# CMC Research at NASA Glenn in 2018: Recent Progress and Plans

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# CMC Research at NASA Glenn

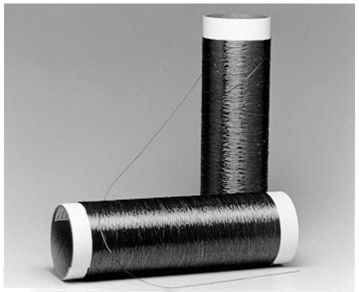
- CMC Development & Characterization
- Modeling & Validation
- Additive Manufacturing

# CMC Development and Characterization

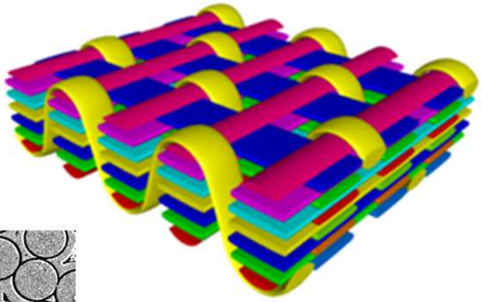
- 2700°F CMC development
- Effects of engine environment on CMC/EBC damage modes

# NASA 2700°F CMC combines three technology advancements

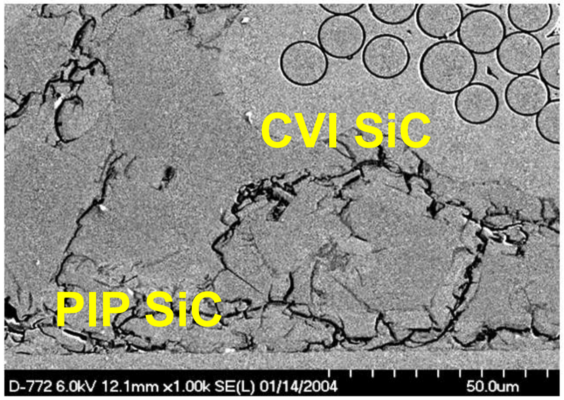
- Creep-resistant Sylramic-iBN fiber



- Advanced 3D fiber architecture



- Hybrid CVI-PIP SiC matrix



# Creep and fatigue tests demonstrated durability of 3D hybrid-matrix CMC at 2700ºF

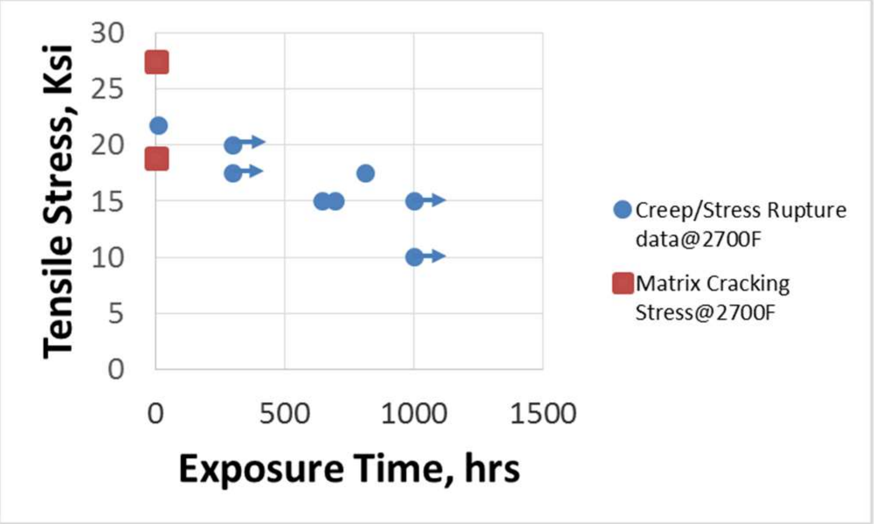
**Challenge**

Durable 2700°F Ceramic Matrix Composites will reduce cooling air required for turbine engine components, increasing engine efficiency and reducing fuel burn and emissions

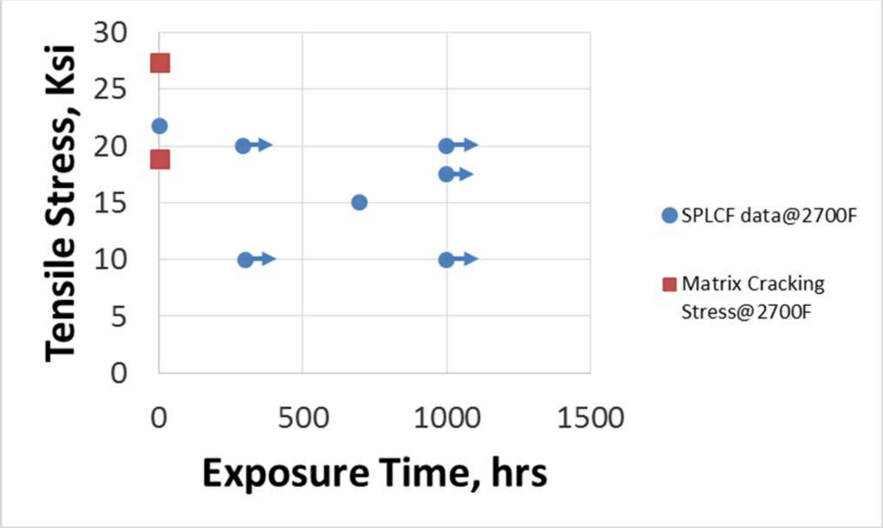
**Approach**

Characterize mechanical properties and durability of TTT-developed CMC at 2700 °F

**Creep Rupture**




**Fatigue (SPLCF)**

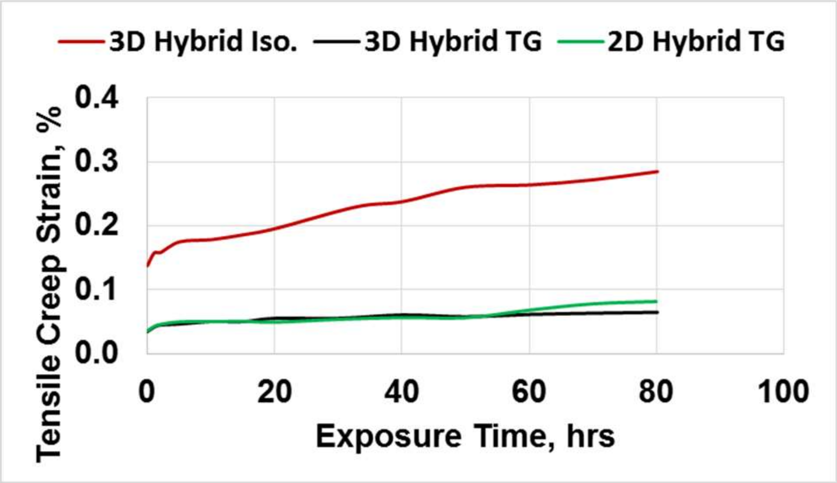


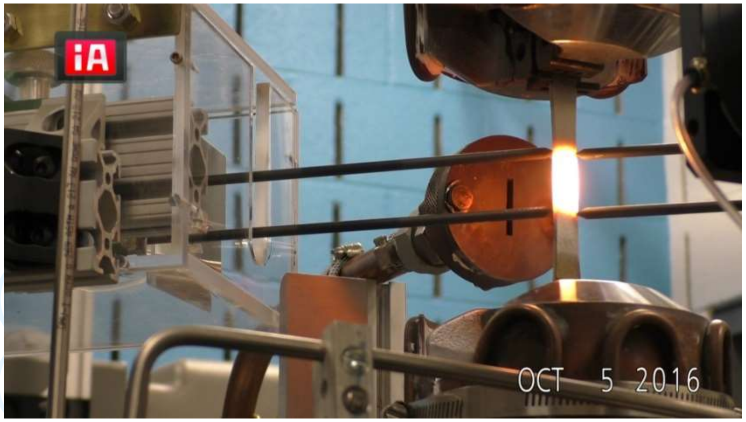

CMC shows 1000 hours durability at 2700ºF and 15-20 ksi in creep and fatigue

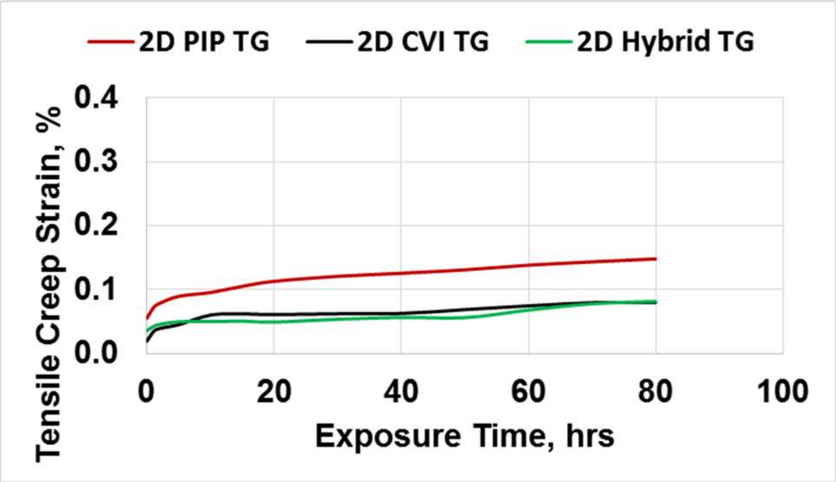
**Contact: Ramakrishna.T.Bhatt@nasa.gov**

# Effect of thermal gradients on creep strains of SiC/SiC CMCs evaluated at 2700 °F

- CMCs with 2D & 3D fiber architectures and CVI (2D only), PIP (2D only), and CVI/PIP hybrid matrices tested for 80 hours in creep at 10 ksi under isothermal & thermal gradient (TG) conditions (2700 °F max temp)
- Through-thickness TGs generated in uncoated SiC/SiC CMCs with laser heating and backside air cooling. Front and back side temp. measured with pyrometers and IR camera




Isothermal test on 3D hybrid CMC generated highest creep strain followed by TG test on 2D PIP matrix CMC. Uncoated CMCs sustained steady thermal gradients with a creep stress of 10 ksi for 80 hours without an EBC. Results of SPLCF tests generated on the same materials are being evaluated.

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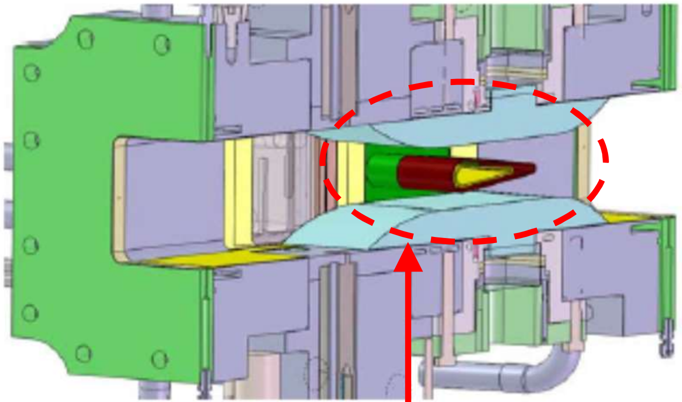
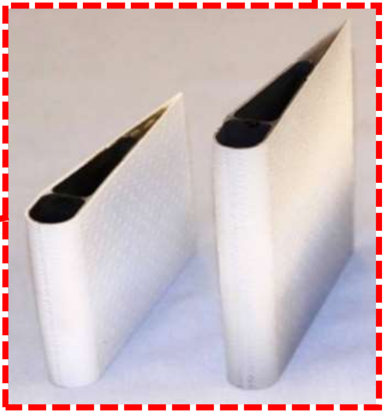
# Rig test evaluation of CMC/EBC underway at UTRC

*CMC subelement will be used to evaluate material capabilities in a simulated turbine environment*

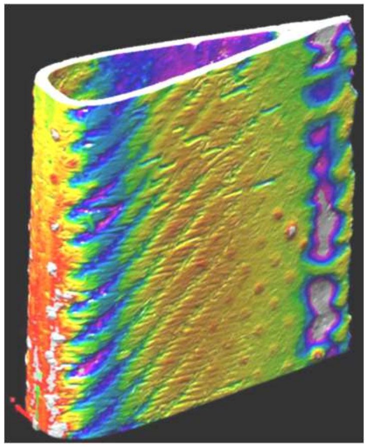
- 2700°F airfoil-shaped test article, 3x3 inches
- Mach No. 0.2 < M < 0.8 in test section
- Rig shakedown complete, test program underway
- Thermocouples, pyrometers and IR camera monitor material temperatures
- NASA / P&W / UTRC collaboration

UTRC JBTS test rig





airfoil subelements



White light imaging shows surface variability of test article



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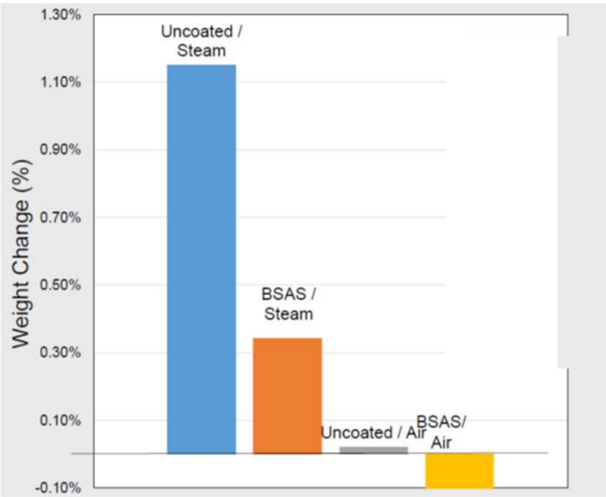
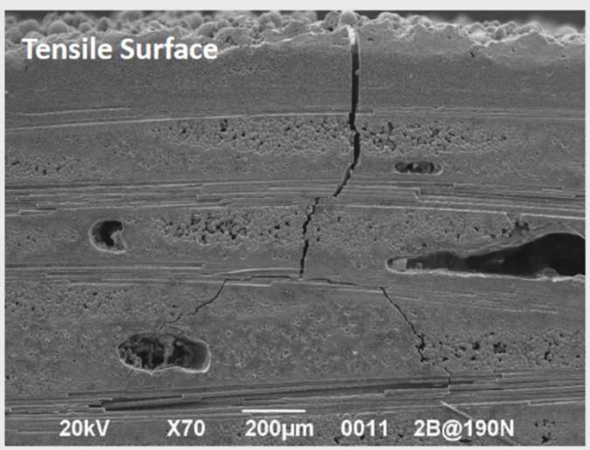
# EBC slows damage accumulation at 2200ºF in steam environment



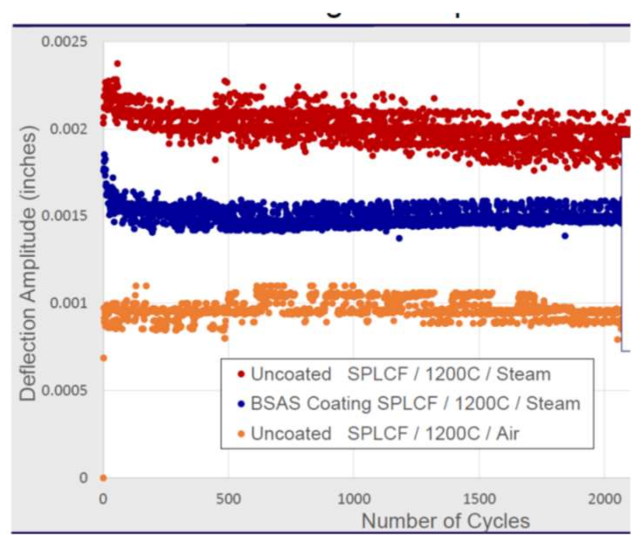

Flexural fatigue tests in steam show mechanics of damage propagation in EBC-coated CMC

EBC slows **weight gain** and **stiffness reduction** in CMC

Flexural Failure at 1200ºC




Cracks initiate in EBC (in tension), propagate into CMC, and branch at ply interface



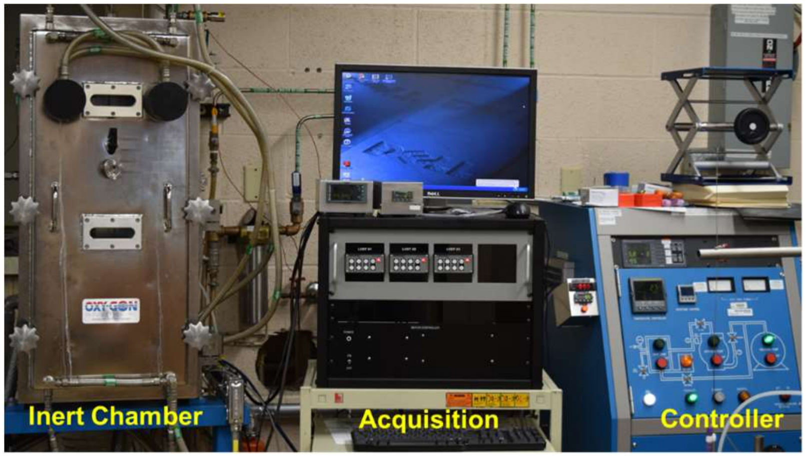

Change in amplitude with fatigue cycles

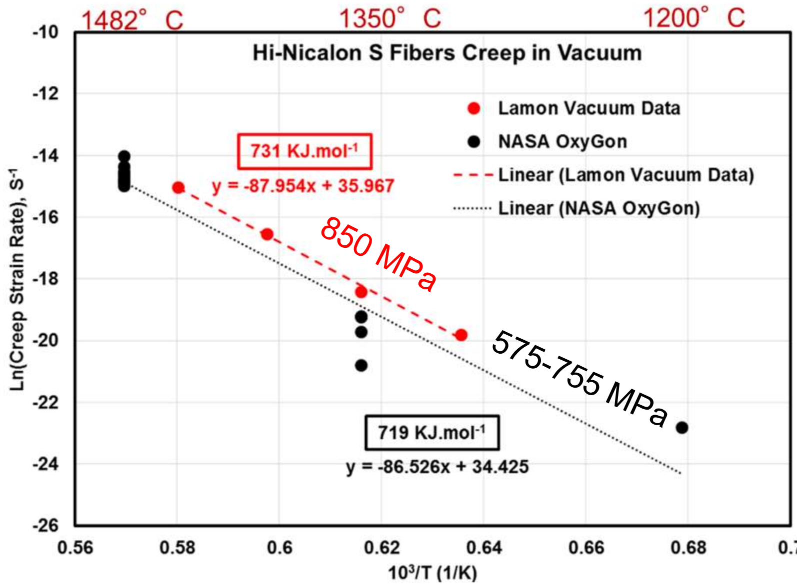
Contact: Martha.H.Jaskowiak@nasa.gov

# New lab measures environmental effect on fiber creep

**Capability:**

- New fiber characterization lab can conduct 3 simultaneous creep tests in Argon or vacuum up to 3000 ˚F.
- Inert environment simulates fiber behavior in un-cracked CMC




***Creep Measurements validated with literature data***

Characterization of creep damage in SiC fibers was used to obtain model parameters for life prediction in ceramic composites

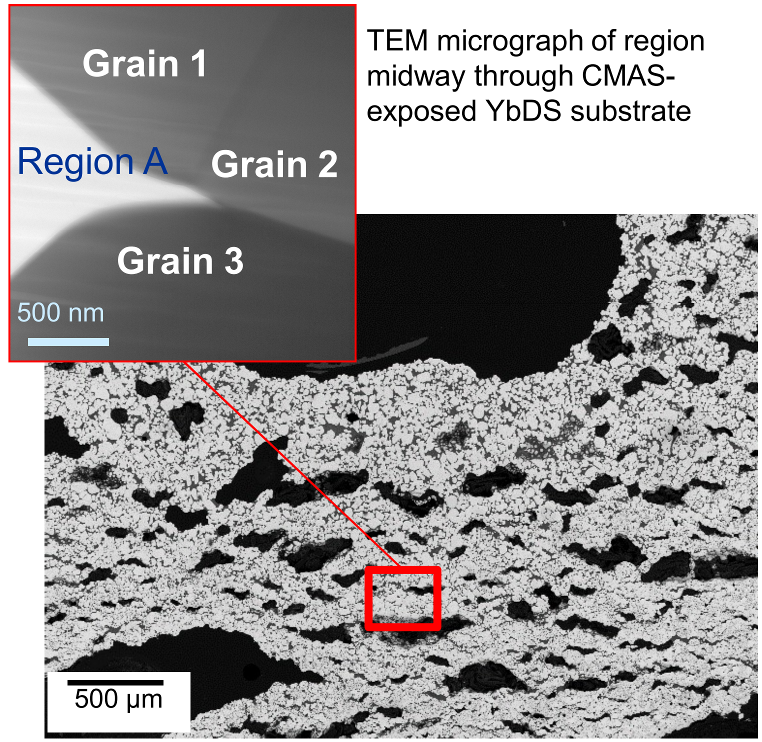
**Contact: Amjad.S.Almansour@nasa.gov**

# Development of CMAS-resistant EBCs

**PROBLEM:** Above 1100°C, molten calcium-magnesium-aluminosilicate (CMAS) can degrade environmental barrier coatings via thermochemical interactions, resulting in premature EBC failure

**APPROACH:**

- Understand causes of EBC degradation by characterizing thermochemical interactions of CMAS with ytterbium disilicate (YbDS) EBC
- Expose hot-pressed YbDS substrates to CMAS at 1200-1500ºC for 1- 50 hour durations
- Evaluate CMAS/YbDS interactions using transmission electron microscopy (TEM), selected area diffraction (SAD) and energy dispersive spectroscopy (EDS) for microstructural and compositional analysis




TEM micrograph of region midway through CMAS-exposed YbDS substrate

CMAS/YbDS substrate after 1500ºC-50h

**OBSERVATIONS:**

- CMAS infiltrated YbDS substrate, suggesting ytterbium disilicate is not effective as a standalone CMAS-resistant EBC
- TEM study revealed no apatite ($Ca_2Yb_8(SiO_4)_6O_2$) phase formation, supporting results from previous characterization

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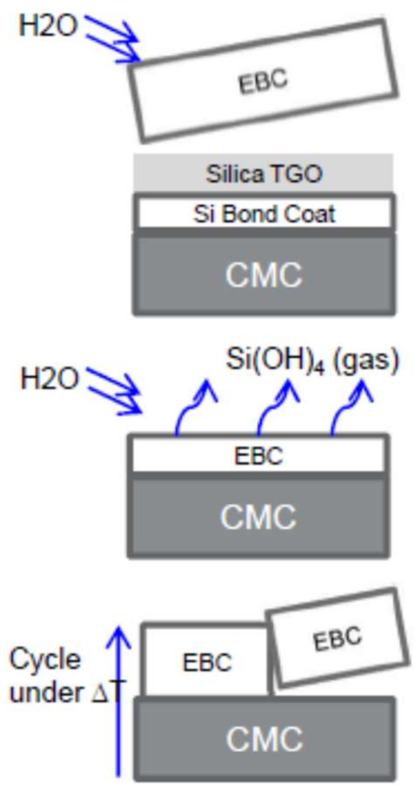
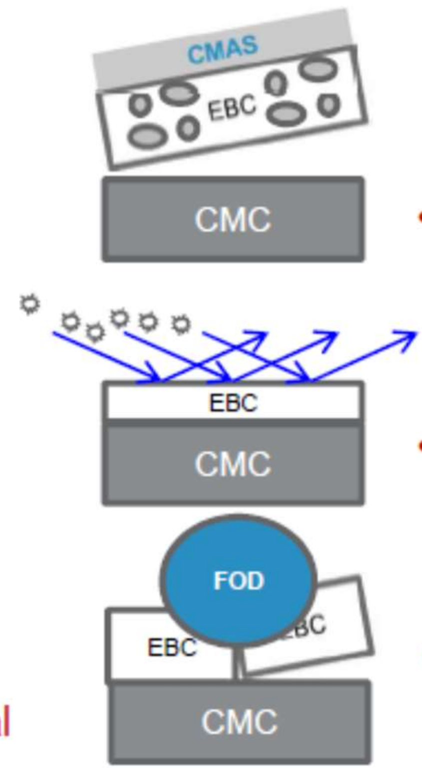
# EBC Failure Modes Investigated




- Steam oxidation
- Recession by water vapor
- Thermal fatigue
- Thermomechanical fatigue




- CMAS degradation
- Erosion
- FOD

**Contact: Ken.K.Lee@nasa.gov**

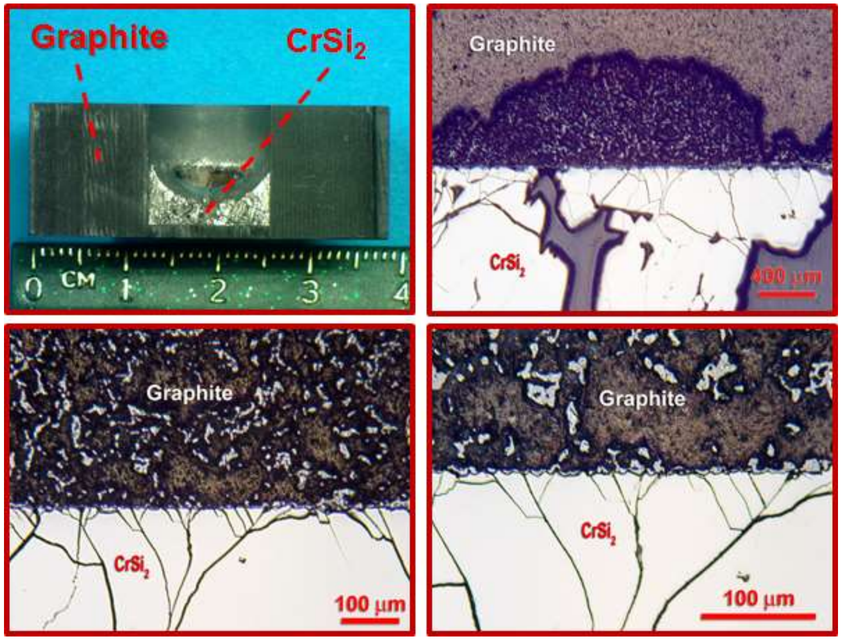
# Constituent Development and Characterization

- Engineered matrix for more durable CMC
- Fiber development and testing
- Mini-composites

# Engineered matrix under development for 2700ºF CMC

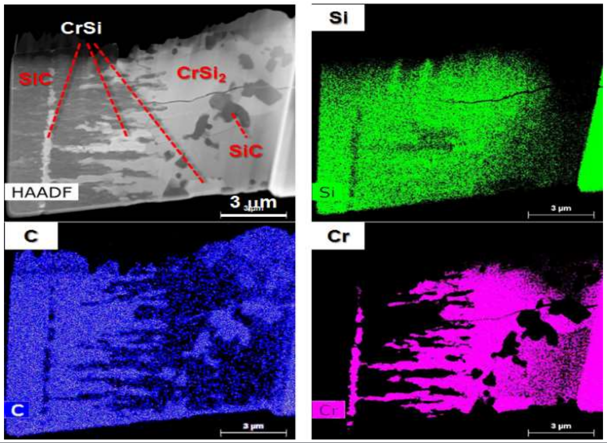
## OBJECTIVE

Develop a durable matrix material for CVI SiC/SiC preforms with improved toughness, fatigue life and self-healing properties




## APPROACH

- Formulate engineered matrix compositions for evaluation
- Optimize slurry infiltration and melt infiltration (MI) processes to densify CVI SiC/SiC preforms
- Identify optimal matrix composition based on toughness, fatigue life and self-healing properties




NASA / AFRL Collaboration

## RESULTS

- High vacuum MI leads to the decomposition of CVI SiC to carbon.
- Carbon reacts with molten $CrSi_2$ to form SiC.
- In the absence of carbon, $CrSi_2$ does not react with CVI SiC.
- Pressure melt infiltration is necessary to prevent the decomposition of CVI SiC and the subsequent reaction of molten $CrSi_2$ with the residual carbon.

Contact: Sai.V.Raj@nasa.gov

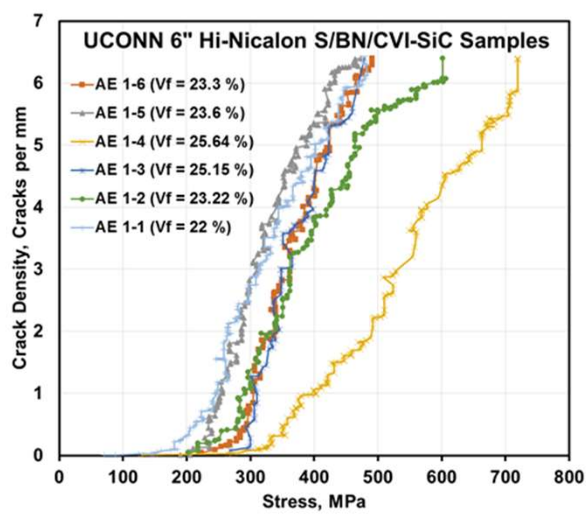
# University of Connecticut fabricated SiC / SiC "mini-composites" by Chemical Vapor Infiltration of fiber tows

## Objective:

Evaluate uniformity, damage initiation and propagation in minicomposites fabricated at the University of Connecticut

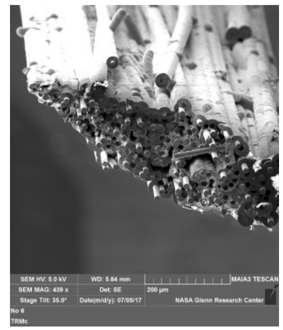
## Approach:

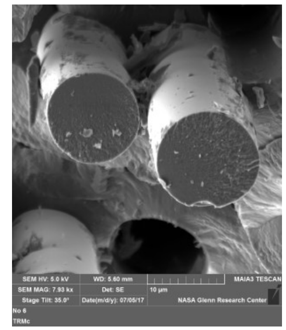
- Use acoustic emission and electrical resistance to estimate matrix cracking stress, damage initiation and progression.
- Compare tensile strength with existing fiber strength data



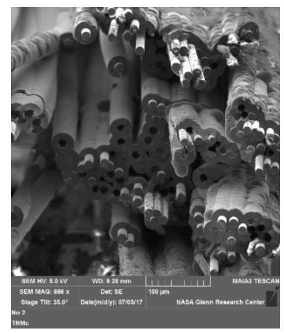

Contact: Amjad.S.Almansour@nasa.gov

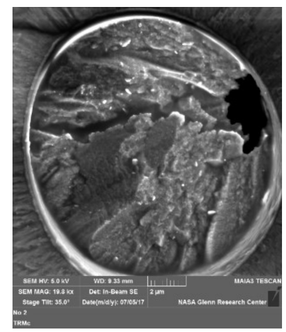
## Results:





HNSUC1-6
$V_f$ = 23.3%
$\sigma_f$ = 2093 MPa
*Low UTS is associated with large fiber's flaw size*





HNSUC1-2
$V_f$ = 23.22%
$\sigma_f$ = 2626 MPa
*High UTS is associated with small fiber's flaw size*

## Summary:

- Mechanical behavior of UConn mini-composites is consistent with existing NASA test data for mini-composites
- Minicomposites will be used for assessment of SiC / SiC environmental degradation

# Consortium Established for CMC/EBC Environmental Durability Testing, Modeling & Validation

## NASA Glenn

- Conduct mechanical testing of mini-composites at 2200-2700°F in air and steam environments
- Optimize EBC/CMC interface based on bonding and crack deflection
- Develop and validate models for mini-composite properties, durability and failure modes

## Rolls Royce HTC

- Fabricate CMC mini-composites using industry fabrication processes and constituents
- Define relevant material operating conditions; stress, temperature, environment

## Univ. California Santa Barbara

- Microstructural characterization of damage progression using Digital Image Correlation, Acoustic Emission measurement and SEM
- NASA Space Technology Research Fellowship

## Air Force Research Labs

- Damage characterization using Digital Image Correlation and AE methods
- Microstructural characterization by High Energy x-ray imaging (w/ UC Berkeley) and automated serial sectioning of test specimens with data reconstruction

**Contact: James.D.Kiser@nasa.gov**

# CMC / EBC Durability

## Modeling & Validation

- **Optimization of CMC cooling for maximum durability**
- **Experimental validation of accelerated matrix cracking model in steam environment**
- **Multi-physics model to relate CMC matrix cracking with Electrical Resistance for NDE applications**

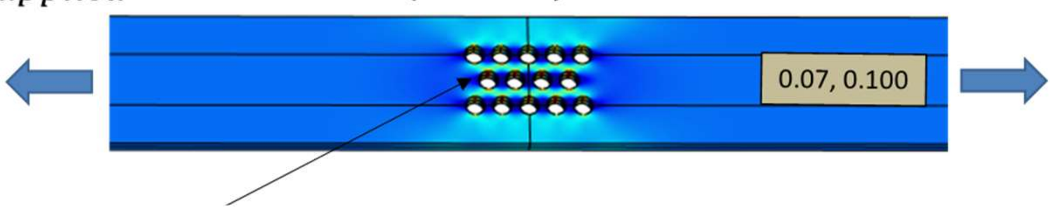
# Effects of Cooling Holes on CMC Durability

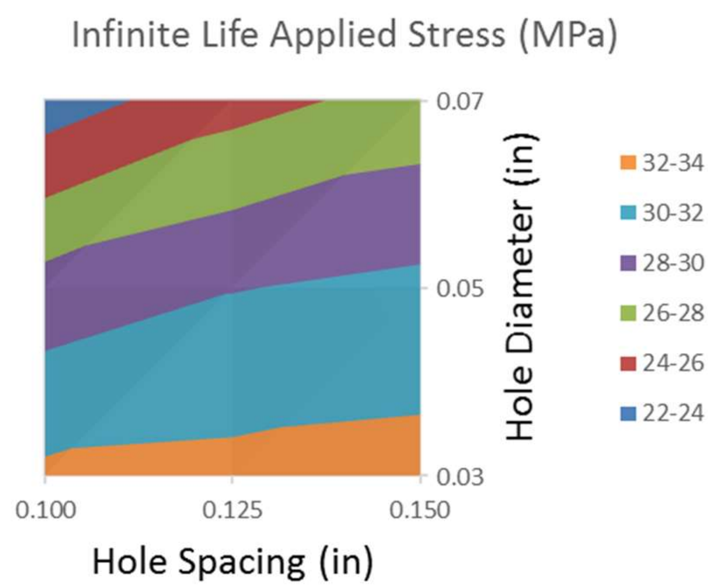
**Objective:** Use finite element analysis and coupon tests to investigate the effects of cooling hole configurations on CMC durability

**Approach:**

- Perform parameter study of effects of cooling hole geometry (spacing, diameter, orientation) on CMC fatigue life using finite element analysis
- Conduct fatigue tests to verify model predictions
- Minimize combined thermal & mechanical stresses for maximum durability of cooled CMC

$\sigma_{applied} = 22.9\ MPa\ (3.3\ ksi)$

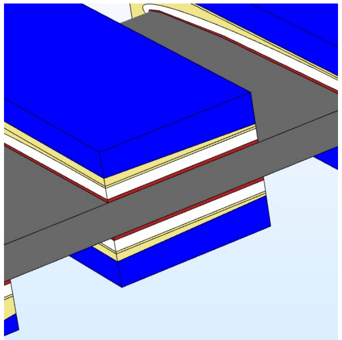


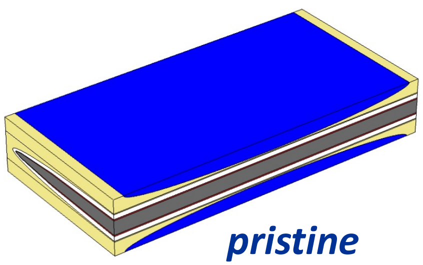

Fatigue tests will be used to verify CMC life prediction model in 2018

Contact: Roy.M.Sullivan@nasa.gov

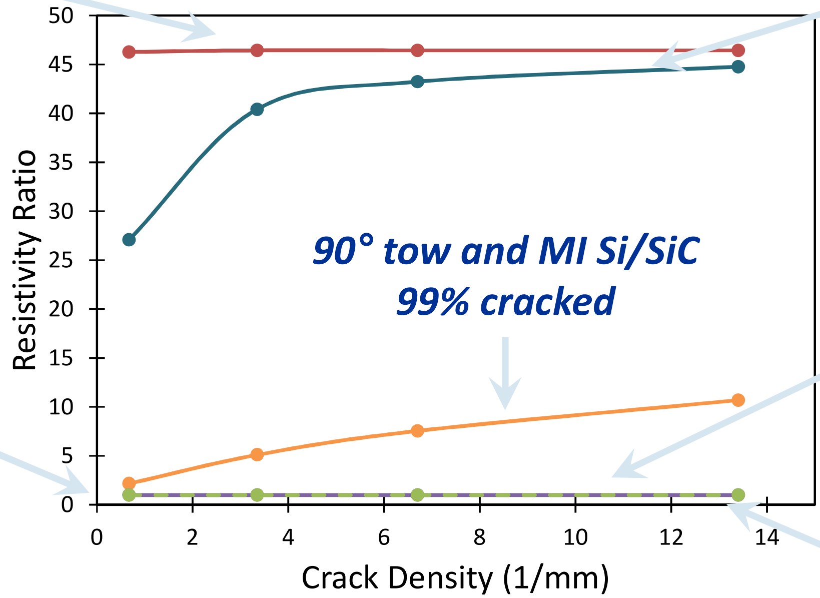
# Finite Element Analysis of unit cell with idealized damage states

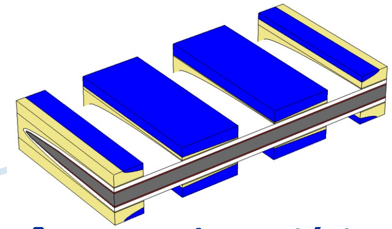


*cracks bridged by fibers*

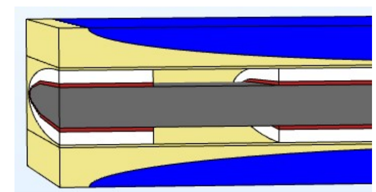


*pristine*

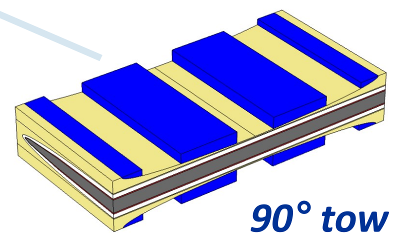


*90° tow and MI Si/SiC cracked*



*SiC and BN cracked in 0° tow*



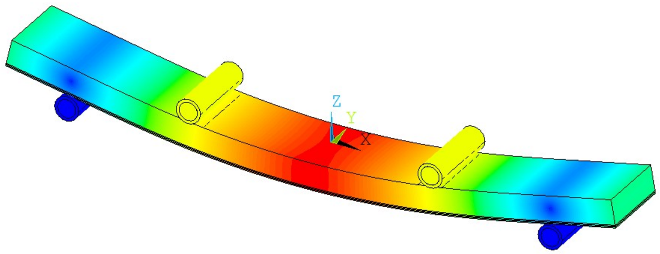
*90° tow cracked*

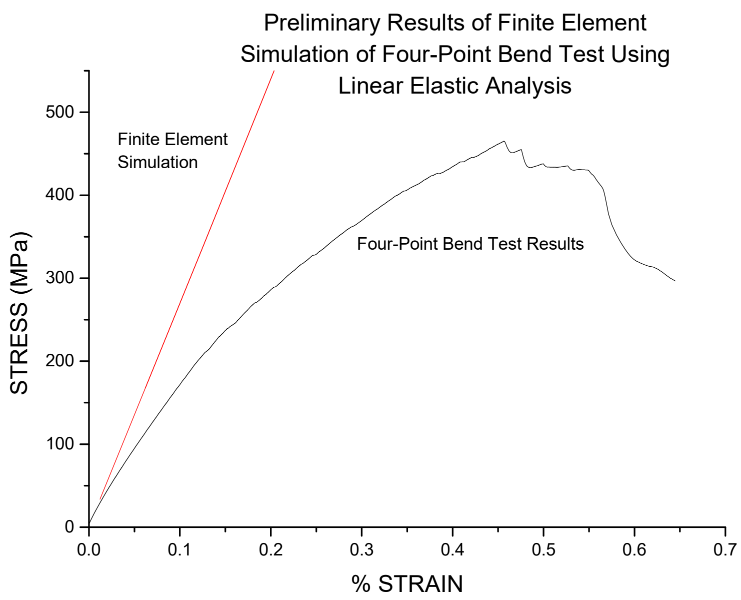
## Observations:

- Cracking within 0° or 90° tows has insignificant effect on resistivity
- Cracking of MI Si/SiC matrix has the most significant effect on resistivity

# Modeling effects of steam environment on CMC durability & failure modes

Finite Element analysis of CMC/EBC deformation under flexural loading without damage effects. Calculated strength and displacement were comparable with measured values



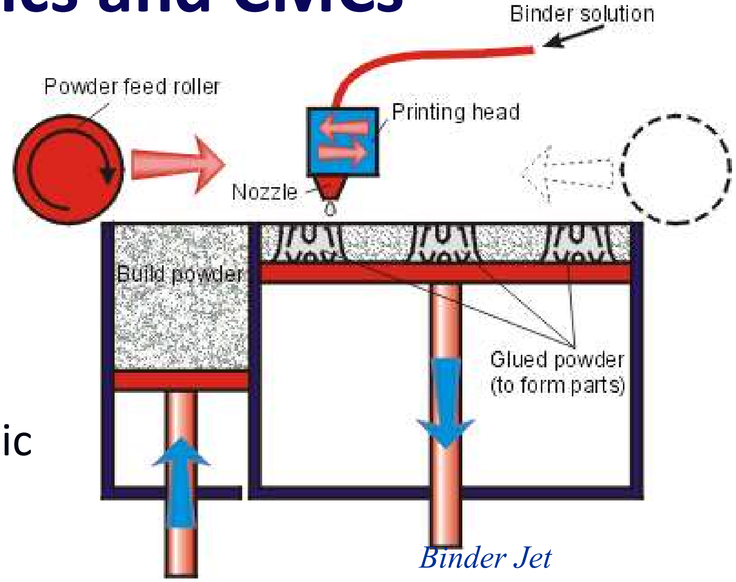




Results will serve as the baseline to assess effects of steam on CMC/EBC fatigue life

# Additive Manufacturing

- **Modified “Binder Jet” process for ceramics and CMCs**
- **Direct Printing for motor components**

# Additive Manufacturing of Ceramics and CMCs




*Binder Jet process*

## Objective

Accelerate the fabrication, testing & process optimization for CMC fabrication at reduced cost

## Approach

- Modify a binder jet machine to fabricate monolithic SiC and SiC CMC
- Characterize the effect of fabrication process parameters and powder composition on microstructure and mechanical properties
- Demonstrate dense monolithic SiC before progressing to chopped-fiber CMC

## Benefit

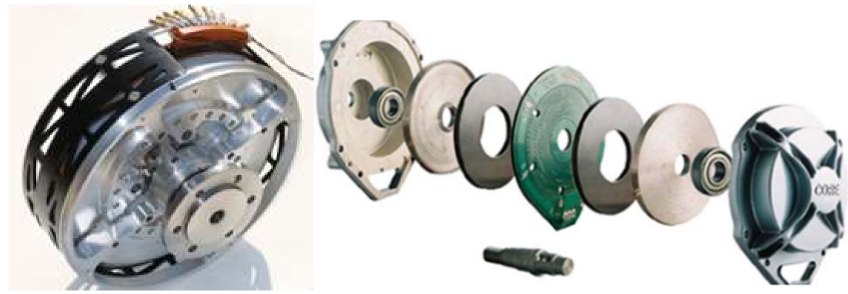
Additive manufacturing of thermally conductive SiC could enable low cost fabrication of lightweight heat exchangers for high power density propulsion systems

**Contact: Craig.E.Smith@nasa.gov**

# Additive Manufacturing for electric motor fabrication

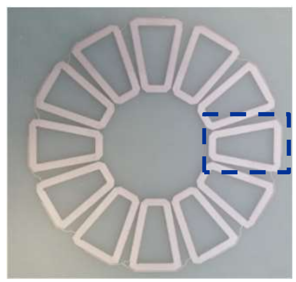
**Objective:** Use additive manufacturing methods to build more efficient, higher power density electric motors

**Approach:** AM is enabling compact motor designs with lightweight structures, innovative cooling, high copper fill, and multi-material components



Axial Flux Machine – pancake motor

Distributed electric propulsion concept



Higher Electrical Conductivity Coils

Improved air flow for better thermal management

Lightweight structures

**Production Benefits:** AM eliminates extensive machining, expensive tooling and design changes and high labor cost of conventional manufacturing.

**Team members:** NASA (GRC, LaRC, ARC) LaunchPoint Technologies and University of Texas - El Paso

Contact: Michael.C.Halbig@nasa.gov

# NASA GRC Focus in 2018

## CMC / EBC Durability Modeling & Validation

- Measure effects of environment (steam, CMAS) and cooling holes on CMC durability
- Complete turbine rig test evaluation of 2700°F CMC / EBC
- Validate CMC creep model at 2700ºF with mini-composite tests
- Validate SiC fiber crack growth model for CMC rupture life prediction

## Additive Manufacturing

- Optimize “binder jet” process for dense SiC and chopped-fiber CMC’s
- Demonstrate Direct Printing for lightweight electric motor components and measure power density improvement in motor tests

# Support for CMC research comes from these NASA programs:

**Advanced Air Vehicles Program**

- Advanced Air Transport Technology Project

**Transformative Aeronautics Concepts Program**

- Transformational Tools & Technologies Project
- Convergent Aeronautics Solutions Project