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

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NASA Aeronautics Six Strategic Thrusts

NASA has identified Six Strategic Thrusts to focus research in response to Three Aviation Mega-Drivers. Subsonic Transport and Vertical Lift are considered separately.

T1 — **Safe, Efficient Growth in Global Operations**
- Enable full NextGen and develop technologies to substantially
- reduce aircraft safety risks

T2 — **Innovation in Commercial Supersonic Aircraft**
- Achieve a low-boom standard

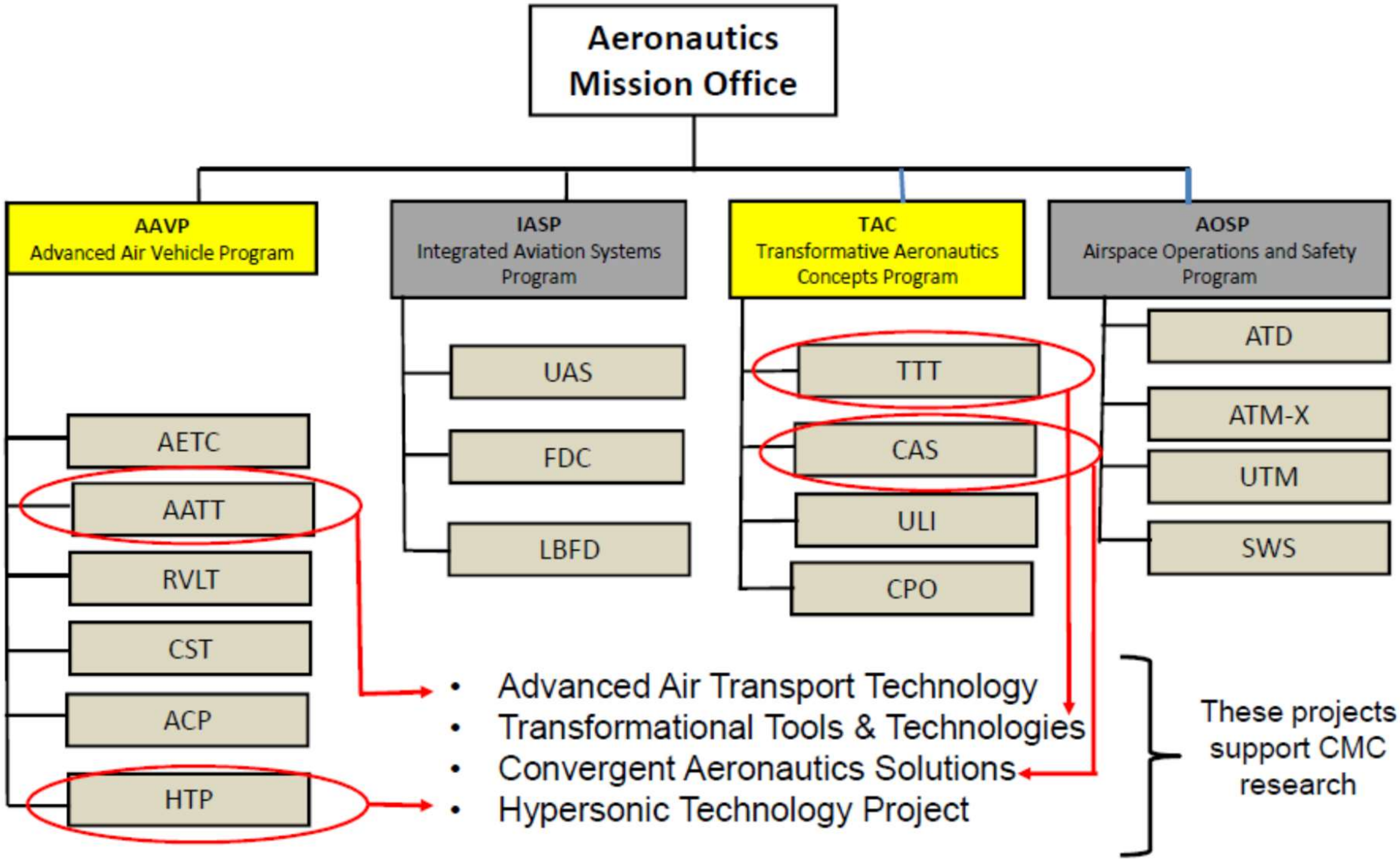
T3A ST
T3B VL — **Ultra-Efficient Commercial Vehicles**
- Pioneer technologies for big leaps in efficiency and environmental performance

T4 — **Transition to Low-Carbon Propulsion**
- Characterize drop-in alternative fuels and pioneer
- low-carbon propulsion technology

T5 — **Real-Time System-Wide Safety Assurance**
- Develop an integrated prototype of a real-time safety monitoring and assurance system

T6 — **Assured Autonomy for Aviation Transformation**
- Develop high impact aviation autonomy applications

Aeronautics Program Structure

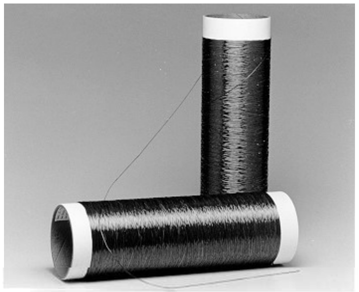


CMC Research at NASA Glenn

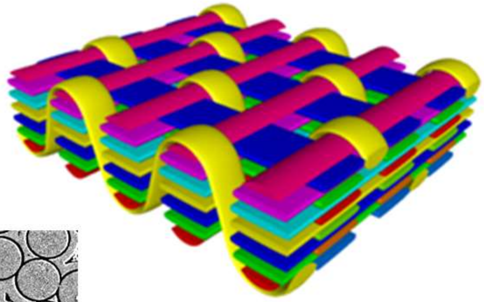
- CMC Development & Characterization
  - 2700ºF CMC development
  - Effects of engine environment on CMC durability
- Life Prediction: Modeling & Validation
- Additive Manufacturing

NASA 2700°F CMC combines three technology advancements

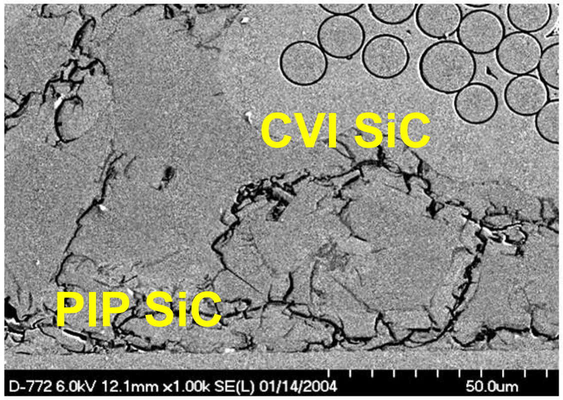
- Creep-resistant Sylramic-iBN fiber



- Advanced 3D fiber architecture

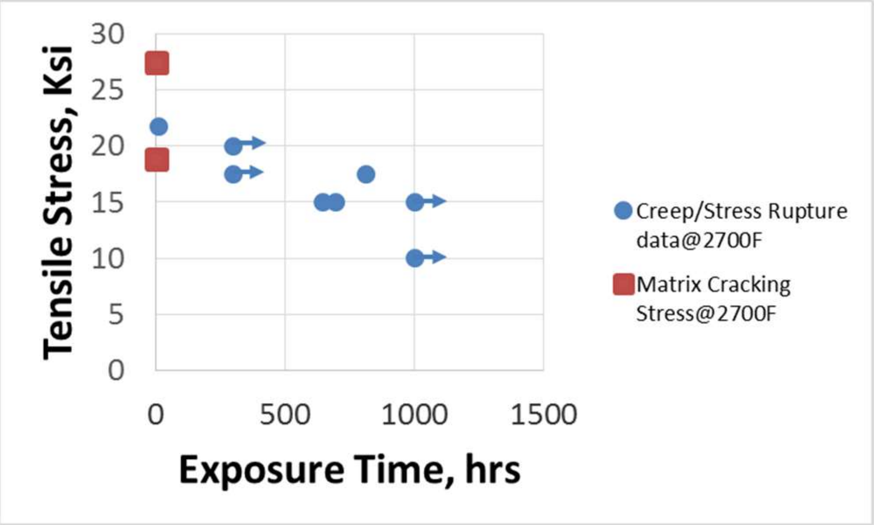


- Hybrid CVI-PIP SiC matrix



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

Creep Rupture



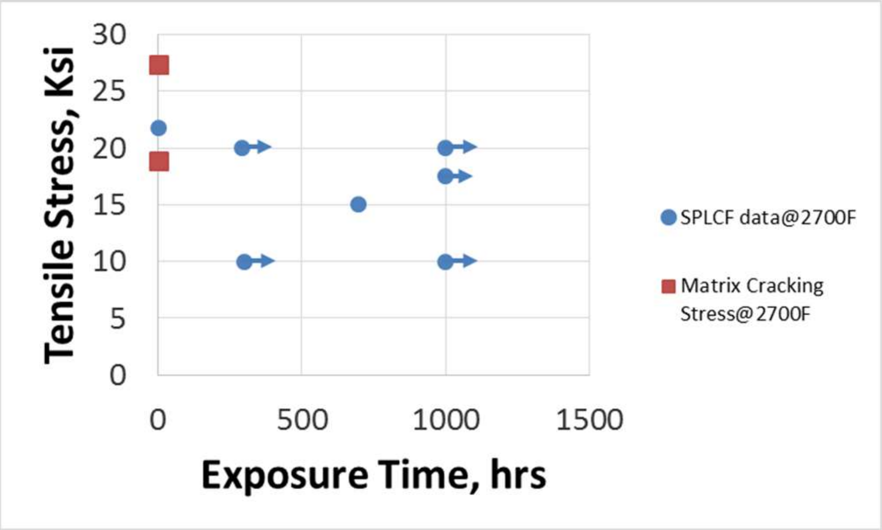
Challenge

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

Fatigue (SPLCF)



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

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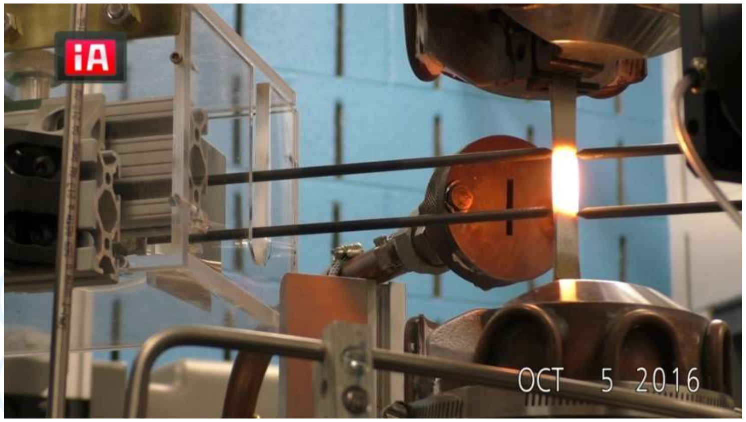
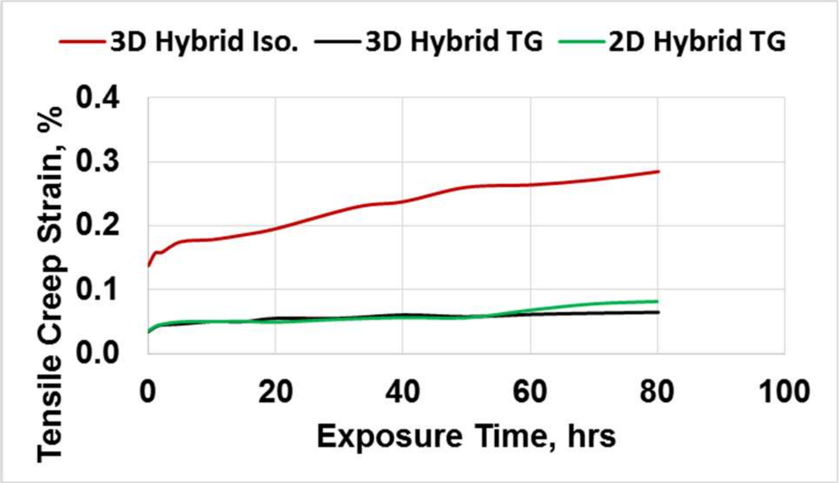
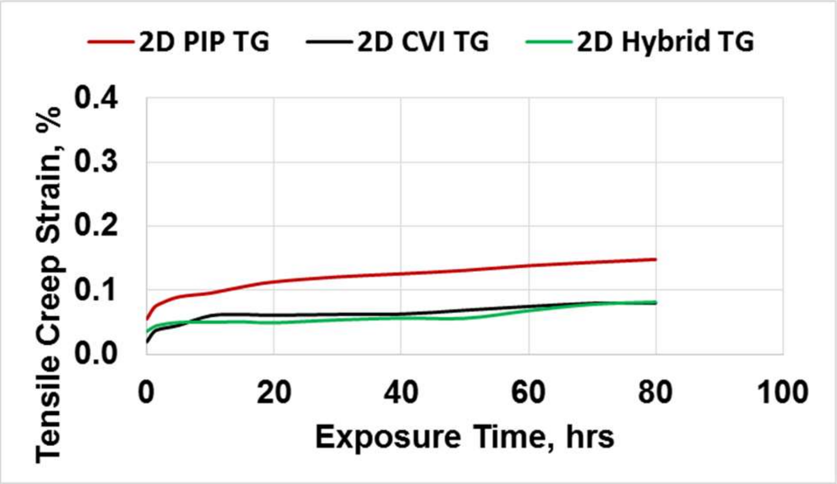
Effect of thermal gradients on creep strains of SiC/SiC CMCs evaluated at 2700 °F

- 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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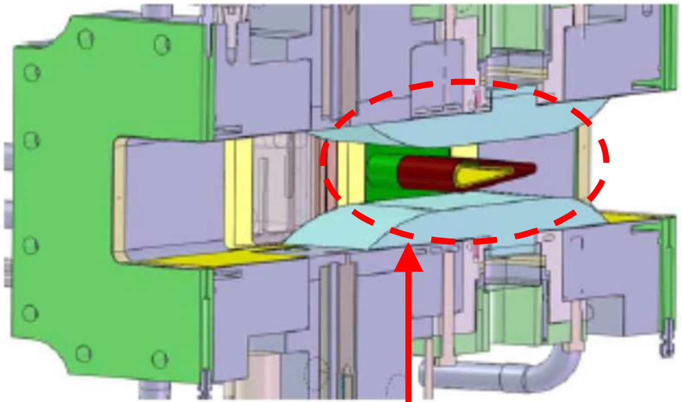
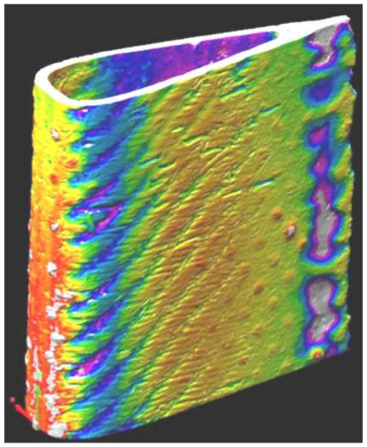
Rig test evaluation of CMC/EBC underway at UTRC

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

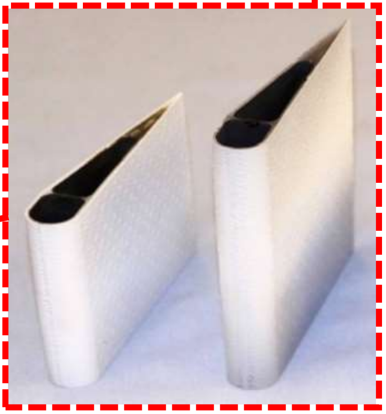
- 2700^oF airfoil-shaped test article, 3x3 inches
- Mach No. $0.2 < M < 0.8$ in test section
- Rig shakedown complete, test program underway
- Thermocouples, pyrometers and IR camera monitor material temperatures
- NASA / P&W / UTRC collaboration

UTRC JBTS test rig





White light imaging shows surface variability of test article



airfoil subelements

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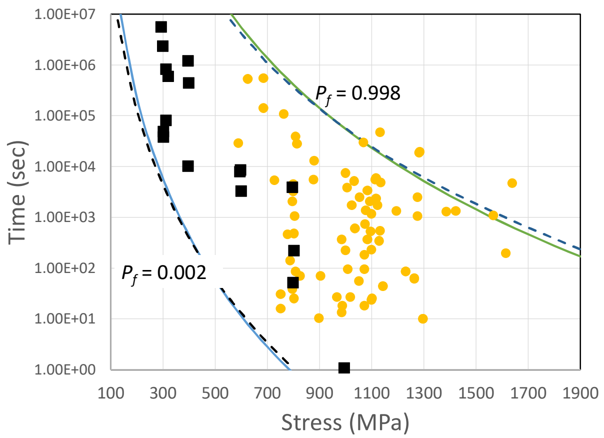
CMC / EBC Durability

Modeling & Validation

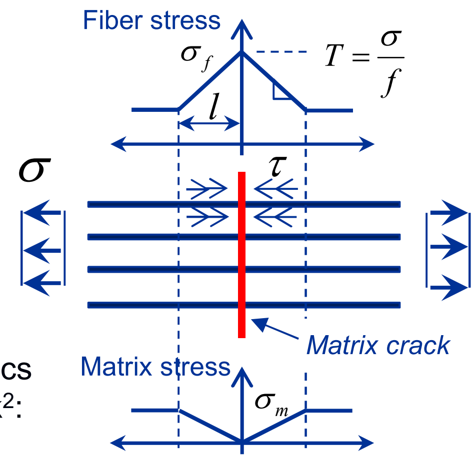
- Fiber Strength Model
- Mini-Composite Consortium
- CMAS / EBC interaction

Time-Dependent Stress Rupture Strength Degradation in SiC / SiC Composites

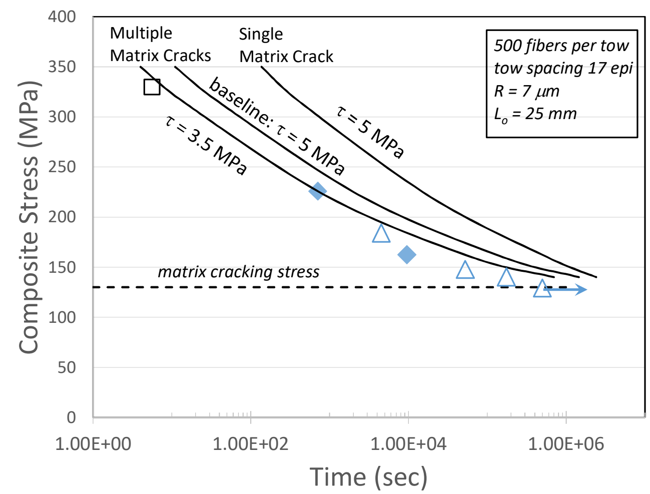


Time-to-failure vs applied stress for Hi-Nicalon fibers[1]

Force equilibrium mechanics at a matrix crack[2]:



Conclusion: *Slow crack growth in fibers is the most significant time-dependent strength loss mechanism in Hi-Nicalon reinforced composites at intermediate temperatures.*



Fiber slow crack growth model explains stress versus time-to-failure data in Hi-Nicalon SiC/SiC composites [2]

Contact: Roy.M.Sullivan@NASA.gov

[1] Gauthier and Lamon, *J. Amer. Ceram. Soc.*, **92** [3] 702-709 (2009).

[2] Sullivan Roy M., NASA TM-2015-218939.

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

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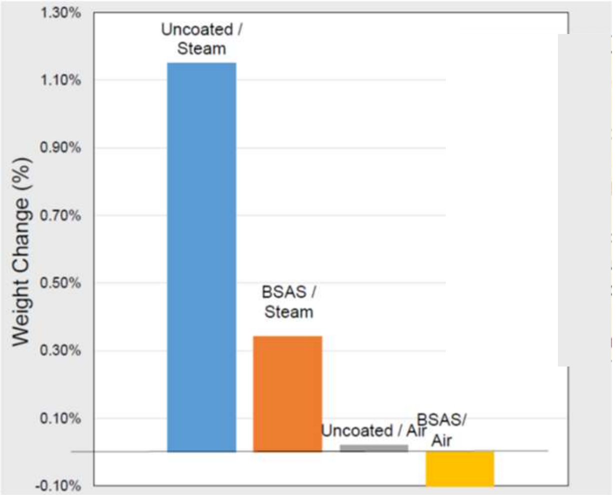
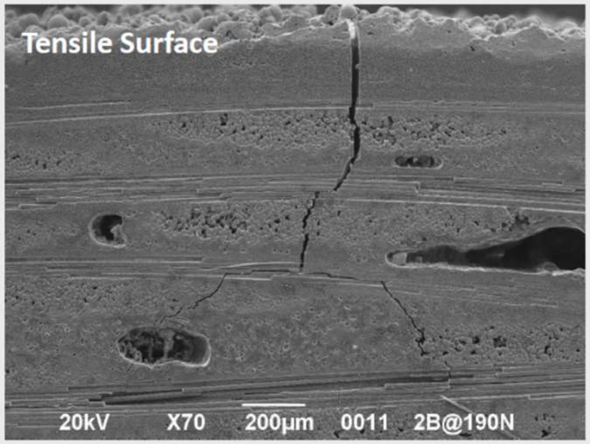
EBC slows damage accumulation at 2200ºF in steam environment



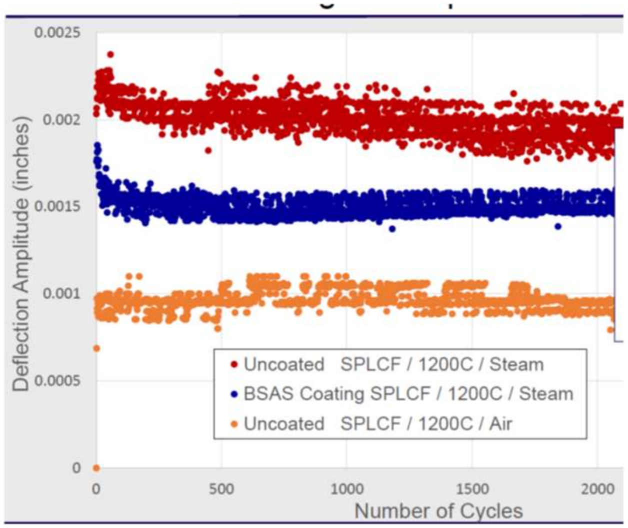
Flexural fatigue tests in steam show mechanics of damage propagation in EBC-coated CMC

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

Flexural Failure at 1200°C



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



Change in amplitude with fatigue cycles

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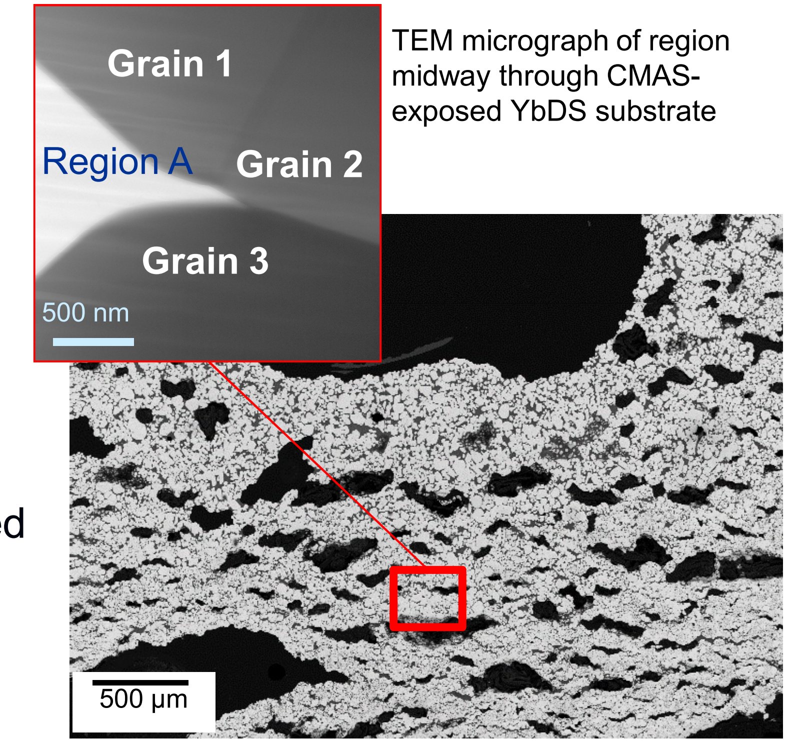
Development of CMAS-resistant EBCs

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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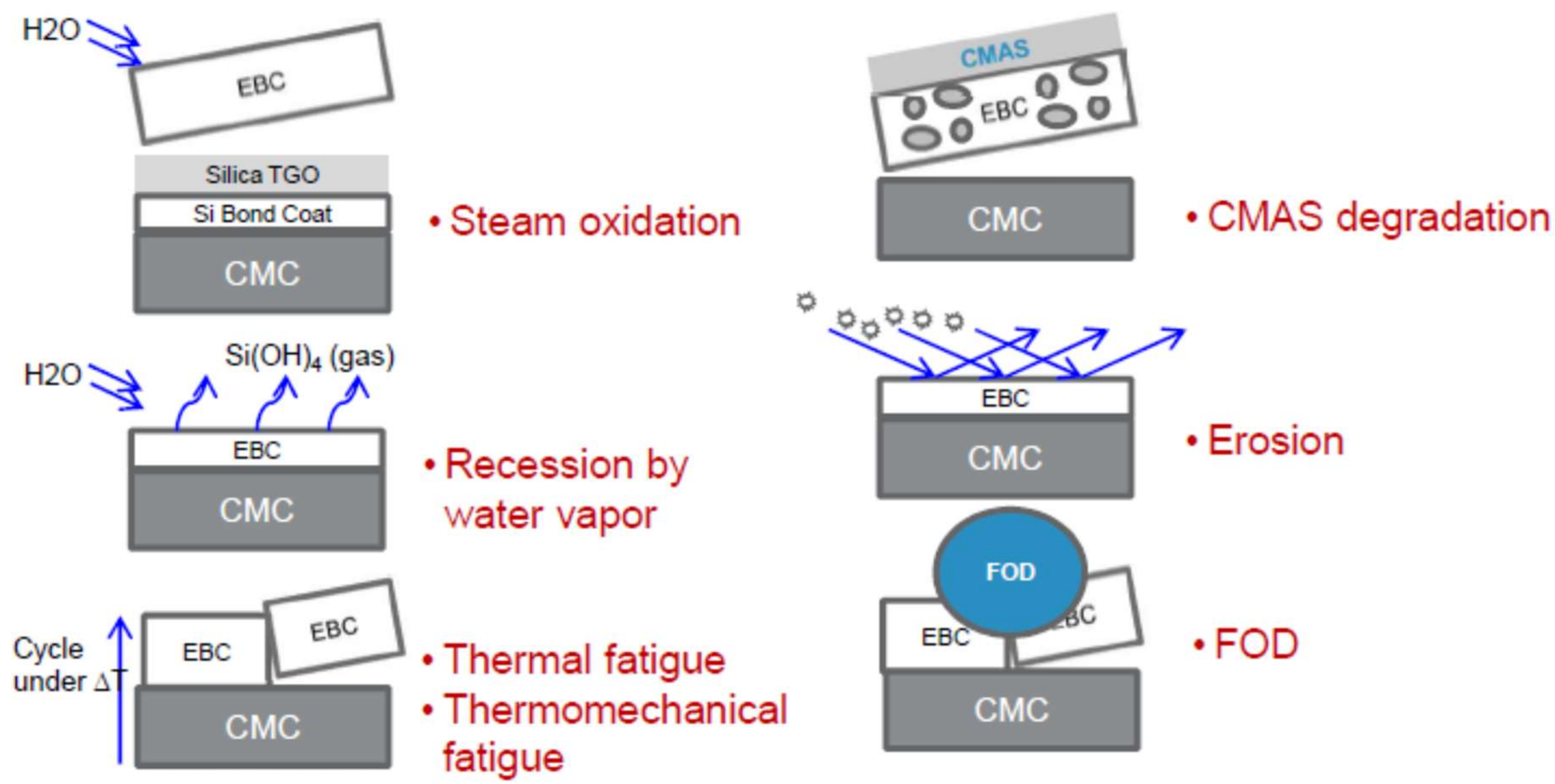
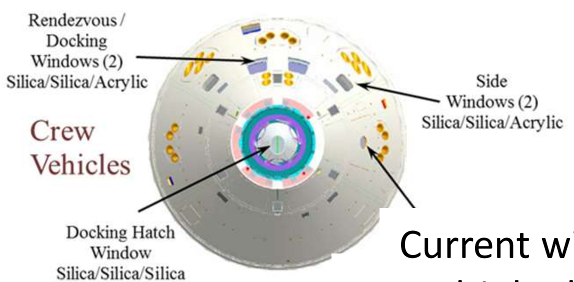
EBC Failure Modes Investigated



Contact: Ken.K.Lee@nasa.gov

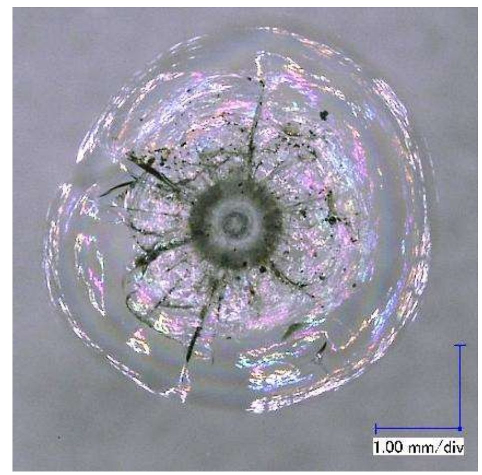
NASA Window Applications of Fused Silica

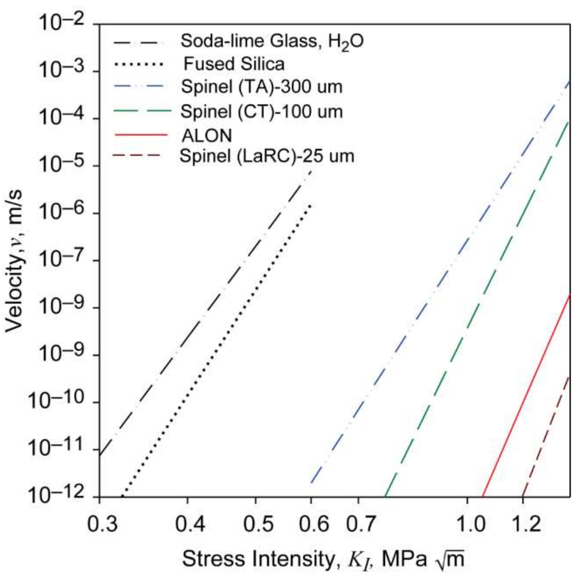
NASA spaceflight roadmap: *"Light-weight, durable windows are required to enable human spaceflight and long-duration deep-space destination systems."*



Current window designs require multiple thick panes to reduce risk

Meteoroid damage to STS-84 window





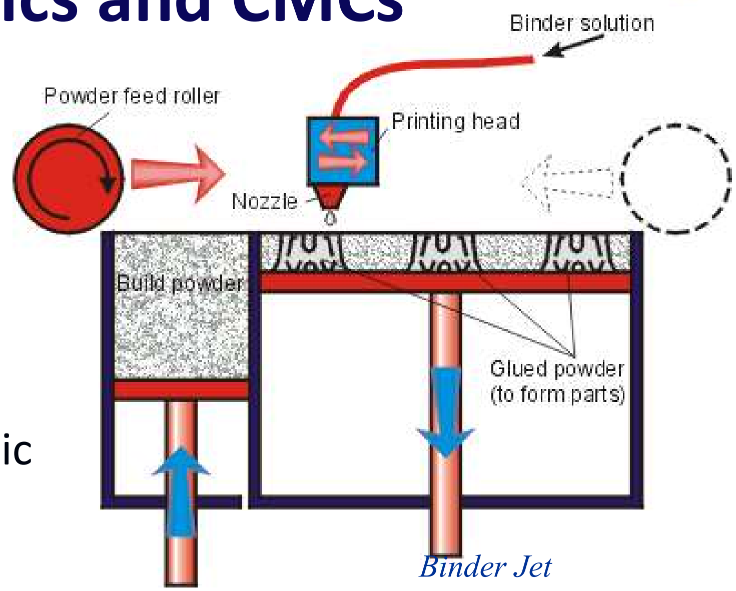
Spinel and AlON exhibit substantially lower crack growth rates than glass, with fine grain spinel giving the best result

Alternate materials include transparent spinels ($MgAl_2O_4$) and AlONs, with higher strength and fracture toughness

Additive Manufacturing

- Modified “Binder Jet” process for ceramics and CMCs
- Direct Printing for high power density electric 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

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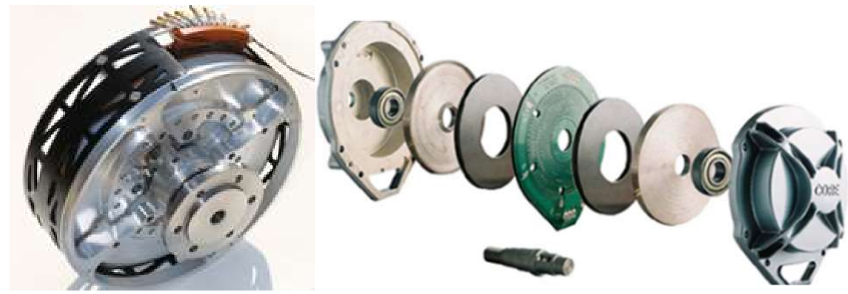
Additive Manufacturing for electric motor fabrication

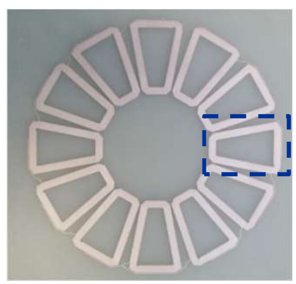
Objective: Use additive manufacturing methods to build more efficient, higher power density electric motors

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

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

Improved air flow for better thermal management

Lightweight structures

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

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NASA GRC Focus in 2018

CMC / EBC Durability Modeling & Validation

- Measure effects of environment (steam, CMAS) and cooling 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