Overview of NASA Transformational Tools and Technologies Project's 2700°F CMC/EBC Technology Challenge

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**Advanced Ceramic Matrix Composites:
Science and Technology of Materials, Design, Applications, Performance and Integration**

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Acknowledgements:

Transformational Tools and Technologies Project's

Project Manager – Mike Rogers (ARC)
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NASA Glenn Research Center Contributors:

CMC	EBC	Modeling
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Sai Raj	Valerie Wiesner	Roy Sullivan
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NASA ARC: John Lawson - **modeling**

Outline

Project Overview

- **Project Vision, Goals, Objectives**

Status

- T^3 Technical Challenge
- CMC Development
- EBC Development
- Testing Development
- Modeling Development
- Partnerships and Collaborations
- Future Direction
- Publications, Awards,

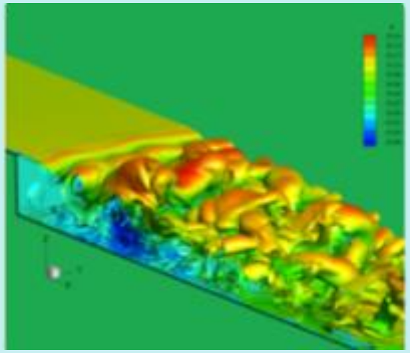
Summary

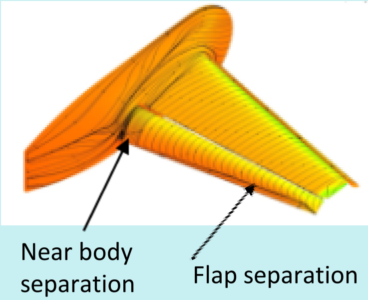
Transformational Tools & Technologies Project

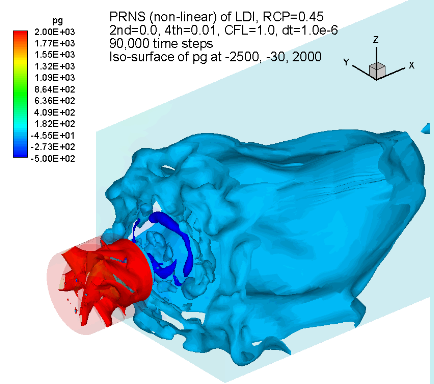
Enable fast, efficient design & analysis of advanced aviation systems from first principles by developing physics-based tools/methods & cross-cutting technologies, provide new MDAO & systems analysis tools, & support exploratory research with the potential to result in breakthroughs.

Scope

- Foundational cross-cutting research and technology for civil air vehicles
- Discipline-based research and system-level integration method development
- Support and enable concept development and benefits assessment across multiple ARMD programs and disciplines



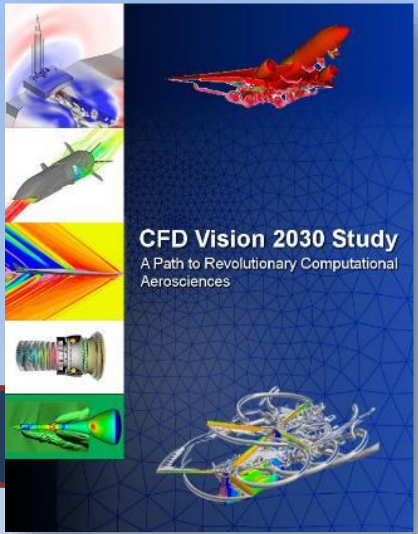




Transformational Tools & Technologies Sub-Projects

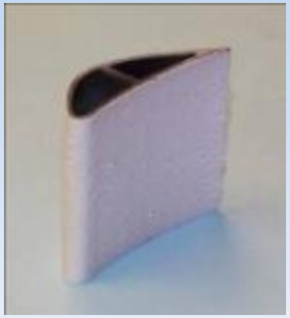
Revolutionary Tools and Methods

- Physics-based Predictive Methods for Improved Analysis and Design
- **Improved CFD Models and Algorithms**
- MDAO/System Analysis Tools
- Materials and Structures Modeling and Simulation
- Combustion Modeling
- Validation Experiments



Critical Aeronautics Technologies

- **High-temperature Engine Materials**
- Multifunctional Materials and Structures
- Combustion Technologies
- Propulsion Controls
- Advanced Flight Controls
- Innovative Measurements



EBC-Coated CMC Vane

NiTiHf Shape Memory Alloy torque tube actuators for UAV

T^3 focuses on transformational cross-cutting foundational research

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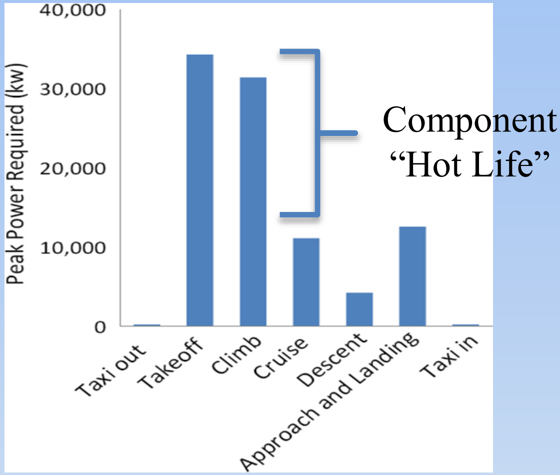
Completion of Technical Challenge TACP02

Assessment of Potential Fuel Burn and NO_X Benefits of CMC Turbine Blades/Vanes on an N+2 Engine

Scott M. Jones and Bill Haller - Provided to Materials & Structures Division (April 2011)

Incorporation of 2700F capable Ceramic Matrix Composites (CMCs) into turbines as HPT and LPT vanes and blades provides a **net overall reduction of 6.0% in fuel burn** and a **greater than 33% reduction in NO_x emissions** (less cooling air, reduced weight).

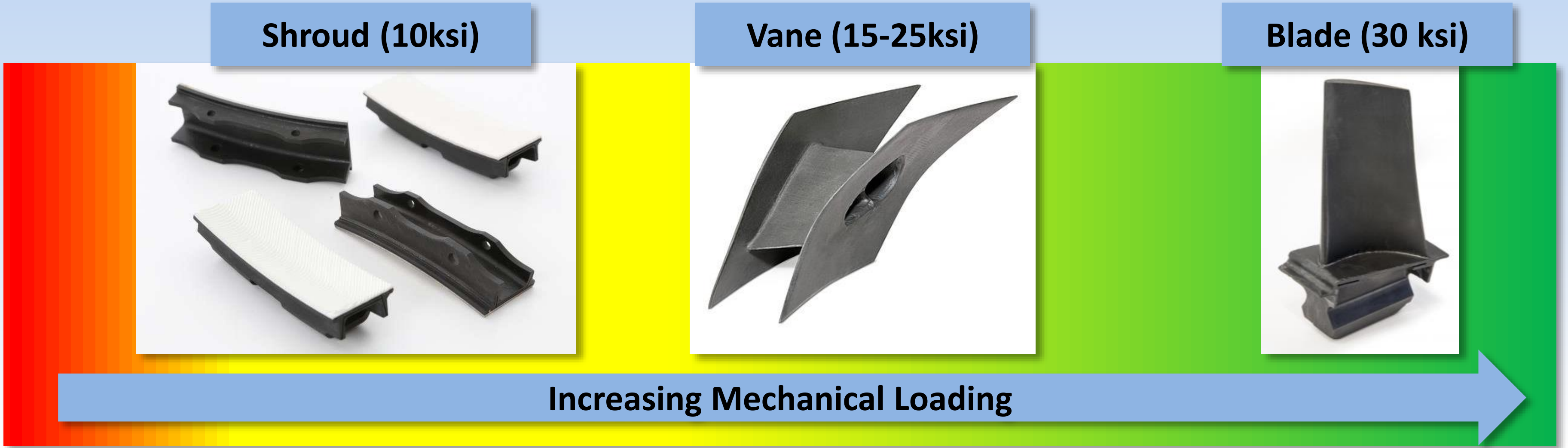


Success Criteria:

Green: Achieve key durability metrics of 1000 cumulative hours at 30 ksi max stress and 2700°F max material surface temperature.

Yellow: Achieve key durability metrics of at least 300 cumulative hours at 20 ksi max stress and 2700°F max material surface temperature.

Red: Achieve key durability metrics of less than 300 hours at 20 ksi max stress and 2700°F max material surface temperature.



M&S - High Temperature Engine Materials (TC #2)

Transformational Tool and Technologies Project

Technical Challenge:

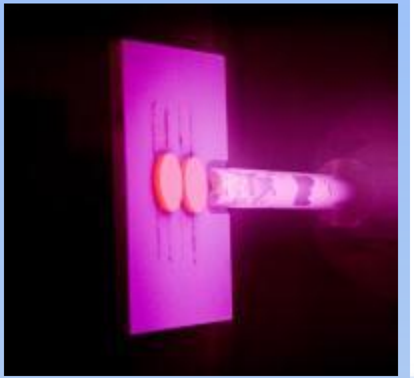
Develop high temperature materials for turbine engines that enable a 6% reduction in fuel burn for commercial aircraft, compared to current SOA materials.

Technical Areas and Approaches:

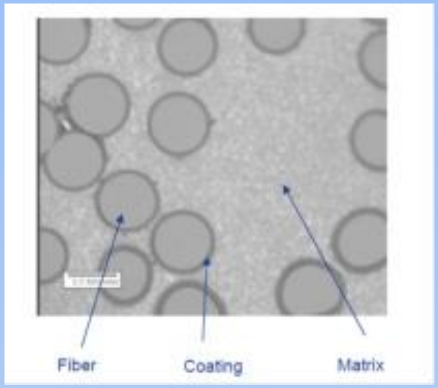
- Ceramic matrix composite (CMC) materials and the required environmental barrier coating (EBC) systems are investigated and developed for 2700F engine environments.
- Models and computational tools for design, analysis, and life prediction are developed.

Benefit/Pay-off:

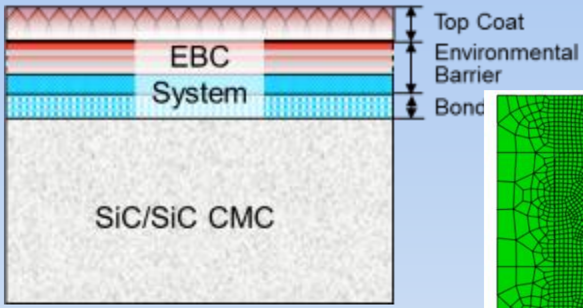
- Enables increase in engine operating temperature, and/or reduced cooling for turbine components.
- Improves fuel efficiency and helps reduce emissions.



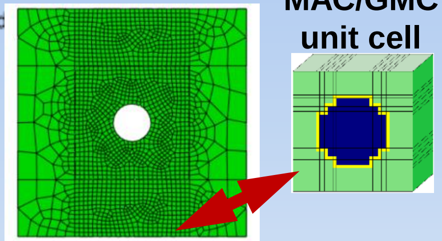
PS-PVD Coating Technique



Fiber/Coating/Matrix Development

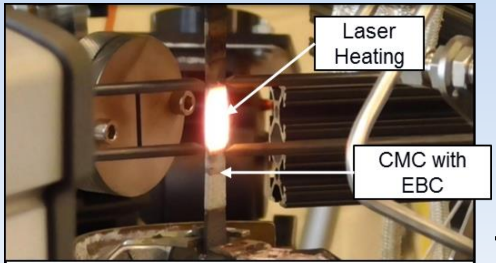


MAC/GMC unit cell



Abaqus FEM Modeling

Analysis Tools Simulate Failure Process



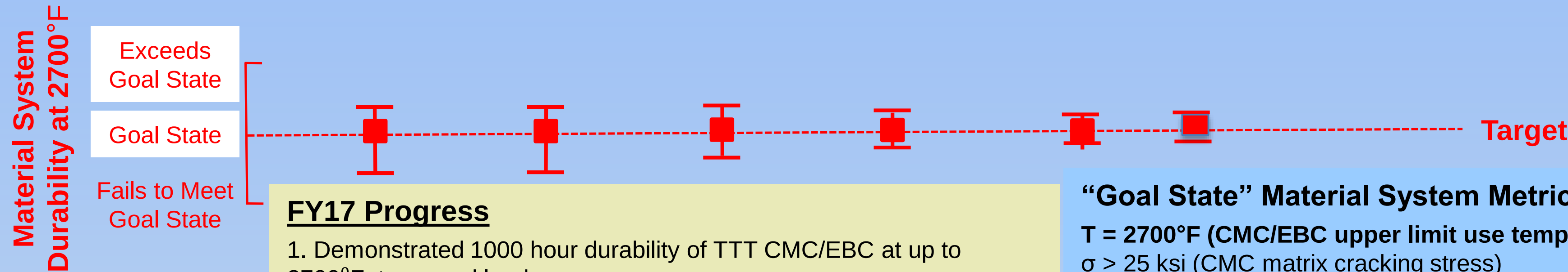
EBC coated CMC under stress heated by a high heat flux laser

Testing and test method development

Technical Challenge - High Temperature Engine Materials

Progress Indicator Chart:
M&S - High Temperature Engine Materials (TC #2)

Technical Challenge: Develop high temperature engine materials for turbine components enabling 6% reduction in fuel burn (requires 2700°F durability, meeting "goal state" metrics)

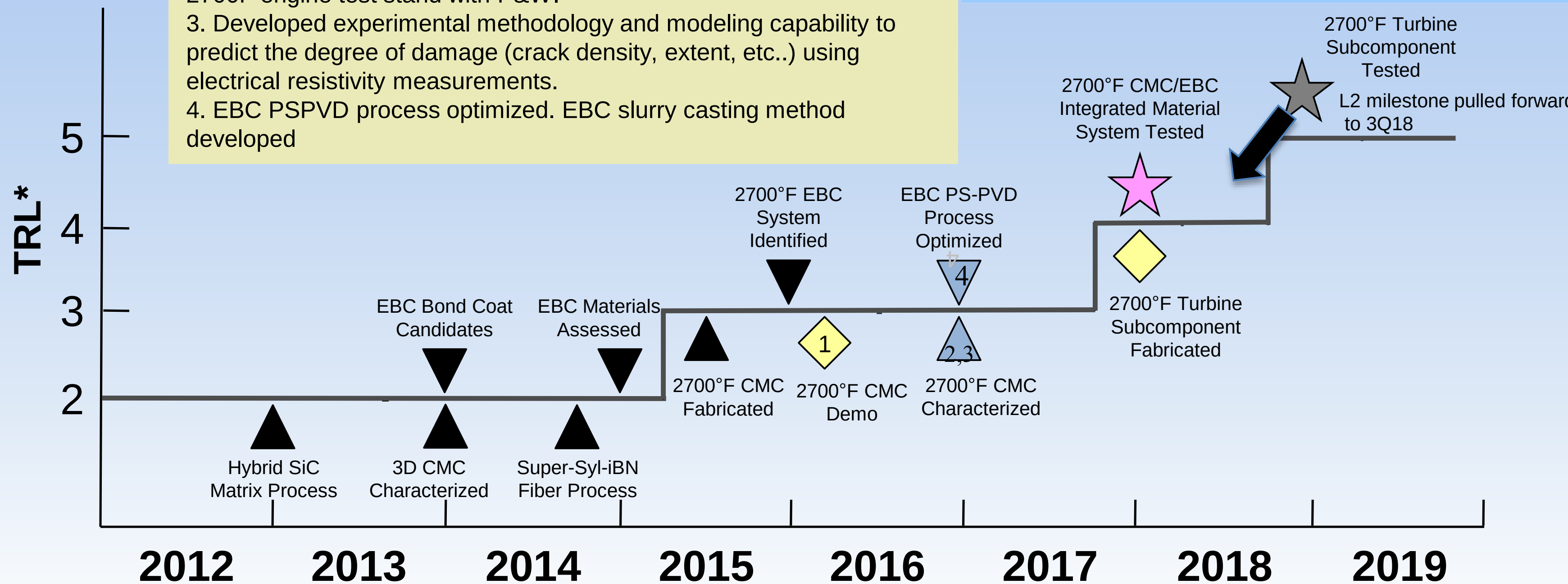


FY17 Progress

1. Demonstrated 1000 hour durability of TTT CMC/EBC at up to 2700°F, temp and load.
2. Developed unique test capabilities for CMC/ebc evaluation, steam oxidation, thermal gradient testing, controlled environment fiber testing, 2700F engine test stand with P&W.
3. Developed experimental methodology and modeling capability to predict the degree of damage (crack density, extent, etc..) using electrical resistivity measurements.
4. EBC PSPVD process optimized. EBC slurry casting method developed

"Goal State" Material System Metrics:

T = 2700°F (CMC/EBC upper limit use temperature)
σ > 25 ksi (CMC matrix cracking stress)
t > 300 hr (cumulative "hot time" life)
h < 0.010 in (EBC thickness)
r < 0.005 mg/g-cm^2-hr (EBC erosion mass loss rate)



*TRL = increasing integration of materials system elements & validated durability

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Introduction

Aircraft engine efficiency can be significantly improved with advanced materials

- Higher temperature materials require less cooling air
- Lower density materials can lead to lower weight of components

Ceramic Matrix Composites (CMCs) offer a significant improvement over metals

- CMCs with 2400°F capability began flying in commercial aircraft engines in 2016
- This is ~300°F higher temperature capability than metals, at 1/3 of the density

CFM LEAP® Shroud
Boeing 737
Airbus A320

NASA is developing a material system with 2700°F capability

- This technology would reduce aircraft fuel burn by approximately an additional 6%, as well as lowering emissions

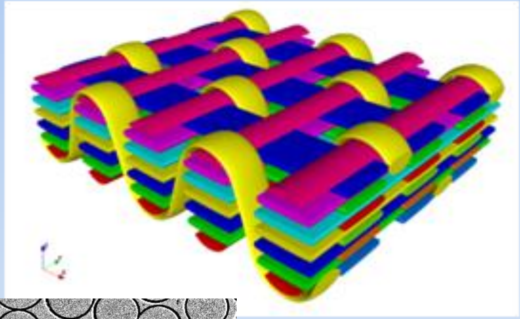
TTT 2700°F CMC Incorporates Three Separate Technology Advancements

Transformational Tool and Technologies Project

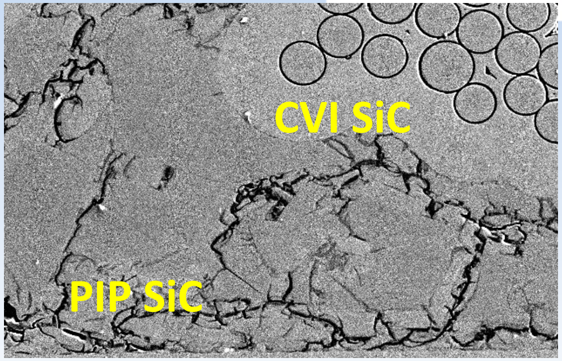
Creep-resistant SiC fiber

Super-Sylramic-IBN

Advanced 3D fiber architecture



“Hybrid” SiC matrix
for reduced porosity



SiC: Silicon Carbide
CVI: Chemical Vapor Infiltration
PIP: Polymer Infiltration and Pyrolysis

Creep- Resistant Silicon Carbide Fibers

Transformational Tool and Technologies Project

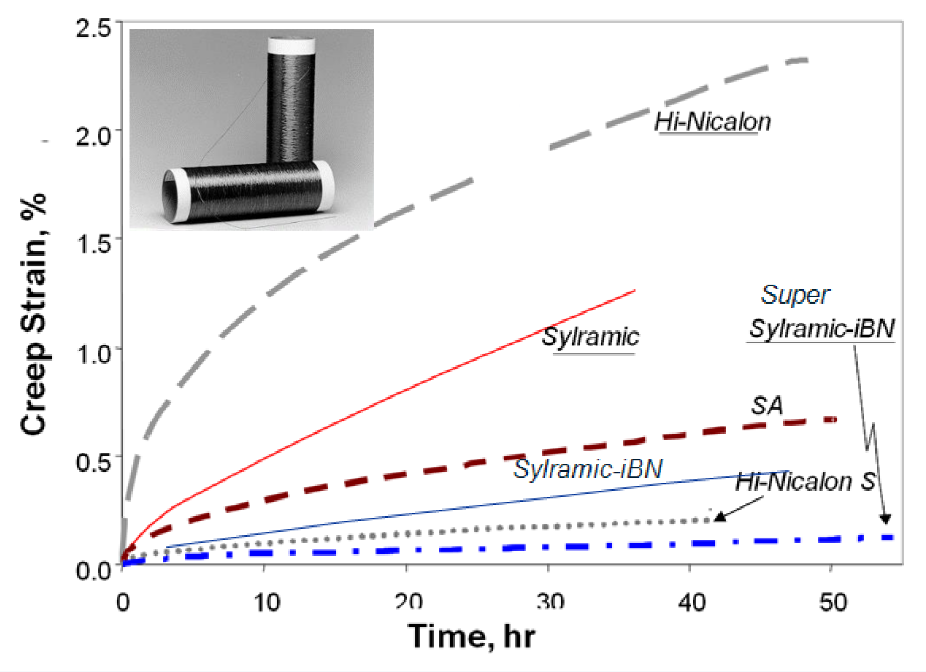
The 3 best fiber types were studied

- Hi-Nicalon S™
- Sylramic™-iBN
- Super Sylramic™-iBN

Produced by NASA-developed heat treatment

- Hi-Nicalon S™ is the least expensive of the three fibers and is used commercially by engine companies
- Super Sylramic™-iBN performs the best in creep

Fiber Creep Data



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3D Fiber Architecture Improves Material Durability

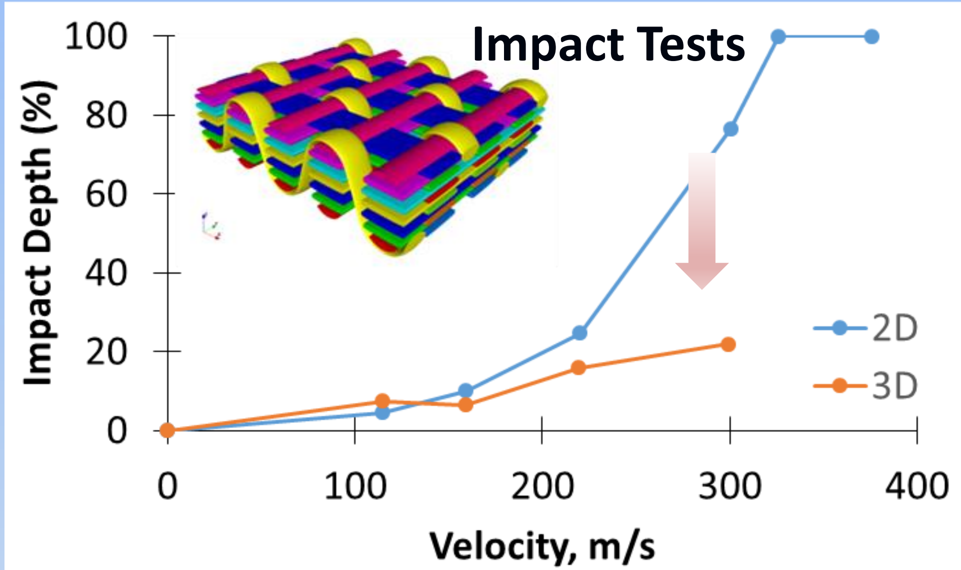
Transformational Tool and Technologies Project

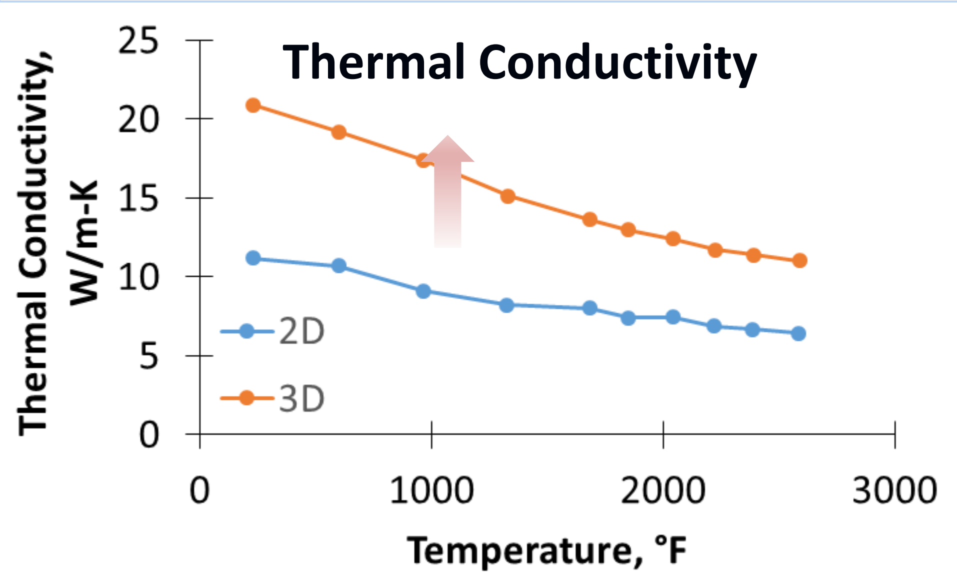
3D means fibers are oriented along X,Y, and Z axes

- Yellow fibers in the diagram are through-thickness reinforcement
- 2D CMCs currently being implemented into engines

3D offers advantages over 2D

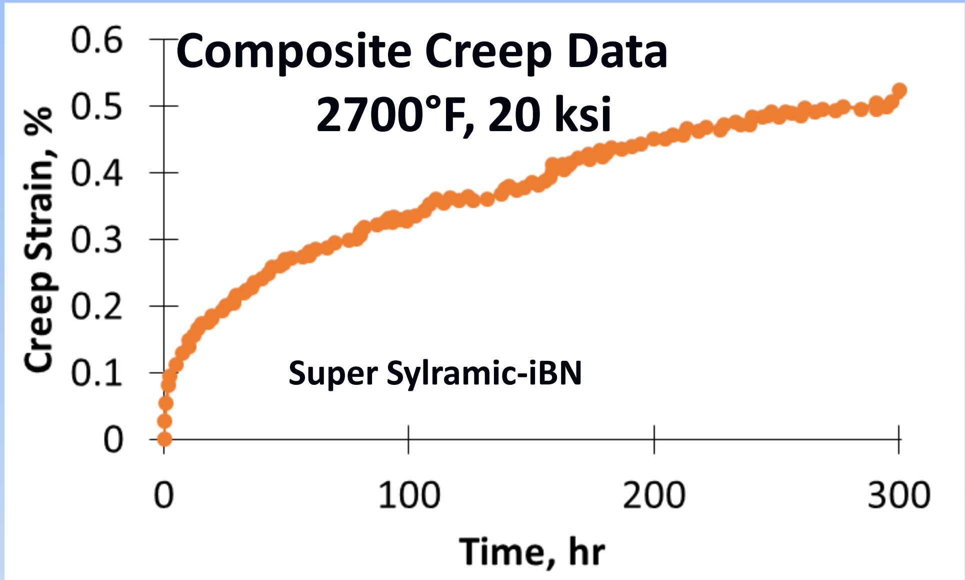
- Improved impact resistance
- Increased through- thickness thermal conductivity
- Better suited to the 3D stress state of a vane
- Could allow machining of cooling holes without cutting fibers

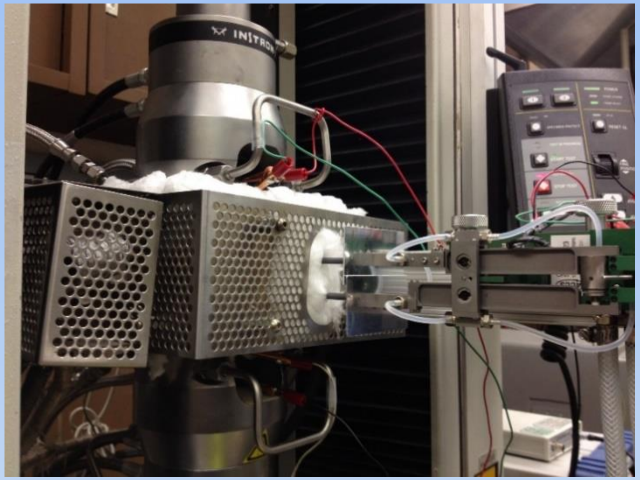




High Temperature Tests Show That TTT Material Exceeds 2700°F Durability Goals

Transformational Tool and Technologies Project





Material has 300 hour creep life at 20 ksi/ 2700°F Meeting the Yellow Exit Criterion

Effect of Advanced Fiber on CMC Creep Life Determined

Transformational Tool and Technologies Project

Hi-Nicalon-S preference due to price and availability

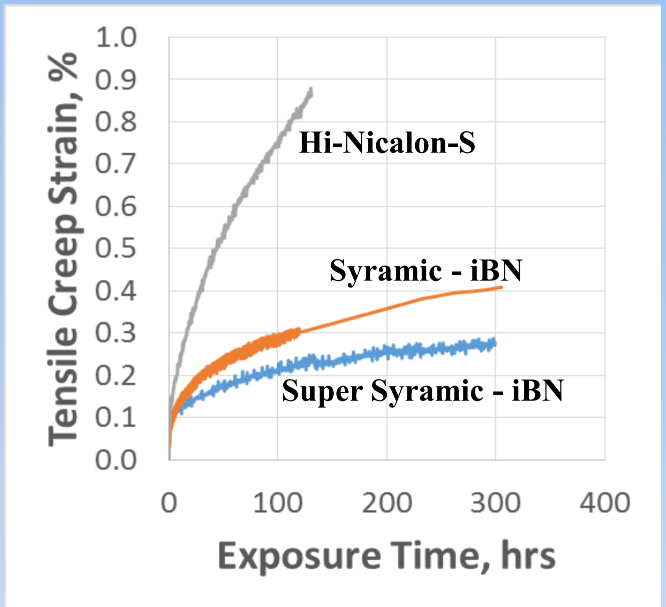
APPROACH

- Fabricate SiC / SiC Ceramic Matrix Composites with NASA 2700^{0}F hybrid matrix composition and 3D fiber architecture.
- Compare creep performance of CMC's with 3 different high temperature fibers (Sylramic-iBN, Super Sylramic-iBN and Hi-Nicalon-S)

SIGNIFICANCE

- Creep life obtained with NASA Super-Sylramic-iBN fiber exceeds life obtained with commercially available fiber by 200+ hours at 15 ksi stress

•Hi-Nicalon S^{TM} composites tested at 15 ksi/2700°F did not reach 300 hour life (TTT goal)

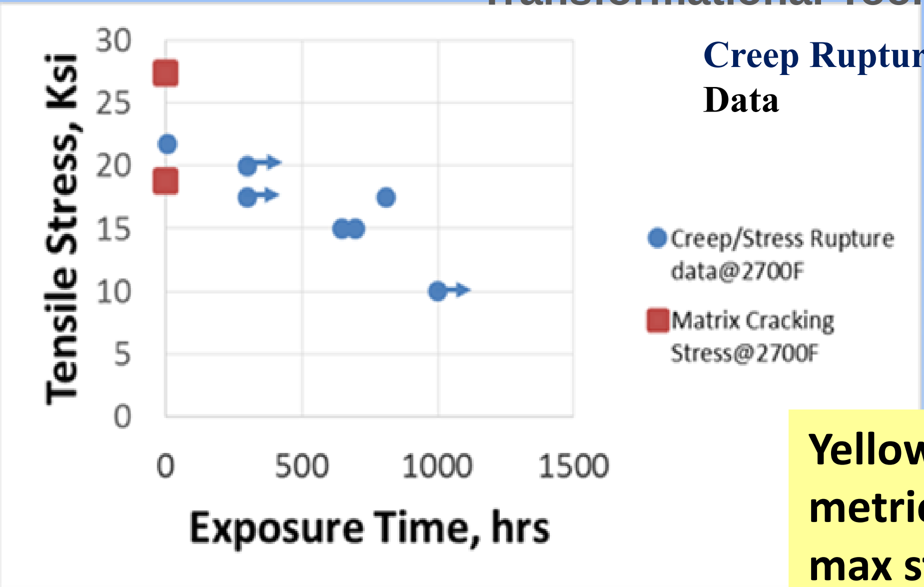


2700 ^{0}F creep strain at 15 ksi stress

CMC's were fabricated with commercially available Hi-Nicalon-S fiber *for comparison of creep properties with TTT CMC's using* Super Syramic – iBN fiber

POC: Ram Bhatt

Long-term tests demonstrate 1000-hour durability of T^3-developed CMC at 2700ºF



10 ksi stress level is representative of a lightly-loaded structural component (turbine shroud) in current engines

Yellow Exit Criterion: Achieve key durability metrics of at least 300 cumulative hours at 20 ksi max stress and 2700°F max material surface temperature.

FY17 Accomplishments:

- Static tensile testing demonstrated onset of damage (matrix cracking) at 18-29 ksi applied mechanical stress at 2700°F
- Isothermal Creep Rupture testing of CMC demonstrated 1000+ hrs durability under 10 ksi, 800+ hours under 17.5 ksi applied mechanical stress, and at 2700°F; other tests at 17.5 and 20 ksi are still underway.
- Isothermal Sustained Peak Low Cycle Fatigue (SPLCF) testing of CMC failed at 780+ hours at 17.5 ksi maximum applied mechanical; Another test at 17.5 ksi has accumulated 100+ hours and is still underway.
- High heat flux SPLCF testing, with laser heating, survived nearly 500 hours.
- Demonstrated several coating methods with a variety of NASA patented coating compositions. Methods include PSPVD EBC coating fabrication, Electron Beam-Physical Vapor Deposition and Directed Vapor Deposition (DVD) and slurry casting EBC.

High Temperature Engine Materials: Ceramic Matrix Composites Development

Transformational Tool and Technologies Project

NDE Technique Extended to 2400°F Applications

PROBLEM

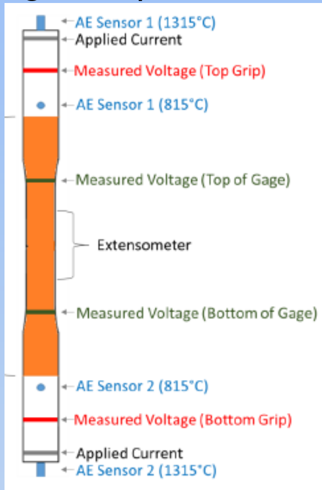
Tracking damage progression in CMCs can not be done at high temperatures

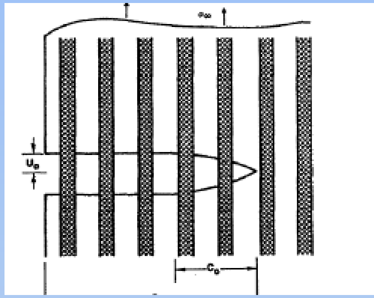
OBJECTIVE

Non-Destructive Evaluation of CMC's is needed at high temperatures to detect matrix cracks that lead to failure

APPROACH

- Conduct long-term tests at 1500°F and 2400°F while monitoring electrical resistance .
- Relate changes in electrical resistance to CMC damage and microstructural changes.

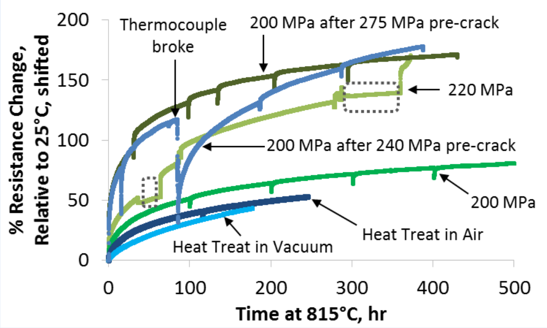




CMC electrical resistance was monitored while matrix cracks formed during long term tests

SUMMARY & RESULTS

- 6,881 hours of long-term tests were conducted at high temperatures
- Changes in electrical resistance at 1500°F were directly related to the density of matrix cracks in the CMC
- At 2400°F, electrical resistance measurements were less sensitive to damage by an order of magnitude



In-situ resistance of stressed-oxidation samples tested at 815°C

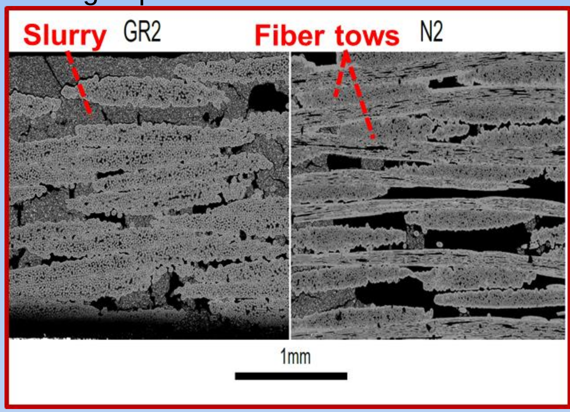
SIGNIFICANCE

The relationship between CMC electrical resistance and damage at high temperatures was determined, establishing the basis of a new experimental method for characterizing CMC durability under aircraft engine operating conditions.

POC: Craig Smith, Ph.D.

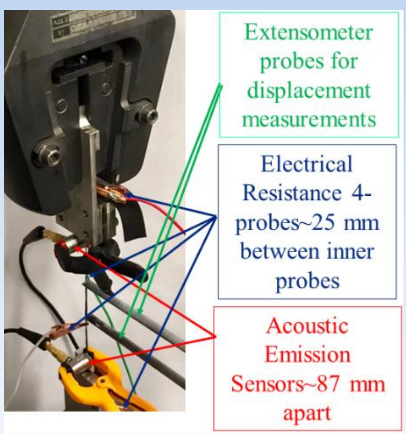
Engineered Matrix

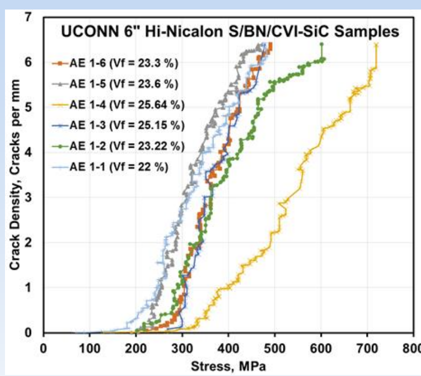
Durable filler matrix for CVI SiC/SiC preforms with properties engineered to increase crack resistance and self-healing capabilities.



Sai Raj - Partnered with ARFL

Minicomposites Evaluated – additional vendor

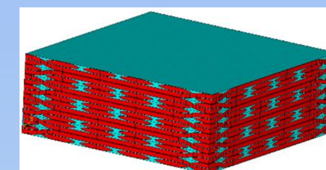


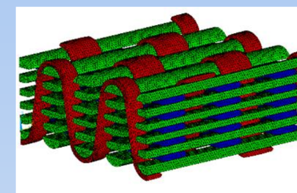


Amjad Almansour/Doug Kiser – with University of Connecticut, and also Rolls Royce; AFRL, UCSB

FEA model of a representative 2700F CMC using known constituent properties and architecture

2-D reinforced 5-harness satin weave



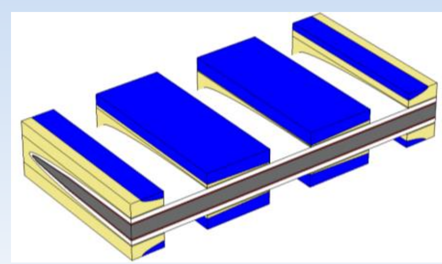


3D orthogonal fiber architecture

Status: Validation of property prediction results has been achieved.
Model calculations were within 10% of laboratory measurements and literature data.

Jerry Lang

Model electrical resistance measurements indicating CMC damage development



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

Cracking within the 0° or 90° tows - insignificant effect
Cracking of (MI) SiC matrix –signicant effect on electrical resistivity.

Roy Sullivan

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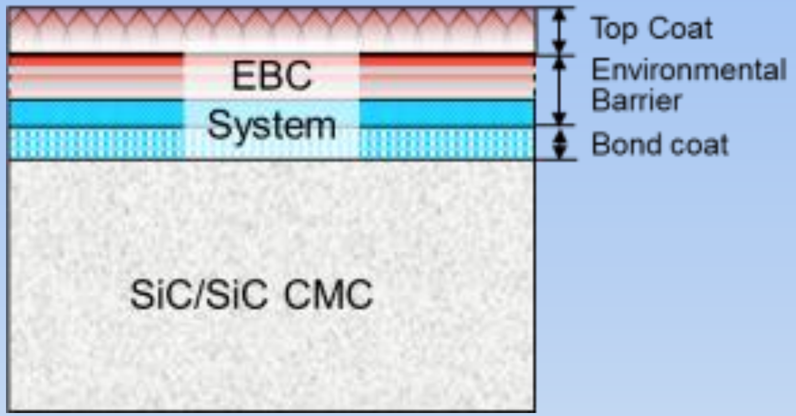
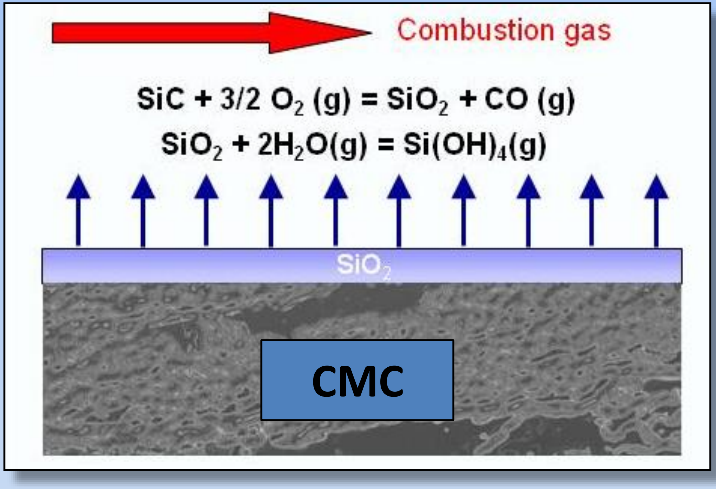


Summary

Degradation of CMCs in Turbine Engines

- Incorporation of CMCs into turbine hot section has substantial benefits
- 1990: Observation that SiC undergoes rapid recession in water vapor (Opila/NASA)
- 1990s: Develop dense oxide coatings to protect against water vapor attack (Lee/NASA)
- 2000s: Development of coatings to minimize water vapor effects at 2400° F: Gov't labs (US, Japan, Germany); turbine companies

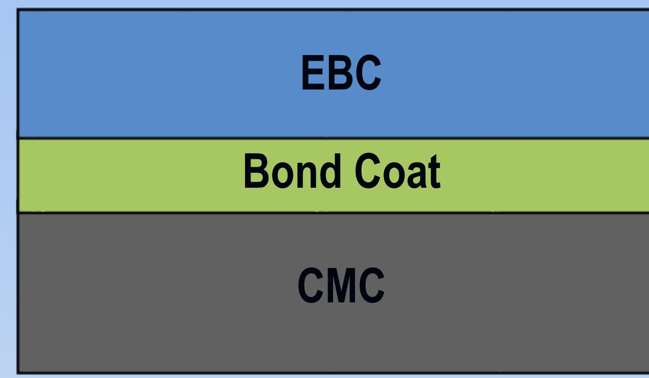


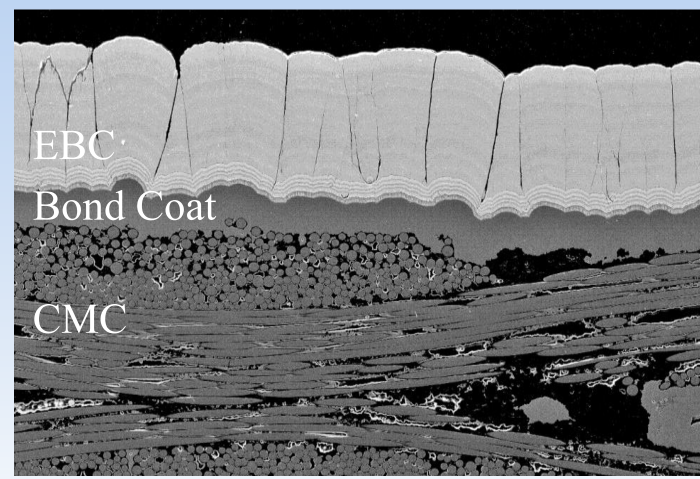
NASA research is focused on the next generation of CMC/EBC systems capable of operating at 2700°F with reduced or no cooling

Candidate Coating System Requirements

- NASA has focused on developing *next generation* environmental and mechanically durable material systems for 2700°F and beyond.

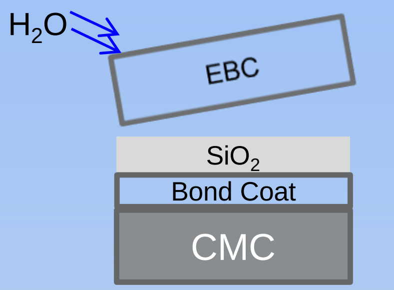
- Environmental Barrier Coating (EBC) System
  - May consist of bond coat and top coat
  - Well matched to CMC
  - Stable above use temperature
  - Low reactivity with H_2O
  - Limited cracking/pathways for oxidants



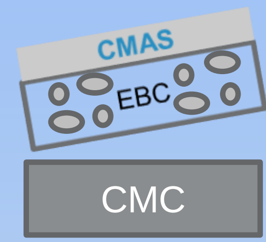


- EBC is essential for CMC operation
  - Uncoated CMC suffers rapid recession
  - 300 hour minimum cumulative "hot time" life

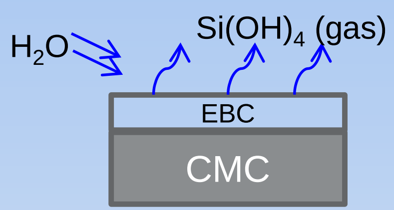
Environmental Barrier Coating Failure Modes



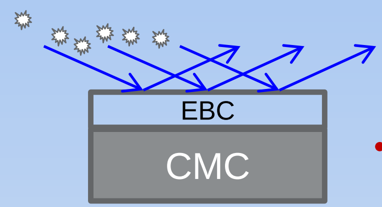
- Steam oxidation



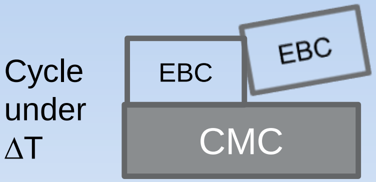
- Sand/Volcanic Ash Ingestion
- CMAS: Calcium-Magnesium-Alumino-Silicate



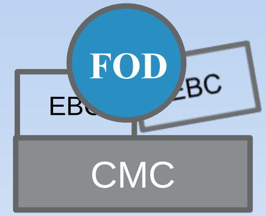
- Recession by water vapor



- Erosion



- Thermal fatigue
- Thermo-mechanical fatigue



- Foreign Object Damage

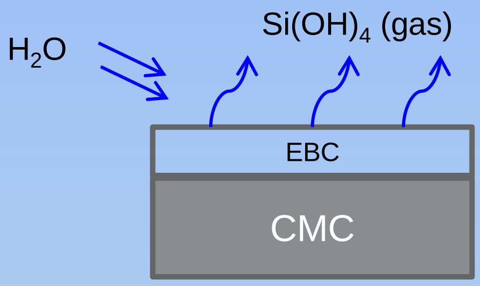
Synergies between failure modes lead to the ultimate EBC failure

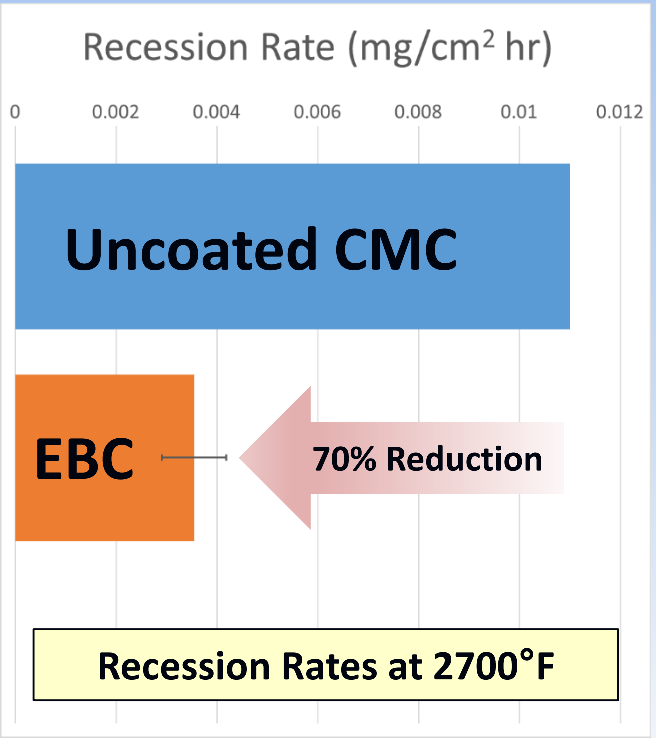
K. N. Lee, "Environmental Barrier Coatings for CMC's"; in *Ceramic Matrix Composites*, Wiley, New York (2015)

Thermochemistry and Modeling

- Stability of prospective EBC materials with water vapor measured
  - Experiments and model based approach
- Evaluated prospective EBC material systems for turbine engine environments
- Determine reaction chemistry and use models to predict recession rates

Prospective Environmental Barrier Coatings reduce recession rates of CMCs by 70%, enabling lifetimes needed for use in turbine engines





High Temperature Engine Materials
Environmental Barrier Coatings Development

OBJECTIVE

Evaluate and Model Environmental Barrier Coating (EBC) – Thermally Grown Oxide (TGO) interaction and impact of EBC chemistry/composition on TGO growth rate and TGO crystallization behavior.

APPROACH

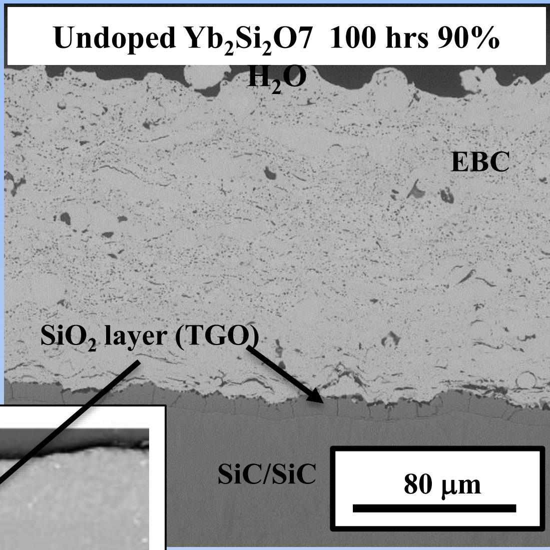
- Examination and testing of multiple coating processing methods for limiting SiO_2 (TGO) growth at the substrate as a function of microstructure and composition and downselect for minimization of TGO growth in cyclic exposure to 90% H_2O/O_2 at 2600F for 100+ hours.

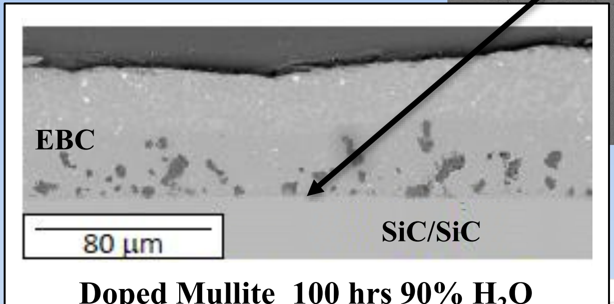
SIGNIFICANCE

Control and minimization of the TGO growth at the CMC substrate is critical to CMC/EBC durability and life. Oxidation in water vapor is an order of magnitude faster than in air and must be addressed for long term CMC/EBC durability.

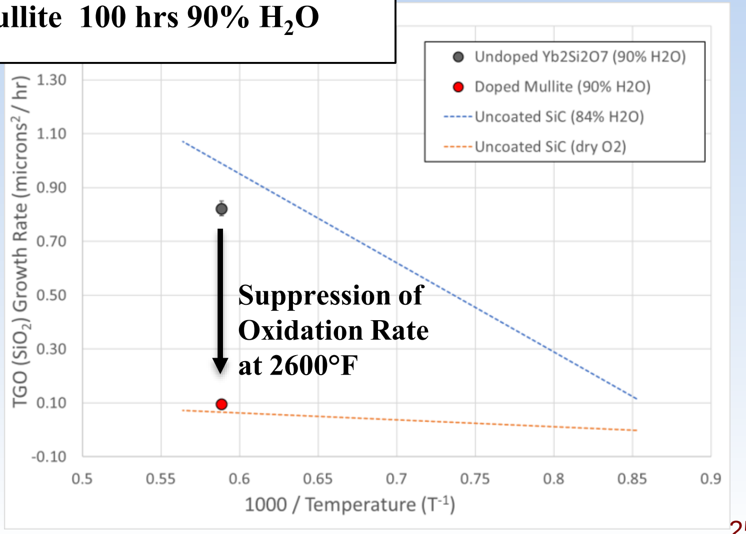
ACCOMPLISHMENTS

- Multiple compositions have been deposited via PS-PVD and slurry processing methods and tested in cyclic steam oxidation at 2600°F in 90% H_2O/O_2 for 100 hours or more.
- All EBCs maintained adherence after 100 hours, and new coating chemistries deposited via slurry methods show promise for further reduction of the oxidation rate beyond 300 hours.
- Additional samples will be processed via both methods and tested to evaluate the composition and microstructural impact on oxidation durability.





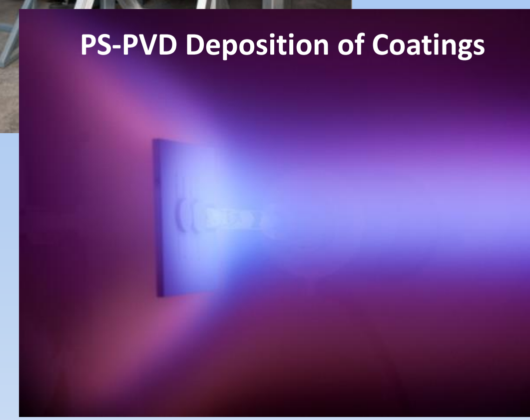
Doped Mullite 100 hrs 90% H_2O



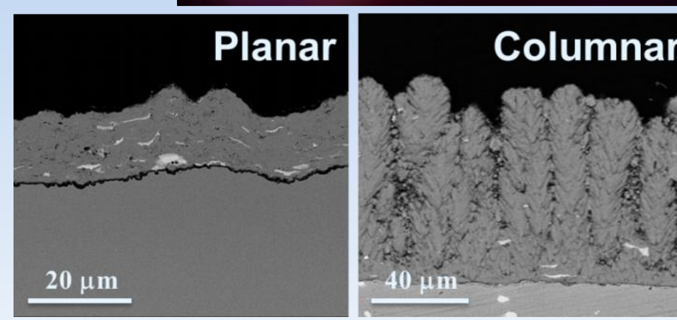
POC: Bryan Harder, Kang Lee (GRC)

Advanced Coating Processing

- New processing methods allow for advanced architectures and compositions
- Plasma Spray- Physical Vapor Deposition
  - Unique facility at Glenn Research Center and one of a handful worldwide
- Some non-line of sight deposition can provide coverage on complex shapes



Advanced Coating Processing Methods have provided new capabilities which are advantageous for cost and performance



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Summary

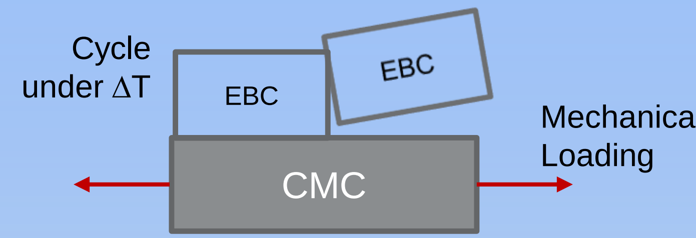
New Facilities Constructed for 2700F CMC/EBC

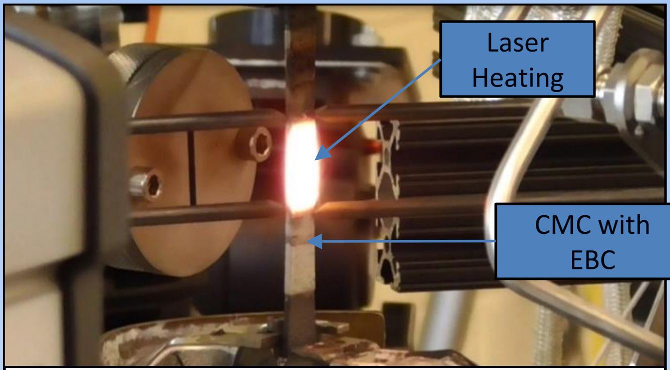
Facility	TTT Funding	Purpose
• CE-5	full	New capability for high TRL level "in-house" combustion testing. Investments include design & build of test fixtures, testing
• Horizontal Cyclic Steam Rig	full	New capability with increased temperature range (>2600 F), multiple sample configurations, higher thruput
• Drop Calorimeter	Full	new capability for thermodynamic studies.
• PSPVD liquid	partial	Existing capability has been highly invested in, added non LOS and feed capabilities
• Laser III	partial	Existing Rig: upgrades to safety systems, new control systems, instrumentation
• Laser IV	partial	New capability (multi-axis mechanical fatigue, additional thermal gradient):
• Slurry cast processing	partial	New capability for processing EBCs
• Natural Gas Burner Rig	partial	New capability for high heat flux, high velocity, volatility in H20, complex geometries
• high temperature furnace	partial	New melt infiltration furnace procured
• Steam Tensile Fatigue	partial	Upgrades to steam rig with durable a) commercially coated and b) EBC coated (developed at GRC) heating elements – 2600F
• Small Loading Fixture	full	For tensile and compressive testing of CMCs and minicomposites in FESEM. Very few in the U.S.
• Fiber Dia. Rig	full	New capability. Accurate fiber diameters prior to creep/stress oxidation testing, should reduce data scatter.
• 5-Fiber Creep Rig	full	New capability. For conducting five fiber creep/stress oxidation tests simultaneously at temperatures up to 2700F.
• Minicomposite RT/HT FF test	full	New capability
• Minicomposite HT creep in air	full	New capability
• Glovebox #2	full	high temperature fiber testing in inert.
• Fiber testing vacuum/inert	partial	Existing rig fixed and modified to test multiple fibers in creep in vacuum/inert
• Erosion/CMAS rig	partial	Enhanced to offer CMAS erosion feed to existing erosion capability
• Flexural Fatigue Steam Rig	partial	New capability for flexural SPLCF testing in steam
• In-Situ Flex Loading	partial	New capability for optical/ electron microscopy of under flexural loading condition.

Thermomechanical Testing of NASA CMC/EBC System

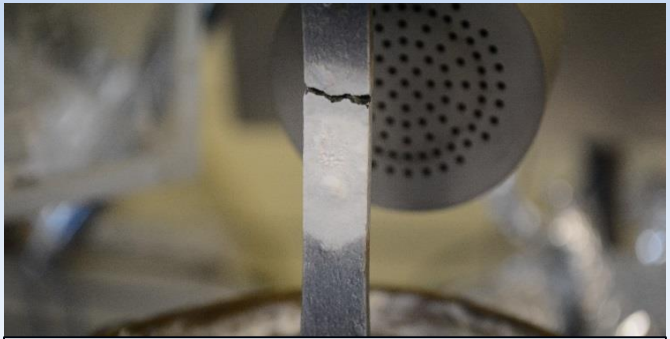
- First integration and testing of NASA developed CMC with the NASA developed EBC system
- Sustained peak low cycle fatigue (SPLCF) test with laser gradient heating for thermomechanical validation
- Milestone set at 300 hours with a 2700°F CMC temperature and 10ksi load

EBC Surface Temperature: 2950°F
CMC Temperature: 2700°F
Load: 10ksi
Total Life: 487 hours





EBC coated CMC under stress heated by a high heat flux laser



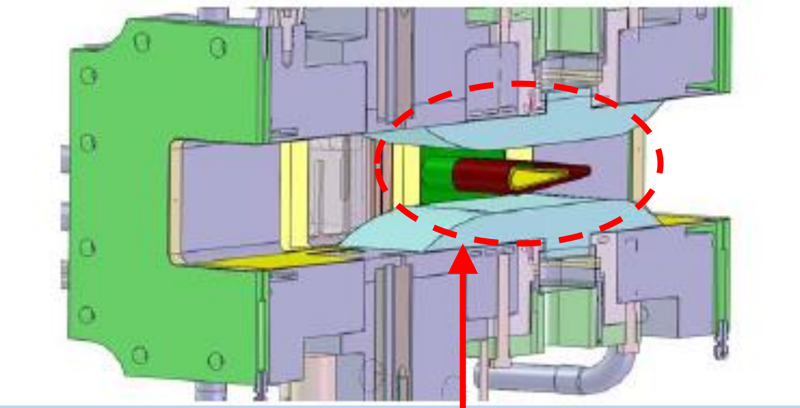
After 487 hour testing

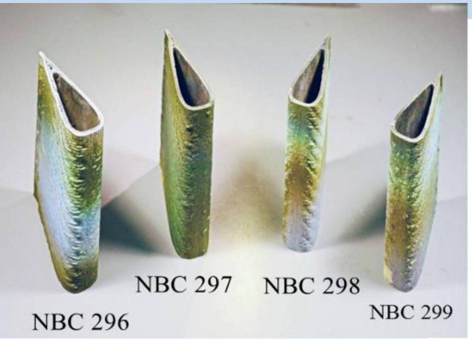
TRL 5 Rig Test Planned for FY18

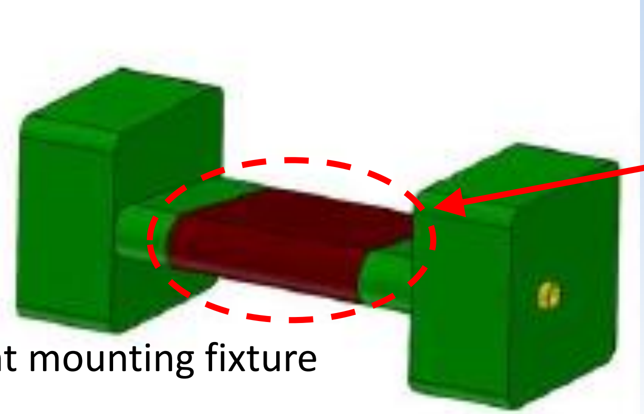
CMC sub-element will be used to evaluate material capabilities in a simulated turbine environment

- 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
- Internal specimen cooling allows for a tunable through-thickness temperature gradient
- Thermocouples, pyrometers and IR camera monitor material temperatures
- NASA / P&W / UTRC collaboration

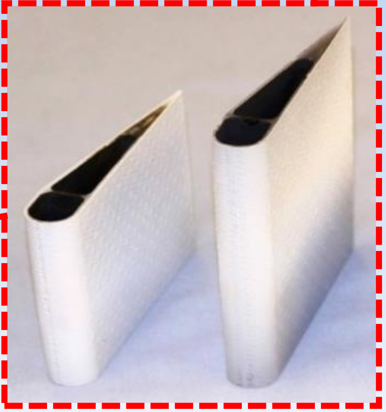
UTRC HPTC test rig







subelement mounting fixture



airfoil subelements

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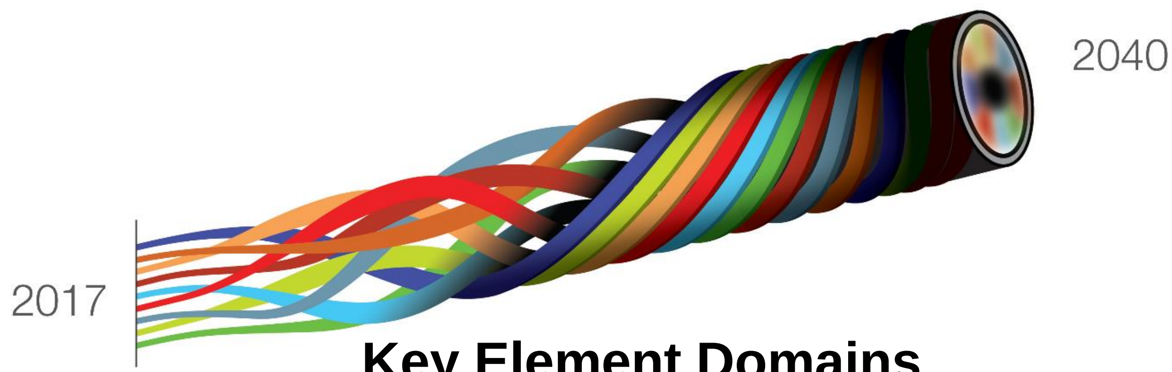
Summary

Vision 2040 for Integrated, Multiscale Materials and Structures Modeling/Simulation NRA



Key Element Domains

- **1.** Models and Methodologies
- **2.** Multiscale Measurement & Characterization Tools and Methods
- **3.** Optimization & Optimization Methodologies
- **4.** Decision Making and UQ
- **5.** Verification & Validation
- **6.** Data, Informatics, & Visualization
- **7.** Workflows & Collaboration Frameworks
- **8.** Education & Training
- **9.** Computational Infrastructure

2040 Vision State

*A cyber-physical-social ecosystem that impacts the supply chain to **accelerate** model-based concurrent design, development, and deployment of materials and systems throughout the product lifecycle for **affordable**, **producible** aerospace applications*

Needed to overcome various gaps and challenges to achieve the fully integrated 2040 Vision end state

Phase II: Pratt & Whitney (A United Technologies Company), NEXIGHT GROUP, esi get it right®, BlueQuartz Software

Phase I: BOEING, Rolls-Royce, UCSB University of California Santa Barbara, United Technologies Research Center

Modeling

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

Goal: Model behavior of GRC Hybrid 3D 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:

Need to:

- **Robust models of woven 3D composites extended to in-house MAC/GMC code**
- **Air, inert, steam, CMAS (calcium magnesium aluminosilicate) and creep / fatigue interaction with environment**
- **Predictive capability**

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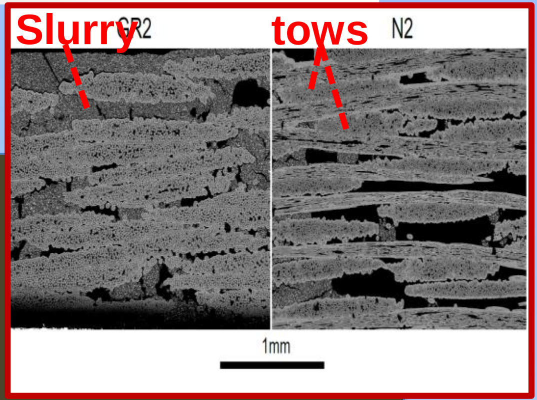
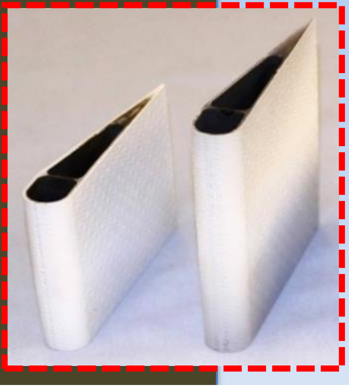
Partnerships and Collaborations



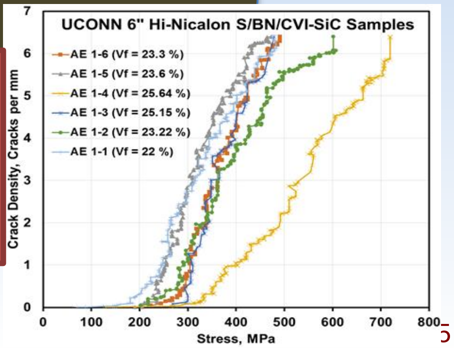
Industry Stakeholders:
- GE
- Rolls Royce
- Pratt & Whitney
- Oerlikon Metco
- Directed Vapor (DVTI)
- Southwest Research
- Boeing
- Blue Quartz

Academia:
- UConn
- U of MI
- Cal Tech
- U of California- Santa Barbara
- U of Virginia
- Purdue U
- Clemson U
- Pennsylvania State U
- Akron U



Government:
- AFRL
- Army
- NAVAIR
- DOE- ORNL
- FAA

Leveraging external collaborations to augment and complement in-house research



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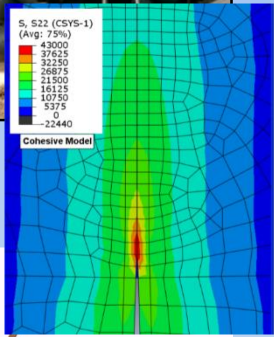
Summary

Next Steps

Develop & validate models to predict environmental effects on CMC / EBC durability

TTT

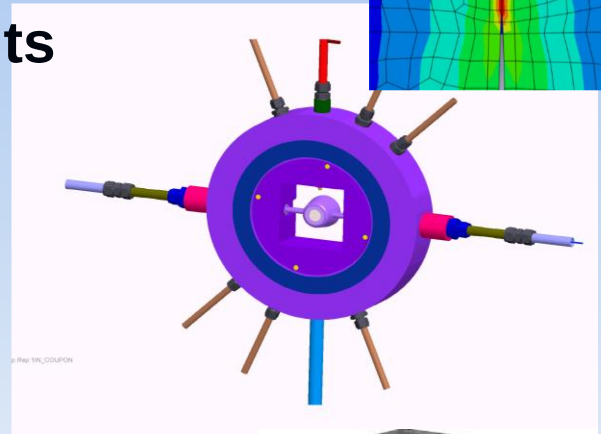
- Create/utilize life prediction models for predictive and prescriptive engineering (Vision 2040)
- thermal / mechanical cycling
- incorporation of steam
- sand/volcanic ash (CMAS) degradation



Address for durable CMC turbine components

AATT

- optimal cooling schemes for turbine blades & vanes
- blade / disk attachment design, analysis & testing
- development of in-house combustion test capabilities

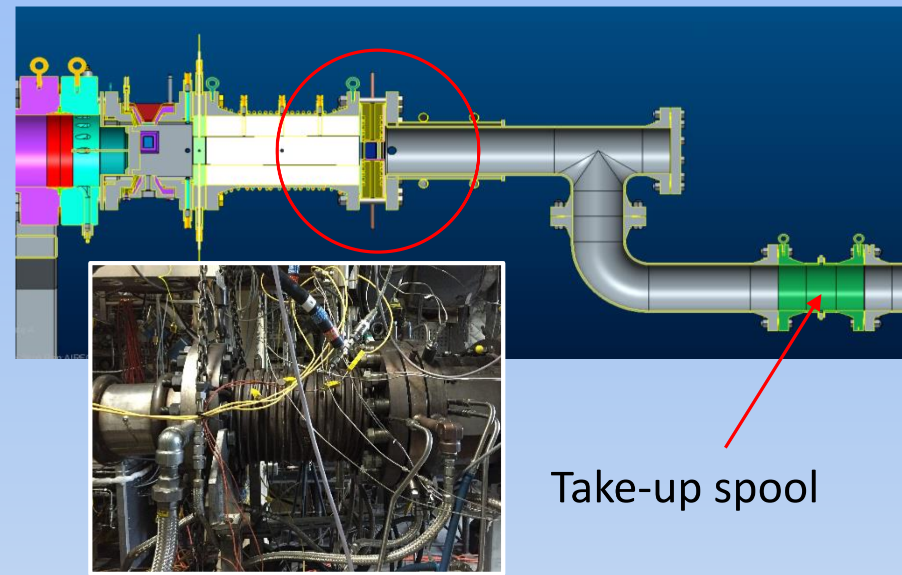


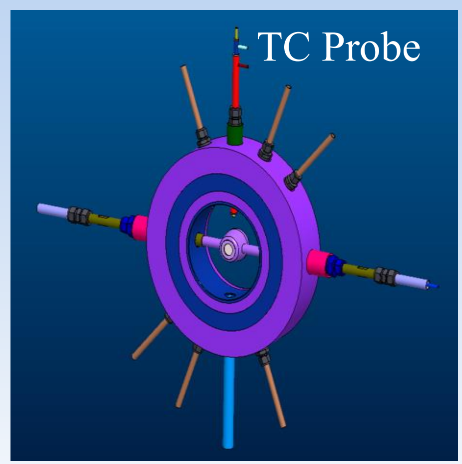
Accelerate engine implementation

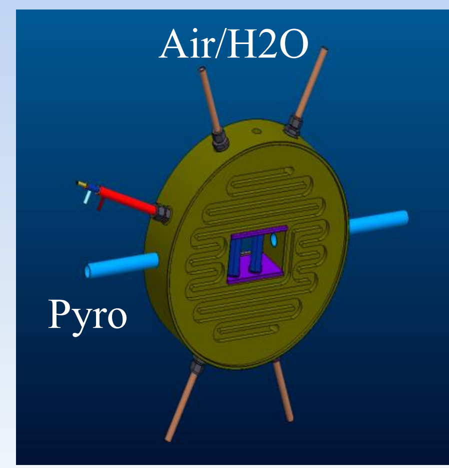
- demonstrate improved fabricability/feasibility of CMC additive manufacturing

CE-5 Test Development

- Coupon & Vane holder Designs
  - 1” cooled Button Sample Holder
    - Mech design & thermals complete
    - Fab underway
  - Vane pack near completion
    - Solving thermal issues with platforms
    - 2”x2” vanes accommodated
- Configuration Flexible
  - Either holder in downstream as piggy-back to injector testing
  - Coupon upstream + Vane downstream as stand alone customer.
  - Reaches 30 atm (vs 6-8 atm for HPBR)
- CE5 combustion rig test fixture design completed
  - Text fixtures for coupons and airfoil sub-components
  - Closest to engine environments among our test facilities
  - EBC-coated CMC durability with and without cooling holes to support TTT and AATT







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Summary

Publications Summary

		Journal articles	Conference presentation	NASA reports	Book chapters
FY14	Structures and Materials	14	47	8	**2**
FY15	Structures and Materials	15	69	9	2
FY16	Structures and Materials	26	46	17	2
FY17	Structures and Materials	13	84	10	4

FY16-17 Patents

High Temperature Materials

Issued Patents:

1. **NASA LEW-18769-1** Utility Patent, "Acoustic Liners for Turbine Engines" James Kiser, Joseph Grady
2. **NASA LEW-18769-2** Utility Patent, "Improved Acoustic Liners for Turbine Engines" James Kiser, Joseph Grady

Patent applications:

1. **NASA LEW-18949-2,** Utility Patent **,**"Advanced High Temperature and Fatigue Resistant Environmental Barrier Coating Bond Coat Systems for SiC/SiC Ceramic Matrix Composites", Zhu, Hurst
2. **NASA LEW-18964-2** Patent App, "Engineered Matrix Self-Healing Composites", Sai Raj
3. **NASA LEW 18970-2** Provisional Patent**, "**Method of Exfoliating BN", Ching-cheh ,Hung, Janet Hurst
4. **NASA LEW 18970-3** Provisional Patent**, "**Method of Exfoliating BN", Ching-cheh Hung, Janet Hurst
5. **NASA LEW-19435-1** Provisional Patent, Patent Application, "Advanced High Temperature Environment Barrier Coatings for SiC/SiC Ceramic Matrix Composites", Dongming Zhu
6. **NASA LEW-19435-2** Provisional Patent, Patent Application, "Advanced High Temperature Environment Barrier Coatings for SiC/SiC Ceramic Matrix Composites", Dongming Zhu
7. **NASA LEW 19456-1**, Provisional Patent " Ultra High Temperature Ceramic Coatings and Ceramic Matrix Composite Systems": Dongming Zhu and Janet Hurst
8. **NASA LEW-19283-1** Patent App "Ultra High Temperature Ceramic Coatings and Ceramic Matrix Composite Systems", Dongming Zhu, Janet Hurst
9. **NASA LEW 19691-1** Patent App**,**"Rapid Processing Method for Tailoring Properties of Silicon Carbide Tows", Maricela Lizcano, Janet Hurst

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Summary

Accomplishments & Challenges for Engine Applications of CMCs and EBCs

TTT Accomplishments (FY13-FY17)

- Determined effect of advanced SiC fiber on CMC durability
- Achieved the TTT goal of demonstrating 300 hour CMC life at 20ksi / 2700°F- yellow success criterion
- Measured prospective EBC material stability in turbine environments
- Established new processing methods for advanced EBC architectures
- Demonstrated 1000 hour durability of TTT CMC/EBC at 2700°F

Future challenges (FY18 and beyond)

- P&W engine rig testing
- Identifying operating limits (temperature/time/stress) of current CMC/EBC
- Physics-based models of environmental effects on CMC/EBC durability

Goal – Understanding/predicting role of engine environment (steam, CMAS) in CMC/EBC life