Development and High Pressure Burner Rig Demonstration of SiC/SiC Ceramic Matrix Composite Combustor Liners with Environmental Barrier Coatings

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  NASA Colleagues ...

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NASA Environmental Barrier Coating (EBC) - Ceramic Matrix Composite (CMC) Development Needs

- NASA Fundamental Aeronautics Program (FAP): Next generation high pressure turbine airfoil environmental barrier coatings with advanced CMCs
  - N+3 generation (2020-2025) with advanced 2700°F CMCs/2700-3000°F EBCs (uncooled/cooled)

- NASA Environmentally Responsible Aviation (ERA) Program: Advanced environmental barrier coatings for SiC/SiC CMC combustor and turbine vane components, technology demonstrations in engine tests
  - N+2 generation (2020-2025) with 2400°F CMCs/2700°F EBCs (cooled)

Outline

- SiC/SiC ceramic matrix composite combustor liner and environmental barrier coating system development
  - ERA SiC/SiC CMC component and EBC objectives
  - SiC/SiC CMC liner components – rig based approach developments
  - Evaluations of material properties
  - Environmental barrier coating developments – compositions, processing and process scaleup
    - Advanced processing using Sulzer Triplex Pro and Praxair DVM based approaches for 3000°F liner EBCs

- Other key combustor durability areas addressed
  - SiC/SiC recession and Computational Fluid Dynamics (CFD) modeling
  - Advanced bond coat developments

- Current testing and development status

- Summary and conclusions
Objectives

- Focus on key SiC/SiC ceramic matrix composite liner technologies, providing research and development to help bring the Technology Readiness Levels from 4 to 5

- Evaluate state of the art CMC material(s), helping better understand current component fabrication, property, and integration issues

- Develop advanced environmental barrier coating technologies for long-duration SiC/SiC CMC liner components, a key emphasis of the program

- Develop material and testing methodologies for long-term durability improvements and demonstrations
  - NASA High Pressure Burner Rig for CMC liner and EBC developments

EBC Development Objectives

OBJECTIVE

- Develop a 2700-3000°F thin (<15 mil) plasma-sprayed, low thermal conductivity EBC system with 2400°F capable SiC/SiC CMC system, demonstrating 1000 hr durability
- Develop robust multilayer coating systems including non-Si bond coats
- Establish EBC-coated CMC specimen and subelement property database incorporating cutting-edge component technologies
- Demonstrate coated CMC liner-EBC system durability in NASA high pressure burner rig

APPROACH

- Advanced combustor coating systems addressing component processing technologies
- Simulated engine thermal gradient biaxial strength, fatigue and rupture testing to improve CMC – EBC processing and design confidence
- High pressure burner rig environment testing of subelements and subcomponents
- An EBC-CMC system downselected for rig demonstration

EBC coated SiC/SiC CMC Inner and Outer Liner components
SiC/SiC Ceramic Matrix Composite Combustor Liners

- SiC/SiC ceramic matrix composite combustor liner components
  - Based on NASA high pressure burner rig configurations, fabricated at GE Aviation, using state of the art GE Gen II Prepreg SiC/SiC material
  - Inner and outer liners (~3.5" and 4" in diameter, and 17 inch in length), along with representative sub-elements with 0/90 and ±45/-45 fiber architecture, fabricated for evaluations
  - Complex shapes such as flanges, machining notches considered
  - SiC/SiC CMC panels also evaluated extensively for various mechanical properties

Some inner and outer liner articles

SiC/SiC Ceramic Matrix Composite Combustor Liners - continued

- SiC/SiC ceramic matrix composite combustor liner components
  - Dimension tolerance met testing requirements
  - Some CMC liner processing and fabrication defects/flaws observed due to relatively complex geometry and size
  - Computed tomography (CT) NDE performed on some test articles at NASA GRC
  - Infrared (IR) thermal imaging NDT performed on test articles at GE

NASA CT scans showing some defective regions of a 0/90 layup element
High Pressure Burner Rig SiC/SiC Liner Test Configurations

- High Pressure Burner Rig modified for realistic cooled liner subelement and liner component testing
  - Film-cooled durability and recession tests
  - CMC liner tests

- 3000F combustor gas temperature
- 16 atm pressure
- Heated cooling air
- Up to 300 m/s gas velocity used

**NASA Combustor EBC Development for ERA Program Demonstrations**

- Focus on high technology readiness level (TRL), high stability multicomponent HfO₂ or ZrO₂, HfO₂-RE₂O₃-SiO₂/RE₂Si₂O₇.₂ₓ environmental barrier/environmental barrier seal coat, with advanced HfO₂-Si first gen bond coat
  - More than thirty compositions were evaluated
  - Second gen 2700F bond coat being developed
  - Calcium Magnesium Alumino-Silicate (CMAS) resistance were addressed

- Developed and evaluated EB-PVD/plasma spray hybrid combustor coatings

- Developed Triplex Pro and DVM based combustor EBC processing with Sulzer and Praxair

- Processing optimizations for improved plasma sprayed coating powders composition controls and coating processing

- Developing 2000F capable oxidation/fretting wear resistant coatings (Ti-Si-Cr/Ta-CN systems and NiAl/NiAl+Cr/high toughness oxide/silicate systems)

- Optimized and developed commercialized HfO₂-Si based series bond coats
Thermal Gradient Tensile Creep Rupture Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

- Advanced environmental barrier coatings – prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at $T_{EBC} = 2700\,\text{°F}$, $T_{CMC} \approx 2500\,\text{°F}$
- EBCs showed promise in extending CMC rupture life
- The HfO$_2$-Si bond coat showed durability

![Graph showing creep rupture testing results for Gen II CMC with advanced EBC.](image)

Prepreg Gen II SiC/SiC CMC showed very limited degradation after short time exposure in the High pressure burner rig (HPBR)
Thermal Gradient Tensile Creep Rupture Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs - Continued

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![EBCs on Gen II CMC after 1000 hr fatigue testing](image1)

![Hybrid EBCs on Gen II CMC after 100 hr low cycle creep fatigue testing](image2)

High Temperature Strengths of Selected Coating Materials and Bond Coat Developments

- Commercial grade HfO$_2$-Si bond coats being developed, with initial designations of AE 10218 and AE 20129
- The initial versions high temperature bond coat tested for 100 hr in air at up to 1500C

![Scale up and down-selections of commercial source NASA HfO$_2$-Si EBC Bond Coating Powders](image3)

![AE 10219 bond coated CMC specimen on test rig after heat flux testing](image4)
Advanced EBC developments – Some Hybrid Systems and Qualification Tests

- EB-PVD HfO$_2$-RE$_2$O$_3$ (Silicate) top coat EBC with plasma-sprayed multi-component advanced silicate sublayer EBC/HfO$_2$-Si bond coat systems
- Determined thermal conductivity and stability of a new series of the hybrid EB-PVD/plasma sprayed environmental barrier coatings coated specimens
- Demonstrated high pressure environmental stability at 2600-2650°F, 160-200 psi (10-12 atm) in the high pressure burner rig

High pressure burner rig tested new ND series Hybrid EBC systems coated on 2" diameter Gen II Prepreg SiC/SiC CMCs
Sub-Element Strength Testing in Heat Flux Bend Test Rig

- CMC subelement specimens (~0.5x2.125" in size) mechanical properties evaluated at room temperature and high temperatures using laser heat flux bend test rig
- Some strength reductions observed for joints regions
- High temperature data are also being obtained

\[
\begin{align*}
\text{~4 inch (100 mm) diameter} \\
45\text{mm}/22.5\text{mm load spans} \\
\text{Curved specimens tested}
\end{align*}
\]

### Sub-Element Strength Testing in Heat Flux Bend Test Rig - Continued

- SiC/SiC CMC subelement specimens (~0.5x2.125" in size) properties evaluated at room temperature and high temperatures
- Some possible strength debit for joints
- High temperature data are also being obtained

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High Temperature Strengths of Selected Coating Materials and Bond Coat Developments

- Scaled-up component EBC systems using Triplex Pro plasma spray down-selected under laser heat flux cyclic testing at 2732°F (1500°C), in conjunction with thermomechanical testing.
- Down-selected system completed 100 hr water vapor steam testing 1500°C.
- Selected EBCs tested in the high pressure burner rig.
- Thermal conductivity of the combustor liner coatings met the ERA goals.

![Graph showing thermal conductivity of different EBC systems.]

Laser heat flux test under thermal gradients.

Recession of Gen II SiC/SiC CMCs Evaluated under NASA ERA Program in High Pressure Burner Rig

- Preliminary film cooled recession of Gen II SiC/SiC evaluated with four cooling-hole configurations.
- Comparisons being made with previous recession data for Prepreg SiC/SiC CMCs.
- CFD model validation and experimental 2-D recession measurements in progress.

![Graph showing recession rates of Gen II SiC/SiC CMCs.]

High temperature Gen II SiC/SiC recession kinetics for film-cooled and non-film cooled specimens.
The first Set Prepreg SiC-SiC CMC Combustor Liners Successfully Tested for 50 hr Durability in NASA High Pressure Burner Rig

- Tested pressures at 500 psi external for outliner, and 220 psi inner liners in the combustion chamber (16 atm)
- Average gas temperatures at 1650°C based on CEA calculations, the liner EBCs tested at 2500°F with heat fluxes 20-35 W/cm², and the CMC liner component at 1800-2100°F
- Hot gas streaks may have had temperatures over 2000°C, with high transfer coefficients
- SiC/SiC CMC liners and EBCs survived well
- Selected film-cooled designs will be used for future liner testing and more sophisticated instrumentation will be incorporated

Ideal Flame Temperature Calculation - Chemical Equilibrium Analysis Codes (CEA-II)

Average test gas temperature 1650°C, heat transfer coefficient 0.05-0.10 W/cm²-K

Some minor coating spalling at hot streak impingement
Summary

- Advanced combustor CMC components developed using GE Prepreg Gen II SiC/SiC CMCs under the NASA programs, in collaboration with GE Aviation.
- Advanced EBCs also developed, evaluated and for 2700-3000F CMC combustor liner applications.
- Simulated engine tests established for CMC liner evaluation and demonstrations.
- The EBC – SiC/SiC liner component demonstrated initial durability in very harsh test conditions, reaching a TRL of 5 under the ERA program.
- Vital EBC and CMC property data also established under the NASA programs.

Conclusions and Future Work

- SiC/SiC CMC liners had some fabrication issues, however, lesson learnt, and final delivery components considered excellent.
- The relatively conservable designed GE Prepreg Gen II performed well in harsh burner rig test conditions.
- EBC and CMC component developments met NASA ERA performance goals, completed 50 hr durability tests, demonstrating TRL 5 for the components.
- Further EBC coated CMC liner sets with state of the art processing will continue to be tested for long term durability.
- Second Gen 2700F EBCs and wear resistant coatings will also be incorporated.