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

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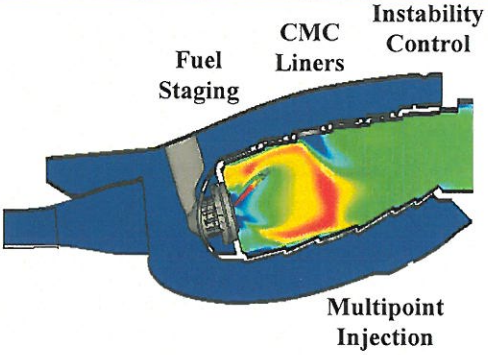
NASA Colleagues …

Joe Halada and Jeff Boy of GE Ceramic Composite Products and GE Aviation, Newark, Delaware, in fabricating the Generation II liner components and sub-elements under the NASA ERA program.

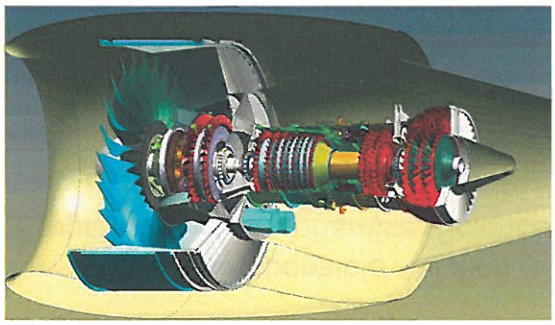
NASA Environmental Barrier Coating (EBC) - Ceramic Matrix Composite (CMC) Development Needs

- **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)



Low emission combustor



High Pressure Turbine CMC vane and blade

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 3000F 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

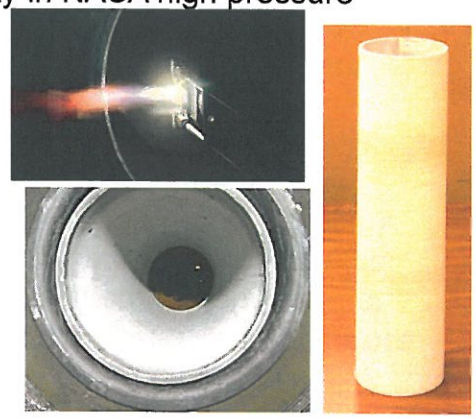
EBC Development Objectives

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**

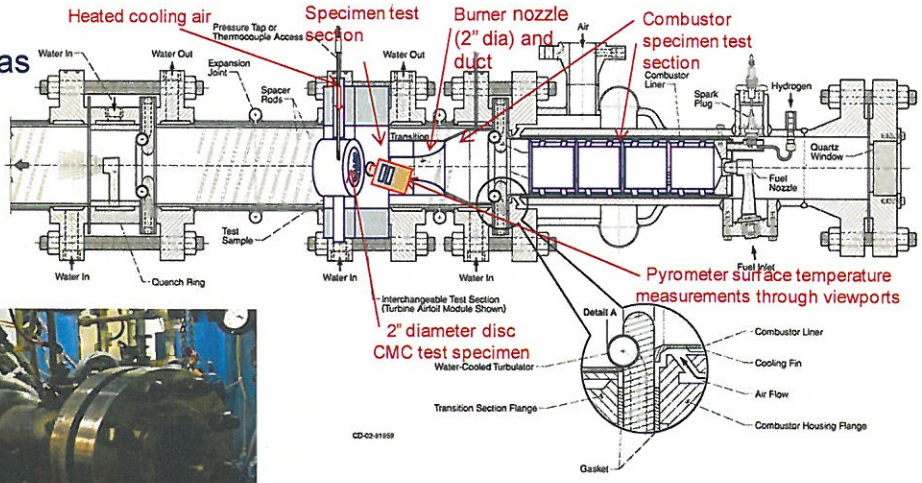
- Dimension tolerance met testing requirements
- Some CMC liner processing and fabrication defects/flaws observed due to relatively complex geometry and size
- Computed tomography (CT) NDE performed on some test articles at NASA GRC
- Infrared (IR) thermal imaging NDT performed on test articles at GE

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

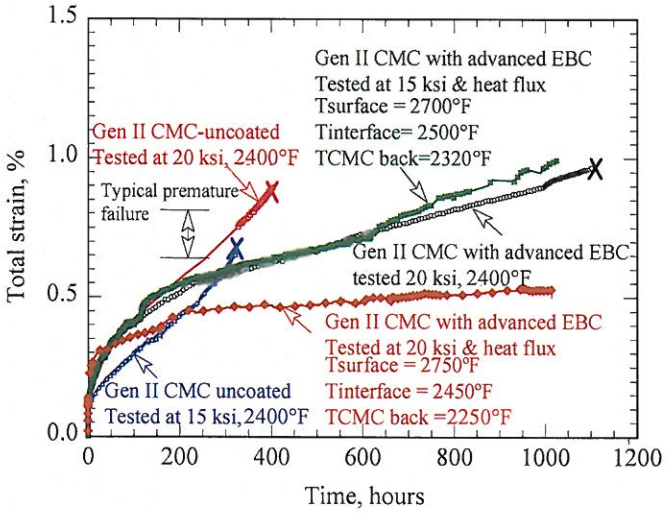


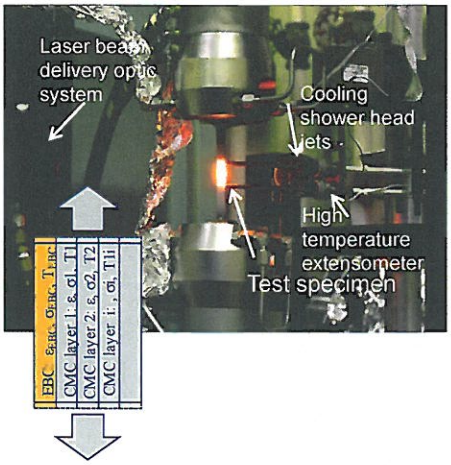
NASA Combustor EBC Development for ERA Program Demonstrations

- Focus on high technology readiness level (TRL), high stability multicomponent HfO_2 or ZrO_2, HfO_2-RE_2O_3-SiO_2/$RE_2Si_{2-x}O_{7-2x}$ / environmental barrier/environmental barrier seal coat, with advanced HfO_2-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 HfO_2-Si based series bond coats

Thermal Gradient Tensile Creep Rupture Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

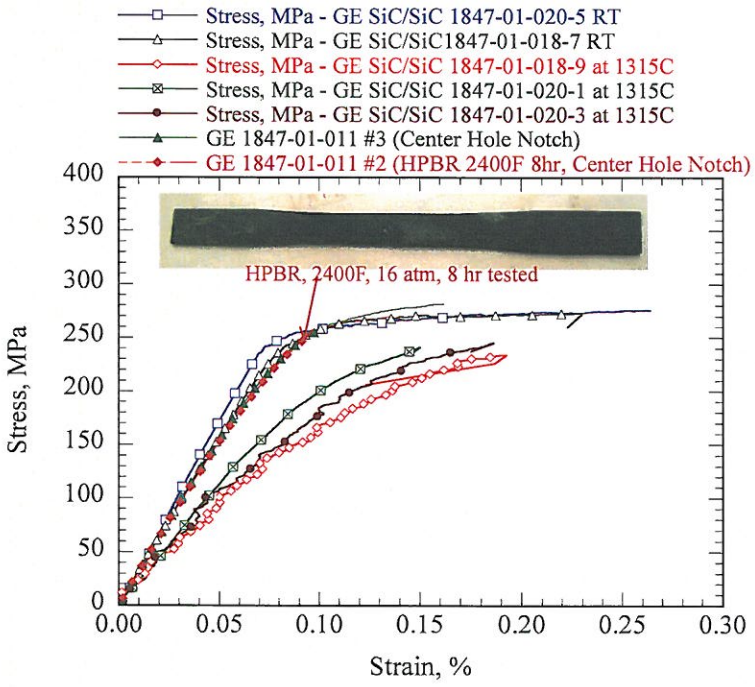
- Advanced environmental barrier coatings – prepreg CMC systems demonstrated long-term EBC-CMC system creep rupture capability at stress level up to 20 ksi at T_{EBC} 2700F, $T_{CMC\ interface}$ ~2500F
- EBCs showed promise in extending CMC rupture life
- The HfO_2-Si bond coat showed durability





Thermal Gradient Tensile Creep Rupture Testing of Advanced Turbine Environmental Barrier Coating SiC/SiC CMCs

- 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

- 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} 2700F, $T_{CMC\ interface}$ ~2500F
- EBCs showed promise in extended CMC rupture life
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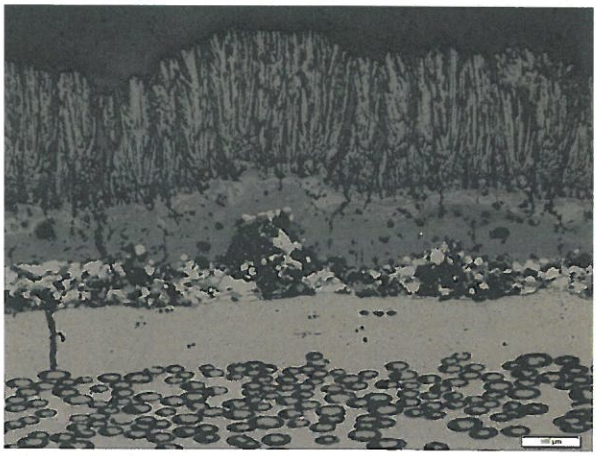
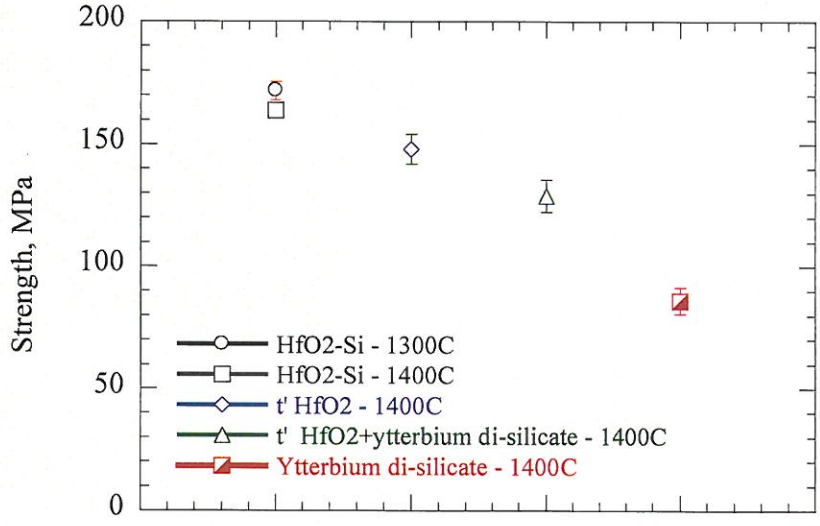
EBCs on Gen II CMC after 1000 hr fatigue testing



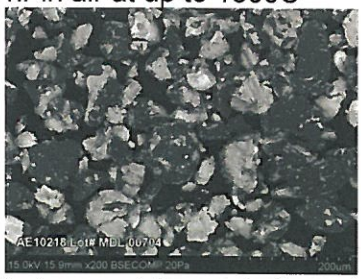
Hybrid EBCs on Gen II CMC after 100 hr low cycle creep fatigue testing

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



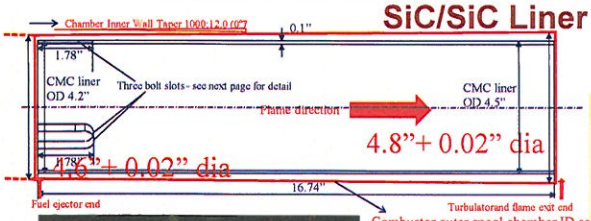
Selected coating materials

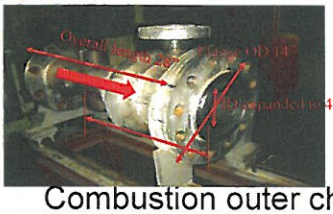


Scale up and down-selections of commercial source NASA HfO_2-Si EBC Bond Coating Powders

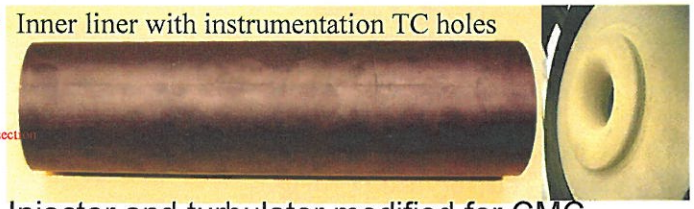
AE 10219 bond coated CMC specimen on test rig after heat flux testing

High Pressure Burner Rig SiC/SiC Liner Test Configurations – SiC/SiC Liner Test Articles Setup





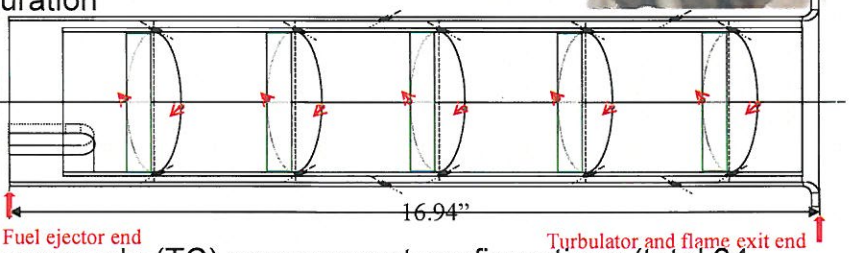
Inner liner with instrumentation TC holes



Injector and turbulator modified for CMC liner integration and testing

TC bundle picture

Combustion outer chamber modified to accommodate increased dimension and tapered configuration

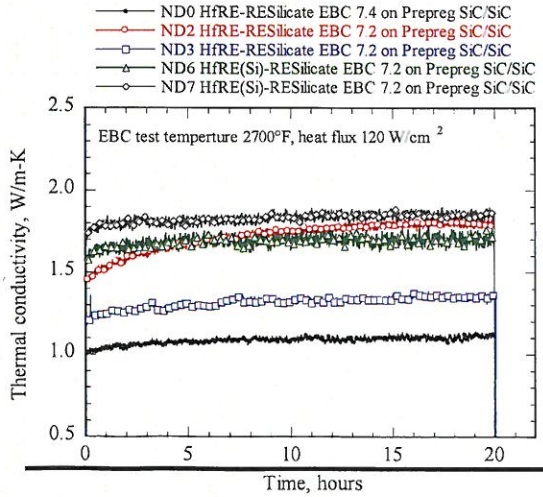


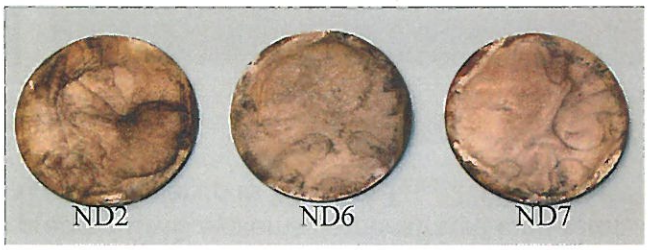
First set SiC/SiC liner Thermocouple (TC) arrangement configurations (total 24 TCs, 1/16" size), film cooled liner planned for second and third set testing

Advanced EBC developments – Some Hybrid Systems and Qualification Tests

- EB-PVD HfO_2-RE_2O_2 (Silicate) top coat EBC with plasma-spayed 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

2" diameter ND3 EBC/SiC/SiC specimen after testing in the high pressure burner rig





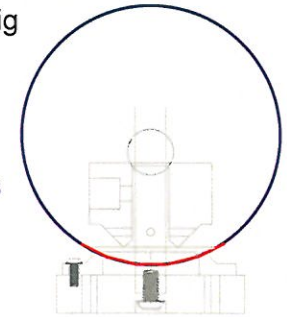
High pressure burner rig tested new ND series Hybrid EBC systems coated on 2" diameter Gen II Prepreg SiC/SiC CMCs

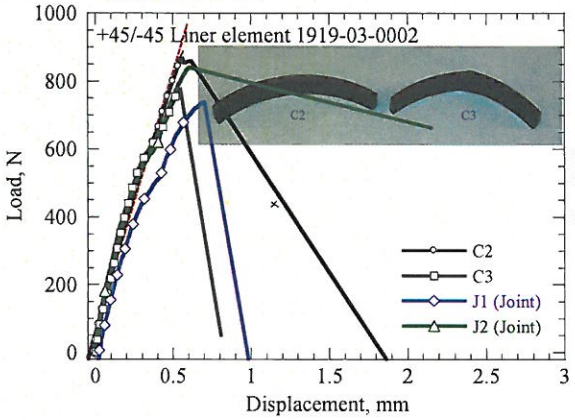
Sub-Element Strength Testing in Heat Flux Bend Test Rig

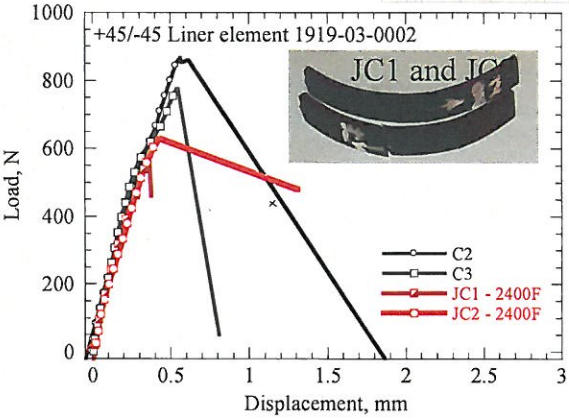
- CMC subelement specimens (~0.5x2.125" in size) mechanical properties evaluated at room temperature and high temperatures using laser heat flux bend test rig
- Some strength reductions observed for joints regions
- High temperature data are also being obtained

~ 4 inch (100 mm) diameter

45mm/22.5mm load spans
Curved specimens tested



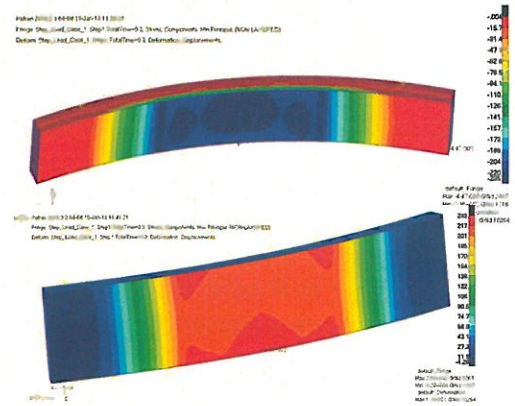


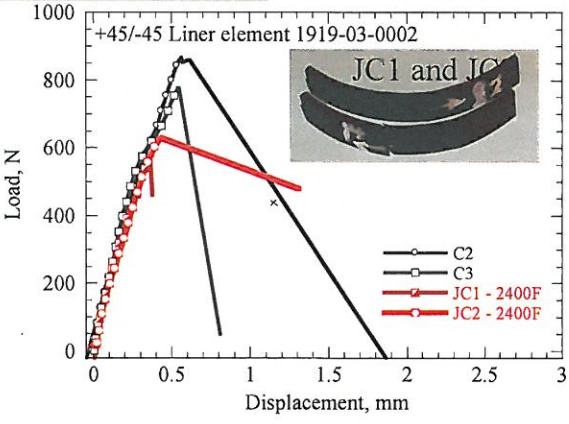


Sub-Element Strength Testing in Heat Flux Bend Test Rig - Continued

- 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

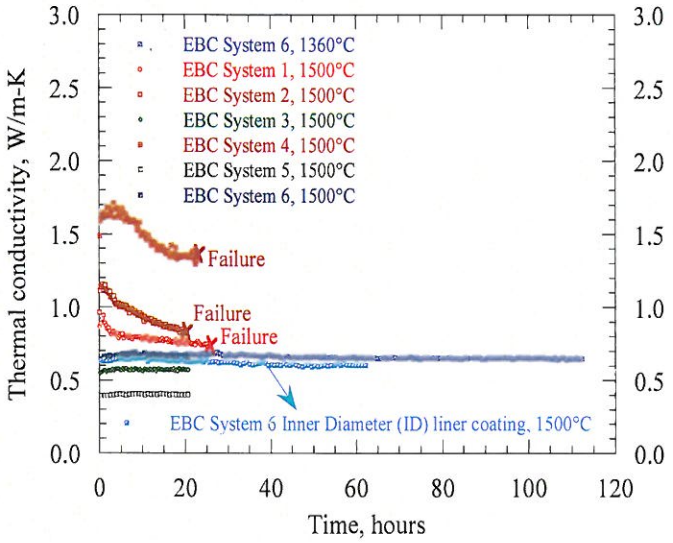
Specimen ID	Failure Load, N	Failure Stress, MPa
C2	867.18	638.97
C3	778.78	573.84
J1	739.69	545.03
J2	840.62	619.40
JC1-2400F	628.12	462.82
JC2-2400F	548.75	404.34

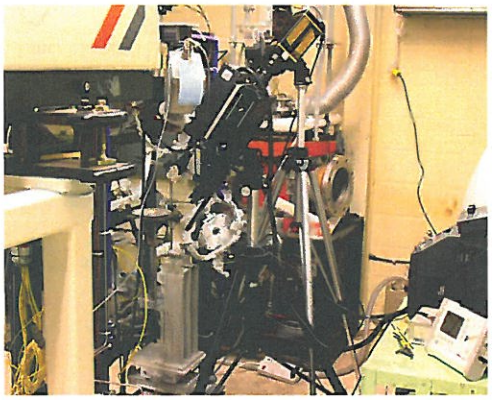




High Temperature Strengths of Selected Coating Materials and Bond Coat Developments

- 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 1500C
- Selected EBCs tested in the high pressure burner rig
- Thermal conductivity of the combustor liner coatings met the ERA goals

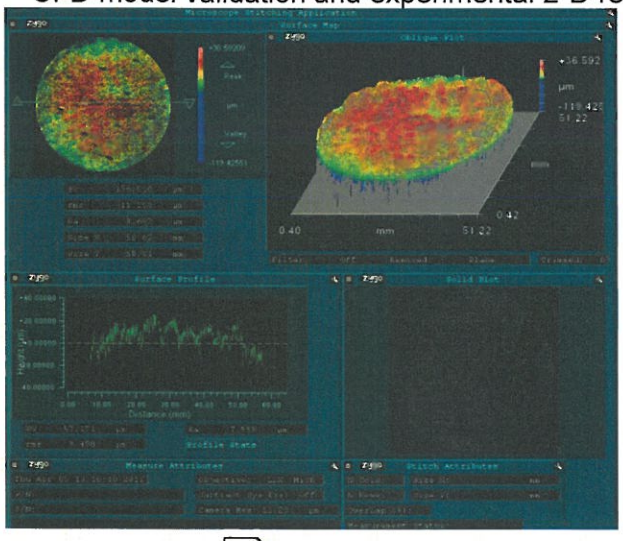




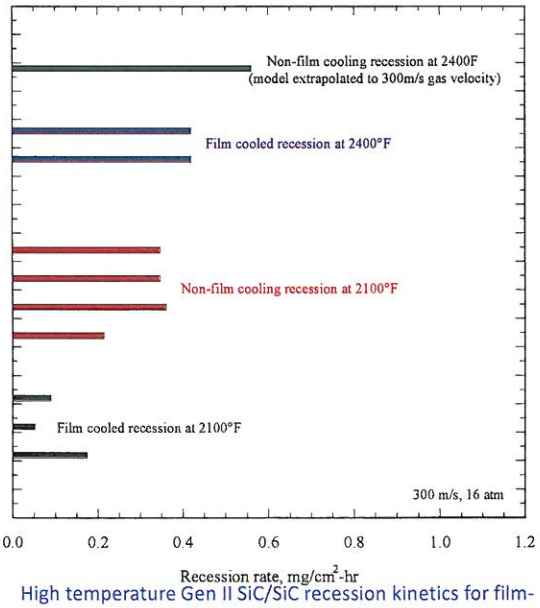
Laser heat flux test under thermal gradients

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

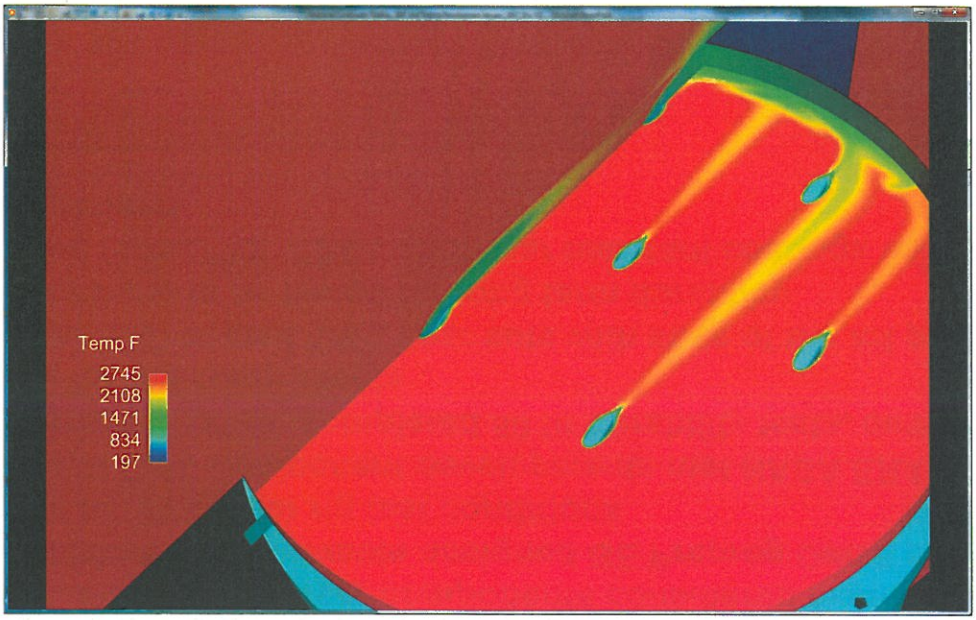


7-hole-RG_KE_801-Temp_F.avi



High temperature Gen II SiC/SiC recession kinetics for film-cooled and non-film cooled specimens

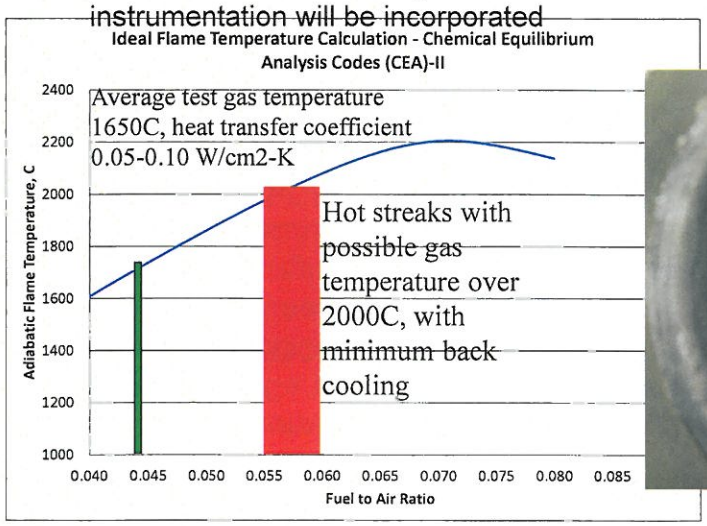
CFD modeling

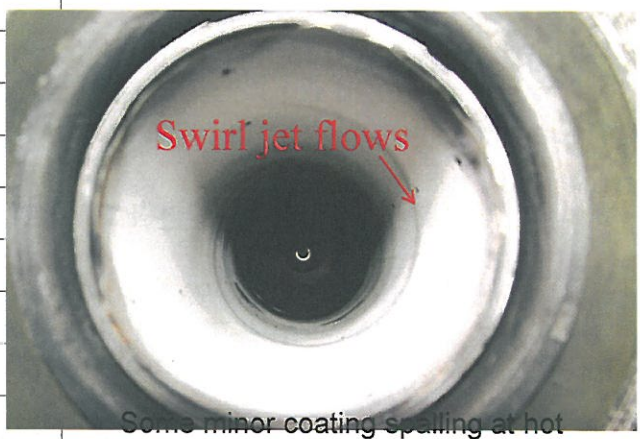


7-hole-RG_KE_801-Temp_F.avi

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 1650C based on CEA calculations, the liner EBCs tested at 2500F with heat fluxes 20-35 W/cm^2, and the CMC liner component at 1800-2100F
- Hot gas streaks may have had temperatures over 2000C, 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





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