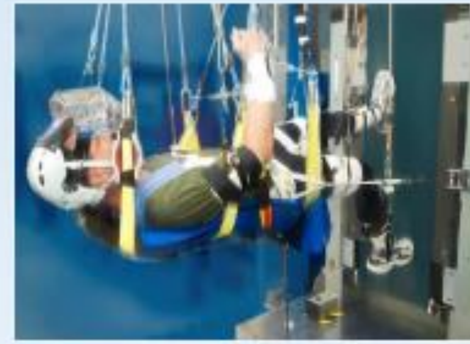
- **John H. Glenn Research Center (GRC) at Lewis Field is one of nine National Aeronautics and Space Administration (NASA) Centers**
- **Originally: NACA (National Advisory Committee on Aeronautics) Engine Research Laboratory (Opened in 1941)**

NASA Glenn Core Competencies

Air-Breathing Propulsion



In-Space Propulsion and Cryogenic Fluids Management



Physical Sciences and Biomedical Technologies in Space

Communications Technology and Development

Power, Energy Storage and Conversion

Materials and Structures for Extreme Environments

Support for our CMC Research in 2016 - 2017 has Been Provided by These NASA Aeronautics Programs:

Transformative Aeronautics Concepts Program

- Transformational Tools & Technologies (TTT) Project
- Convergent Aeronautics Solutions (CAS) Project

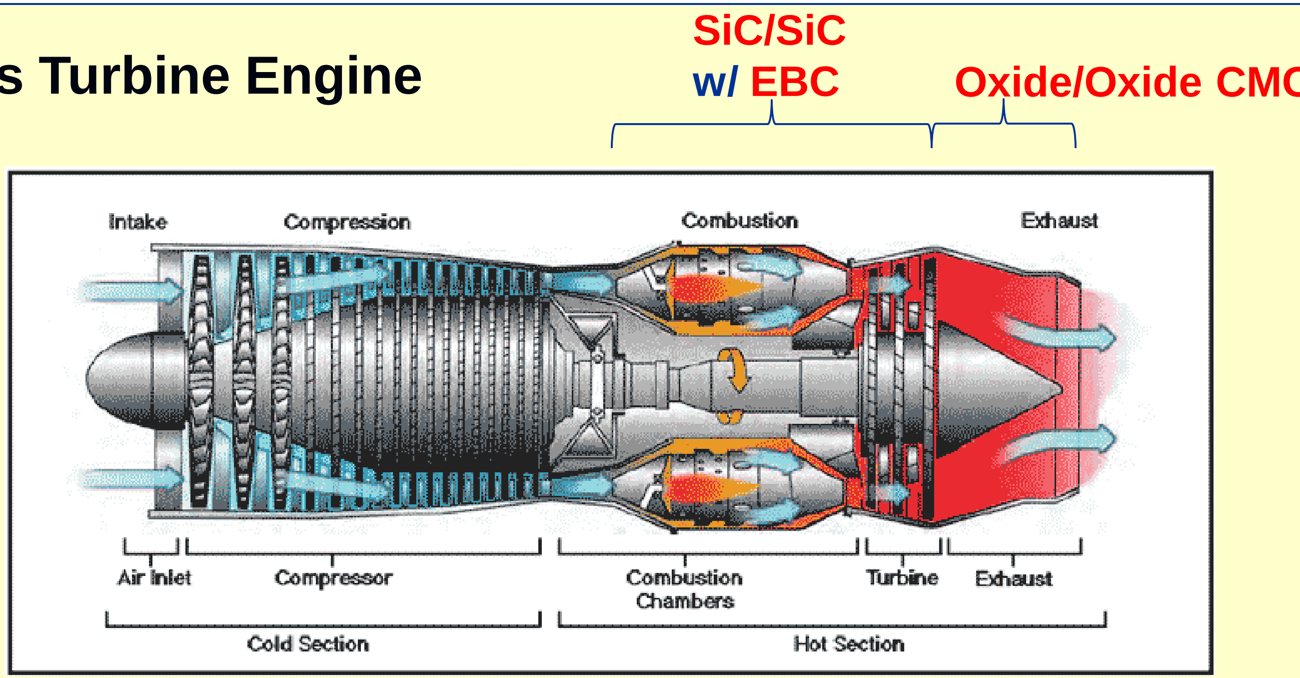
Advanced Air Vehicles Program

- Advanced Air Transport Technology (AATT) Project

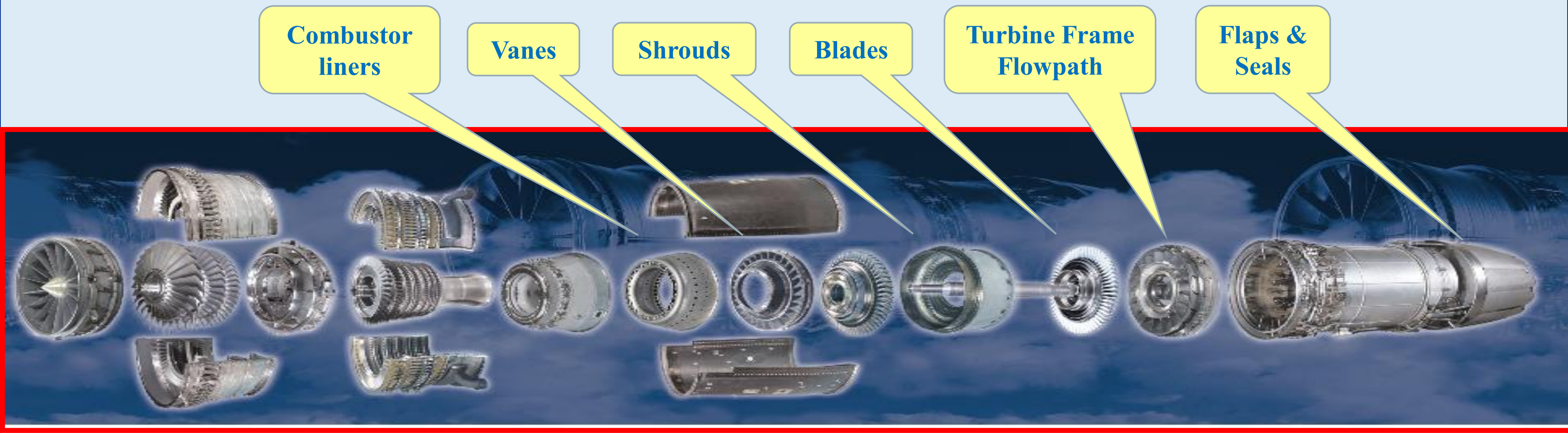
SiC/SiC CMCs: Applications and Need for Coatings

- SiC/SiC (SiC fiber reinforced SiC matrix) CMCs are being developed for / utilized in aircraft gas turbine engine hot section component applications (T ≥ 2200°F (1204°C))
- These CMC components will have an environmental barrier coating (EBC), which is a protective, multilayer oxide surface coating to prevent environmental degradation

Aircraft Gas Turbine Engine



Ceramic Matrix Composites (CMCs) for Gas Turbine Engines



- CMCs enable higher temperature capability with 200 - 500 F + temperature advantage over metals for gas turbine engine hot section components
- Density / weight = 1/3 of metals

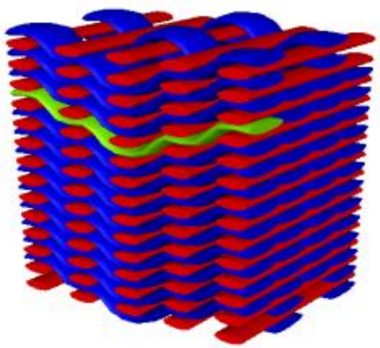
2400°F (1316°C) Today → **2700°F (1482°C)+ Future**

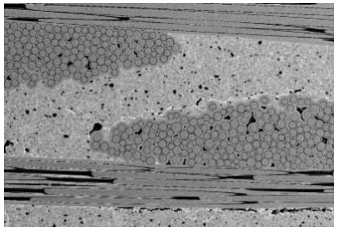
Development of a 2700°F capable CMC offers the potential of 6% fuel burn reduction

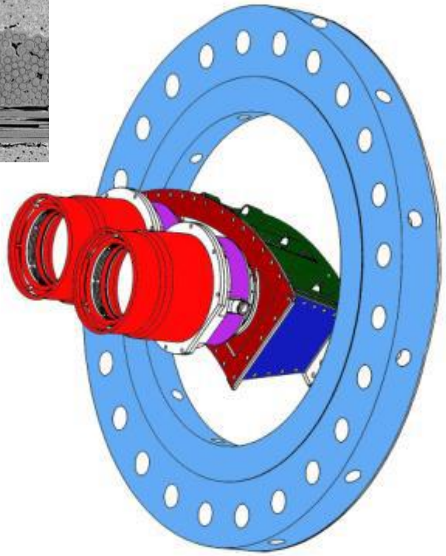
NASA Glenn — *Supporting Aeronautics via* Fiber / CMC / EBC R&D, Leadership, and Teaming

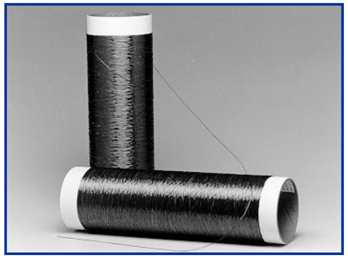
- **We have been a leader in the assessment and development of SiC fibers, SiC/SiC CMCs, and EBCs for application in advanced, efficient aircraft gas turbine engines for decades**

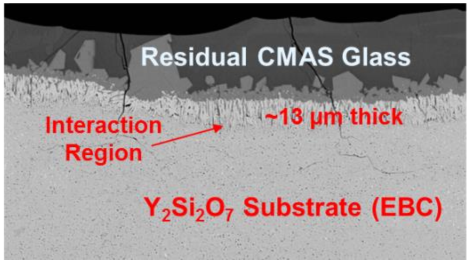
- **We have collaborated with U.S. industry, academia, and other U.S. Govt. Labs for over 25 years**

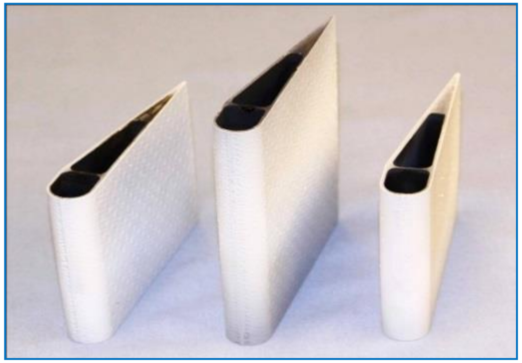












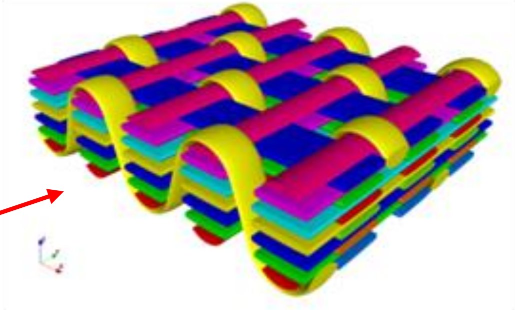
NASA GRC Development of 2700°F - Capable CMCs Incorporates Several Technology Advancements

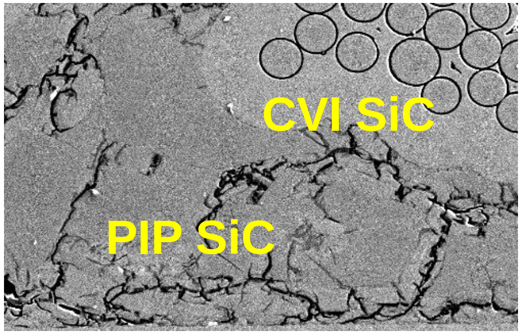
Issue: **Need for a SiC/SiC CMC with high strength, excellent creep resistance, and good transverse strength and thermal conductivity, for use at 2700ºF.**

Addressed by:

Exploring the combination of:

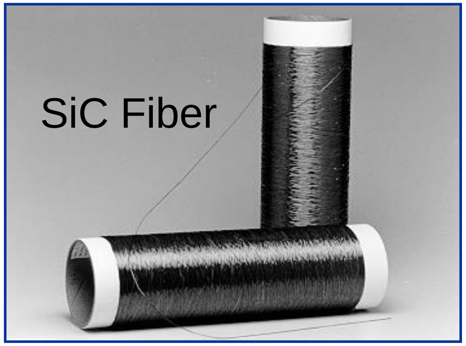
- ***Creep-resistant SiC fiber***
  - **Evaluated Hi-Nic S™, Sylramic™-iBN, and Super Sylramic™-iBN**
- ***Advanced 3D fiber architecture***
  - **Evaluated weaves including orthogonal and angle interlock with high fiber content in the "loading" direction**
- ***"Hybrid" SiC matrix***
  - **CVI SiC matrix around BN-coated SiC fibers, with 30 - 35% porosity remaining, followed by PIP**



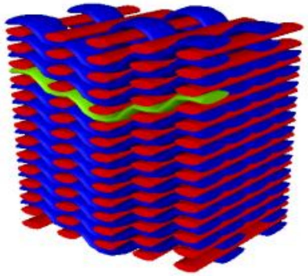


Contact: Ramakrishna.T.Bhatt@nasa.gov

Hybrid (CVI + PIP) SiC/SiC CMC Manufacturing Process



Weave into 2D Fabric
or ***Designed*** 3D Preform



Stacked 2D Fabric
or 3D Preform

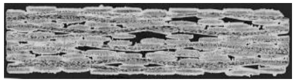
Place in
Tooling

CVI Interphase
(Fiber Coating)
Deposition
[BN]

Reactor

CVI SiC Matrix
Deposition

Reactor



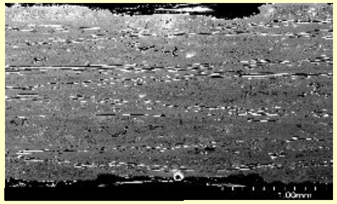
Porous "Preform"

PIP –

Polymer
Infiltration and
Pyrolysis SiC
Matrix

Furnace

Dense Hybrid SiC/SiC
For 2700°F Application



no free silicon in matrix

Contact: Ramakrishna.T.Bhatt@nasa.gov

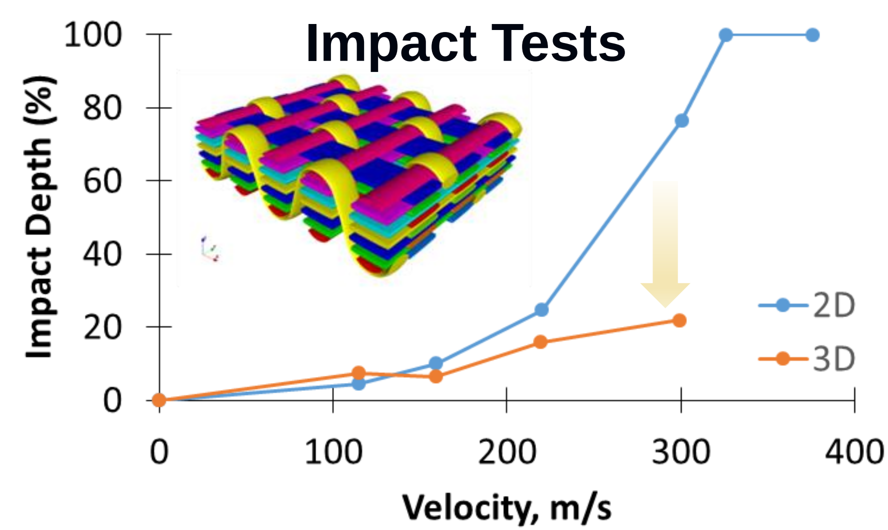
NASA GRC Development of 2700°F - Capable CMCs Incorporates Several Technology Advancements

Issue: **Need for a SiC/SiC CMC with high strength, excellent creep resistance, and good transverse strength and thermal conductivity, for use at 2700ºF.**

Addressed by:

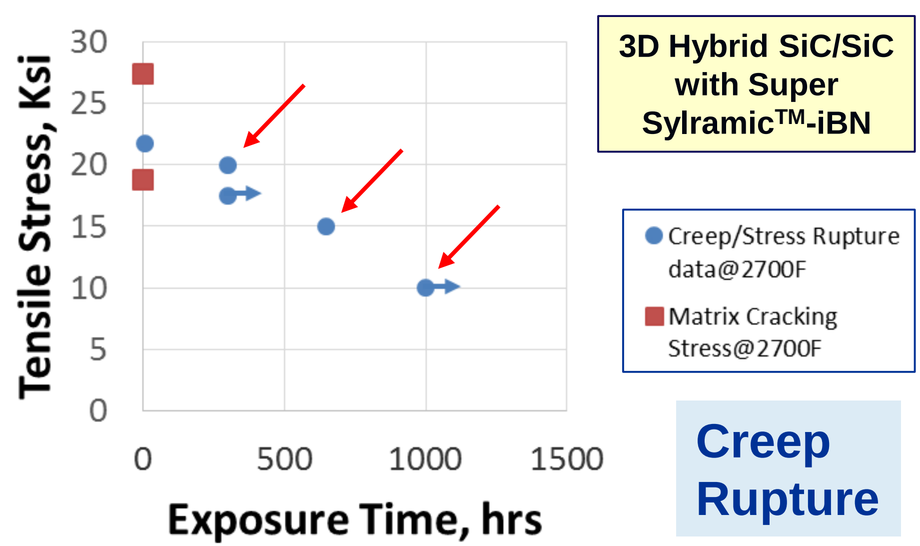
3D Architecture offers advantages over 2D Architecture (Hybrid SiC/SiC):

- **Improved impact resistance**
- **Increased through - thickness thermal conductivity**
- **Better suited to the 3D stress state of a vane**



3D Reinforced Hybrid SiC/SiC CMC:

- **Demonstrated 1000 hrs durability under 10 ksi stress at 2700ºF**
- **Demonstrated 600 hrs durability under 15 ksi stress at 2700ºF**
- **Demonstrated 300 hrs durability under 20 ksi stress at 2700ºF**



Contact: Ramakrishna.T.Bhatt@nasa.gov

Fatigue Testing of NASA CMC / EBC System Under Thermal Gradient Conditions

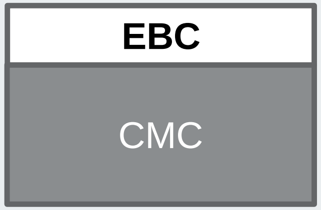
Issue: **Assessment of NASA Hybrid SiC/SiC CMC / NASA developed EBC system**

Addressed by:

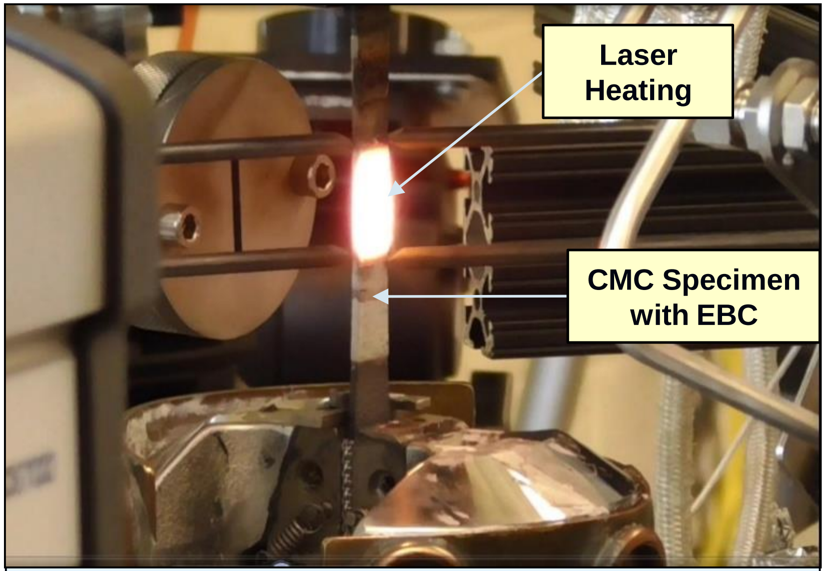
- **Laser heating with backside air cooling generates through-thickness thermal gradient. Surface temperatures measured with pyrometers and IR camera.**
- **Sustained peak low cycle fatigue (SPLCF) testing for durability assessment under thermal gradient conditions.**
- **Coated 3D Hybrid (CVI / PIP) SiC/SiC CMC demonstrated 487 hours of life under mechanical fatigue (10 ksi max stress) and sustained thermal gradient (≈ 2700°F CMC max temp).**
- **Additional testing being planned in steam environment under isothermal and thermal gradient conditions.**

Thermal gradient:
EBC Surface Temperature: 2950°F
EBC/CMC Interface Temperature: 2740°F
CMC Backside Temperature: 2440°F

Cyclic Mechanical Stress up to 10 ksi



R = 0.5 & 2 min. Hold at Max. Tensile Stress Each Cycle



EBC coated CMC under cyclic stress; one side heated by a high heat flux laser, other side air impingement cooled

Contact: Sreeramesh.Kalluri-1@nasa.gov

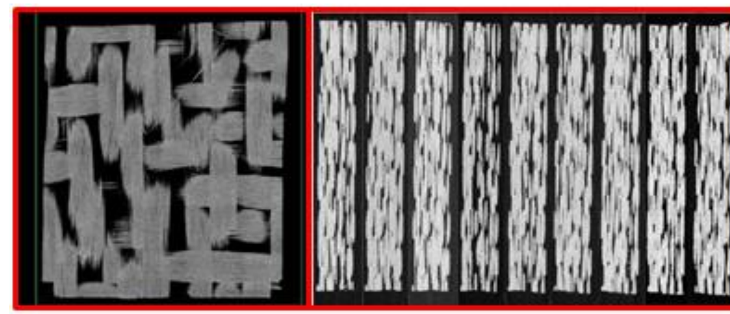
Engineered Ceramic Matrix Composite (E-CMC) Development

NASA GRC - AFRL Collaboration

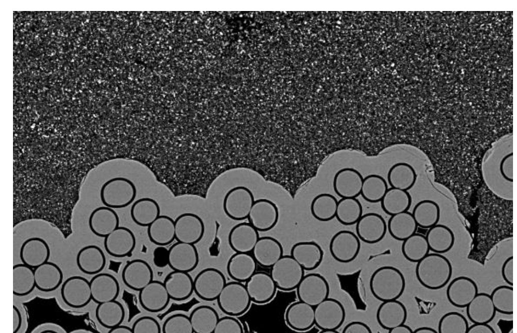
Issue: **Concern about crack formation and propagation in high temperature SiC/SiC CMCs allowing fiber degradation.**

Addressed by:

- **Develop engineered ceramic matrix composite (E-CMC) technology, featuring a filler matrix that can plastically blunt and self-heal cracks for 2700ºF (1482 ºC) applications.**
- **Filler matrix is added to CVI SiC/SiC preforms having approx. 35 vol% porosity.**
- **Engineered filler matrices formulated to match the thermal expansion of SiC fibers and possess self-healing capabilities.**
- **Engineered filler matrices have RT fracture toughnesses 2.5x that of monolithic SiC.**
- **Optimization studies of slurry infiltration of Goodrich Hi-Nic-S preforms are in progress.**
- **Melt infiltration of additional alloy can fill remaining porosity.**



CT Scan Images of As-fab CVI SiC/SiC "Preform"



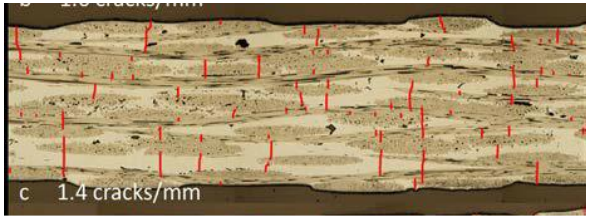
Slurry Infiltrated SiC/SiC Preform

Modeling the Effect of Damage on the Electrical Resistivity of Melt Infiltrated (MI) SiC/BN/SiC Composites

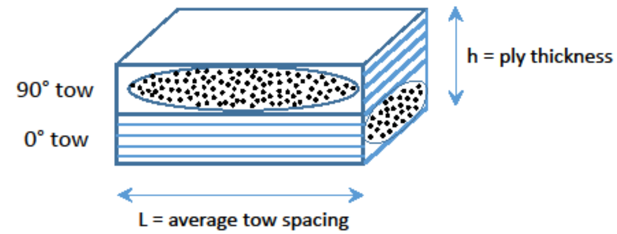
Issue: **Need for accurate damage detection and health monitoring techniques for SiC/SiC CMCs.**

Addressed by:

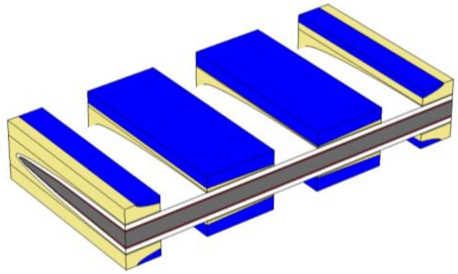
- **Developing models to help understand the effect of mechanical damage (crack density, extent, etc.) on the electrical resistivity (ER) of the composite.**
- **Focus on a specific MI SiC/SiC composite (EPM-type) at room temperature.**
  - **Previously well-characterized wrt cracking**
  - **ER of constituents measured or deduced**
- **Multi-scale finite element analysis solutions to simulate the flow of electric current through tensile dog bone specimens and mini-composites with and without damage.**
- **Compare numerical / analytical results with experimental measurements.**



Characterization of cracks in melt-infiltrated SiC/SiC CMC.



Repeating Unit Cell (RUC)



Model of unit cell with cracks in 90° tow and melt-infiltrated SiC matrix.

Contact: Roy.M.Sullivan@nasa.gov

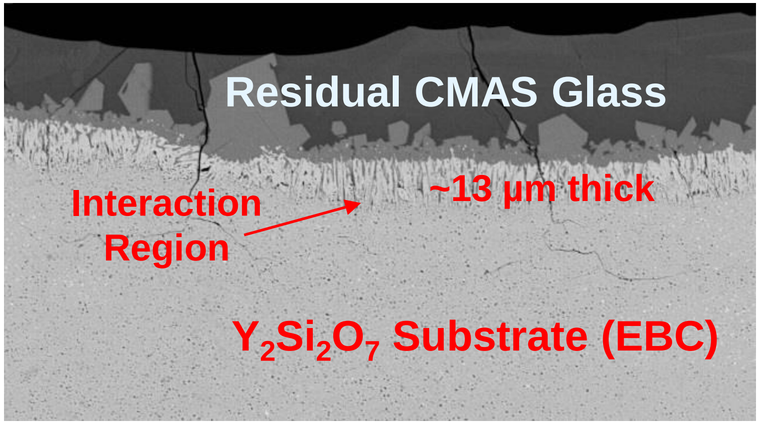
Investigation of CMAS (Calcium magnesium aluminosilicate) Properties and Interactions with EBC Materials

Issue: **Ingested particulates (e.g., sand, volcanic ash) can form molten CMAS glass deposits on EBCs in the engine hot section, with coating degradation occurring due to reaction and infiltration of the coating.**

Addressed by:

- **Characterization of thermal and mechanical properties of CMAS glass provides fundamental knowledge that will help to mitigate damage and improve EBC durability**
- **Evaluation of interactions between heat treated EBC substrates with CMAS glass pellets. EBC materials evaluated include:**
  - **Yttrium disilicate ($Y_2Si_2O_7$)**
  - **Hafnium silicate ($HfSiO_4$)**
  - **Ytterbium disilicate ($Yb_2Si_2O_7$)**

Aircraft Engines Ingesting Sand on Runway



$Y_2Si_2O_7$ Substrate Exposed to CMAS at 1200°C for 20h

Contact: Valerie.L.Wiesner@nasa.gov

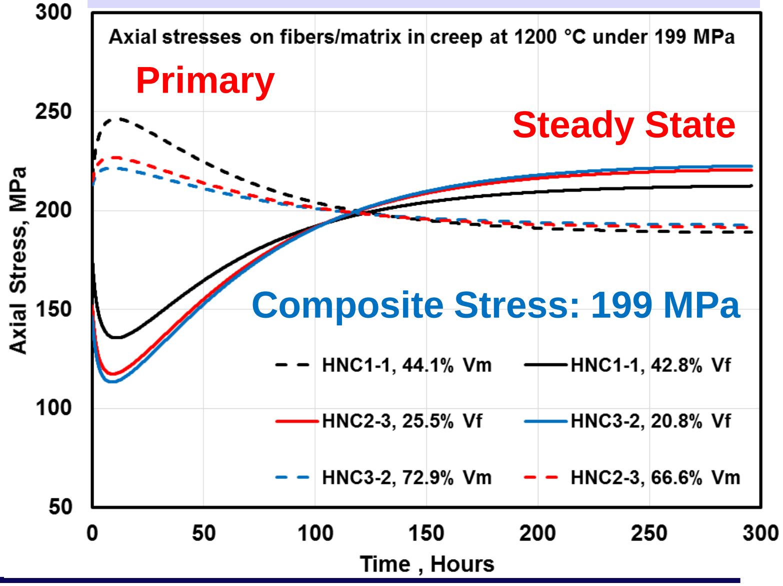
SiC_f /SiC Minicomposites Testing and Characterization

Issue: **Improved understanding of durability of NASA Hybrid SiC/SiC CMC via assessment of creep behavior of the different constituents**

Addressed by:

- **Studying stress dependent matrix crack initiation and propagation (onset and evolution at RT).**
- **Teaming with AFRL and UCSB to study different aspects of damage, including testing coated samples (CVI SiC matrix and Hi Nic Type S™ SiC fibers—from RR).**
- **Creep testing of different SiC_f /SiC minicomposites (fibers and vendors).**
- **Minicomposite creep tests in air up to 2820°F (1” hot zone).**
- **Analyzing creep behavior of the different constituents of the composite (matrix and fiber) and load transfer.**

Creep Stress Transfer Modeling Results



Contact: Amjad.S.Almansour@nasa.gov

Fiber Creep Testing and Characterization

Issue: **Improved understanding of durability of NASA Hybrid SiC/SiC CMC via assessment of creep behavior of the different constituents**

Addressed by:

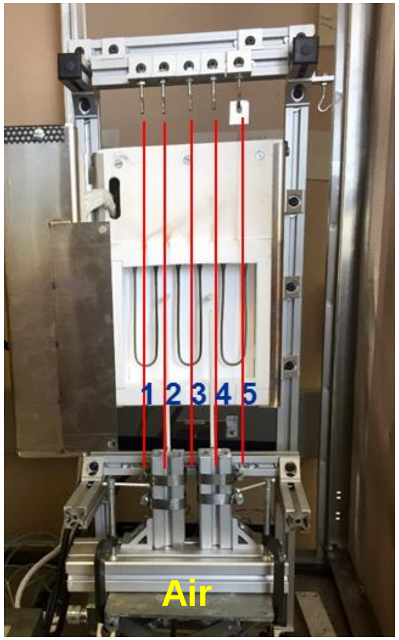
- **Testing different types of SiC fiber.**
- **Single SiC fiber creep / stressed oxidation tests in air and creep in vacuum or argon.**

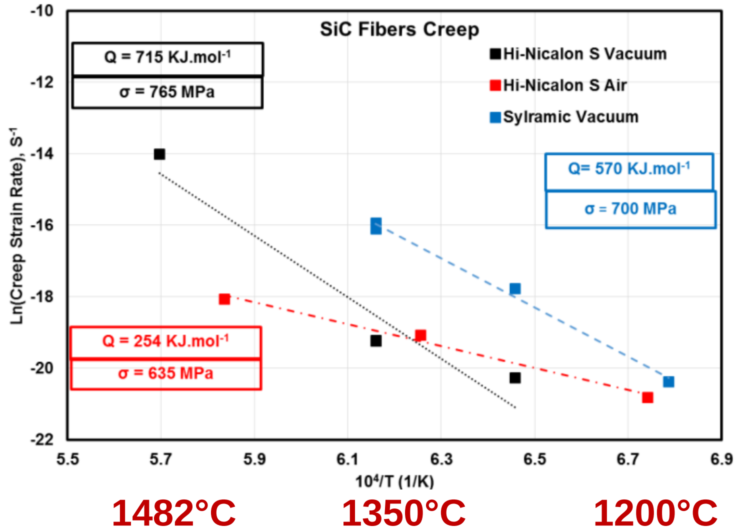
Air: 1 inch or 4 inch hot zone furnaces

- **Results are used to understand fiber creep, creep rupture, and slow crack growth (testing to 2700°F)**

Argon or vacuum: 4 inch hot zone furnace

- **Vacuum or argon environments simulate fiber conditions in uncracked composites (testing to 3000°F)**
- **Results are used in modeling creep behavior of SiC/SiC composite coupons and sub-elements**





Contact: Amjad.S.Almansour@nasa.gov

Collaborations With Other U.S. Organizations

- ***Other U.S. Govt. Labs / Organizations:***

  Air Force Research Lab (Wright-Patterson Air Force Base), Federal Aviation Administration, Office of Naval Research, National Energy Technology Lab, NASA Langley Research Center, NASA Armstrong Flight Research Center

- ***Industry:***

  General Electric Aviation, Rolls-Royce Corporation, Pratt & Whitney / United Technologies Research Center, Honeywell Aerospace, COI Ceramics, Inc., The Boeing Company, Teledyne Scientific Company, MR&D, TEAM, General Atomics, Southern Research Institute

- ***Academia:***

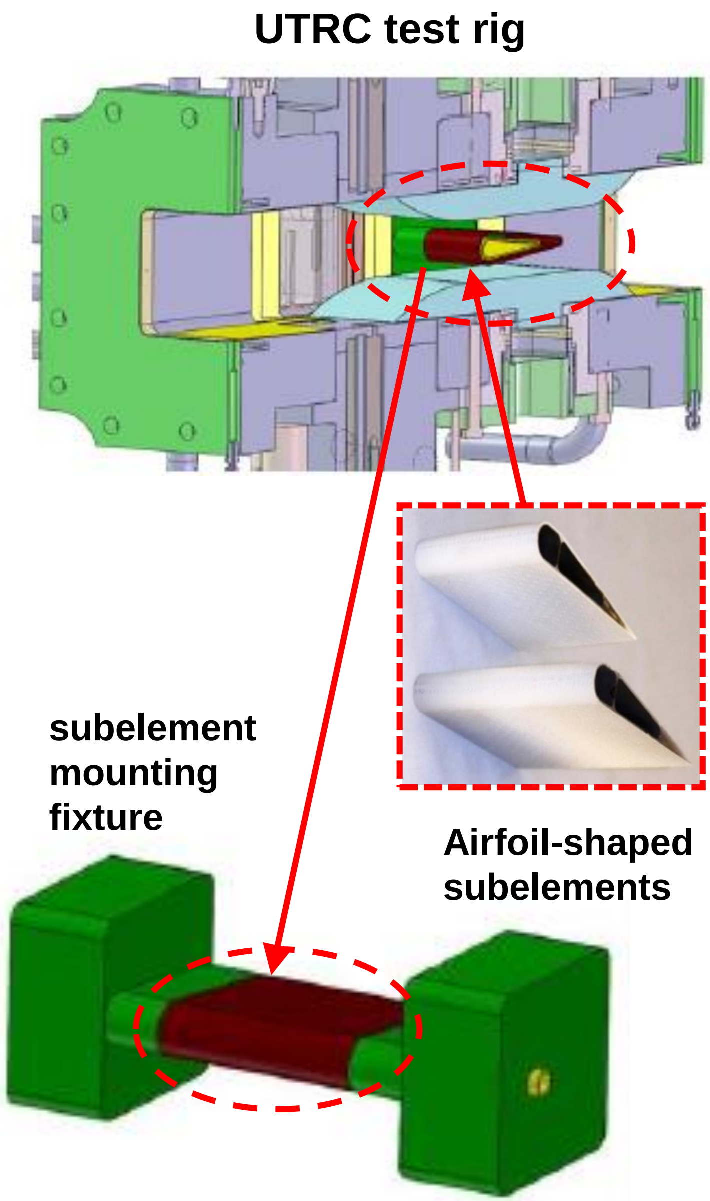
  University of Akron, University of Connecticut, Penn State University, University of Michigan, University of California at Santa Barbara, Purdue University, Wichita State University

TRL 5 Rig Test of Airfoil-Shaped Articles

Issue: **Desire to test cooled NASA Hybrid SiC/SiC CMC / NASA EBC airfoil subelements in simulated turbine engine conditions**

Addressed by: **Coated CMC subelements will be tested in UTRC test rig**

- **NASA / P&W / UTRC collaboration**
- **Airfoil-shaped test article, 3x3 inches**
- **Gas temperature up to 3600°F**
- **Mach No. 0.2 < M < 0.8 in test section**
- **1.5 lb/s airflow at 220 psia (15 atm)**
- **Internal specimen cooling allows for a tunable through-thickness temperature gradient**
- **Thermocouples, pyrometers and IR camera monitor material temperatures**



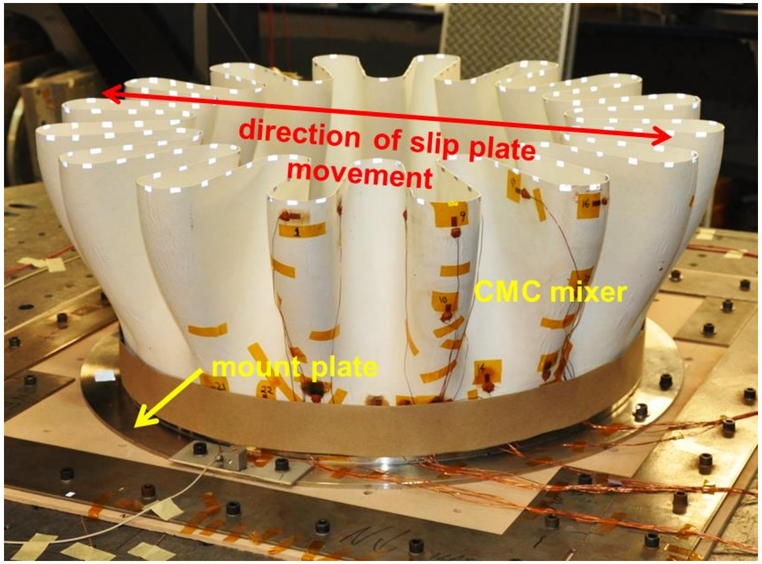
TRL 5 Room Temperature and Hot Vibration Testing of Full Scale Ox/Ox CMC Mixer

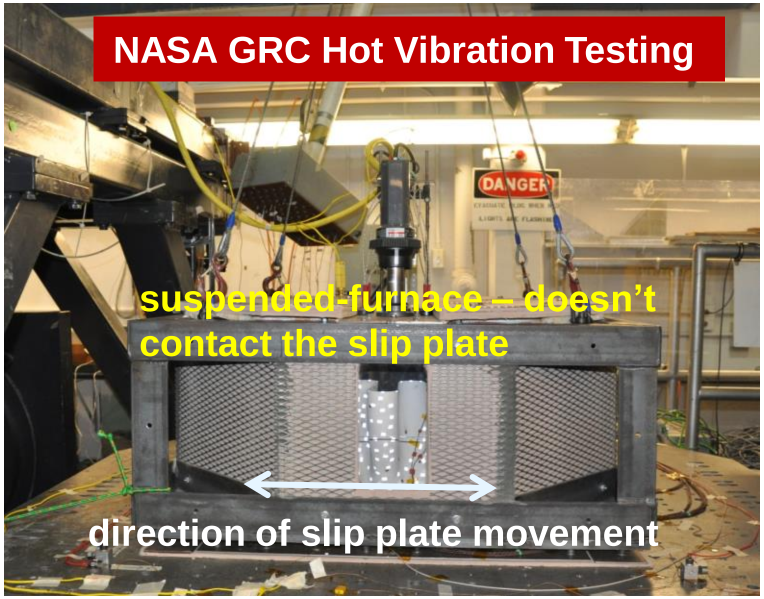
Issue: **Demonstration of an acceptable level of structural integrity during vibratory testing of a full scale oxide/oxide CMC (ceramic matrix composite) mixer**

Addressed by: **Testing in GRC Structural Dynamics Lab**

1) **Room Temperature Vibratory Tests**
   - 0.25, 0.50, 0.75, 1.00 inches/sec$_{rms}$ sine sweeps to simulate start to max. speed acceleration
   - Two 1 million cycle dwells at 2nd natural frequency and a specified maximum microstrain level
   - One million cycles completed before and after the hot vibratory testing
   - No significant anomalies noted

2) **700ºF (371ºC) Vibratory Tests**
   - 0.50, 1.00 inches/sec$_{rms}$ sine sweeps
   - 100,000 cycle dwell at 2nd natural frequency and a specified maximum microstrain level
   - Test set-up limited the length of the dwell test
   - No significant anomalies noted





Contact: James.D.Kiser@nasa.gov

GRC Modeling of CMC/EBC Behavior/Properties/Durability

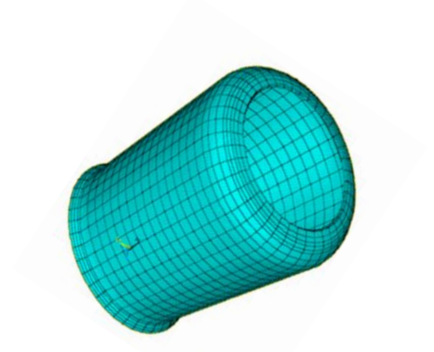
Modeling: GRC works with a range of other organizations and has a broad perspective

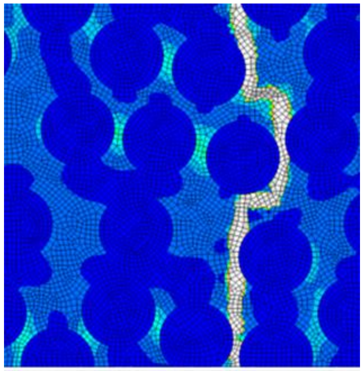
Issue: **Need for a wide range of approaches (different scales) for CMC and CMC/EBC system modeling to provide understanding of behavior / performance;**
- enabling life prediction and understanding of effects of coating and constituents.

Addressed By:

- **Goal: Model behavior of GRC Hybrid SiC/SiC / GRC EBC system**
- **Multiscale / Multiphysics Modeling**
  - **Large portfolio of internal codes / software, many of which couple with commercial codes (e.g., Abaqus, Ansys, Comsol, etc.)**
  - **Computationally-efficient methods / tools**
  - **Nonlinear deformation and damage modeling capabilities**
  - **Have modeled CMC laminate systems, SiC fibers, and CVI SiC/SiC mini-composites**
- **Conducting test plan to identify environmental effects:**
  - **Air, inert, steam, CMAS (calcium magnesium aluminosilicate) and creep / fatigue interaction with environment**
- ***Strong collaboration with industry/academia***

- **CMC & CMC/EBC system characterization & validation of models**
- **Understand effects of constituents / microstructure / environment**





Future Direction – Continue Multidisciplinary Research

AATT objectives are to address challenges unique to the implementation of CMC/EBC materials in turbine engines, specifically to:

- Determine how cooling schemes can be optimized for maximum durability of CMC/EBC turbine components*
- Develop computational models to determine optimal cooling hole configurations under combined thermal and mechanical stresses typical of a turbine engine
- Conduct thermomechanical fatigue tests to validate the model results

TTT objectives are to develop Environmental Durability Models of 2700F CMC/EBC System, specifically to:

- Develop validated models for physics-based multiscale modeling of environmental^ effects on high temperature CMC/EBC material systems
- Follow a dual path of empirical and computational model development based on both first principals methods and continuum modeling

* Using MI SiC/SiC

^ Emphasis on testing in steam

Summary

- **The push for aircraft gas turbine engines to operate at *higher temperatures* will continue, and there will be a need for higher-temperature (>2500°F/1371°C) SiC/SiC CMCs and EBCs.**

- **Our research has primarily been focused on the next generation of CMC/EBC systems capable of operating at 2700°F with reduced or no cooling.**

- **Analytical modeling of material behavior is needed to help understand CMC/EBC durability issues. That modeling will also provide guidance for material development.**

- **Future research will study cooling schemes for CMC/EBC turbine components and modeling of environmental effects on the NASA CMC/EBC system**

- **NASA GRC has a wide range of capabilities and we collaborate with U.S. industry, academia, and U.S. Govt. Labs.**

Abstract

In support of NASA's Aeronautics Research Mission, the Glenn Research Center in Cleveland, OH, has been developing and assessing the performance of high temperature SiC/SiC ceramic matrix composites (CMCs), both with and without protective coatings, for turbine engine applications. Combinations of highly creep-resistant SiC fibers, advanced 3D weaves, durable environmental barrier coatings (EBCs), and a 2700°F-capable hybrid SiC matrix have been evaluated. The effects of steam and thermal gradients on composite durability and means of monitoring and modeling damage are also being investigated. Additional studies focused on understanding the creep of SiC fibers and the behavior of SiC/SiC minicomposites that are being tested under a range of conditions are helping GRC model the thermomechanical behavior of SiC/SiC CMCs. Higher TRL (Technology Readiness Level) testing is being pursued, and SiC/SiC composites with alternate matrices providing self-healing capability are being explored. An overview of those studies will be provided. The development and validation of models for predicting the effects of the environment on the durability of CMCs and EBCs and other operating-environment challenges including the effect of CMAS (calcium magnesium aluminosilicate) degradation of EBCs will be discussed. Previous oxide/oxide composite development efforts will also be reviewed.